Advances in Military Geosciences

Eric V. McDonald
Thomas Bullard
Editors

Military Geosciences and Desert Warfare

Past Lessons and Modern Challenges

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Preface: Military Geosciences: Past Lessons and Modern Challenges

Military activities—past, present, and in the future—will always be strongly integrated with a wide spectrum of geosciences. From providing the stone resources for primitive weapons to utilization of terrain in offensive and defensive strategies, warfare has had an intimate relationship with geology and terrain. The decisive outcomes of numerous battles on land throughout history have been dictated in large part by the terrain and environmental setting. Modern military operations rely on a wide range of land-, air-, sea-, and space-borne intelligence and knowledge of dynamic terrain processes and conditions. The modern study of geological-based environmental sciences is critical for both the sustainable management of military reservations and installations as well as evaluation of how the terrain and environmental conditions may impact military equipment and operations.

The study of the role of geology and geography in military affairs is not a recent phenomenon. The organized interest in meeting biennially to present and discuss things geologic and military, which since 2009 is known as the International Conference on Military Geosciences (ICMG), is, however, relatively new. The meaning of the term 'geosciences' by ICMG has evolved to include nearly all traditional research aspects of the fields of geology and geography as well as overlapping fields of hydrology, archeology, and history. During the general course of ICMG's existence, from a GSA symposium held during the 1994 Geological Society of America Annual meeting in Seattle through a 5-day conference held in Las Vegas in 2011, there have been generally two topical themes. The first theme has been studies focused on how geologic and geographic settings have influenced both past military history, especially battles and campaigns of historical significance, and modern warfare and conflict in the twenty-first century. The second theme includes studies with an emphasis on the influence of geosciences, in particular surficial processes and landscape history, on environmental issues related to management and sustainability of military installations, environmental health and safety of military personnel, effective management of cultural resources, and environmental security (e.g., water resources, climate change). The second theme area also has seen an increasing use of remote sensing, digital elevation modeling, and numerical modeling in regards to military activities. The growing modern emphasis on environmental, natural, and cultural resources reflects changing global views and attitudes toward the environment, which are not limited just to the battlefield, but also extend to peace-keeping operations, counter insurgency, and disaster recovery. Presentations related to environmental and cultural resources in recent years have shown geologic and terrain relevance to in-theater operations as well as environmental sustainability at installations with active training and testing programs.

This volume is the most recent contribution from a series of published conference proceedings that have evolved over the years since the first military geoscience meeting was convened in Seattle in 1994. Five previous volumes are based on papers presented at previous themed ICMG conferences, held under various conference names and sponsorships. Volumes represent military geoscience papers presented as part of symposium and conferences convened in Seattle (Underwood and Guth 1998), London (Rose and Nathanail 2000), Greenwich (Doyle and Bennett 2002), the U.S. Military Academy, West Point (Caldwell et al. 2005), Nottingham (Nathanail et al. 2008), and Vienna (Häusler and Mang 2011). Three other notable volumes that complement the ICMG series, Ehlen and Harmon (2001), Rose and Mather (2012), and Harmon et al. (2014), each contain a range papers on military geosciences presented at several other military geoscience-themed workshops, symposium, and conferences held in the United States and the United Kingdom.

This book contains twenty-two papers, the majority of which were presented at the 9th International Conference on Military Geosciences (ICMG) held in Las Vegas, Nevada (USA) from June 20 to June 24, 2011. The conference provided a venue for military personnel, academics, and practitioners from government service and commercial enterprises to explore a wide range of military geosciences. The overarching theme of the 2011 meeting in Las Vegas was the role of deserts in past and modern warfare, issues with management of military lands in desert regions, and how desert environmental conditions can impact military equipment and personnel. The program of oral and poster presentations contained a wide array of topics on how the desert landscape has impacted military history as well as providing unique challenges to the sustainability of military lands. Many of the papers presented in this book have a focus on desert terrain. All papers present examples of the role of geoscience to add clarity about how the basic nature of landscapes and geomorphic processes have influence the outcomes of past battles to the modern challenges of integrating geoscience into a wide range of military activities. Many of the modern challenges extend well beyond the battlefield and commonly include developing strategies to increase environmental sustainability of military installations to numerical modeling of complex terrestrial processes.

This book is divided into three parts each reflecting a different theme of military geosciences. Part I: *Geoscience and Military History Military Geosciences: Past Lessons and Modern Challenges* (Chaps. 1–7) presents a series of papers that combine geoscience with a wide range of military history and terrain attributes. Papers include military campaigns or activities that occurred in the desert or dryland settings of Gallipoli (Turkey), Arizona, California, and eastern Washington state (U.S.) and Tunisia, and more humid settings in the U.S at Gettysburg (Pennsylvania) and coastal North Carolina. These papers integrate a combination of terrain analysis, Geographical Information System (GIS) methods, and digital photography to examine linkages between landscape history, geology, and military history. Part II: *Military and Defense Interests and the Environment* (Chaps. 8–16) contains nine papers that examine the linkage between military and defense interests and related environmental impacts and resource needs. Several papers in this section include environmental impacts from military activities related to uranium in the environment, growth and sustainability of military infrastructure, and environmental awareness by military personnel. Papers in this section also examine a range of environmental security issues including trans-border water issues, geographic controls on forward operating bases, distribution of dust-rich soils, and agricultural development teams in southwest Asia in support of recent military activities. Part III: *Geoscience Technology in Support of Military Activities* (Chaps. 17–22) presents papers that examine the development and application of recent geoscience technology in support of modern military activities. Papers include the use of remote sensing information, including digital elevation models, Aster imagery, and multispectral imagery, for the characterization of terrain in support of military operations. Papers in this section also include military aspects of direct measurement of soil surface properties including use of ground-based lidar for detection of IED command wires, training future Army officers on collecting ground mobility data, and examples of how agricultural soils impact tank mobility.

In addition to the participants, many people contributed to the development of this volume. First we would like to thank the nearly forty scientists and military professionals who reviewed the chapters in this volume (each paper underwent peer-review by two anonymous reviewers); including several reviewers who handled multiple papers. Nearly all of the reviewers have participated in past military geoscience conferences and their knowledge of military history and science promoted and encouraged a high level of academic quality of the papers. We also thank Ron Doering (Springer Science) whose encouraging patience persisted throughout the time required to complete this volume. Finally we want to acknowledge and sincerely thank Marie Dennis (DRI/UNR) who assisted with tracking manuscripts and reviews and Sophie Baker (DRI) who was responsible for the seemingly, never ending task of working all papers, figures, and tables into the proper format in order to bring this volume to a successful conclusion, we are forever grateful.

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Part I
Geoscience and Military History

An Unfortunate Accident of Geography: Badlands and the ANZAC Sector, Gallipoli, April–December 1915

Peter Doyle

Abstract Gallipoli continues to be a cause célèbre for those seeking to assign blame for this ill-fated military campaign fought against the Ottoman Empire from April to December 1915. Variously blamed are weak generals, poor planning and preparation—and even inadequate topographical mapping. Intended to assist the Allied naval fleet in breaking through the Dardanelles Straits, thereby threatening the Ottoman Capital of Constantinople (and, it was hoped, forcing the Ottomans out of the war), the military campaign was certainly hastily conceived and under-resourced. Commencing on 25 April 1915 as an amphibious landing, the campaign soon degenerated into a desperate struggle, as the Allies attempted in vain to break out of tightly constrained beachheads. This study investigates the role of terrain in the warfare of the ANZAC (Australian and New Zealand Army Corps) Sector, from initial landings in April, to attempted breakout in August. At ANZAC, an 'unfortunate accident of geography' brought, dry, mostly fine-grained Pliocene sediments to the coast. An upland area created by the North Anatolian Fault System, the fine sediments were (and are) quickly weathered and eroded to form topographically complex gullied surfaces. This would be the almost hopeless battleground of the Australians and New Zealanders in April–December 1915. With the Ottomans holding a firm grip on the ridge top, the ANZAC troops were constrained to a small, deeply dissected and mostly waterless sector of the scarp slope of the Sari Bair Plateau and ridge system. The war here would be hard fought and bloody, with geology having a major impact on its outcome; the withdrawal of ANZAC troops in December 1915.

Keywords Dardanelles · Gallipoli · Amphibious landings · Badland topography · Ottomans · ANZAC · Water supply · Trenches · Tunneling

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1 Introduction

The Dardanelles, a narrow passageway between European and Asian Turkey, is a tightly-constrained waterway that was created by movement along the still seismically-active North Anatolian Fault system. This strategic waterway connects the Aegean Sea and Mediterranean with the Sea of Marmara and ultimately, through the Bosphorous, to the Black Sea, and has been a point of military interest for centuries. In European Turkey, the shores of the Dardanelles are guarded by the Gallipoli Peninsula, a narrow finger of land named after its principal settlement (Gelibolu, or Gallipoli). Opposing this is the Asiatic shore, the Aegean expression of the great Anatolian Peninsula, the greater part of modern Turkey, and the heart of the ailing Ottoman Empire in 1915.

Constantinople, (now the modern city of Istanbul), sits astride the Bosphorous and guards the entrance to the Black Sea, thereby controlling entry to the winter ports of Russia. The city had been coveted for centuries, particularly by the old enemies of Greece and Russia. With the Ottoman Empire finally committed to the Central Powers late in 1914, the sights of the Allies turned once again to the Dardanelles and Constantinople, with the hope that the Ottomans could be persuaded by a show of arms to retreat from their alliance, and sue for peace—thereby allowing Russia to be supplied from the south through the Dardanelles and Bosphorous, and on to the Black Sea. That show of arms was to be by an Anglo-French naval demonstration, with out-dated ships pitted against the fortresses of the Dardanelles, the intention being for these naval vessels to press on regardless, and appear off the Golden Horn in Constantinople—thereby, it was hoped, forcing the hand of the Ottomans (Aspinall-Oglander 1929). Long-fortified, the idea of squeezing a fleet of ships between the beetling brows of the shores of the Dardanelles had exercised the mind of the military of many nations for centuries, particularly so in the complex diplomacies of two centuries before the Great War.

Arguably doomed to failure from its inception, the Naval Campaign began on 19 February and was abandoned just under a month later, on 18 March 1915, partly a result of the severe loss of men and capital ships to minefields. The next phase was the invasion of the Peninsula, with the sole purpose of removing enemy minefields and shore batteries, thereby allowing the ships once again to pass through the straits. It was not intended, however, that ground forces would press on to capture Constantinople; that would still be left to the Navy (Aspinall-Oglander 1929; Rhodes James 1965; Travers 2001; Carlyon 2003; Prior 2009; Doyle 2011). Thus, on 25 April 1915, landings were made on several of the beaches at Gallipoli in two main sectors: Cape Helles at the tip of the Peninsula, scene of the landings of the British 29th Division, (most recently discussed by Doyle 2008), and farther up the coast, in the 'badland' topography of what became known as the ANZAC sector (Fig. 1), named after the Australian and New Zealand Army Corps that landed there.

For all the attention focused upon the ANZAC Sector (e.g., see Rhodes James 1965; Travers 2001; Carlyon 2003; Prior 2009; Crawley 2014 and books therein), there have been few detailed studies of the military geography of this important

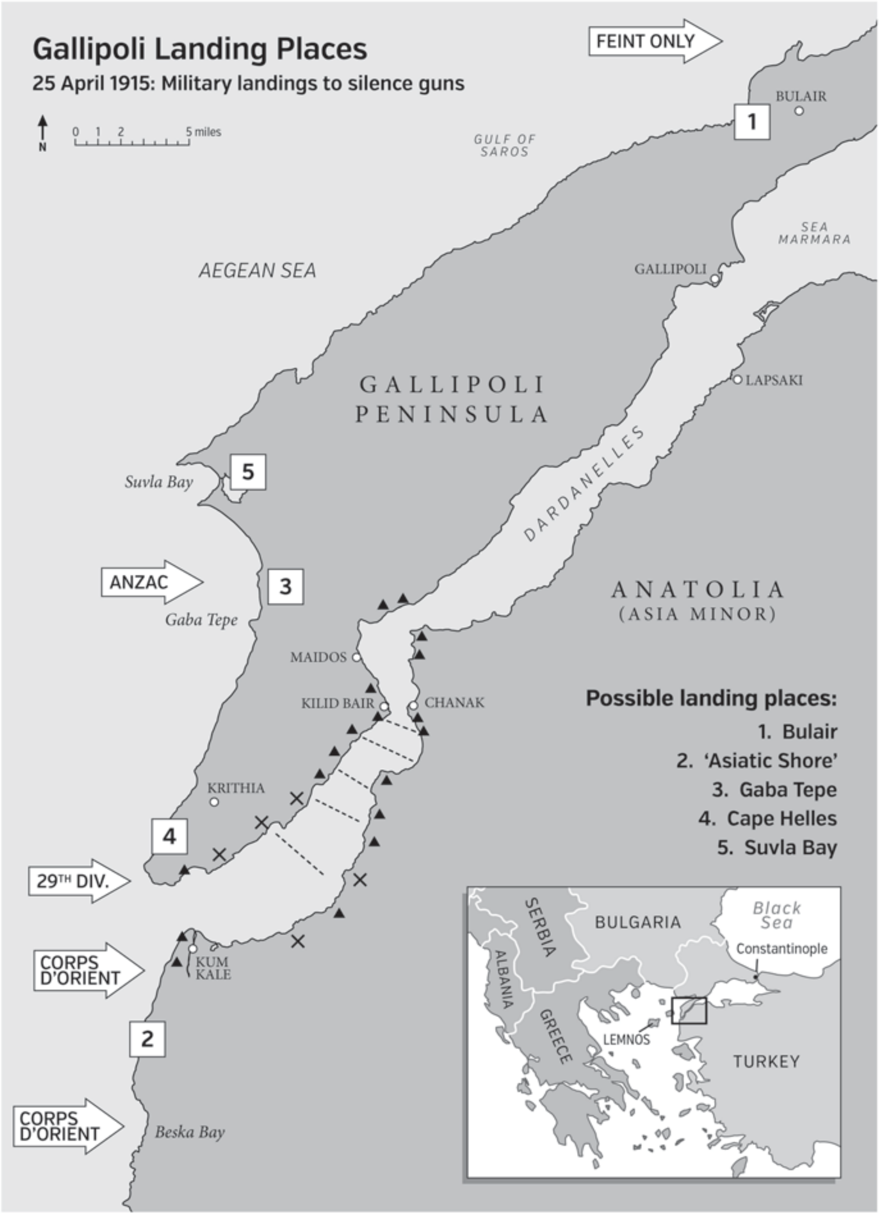

Fig. 1 The potential landing sites at Gallipoli; the landings were planned to 'silence the guns' and permit the removal of the Ottoman minefields, so hazardous to the passage of the Allied ships. Landings made on 25 April are indicated by the *main arrows*. (Based on illustration in Doyle and Bennett (1999))

part of the Gallipoli battlefield. Some aspects of its military geology have been discussed by Doyle and Bennett (1999, 2002), and the topographical intelligence gathered for the landings has been described by Chasseaud and Doyle (2004). This paper examines the role of terrain in the warfare of the ANZAC Sector, from initial landings in April, to the development of trench warfare. At ANZAC, what might be termed an 'unfortunate accident of geography' brought, dry, mostly fine-grained Pliocene sediments to the coast, the only location upon the Peninsula where this is the case. An upland area due to the North Anatolian Fault System, the fine sediments were (and are) quickly weathered and eroded to form topographically complex gullied surfaces. This created an almost hopeless battleground for Australians and New Zealanders during the latter part of 1915. With the Ottomans holding a firm grip on the ridge top, ANZAC troops were constrained to a small, deeply dissected and mostly waterless sector of the scarp slope of the Sari Bair Plateau and ridge system. The war here would be hard fought and bloody, with the local geology having a major impact on its outcome.

2 Campaign Summary

The land-based Gallipoli campaign was planned originally for 23 April 1915, following the failure of the naval engagement, and concerns over the continued loss of ships and naval personnel. Troops intended for the landings were drawn from Britain (29th and Royal Naval divisions), Australia, New Zealand (Australian and Zealand Army Corps: ANZAC), and France (Corps Expéditionnaire d'Orient), gathered together on the Greek islands of Lemnos and Imbros under the overall command of General Sir Ian Hamilton.

It was understood by both sides that there were a limited number of locations, a factor that is typical of all amphibious operations (Palka and Galgano 2005), determined largely by the disposition of major terrain elements, where a landing could be successfully executed: (1) in the northern part of the Peninsula near Bulair, the narrowest part of the isthmus connecting Gallipoli with the rest of Thrace; (2) on the Aegean coast of Anatolia—known in contemporary accounts as the Asiatic shore—notably at Kum Kale at the entrance to the Dardanelles; (3) on either side of the promontory known as Gaba Tepe, in a depression separating the two main massifs of the southern peninsula; (4) at the narrow beaches of Cape Helles, threatening the southern slopes of the Kilid Bahr Plateau; and (5) at Suvla Bay (Fig. 1; Nevinson 1920; Aspinall-Oglander 1929; Callwell 1924; Rhodes James 1965; Travers 2001; Chasseaud and Doyle 2004; Prior 2009).

As described by Doyle and Bennett (1999, 2002) (and the commander himself, Hamilton 1920) the Allied commander rejected both Bulair and the Asiatic shore as main landing sites, due to the strength of the enemy positions there and the increased proximity of Ottoman troops. Instead, a concentration of effort was to be made in the southwestern part of the peninsula, the intention being the capture the Kilid Bahr Plateau, which overlooked the main fort of the same name, and the narrows of the Dardanelles. This, it was hoped, would achieve the main objectives of the landing, the support of naval operations. Suvla Bay was ruled out as it was too far away from the Kilid Bahr Plateau to be of value, and because there was little reliable information about its terrain characteristics. The main landings were therefore to be made at the southern end of the Peninsula at Cape Helles, and on the west coast at Gaba Tepe, in what would become known as the ANZAC Sector (Fig. 1).

The German commander of the Ottoman troops, General Liman von Sanders, considered the most likely landing places to be Bulair and the Anatolian Coast; the former because of its strategic position in controlling the neck of the peninsula, the latter because of the possibility provided by its relatively wide beaches. It was for this reason that he created heavily fortified positions in these areas. Von Sanders also realised the threat from attacks at Gaba Tepe and Cape Helles; the former because of the low ground crossing the peninsula between the Sari Bair and Kilid Bahr plateaux, threatening Maidos, the latter because of the long slope up from the beaches to the peak of Achi Baba which could easily be threatened by naval gunfire. Not surprisingly, all of these areas were protected by extensive trenches and barbed wire entanglements in the month preceding the Allied landings in 1915 (Aspinall-Oglander 1929; Rhodes James 1965; Doyle and Bennett 1999, 2002; Travers 2001; Chasseaud and Doyle 2004; Prior 2009; Doyle 2011).

The Cape Helles landings were made by the men of the British 29th Division at five beaches, code lettered S, V, W, X, Y. The landings at S, X and Y were virtually unopposed, but due to poor communications, the tactical advantages of the situation were not exploited. The landings at V and W met fierce opposition from the Turks in their well-prepared positions (Aspinall-Oglander 1929; Rhodes James 1965; Doyle 2008). The landings north of Gaba Tepe at Z beach were to be made by the men of the ANZAC Corps. They were to be beached from towed open boats commanded by junior naval officers who had orders to stay in set positions as they approached the shore. Constant readjustment to retain these positions, and a gradual northwards drift, meant that the troops landed at the northern extremity of the beaches, a feature that has received much comment and discussion (e.g. see Aspinall-Oglander 1929; Rhodes James 1965; Carlyon 2003; Doyle 2011). In fact, the landing zone was not as tightly constrained as has been previously discussed (see Prior 2009 for discussion), and the landings were actually spread out along the beach, in front of what would become known as Plugge's Plateau, and close to the small cove, now known as Anzac Cove.

After 25 April 1915, the 'Battle of the Beaches', static trench positions similar to those of the Western Front developed. In the ANZAC Sector, the Allied objectives were the summit of the Sari Bair ridge, though some troops did manage to reach the subsidiary peak of Chunuk Bair in the opening days of the campaign. Very quickly the ANZAC troops became committed to static trench warfare, although some actions, such as the battles for the Lone Pine and the Nek in August of the same year, gained legendary status in Australia and New Zealand. However, throughout the campaign the troops at ANZAC were in a very difficult position, cramped by the narrowness of the beach and hemmed in by the precipitous slopes.

Following the failure of the summer offensives (Crawley 2014), and the replacement of General Sir Ian Hamilton as Allied Commander, it realised by his replacement, Sir Charles Munro, that it would be impossible to sustain the campaign, break the stalemate, and achieve the strategic objectives without a significant diversion of men and resources away from the Western Front. For these reasons, first a partial, and then a complete, withdrawal were planned. These took place, with complete success and few casualties, in December 1915 and January 1916.

3 Geological Setting of the Gallipoli Peninsula

Doyle and Bennett (1999, 2002) and Doyle (2008) have provided an overview of the geology and topographical features of Gallipoli, which is the basis, together with the available geological map (Ternek et al. 1987) for this summary. The Gallipoli Peninsula forms part of the Alpine Pontide range, with a strong east-west structural grain, and comprises ancient crystalline massifs developed in Anatolia, and folded Mesozoic-Cenozoic sediments in Thrace and basement margins of Anatolia. The most dominant feature is the North Anatolian Fault zone, separating the European and Anatolian plates, which runs under the Sea of Marmara and crosses the Peninsula to the Gulf of Saros, forming the northern, rifted and strongly rectilinear margin of the peninsula and the Dardanelles Straits, and separating it from the rest of Thrace. This fault zone has predominantly strike-slip movement, and is complex, as other branches of it form the Dardanelles and the Sea of Marmara, and is still active today. During the Neogene fault movement developed a trans-tensional basin and produced the Sea of Marmara, with a maximum depth of 1000 m, and led to the deposition of the thick Neogene sediments on either side of the Dardanelles. The Gallipoli Peninsula is therefore mostly composed of Palaeogene and Neogene sediments in a simple, relatively undisturbed relationship (Fig. 2). The oldest Palaeogene beds consist of Middle and Upper Eocene sediments that form the northern coast of the Peninsula. These Eocene beds are succeeded by continental Oligocene deposits, followed by marine sediments of Miocene age. Continental Pliocene caps most of the upland areas, and Quaternary alluvium and related sediments are found in valleys. It is these Pliocene–Quaternary rocks that were to have a major impact on the development of the Gallipoli Campaign at ANZAC.

3.1 Relief

The relief of the southern part of the Gallipoli Peninsula is relatively subdued, with a series of ridges in the north and two northeast-southwest trending plateaux in the south (Fig. 2). The southern plateaux are formed from Pliocene sediments, overlying bedded Miocene limestones. The margins of the plateaux are heavily dissected, forming a complex network of sharp-crested interfluves. In most cases the slopes are

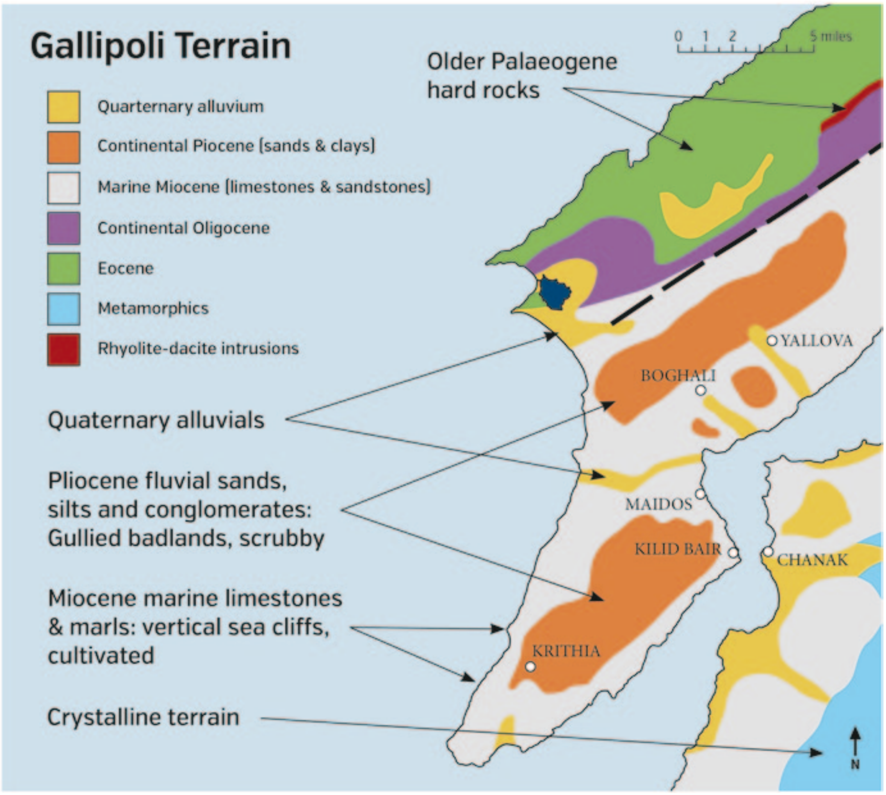

Fig. 2 The basic geology of the Gallipoli Peninsula, showing the Miocene soft sediments capping the Sari Bair range at Anzac. (Based on illustration in Doyle and Bennett (1999))

vegetated with scrub, but where the slopes are marked, there is active downcutting and erosion, creating a heavily dissected 'badland', typical of arid environments with soft, easily eroded sediments. The northern margin of the Sari Bair plateau is marked by a fault line scarp, and this is indicative of the active nature of the uplift caused by movement along the North Anatolian Fault Zone, itself exacerbating the erosion. Beneath the steep upper face of the scarp the slopes are heavily gullied and are barren of vegetation, forming classic 'badland' topography. In the southeastern part of the peninsula, the slopes of the Kilid Bahr Massif are strongly gullied, in some cases forming deep ravines. These ravines exploit the structural grain of the Peninsula, to give a parallel-alignment to the drainage of the southern peninsula.

The majority of rivers within the southern Gallipoli Peninsula are seasonal, and most valleys are dry for much of the year. Exceptions occur in the northern part of the study area, on the margins of the Suvla Plain, where there are some perennial streams. All the major lithological units have potential as aquifers. However, it is clear from studies of Neogene and younger sediments on the southern margin of the Dardanelles that the main aquifer potential lies with the Miocene limestones and the Quaternary alluvial deposits.

4 The ANZAC Landings, 25 April 1915

The Australian and New Zealand Army Corps were to be landed at the beach ('Z' Beach) north of Gaba Tepe (Fig. 1), facing the formidable, dissected landscape of the Sari Bair Range. The range terminated to the northwest, its steep face created by the actions of fractures in the underlying soils, part of the same fault system that had created the Dardanelles. The underlying rocks were easily eroded from fluvial action and intermittent rainfall over centuries producing a rugged landscape. The vegetation consists of a low, unforgiving scrub; with rough and easily disturbed soils, resulting in little flat ground.

Behind 'Z' Beach (soon to be dubbed Brighton Beach after its namesake in Melbourne, Australia), three parallel ridges (first, second and third) seemed to provide the best means of assaulting the peak in the initial stages of the operation. These ridges are a function of the activity of the North Anatolian Fault system, and mirror the structural grain of the Peninsula. If the ANZACS could get ashore in this inhospitable place, then they could clamber up the slopes that led to Second Ridge; moving through the scrub along the ridge, where they would be in a position to 'take the high ground' and dominate the ridge top. From here there would be views across Suvla Bay and its plain to the northwest, and back down to the southeast in the direction of Helles. 'Z' Beach (between Gaba Tepe and Ari Burnu) was to be assaulted by the Anzacs at 1 h before dawn, in an effort to maximize surprise, and to try and reach the first positions before daybreak. Three battalions of the Australian 3rd Brigade (together with supporting troops) would lead the assault landed from seven destroyers, which were to approach close in to the beach. The main force would land from transports (Aspinall-Oglander 1929; Rhodes James 1965; Travers 2001; Carlyon 2003; Prior 2009; Doyle 2011).

With the three ridges leading to the summit of the Sari Bair Range (Fig. 3) as the target, and Second Ridge just behind the beach, the 3rd Brigade was ordered advance over its slopes, thereby gaining—and holding Third Ridge. Following on closely, the Australian 2nd Brigade, would then be in a position to advance up the ridge, taking the nearest summits, Chunuk Bair at the flat plateau top joined by the three ridges, and 'Scrubby Knoll' a prominent feature on Third Ridge. The main force would then arrive to press on to a hill known as Mal Tepe, on the Dardanelles side of the Peninsula—which, it was hoped, would serve as a strong point that would help secure the Dardanelles defences. In taking the ridge tops, the ANZACs hoped to be able to deny them to the enemy—and ultimately link up with the British advancing from Cape Helles to conquer the northern shore of the Dardanelles and silence the guns.

Gaining the shore at about 4.30 am, the Australians struggled up the shingle beach in their combat equipment. The water was deeper than expected as the soldiers leaped out of the boats; several must have been dragged under. Ahead of them were unfamiliar slopes that would lead up to the top of Sari Bair. Small arms fire was directed at them by the Ottoman defenders. It was heaviest at the northern part—the promontory known as Ari Burnu, and close to the small ramshackle building known as Fisherman's Hut. But this was not the only resistance facing the Australians. In

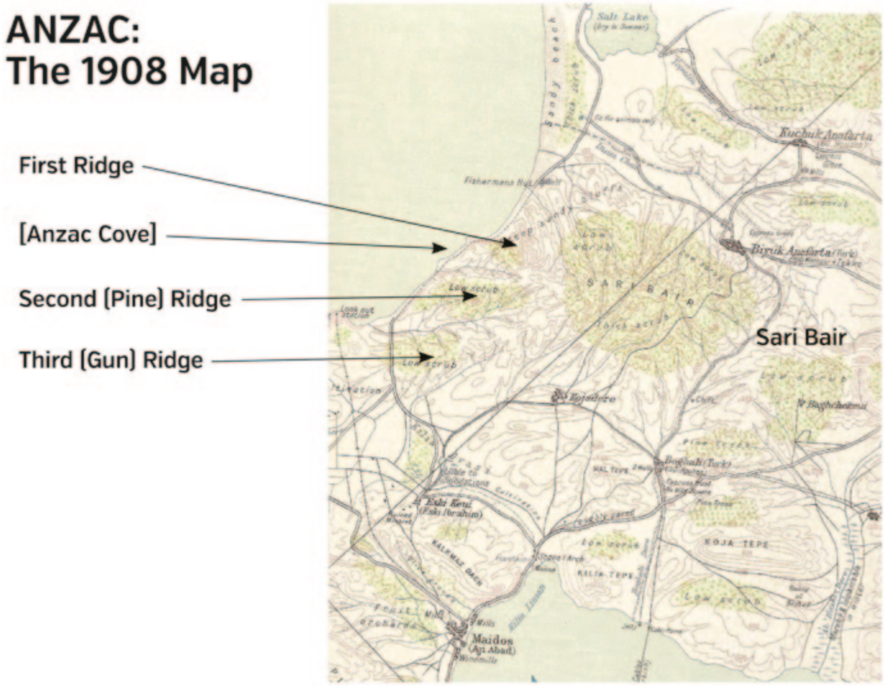

Fig. 3 The 1908 map, showing the continuous nature of First Ridge, a feature found to be impassable on 25 April 1915. The location of the Second and Third ridges, and the summit of the Sari Bair Plateau, is marked

front of them were the first slopes that they knew would lead up to the top of the Sari Bair range. The Australian battalions struggled to the top of a slope vegetated with thick scrub that was later to be called Plugge's Plateau—a small flat-topped extension of what was the First Ridge (Fig. 3). They were unable to push on—confronting them was a bald, narrow ridge that the forces of nature had eroded from both sides—the Razor Edge. This was to be impassable; north of this feature was a forbidding bowl of bare earth that sat at the foot of what the soldiers (in memory of their time in Egypt), would later call 'The Sphinx'. This steep-sided cliff, part of Walker's Ridge, that had been created by the erosion of a particularly hard band of cemented conglomerate that was resistant to weathering. This was in contrast to most of the Sari Bair Range, made up of fine Miocene sediments that were easily eroded by both wind and water action, creating a myriad of gullies, sharp spurs and innumerable dead-ends. Devoid of much water, these soils promoted the growth of stunted bushes and shrubs. The Razor's Edge came as a complete surprise to the Australians. The 1908 vintage map supplied to the troops indicated a continuous ridge that could be easily traversed (Fig. 3). This was not to be the case, and became a major point of contention in post-war discussions of terrain intelligence failure, starting with the British Official History (Aspinall-Oglander 1929; see Chasseaud and Doyle 2004).

For the men landing north of Ari Burnu, not only would the harsh terrain of the Sphinx and Walker's Ridge be in their way, so would the fire of the defending Ottomans at Fisherman's Hut. The next wave of men came ashore from the boats also released by the seven destroyers standing off the coast. Now daylight, the boats were more spread out, delivering men onto a beach that was in the order of 1500 yards wide, part of them to the north of Ari Burnu, the remainder to the south. By 4.45 am, some 4000 men of the ANZAC covering force were released into the confusing and inhospitable badland landscape of the sector—much easier to defend than attack. Under attack from the defenders in the north, and facing uncertain terrain in front of them, it was difficult to know in what direction they should press ahead. Led my officers as unsure of the terrain as their men, the ANZACs scrambled through the unforgiving terrain towards their target, Hill 971 and 'Baby 700' at the junction of the three main ridges.

The remainder of the Australian troops began landing from the transports at 5.30 am, the press of men adding to the confusion of those already onshore. As they advanced farther up the coast past Ari Burnu and Walker's Ridge, and close to the 'Fisherman's Hut', the ANZAC troops were once more engaged by the Ottoman defenders—at a high cost to the attackers. Men from the second wave were pressed into the attack. The commander of the Covering Force was aware that he had to press on from the beaches to capture the Third Ridge (Fig. 3), hold it and force his troops on to the high ground. Yet with passing time, the cohesion of his fighting units was breaking down, and it was difficult to identify just who was where, with small groups of men engaged in their own battles with the landscape. It was more realistic to try and concentrate on Second Ridge, securing its length from close to Hell Spit, at the southern end of Anzac Cove, upwards from the beach until the ridge coalesced with the great mass of summit of the Sari Bair Range. Though some scouts had reached Scrubby Knoll at around 9.00 am, briefly viewing the Narrows in the distance, they soon had to withdraw. No other ANZACs would stand on the knoll during the war.

With Third Ridge seemingly out of his grasp, the ANZAC commander directed his forces to form strong posts along the edge of the Second Ridge, posts that would hold throughout the campaign (soon to become named after their commanders—'Courtney's', 'Steele's' and 'Quinn's'; Fig. 4). Baby 700, sat at the junction of Second Ridge with the main mass of the mountain, would also have to be held. Not for the last time, the deep, scrub-filled gully that divided the First from the Second Ridges, Monash Valley, would serve as a route towards the apex of the ANZAC line. The line would also have to hold across the broader expanse of the 400 Plateau, a wider area on Second Ridge covered in dense scrub. (The eastern part of the Plateau, soon to be christened 'Lone Pine' after its single pine tree, was to see some of the bloodiest hand-to-hand fighting of the whole campaign, in August).

On Second Ridge, a flat plateau that was the scene of fierce fighting within the scrub vegetation in the first hours of the campaign, still presented difficulties. Attack and counterattack followed each other over possession of Baby 700. Holding out until 4.00 pm, the ANZAC line finally broke, the hill lost, when the Ottomans made a concerted effort to drive them from it. With the benefit of artillery support (naval gunfire in this opening part of the campaign), the ANZAC line melted away, its survivors streaming back over the narrow saddle of land that connected First Ridge with the plateau top.

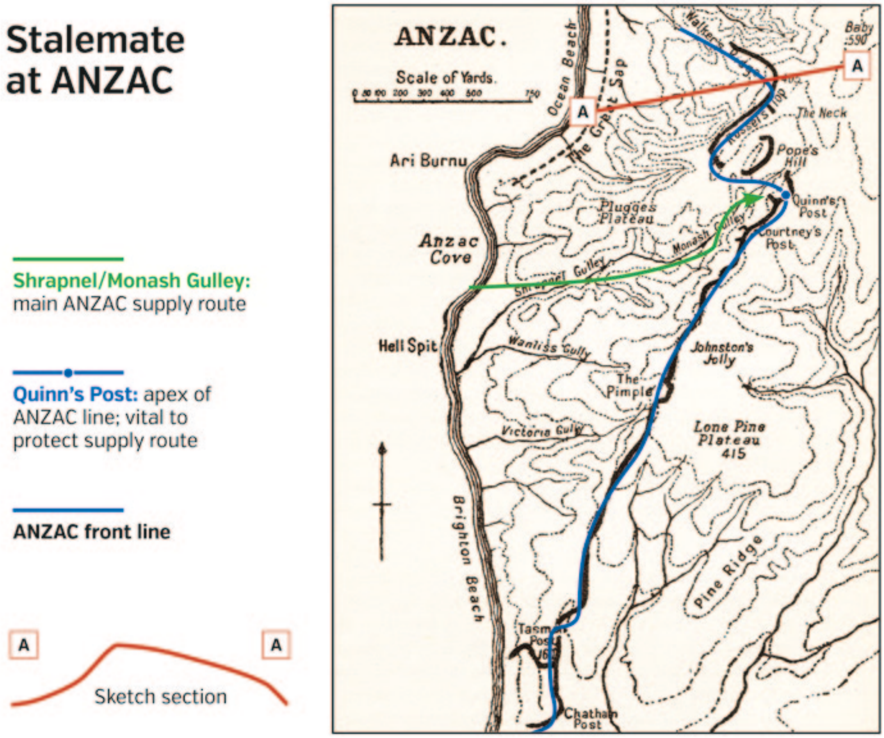

Fig. 4 Stalemate at Anzac: the relatively static trench lines, defining the most dissected part of the Sari Bair range. (Map from Callwell 1924)

As night descended on the scene, both defenders and attackers were in a perilous state. The line was held in an arc rising from the beach along Second Ridge (leading to 400 Plateau) through the isolated posts (Steele's, Courtney's and Quinn's) to the head of Monash Gully; from there it descended down to the sea on the other side of the Sphinx, along Walker's Ridge. The front line formed an arc of rilled and gullied ground, just less than one and a half miles in length, its greatest penetration amounting to no more than a mile. Having landed and dug-in, the ANZACs were now told to wait events, and hold the line. In total, 15,000 ANZAC troops had landed; but there were now 2000 dead and wounded, with the living crowded into open boats waiting to be re-embarked.

5 Trench Warfare

With the landings stalemated, came the onset of trench warfare (Fig. 4). Making the best of it, the Australians and New Zealanders fell into a routine that would ensure their part of the line was protected from Ottoman attacks. Everywhere in the frontline the conditions were poor. The relatively soft Pliocene sediments enabled the relatively rapid development of rudimentary trench systems, although this was hampered in the opening hours of the campaign by an absence of adequate construction tools, and by the degree of root penetration. By the end of the campaign, the trench systems were complex with a parallel underground system of tunnels and saps. In addition, many terraces were cut in the reverse slope to provide rudimentary dwelling areas (Aspinall-Oglander 1932; Rhodes James 1965; Carlyon 2003; Stanley 2005).

In general, few drainage problems were encountered early in the campaign, given the paucity of rainfall, in the summer months at least, the relative permeability of the trenches, and the depth to the water table. Trench construction was nevertheless an important consideration for the military engineers. Revetment was usually achieved using locally derived or shipped in timber, and both sides used covered trench systems, roofed by timber baulks and earthworks, in order to mitigate against the effects of shrapnel and small arms fire, although largely useless against direct hits from high explosive shells. Covered trench systems were created and there was extensive use of loopholes for snipers. New trenches were often dug by the use of shallow tunnels, which were then roofed with timber before loopholes were cut (Aspinall-Oglander 1932; Prior 2009).

As with the Western Front, dugouts at Gallipoli varied from the deep, shell-proof dugout to the shallow recess or 'funk-hole' intended only as a limited shelter (Doyle and Bennett 1999). Extensive dugout systems were cut into the seawards slopes of the Sari Bair Plateau providing shelter for a variety of administrative and service personnel. These were linked to the beaches by transport routes along gullies on the scarp slope of the plateau in the ANZAC Sector. Transport routes to the beaches were hazardous; here Monash Gully, leading to Shrapnel Gully, was be developed as a transport thoroughfare, with pack animals moving to and fro (Fig. 4).

While ostensibly static, the frontline trenches were actually alive with activity. In an echo of ancient siege warfare, mines were dug by both sides beneath each other's forward trenches, in order that explosives could be placed to destroy the trenches above (Aspinal-Oglander 1932; Branagan 1987; Stanley 2005; Prior 2009). Mining was also used for the construction of dugouts intended as dressing stations, operating theatres, headquarters and for other uses (Fig. 5). Harder conglomeratic levels (such as that at 'The Sphinx' were exploited as mine gallery roofs, though were hard to cut down through (Fig. 6). Nevertheless, mines were dug throughout the frontlines, but perhaps none so much as at Quinn's Post (Stanley 2005), at the head of Monash Gully, the main supply line (Fig. 5). It was described by some as the key position at Anzac:

> Quinn's had a fatal fascination for the Turk. Quinn's was a position that was to be held at all cost; with limited space, a complex terrace had to be constructed to its rear in order to provide sufficient room to create adequate fire and communication trenches. During May the enemy commenced mining in earnest, and this was a serious menace to the safety of the ANZAC area. Successful underground operations by the enemy would mean that Quinn's might slide down into Monash Gully, so vigorous countermining was resorted to. The object of this countermining was to get under or near the opponent's drives [tunnels], and destroy them by means of small charges. Major Fred Waite, NZ Engineers (Waite 1921).

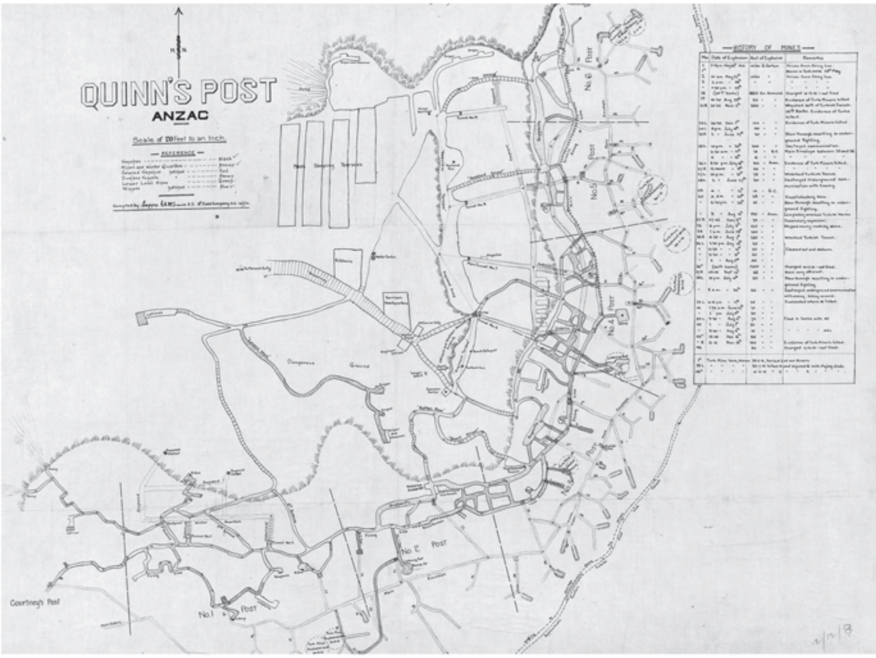

Fig. 5 A contemporary map of mining activity close to Quinn's Post, ANZAC Sector, 1915

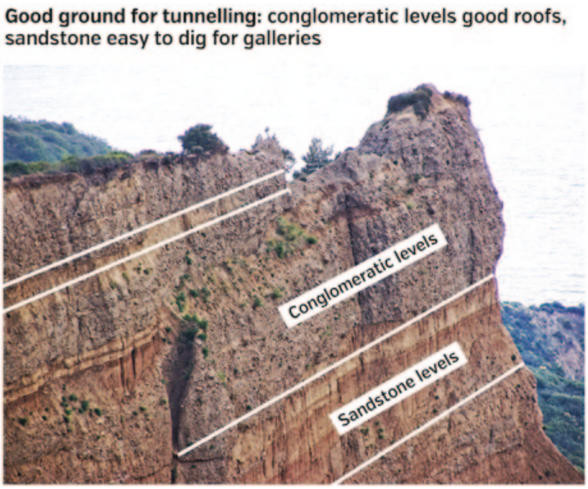

Fig. 6 Harder conglomeratic levels within the sediments at Anzac, here helping to form the distinctive feature known as 'The Sphinx', the main flank of which is illustrated

Water supply was a major pre-occupation in the ANZAC Sector, as elsewhere on the peninsula, though the combination of geological circumstances discussed above meant that it was perhaps more acute here. The German commander, Linman von Sanders considered that one of the most decisive factors responsible for the Turkish success was the availability of water behind their lines (Hamilton 1920; Nevinson 1920; Aspinall-Oglander 1932; Doyle and Bennett 1999, 2002; Prior 2009); something that was lacking for the Allies One of the biggest issues was a lack of reliable groundwater supplies in the ANZAC Sector. Here, the main limestone aquifer found in the southern peninsula (Fig. 2) was at depth, overlain by largely dry sediments. Some water supplies were found perched on impermeable strata, but were difficult to accurately locate (Beeby-Thomson 1924). Some seasonal exploitation of water courses in the Sector was theoretically possible, but like the perched sources were ephemeral. Many of the wells dug in the surrounding gullies began to dry up with the approach of summer, and though others were found at depth. This meant that the daily ration from local sources in the 1st Australian Division was rarely more than one third of a gallon per man; today, in arid conditions, two gallons might be expected for combat effectiveness (Anon 2012). Most water supplies for these areas was from imported water (Aspinall-Oglander 1929, 1932), and the large water-lighters used had to be towed from Alexandria and Malta and moored alongside the piers at Anzac Cove. The water could then be pumped by hand into iron tanks on the beach, whence it was taken by mules to other tanks in the hills, and thence by hand to the troops holding the line.

Later, a pumping plant and a number of larger storage tanks were obtained from Egypt. These were hauled to specially constructed platforms on the slopes of Plugge's Plateau, Walkers Ridge and other points near the front line. They were connected to the beach, and thereafter water could be pumped straight into them from the lighters, and then distributed to smaller tanks by gravitation (Aspinall-Oglander 1932, p. 117).

> As to water, that element of itself was responsible for a whole chapter of preparations. An enormous quantity had to be collected secretly, and as secretly stowed away at Anzac, where a high-level reservoir had to be built, having a holding capacity of 30,000 gallons, and fitted out with a regular system of pipes and distribution tanks. A stationary engine was brought over from Egypt to fill that reservoir. Petroleum tins, with a carrying capacity of 80,000 gallons, were got together, and fixed up with handles, etc. General Sir Ian Hamilton (1920).

6 Discussion

The geological and topographical issues of the ANZAC Sector were extremely challenging. The ANZACs were committed here in April 1915 as with their 'Colonial experience' in Australia it felt that they might be best suited to the terrain. That terrain was broken, gullied and rilled, the result of millennia of fluvial erosion of weak Pliocene sediments—held up here and there by more coherent beds of conglomeratic material, creating a feature named by the ANZAC troops as the Sphinx

(Fig. 6). Such hard bands could be breached, however, and such breaches meant that potential routes, such as that presented tantalisingly, but erroneously, by the 1908 topographical map (Fig. 3), were reduced to razor-sharp ridges with precipitous drops. This has been argued as being a significant factor in the failure to make progress to the top of Sari Bair on the first day; though there are other reasons, such as lack of experience of the attacking troops (Aspinall-Oglander 1929; Rhodes James 1965; Travers 2001; Carlyon 2003; Prior 2009).

The challenging nature of the terrain also meant that communication between the attacking troops was reduced, and that the momentum of the attackers was easily spent. This resulted in the Australian and New Zealand troops establishing a front line that was to cling to the seaward side of the Sari Bair scarp, but would not reach the ridge tops. This line formed an arc that was difficult to break out from, and which was difficult to fortify and defend. The defensive line thus created was actually series of outposts; outposts that would require considerable engineering effort to extend and fortify. It also meant that artillery fire up towards the Ottoman lines was limited in its effectiveness; the ANZACs were mostly only equipped with low trajectory field guns that would have difficulty sighting their enemy—or use naval guns from off shore. Mine warfare would be resorted to by both sides.

Like most other problems, supply issues were magnified at Anzac; all men and materiel would have to travel up the gullies that led to the front line, up Shrapnel and Monash gullies to Quinn's and other fortified positions. Water in particular was a considerable issue, especially so since there was no opportunity to exploit aquifers, and that water had to be derived from the beach, imported from Egypt. It was these issues, as much as the failure to exploit early momentum, that would see the failure of the campaign at Anzac, and that would see the withdrawal in December. It would also ensure that the battles of August, intended to break out of the ANZAC Sector would be the bloodiest of the campaign, and would still not create the desired result—the break through that would silence the guns of the Dardanelles, remove the threat of the minefields, and allow the Allied ships through. The terrain had significantly impeded the ANZACs at Gallipoli, an unfortunate accident of geography bringing the least favourable geology of the whole peninsula—Miocene–Pliocene sediments that tended to badlands—to the very spot where the Anzacs would land and attempt to prosecute their war against the Ottomans.

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From Army Outpost to Military Training Installations for Worldwide Operations: How WWII Transformed the Military Presence in the Southwestern United States

Donald E. Sabol and Eric V. McDonald

Abstract The southwestern United States contains the largest and most technologically advanced military training and testing installations in the world. Many of these of these installations range in size from 1000 to 7000 km^2 (386–2700 mi^2) and are surrounded by several large metropolitan centers that have greatly expanded since 1970. The establishment of these installations was, in part, a serendipitous timing of the evolving and increasingly mechanized military during early World War II coupled with the availability of an extremely desolate and expansive region of the deserts in the southwestern United States. Prior to WWII, the United States military presence consisted of widely scattered and small forts that existed between 1847 and 1900 for the protection of settlers and supply routes. Military interest in the desert radically changed with the entry of the United States into WWII and with the need for troops trained for desert warfare in Northern Africa. General George Patton, clearly seeing the advantages of training in the southwestern deserts, established the Desert Training Center (DTC). The DTC, later the California-Arizona Maneuver Area (CAMA), covered extensive parts of California, Arizona, and Nevada was the first of its kind in that it allowed large-scale maneuvers and training of mobile military operations including armor, mechanized infantry, and supply and logistics. Many additional training facilities were also established during WWII to support the war effort. At the end of WWII, many of the military installations in the regions (including the CAMA) were deactivated. The onset of the Cold War, with combat in Korea and later in Vietnam, several of the former WWII installations were reactivated and expanded in the size and capabilities due to the rapid evolution of military equipment and the increasing need for joint service military training. These large installations, including the Yuma Proving Ground, the National Training Center, Nellis AFB, and the Marine Corps Air Ground Combat Center at Twentynine Palms, all originated during WWII and have evolved into world-class training and testing facilities for world-wide operations.

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1 Introduction

The southwestern United States contains many of the largest and most technologically advanced military training and testing installations in the world. The establishment of these installations was, in part, a serendipitous timing of the evolving need for increasingly mobile and mechanized military forces early in World War II (WWII) coupled with the availability of an extremely desolate and expansive region of deserts in the southwestern United States. Multiple camps for training as well as for testing field equipment were established in the deserts of California, Arizona, and Nevada during WWII. The largest training site was the Desert Training Center, initially established under the direction of General George S. Patton, Jr. for large-scale desert warfare training to prepare American troops for combat in North Africa (Bischoff 2000). The Desert Training Center (later the California-Arizona Maneuver Area) was closed near the end of WWII along with most of the training camps in the area; however, a few of the camps and other facilities established during the war were maintained through the 1950's and 1960's and were instrumental in establishment and growth of local communities. Many of these camps eventually evolved into major military installations which, because of their desert locations, became more important for training and equipment testing with the First Gulf War in 1990 and subsequent military operations worldwide. Expansion of these critical military installations occurred largely before the 1990's when considerable increases in population in the desert southwest began. This area continues to fill the military's need for expansive, unpopulated, and electronically unpolluted space for large-scale integrated military training and it is the home of several Army, Air Force, Navy, and Marine key training installations. The focus of this paper is to describe the setting and timing for expansion and development of DoD training and testing operations in the Southwestern United States.

2 Southwest Military Facilities Prior to WWII

Much of southwestern North America became part of the United States with the end of the Mexican-American War, when the region was seceded to the United States by Mexico as part of the Treaty of Guadalupe Hidalgo (1848). That same year, gold was discovered in California and the "California Gold Rush" began, bringing an influx of settlers into the region. The increasing population required continual presence of United States soldiers to protect both settlers and the local native population. These early Army installations were generally sited in posts previously occupied by Mexican troops. Inland garrisons, typically small and scattered, were established to protect travel, supply, and communication routes and usually served their purpose after just a few years when they were subsequently abandoned or moved (Fig. 1) (Beck and Haas 1974). This general trend of temporary military occupation in the southwestern United States continued up near the end of the 1800's. Most of these Army posts were abandoned because the expansion of railroads made supply less of a problem and issues with Native Americans had declined (Frazier 1972). Military concerns with national security became focused on coastal defenses and military activity in the deserts was minimal (Frazier 1972). Except for the Civil War (mostly confined to the eastern United States), up until WWI, the military force was relatively small (Fig. 2). With a large number of citizens called into military service during WWI, 32 new camps were created by the Army for mobilization and training of troops. One of these was in the Southwest United States at Camp Kearny, which later evolved into the Marine Corps Air Station (MCAS) Miramar.

The close of WWI signaled the beginning of a need for a mechanized military force. As a result, increases in land for military training were required to coincide with the development of tanks, transported vehicles, and combat aircraft. Although the size of the American armed forces remained relatively small between WWI and WWII (Fig. 2), the southwestern United States became an important military training area with the establishment of several new military installations including Las

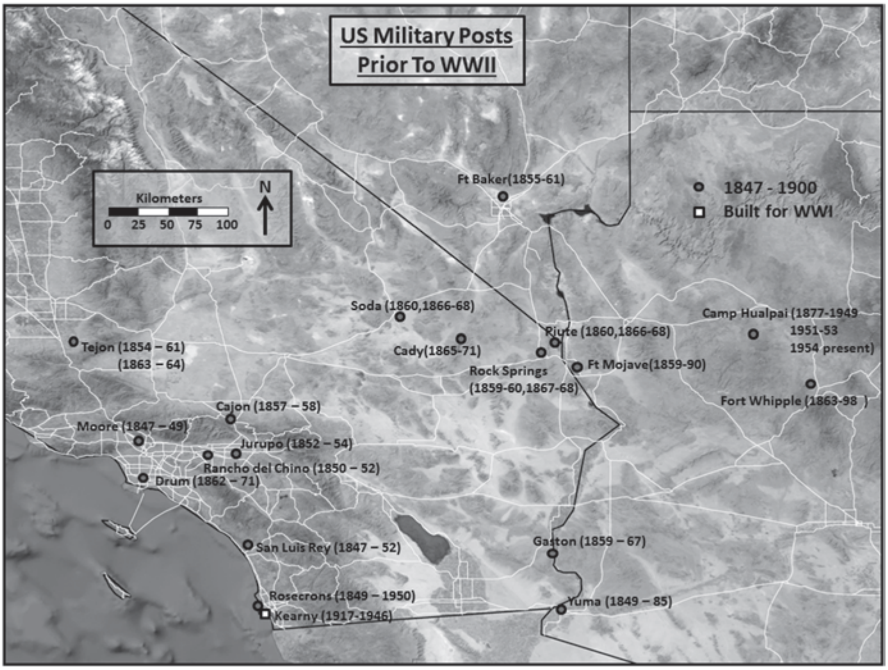

Fig. 1 United States Military posts in the southwest United States prior to WWII. (modified from Beck and Haas 1974, p. 54; These posts were generally small and existed for several years before closing)

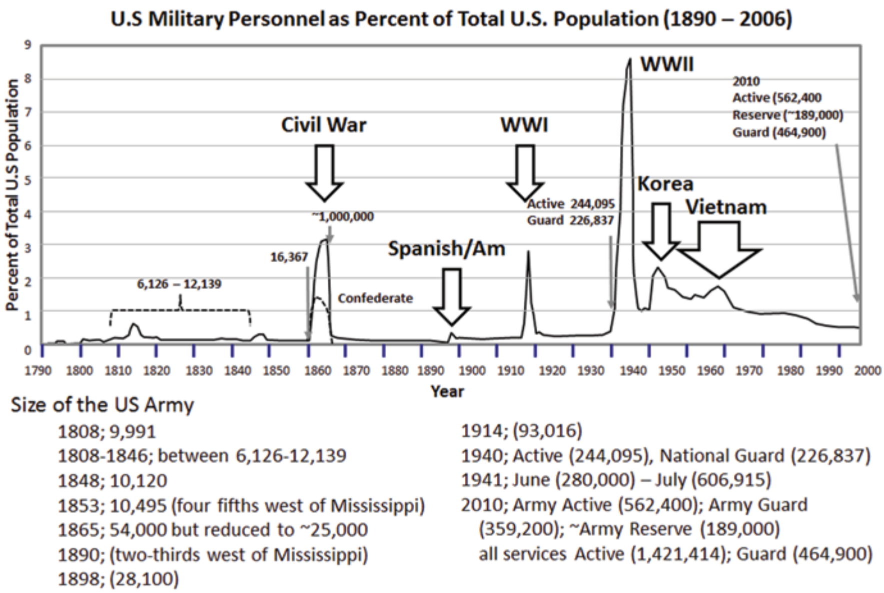

Fig. 2 United States military personnel as a percent of the total U.S Population (1890–2006). (modified from Department of Defense Selected Manpower Statistics (2003) and Segal and Segal (2004)). WWII signaled the beginning of a relatively large standing armed force

Vegas Army Airfield (now Nellis AFB), the Desert Test Facility near Yuma, AZ, an artillery training area near Indio, CA, Camp Haan in Riverside, CA, an antiaircraft training ground (now Ft. Irwin), and Blythe Army Air Field, CA. All of these installations would expand in size and new installations would be established with the United States involvement in WWII, but the greatest impact in the region would come with establishment of the Desert Training Center in April, 1942.

3 WWII: Rapid Growth of Southwest Military Facilities

3.1 The Desert Training Center

On its entrance into WWII, the United States primary divisional training centers were located in Louisiana and Tennessee. These were designed to handle a maximum of two corps in a confined military environment (Crossley 1997). With the United States now involved in a global conflict, the War Department decided that the armed forces needed special training, which resulted in the opening of four special training camps. Three of the camps were located in other parts of the U.S: the Airborne Training Command at Camp Benning, GA; the Amphibious Training Center at Tallahassee, FL; and the Mountain Training Center at Camp Carson, CO.

When the decision was made to invade North Africa, it became clear that the United States Army needed large-scale training in desert warfare. The army's Chief of Staff, LTG Lesley J. McNair, envisioned a desert training center and, in early 1942, assigned General George S. Patton, Jr. to locate a suitable training area (Henley 1989). Patton, an ex-cavalryman who had turned into an expert on tank warfare, was a tough no-nonsense soldier who would expect a similar attitude toward training and combat from his troops (Fig. 3). A 1909 graduate of the United States Military Academy at West Point, he saw action during the 1916 punitive expedition against Poncho Villa and was a decorated for his service during WWI.

Patton took command of the I Armored Corps and by early March 1942 scouted the deserts of eastern California and western Arizona by jeep, horseback, foot, and private plane (Bischoff 2008). A native Californian, Patton was familiar with the area from his youth and from having participated in Army maneuvers in the Mojave Desert in the 1930's (The California State Military Museum 2012). He loved what he saw. An expansive area, with a small population, minimal radio interference and demanding weather, with terrain he deemed similar to the deserts of North Africa. Water resupply was possible from the Water District of Los Angeles and rail was accessible for bringing in troops and supplies (Bischoff 2008). In addition, most of the land was government-owned and the rest was sparsely populated making it relatively easy for the government to acquire for training. Many of the inhabitants in the area were forced to leave their land until the end of training activities near the end of WWII (Bischoff 2000).

Fig. 3 LTG George S. Patton Jr taken on 30 March 1943. (Source: United States Library of Congress, ID: LC-USZ62-25122)

Patton returned to Washington D.C. to report recommendations and findings and immediately received the go-ahead to establish training activities in the desert (Bischoff 2008). By late March 1942, the first camp was established, Camp Young, named for the army's first chief of staff, GEN Samuel Young (Bischoff 2008). Camp Young, designed according to Patton's instructions, was simple and would mimic accommodations similar to those in the North African Theater of operations (Bischoff 2008). Very few wooden structures such as administrative centers and hospitals were to be built and the troops would live in large tents with no electricity. The other 13 camps that would be built would follow this model (Bischoff 2008).

The Desert Training Center (DTC) was officially established on 30 April 1942 and covered 26,000 km^2 (10,000 mi^2) in California, Arizona, and Nevada (Henley 1989). By mid-1943, this would grow to an enormous 73,000 km^2 (28,000 mi^2) and include 14 divisional camps located across a significant portion of the Mojave and Sonoran Deserts (Bischoff 2008) (Fig. 4). Within days of the DTC establishment, the I Armored Corps began arriving on troop trains and were initially located at Camp Young. Soon, the other 13 camps were built for other arriving divisions. These camps centered on all aspects of mobile military operations including armor, mechanized infantry, and supply and logistics. The vast expanse of the DTC allowed the Army to operate any size of combined aircraft and ground unit operation

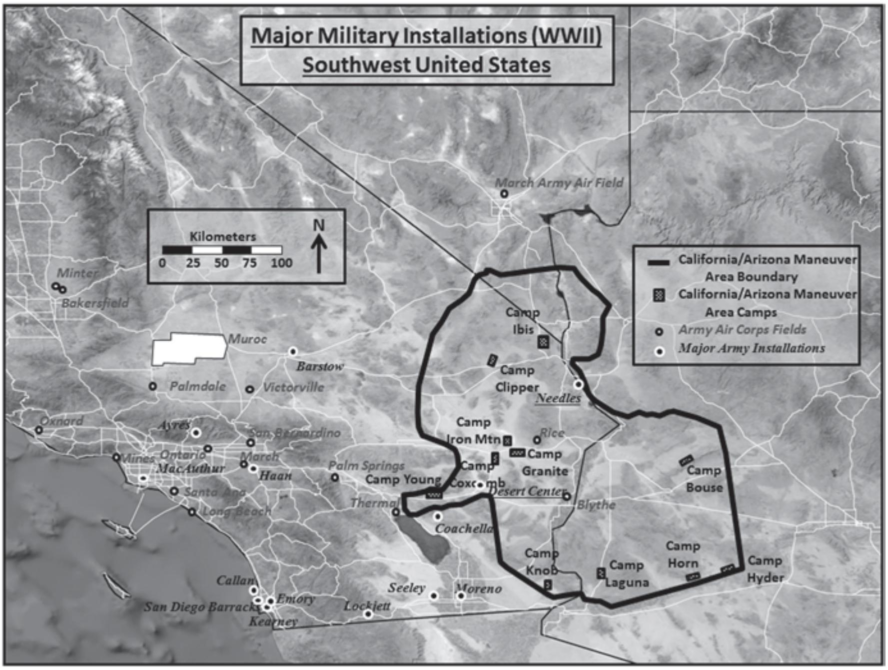

Fig. 4 Major military installations in the southwest United States during WWII. (modified from Beck and Haas 1974, p. 87; Bischoff 2008)

Table 1 The California/Arizona Maneuver Area general training program. (Lynch et al. 1986; Henley 1989; Bischoff 2008)

Week	Unit size training	Focus
1	Individual, crew, and squad	Teamwork; Junior Officer Leadership
2	Company/battery	
3	Battalion	
4	Regimental	Testing vehicles, equipment, weapons
5–7	Divisional field exercises	
8–13	Corps Maneuver	

and tactical maneuvers and under realistic conditions (Lynch et al. 1986; Henley 1989). This was not possible at any other military installation in the United States.

By the fall of 1942, more than seven stationary and two moving target ranges were established, as well as one infantry and two mechanized combat ranges (Bischoff 2008). Training followed a strict training regimen. Patton established an intensive 13 week program that emphasized teamwork and leadership development. The size and scope of training progressively increased by incorporating a greater number of units involved during training as the weeks progressed (Table 1). Adequate physical conditioning was an essential part of the training. Troops made their first desert march within 4 days of their arrival (Henley 1989) and all soldiers were required to run 1.6 km (1 mi) in 10 min with full combat gear, including rifles.

The final weeks of training involved large-scale exercises involving over 10,000 men and covering several hundred square kilometers. This scale of training allowed the troops to directly learn the capabilities and limitations of weapons and vehicles (Blake 1987).

In late summer of 1942, Patton and the I Armored Corps departed the DTC to be part of the invasion of North Africa (Operation TORCH) and were replaced by MG Alvan Gillem and the II Armored Corps. In early 1943, with the campaign in North Africa coming to a close, the concept changed training for operations in Africa to general large-scale training and maneuvering. This led to a name change for the DTC to become the California-Arizona Maneuver Area (CAMA) (Bishoff 2008). Successive units training at the CAMA following the II Armored Corps were: the IX Corps, XC Corps, IV Corps, and the X Corps. Overall, 20 separate divisions consisting of more than 1 million men trained at CAMA during WWII (Bishoff 2000).

By late 1943, the CAMA was experiencing a personnel shortage in service specialists (communications and transportation to maintain needed services) because they were needed overseas, and by 30 April 1944, combat training at CAMA ended and the area was turned over to the Army Service Forces (and eventually back to the Department of Interior and to private land owners (Bureau of Land Management 2012; Bischoff 2008)).

3.2 Other Military Installations Established During WWII

Many other training areas, especially gunnery and artillery trainings ranges, were also established across the deserts of the United States during WWII in addition to CAMA (Fig. 4). Although not nearly as large as CAMA, many of these installations, which served specific training needs during WWII later evolved into contemporary military installations. A full discussion of all the installations is beyond the scope of this paper, but the evolution of six installations is summarized in Table 2. As WWII wound down, training areas in the southwestern United States largely became de-militarized.

3.3 Rapid Regional Population Growth Follows WWII

Fortunately, the critical requirement to establish large training areas for division-scale military training in the southwestern American deserts occurred at the time were sparsely populated and provided an ideal setting to fill these needs. As the military expanded its presence in these deserts, the population also dramatically increased. This expansion resulted in improvements to the infrastructure (e.g. roads, highways, water resources, and railroads) that helped support a rapid population increase in the region (Fig. 5). The population trend shown in (Fig. 5) depicts the increase in permanent population and does not show short-term spikes associated with 1–2 month deployment of military units in the area for training. The population of this area grew from 404,072 in 1940 to 625,499 in 1950. This is a 54.8% increase as compared to an 18.5% increase in the population between 1930 and 1940 for the same area. Between 1950 and 1980, population had increased another

Table 2 Six of the military installations during WWII and their current names and purposes. (GlobalSecurity.Org 2011, 2014a, b, c; WWW.YUMA.ARMY.MIL n.d.a; MilitaryBases.Com 2014; Nellis Air Force Base n.d.a; O'Hara 2007)

Installation name (WWII)	Purpose (WWII)	Current installation name	Purpose (current)
Las Vegas AAF	Advanced flight training; gunnery training	Nellis AFB	Fighter pilot training
Condor Field	AAC air field; glider training	Marine Corps Air Ground Combat Center Twentynine Palms	Marine Corps warfare training
Mojave Anti-Aircraft Range	Anti-aircraft training	Fort Irwin	Army National Training Center
Camp Pendleton	Marine amphibious/land combat training	Marine Corps Base Camp Pendleton	Marine amphibious/land combat training
Camp Laguna	Equipment testing/troop training	Yuma Proving Ground	Equipment testing/troop training
Muroc Remote Bombing Range	Bomb range; rocket test site	Edwards AFB	Military aircraft testing

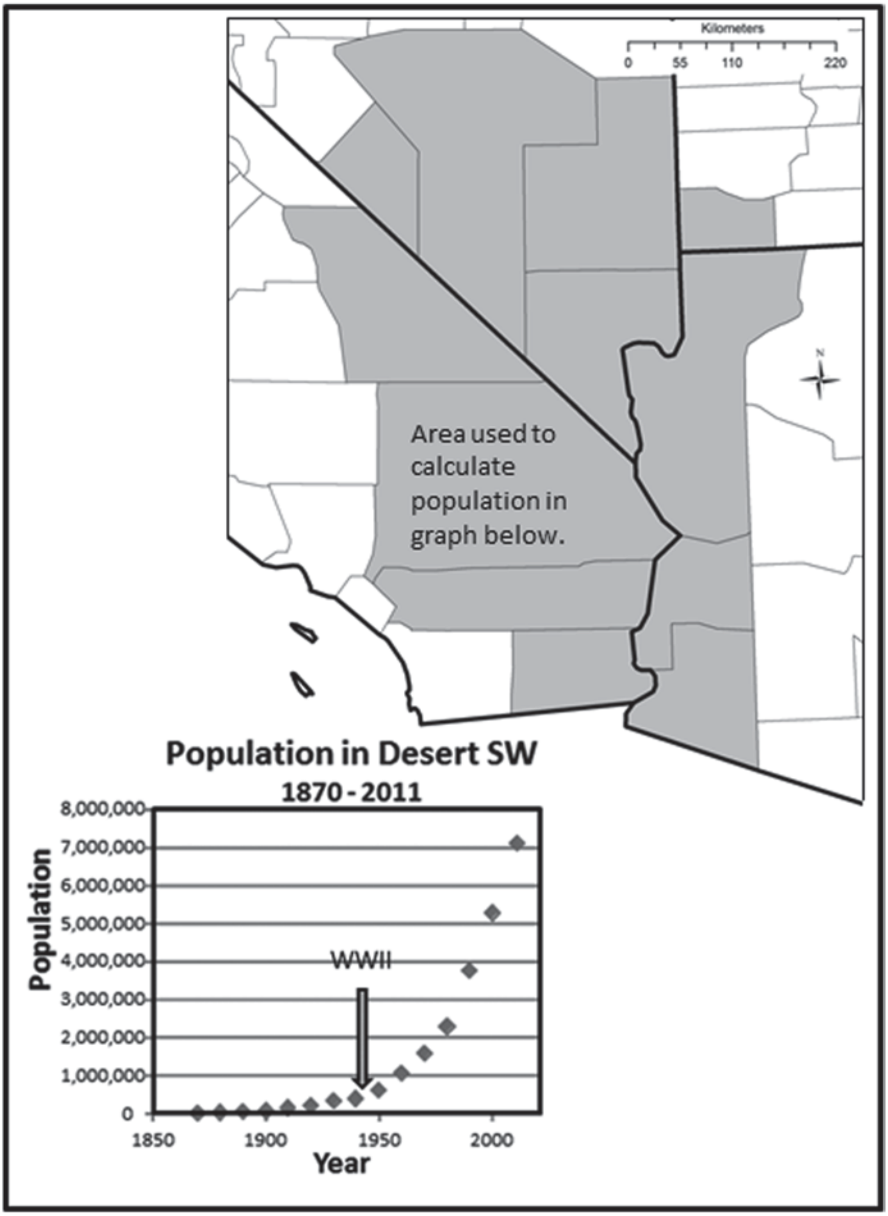

Fig. 5 Change in the population of the southwestern deserts since 1870. Produced using data from the California State Data Center (March 2013). The United States federal census for the counties shown in *gray* were used to create the graph

~350% and exceeded 2,000,000. The exponential increase in regional population after 1950 may be due in part, to the establishment of major cities and urban areas near military installations.

The seeds of large scale, modern United States military facilities in the southwestern American deserts (discussed below) were sown with the military requirement for expanded training and testing facilities during WWII. With the exponential increase in the population in the southwestern deserts since WWII, it is unlikely that large military facilities could be readily established today.

4 Post WWII: Regional Expansion and Development of Southwest Military Facilities

With the onset of the Korean and Vietnam Wars in the 1950s and 1960s, many former WWII installations in the desert southwest were expanded and several former training ranges where re-activated. In addition, a large-scale joint Army and Air Force training exercise called "Desert Strike" was held in May 1964 to test tactical operations on a nuclear battlefield. This exercise, lasting 2 weeks, involved more than 90,000 Army and 10,000 Air Force personnel, 780 aircraft, 1000 tanks and 7000 wheeled vehicles (Exercise Desert Strike 1964). The training exercise covered 13 million acres in California, Arizona, and Nevada (Fig. 6), overlapping much of the same area that comprised CAMA during WWII. The ongoing Cold War and lessons from the Desert Strike exercise resulted in further expansion in the size and capabilities of military training and testing installations. This period of expansion coincided with a need for large areas to conduct military operations, which was driven by a rapid evolution of the capabilities of military vehicles, aircraft, and weapons after WWII and the increasing need for joint service military training. This post-WWII history of tremendous expansion resulted in the transformation of numerous WWII training facilities into an extensive array of Army, Navy, Marine, and Air Force installations that currently stretch across a wide swath of the desert southwest (Fig. 7). The military mission also expanded with training designed to prepare the armed forces for conflict throughout the world and development of extensive military test and evaluation centers. Several examples of these premier military installations that were primarily established during WWII include: the Yuma Proving Ground, the National Training Center, Nellis AFB, and the Marine Corps Air Ground Combat Center at Twentynine Palms. The following sections of this study briefly describe the history and current style of military activities for these four installations.

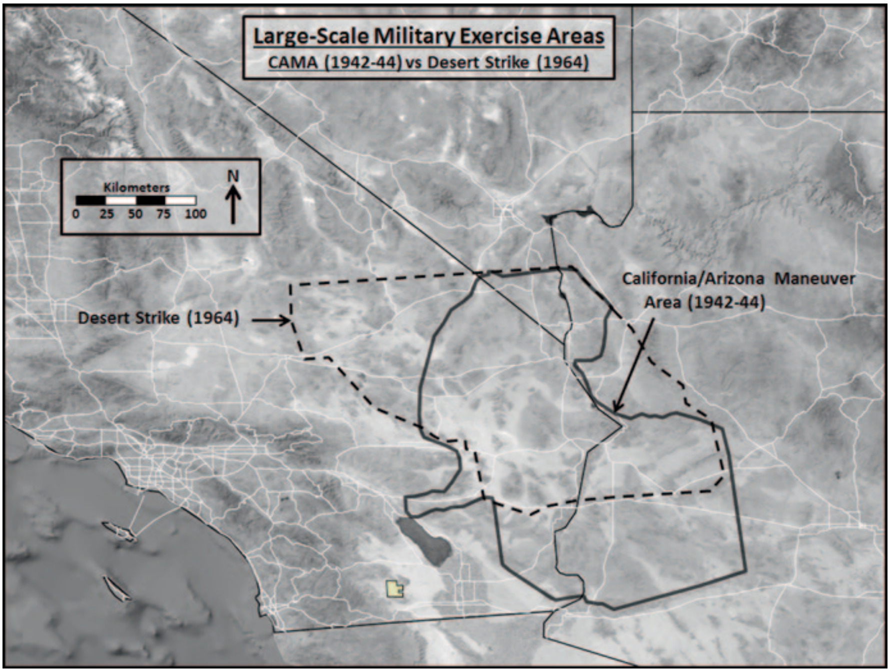

Fig. 6 Boundaries for two the large-scale military exercises in the southwestern United States. *Solid line* is the California/Arizona Maneuver Area (1942–1944) and *dashed line* is Desert Strike (1964). (after Prose 1986; Prose and Wilshire 2000; Bischoff 2008)

4.1 WWII Legacy Installations Evolve into World-Class Military Installations for Worldwide Military Operations

4.1.1 Yuma Proving Ground

Military facilities near Yuma, AZ started as Fort Yuma on the California side of the Colorado River in 1850 (California State Military Museum n.d.). This fort was built overlooking the Yuma crossing of the Colorado River and was established to maintain peace with the local Native Americans and to protect travelers. In 1865, the Yuma Quartermaster Depot a separate facility located across the river in Arizona (Fig. 8) was established. This facility served as a military supply center for 14 military posts in Arizona, New Mexico, Nevada, Southern Utah, and West Texas and maintained a 6 months' supply of ammunition, clothing, and food at all times (WWW.YUMA.ARMY.MIL n.d.a).

Both Fort Yuma and the Yuma Quartermaster Depot were closed in 1883. Military facilities were once again established near Yuma in early WWII as Camp Laguna, part of the expansion of CAMA. The Army Corps of Engineers Yuma Test Branch was also established near Yuma and Camp Laguna to provide field testing of combat bridges, amphibious vehicles, and boats (GlobalSecurity.Org 2014a). WWII

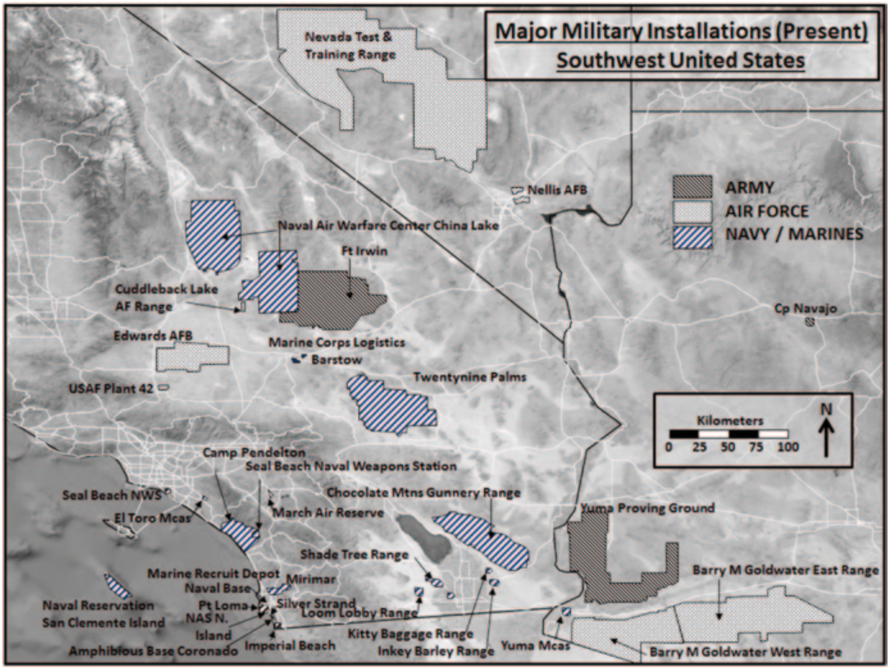

Fig. 7 Present major military installations in the southwest United States. (modified using U.S. Military Installations, 2014, GIS shape file, Bureau of Transportation Statistics, DOD-2639)

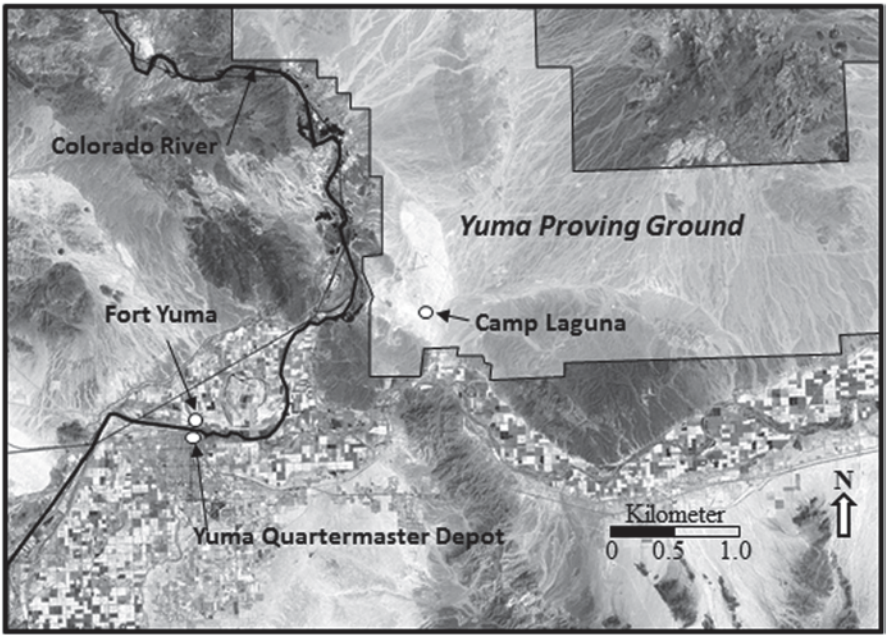

Fig. 8 Location of historic and current Army installations near Yuma Arizona. (compiled using data from Military Reservations (2008), and Beck and Haas (1974), p. 54 and 87)

Camp Laguna was closed near the end of WWII as the need for large-scale training decreased. The Yuma Test Branch, however, remained open conducting river and desert environment tests until 1950 (WWW.YUMA.ARMY.MIL n.d.a). This test facility was quickly reopened as the Yuma Test Station in 1951 with an expanded mandate to include artillery testing, armored vehicles and air delivery systems. Renamed the Yuma Proving Ground (YPG) in 1963 it was later designated as a Department of Defense Major Range and Test Base in 1971 (GlobalSecurity.Org 2014a).

YPG covers 5975 km^2 (1307 mi^2) and includes the longest overland artillery range in the world. The post's geology, especially the soil cover and terrain roughness, and the hot and arid climate, provide an ideal location for testing military equipment for the extreme desert environmental conditions that occur in many of the World's deserts (Gilewitch et al. 2014). YPG has over 322 km (200 miles) of unpaved roads used for testing vehicle performance, mobility, and durability. In addition, it has the world's most highly instrumented helicopter armament test range, a large mine and demolition test facility, and conducts hundreds of tests of unmanned aerial vehicles. The facility is also extensively used for parachute training and testing (WWW.YUMA.ARMY.MIL n.d.b). It is also becoming the Department of Defense's premiere test site for IED's (improvised explosive devices) with simulated southwest Asia (e.g. Iraq, Afghanistan) villages and roads. A typical year of test operations at YPG include -over tens of thousands of artillery, mortar, and missile rounds are test fired, 36,000 parachute drops, 209,215 km (130,000 miles) driven for military vehicle testing, and over 4000 sorties are flown (WWW.YUMA.ARMY.MIL n.d.a).

4.1.2 National Training Center (NTC)

This area in the central part of the Mojave Desert was first visited by the United States Army in 1844 by Captain John Fremont and Kit Carson; who set up a camp near Bitter Springs to serve travelers on the trail between Salt Lake City and California. During the California Gold Rush, the area was patrolled by the Mormon Battalion to curb raiding (California State Military Museum 2014). Few military activities occurred in the area until 1940 when the Mojave Anti-Aircraft Range was established (MilitaryBases.Com 2014). This training range was renamed Camp Irwin in 1942 in honor of Major General George Irwin and made part of the Desert Training Center (and later CAMA). Camp Irwin was deactivated in 1944 but reopened to train artillery and engineers during the Korean War as the Armored Combat Training Area and was renamed Fort Irwin during the Vietnam War. Fort Irwin was deactivated again in 1971 but was used for training by the California National Guard from 1972 to 1980 (California State Military Museum n.d.).

In 1981, Fort Irwin was designated as the National Training Center for the purposes of training ground, armored, and aviation brigades for combat by creating a realistic battlefield environment by conducting brigade-size force-on-force maneuvers and live–fire training (GlobalSecurity.Org 2011). Brigades rotated in and trained against a well-trained professional opposing force. The NTC is one of the largest Army training centers and has over 2590 km^2 (1000 mi^2) of restricted airspace that is isolated from populated areas and has an uncluttered electromagnetic spectrum and includes numerous high-tech facilities for monitoring and evaluating training of visiting troops (GlobalSecurity.Org 2011). The extensive open desert terrain that is subdivided by rugged mountains provides an ideal setting for conducting large-scale and integrated military training. The primary training mission at the NTC changed after 2001 with an increasing focus on counterinsurgency operations and training scenarios include cave and urban complexes that replicate combat conditions in theaters of engagement such as Afghanistan and Iraq (Gregory 2013). Training activities include operations using mock "villages" which mimic real villages from Iraq and Afghanistan. These training villages contain a wide variety of building including mosques, hotels, traffic circles and are commonly inhabited by Arabic-speaking actors portraying both villagers and insurgents (Gregory 2013).

4.1.3 Nellis Air Force Base

Nellis Air Force Base began as an aerial gunnery school for the Army Air Corps in 1941 and was initially named the Las Vegas Army Airfield. By 1942, aerial gunnery training included gunnery operations associated with a wide range of aircraft including the Martin B-10, North America AT-6, Douglas A-33, and the Boeing B-17, B-24, B-26. In early 1945, it converted to the Boeing B-29 gunnery school (Nellis Air Force Base n.d.a). The gunnery school was inactivated in 1947 but was reactivated in 1949 and renamed the Las Vegas Air Force Base for use as an advanced single-engine fighter school (MyBaseGuide n.d.). The facility was renamed as the Nellis Air Force Base in 1950 and also launched a period of growth over time (Nellis Air Force Base n.d.a). The Air Force demonstration team "Thunderbirds" made the base their home in 1956 and in 1966, the Tactical Fighter Weapons Center was established. In 1969, the USAF Fighter Weapons school was added, and in the 1970's, in response to lessons learned in Vietnam, an aggressor squadron was established to simulate doctrine and tactics of possible enemy forces. This unit engages in mock dogfights with visiting USAF squadrons (Nellis Air Force Base n.d.b). The USAF Weapons School conducts advanced weapons instructor courses that include fighters, bombers, helicopters, intelligence, and space. In a typical year, over 40,000 sorties are flown (GlobalSecurity.Org 2014b).

Flight operations include the extensive Nevada Test and Training Range (formerly the Nellis Air Force Range) which is located approximately 46 km (28 mi) northwest of Nellis AFB (Fig. 7). The Nevada Test and Training Range (2.9 million acres of and 500 square miles of airspace) is the largest land-based military range in the United States, providing the largest contiguous air and ground space for training in the free world (Nellis Air Force Base n.d.c).

4.1.4 Marine Corps Air Ground Combat Center at Twentynine Palms

This premier Marine Corps training facility began as a civilian air field in 1937 and was first used officially by the military in 1942. Renamed Condor Field, the facility became the primary Army glider school of WWII (O'Hara 2007). The Army closed the field in 1944, but it was later reopened in late 1945 to briefly be used by the Navy. In 1952 with the build-up for the Korean War, Condor Field was renamed the "Marine Corps Training Center, Twentynine Palms" and used for live-fire training (Marines.Com n.d.). The facility was expanded and renamed the "Marine Corps Air Ground Combat Center" in 1979. This base is 2400 km^2 (932 mi^2) in size and hosts one-third of the Fleet Marine force and reserve units for training each year (GlobalSecurity.Org 2014c). Up until late 2012, these troops received a month of "Mojave Viper" (live-fire exercise with artillery, tank, and close air support) training before deploying to Iraq and, if deploying to Afghanistan, training at the Mountain Warfare Training Center (Marines.Com n.d.). This included a simulated Middle Eastern village with role-players for urban combat and IED training. Late 2012, with the reduction of deployments to the Middle Ease, Mojave Viper was replaced with Integrated and Large Scale Training Exercises that primarily occur at Twentynine Palms but utilize other west coast military facilities as well (Army Times 2012). These exercises are designed to prepare troops for military operations worldwide.

5 Conclusions

The current expanse of the largest and most technologically advanced military training and testing installations in the world that are located in the southwest US owe their presence to the expanded military buildup in the southwestern deserts of the United States during WWII. The development of new training activities in the southwest was fortuitous timing in that: (1) the military needed large areas to train men, develop tactics, and test equipment for large-scale mechanized combat operations (particularly desert warfare at the beginning of United States involvement of the war), (2) the availability of relatively unpopulated and large tracts of desert land in the United States, and (3) the early involvement and wisdom of General Patton in locating and establishing an extensive network of desert sites for training. Although the military temporarily reduced its presence after WWII, the desert southwest remained important for military training and testing. The size of the military presence substantially expanded between the 1950's–1970's. Many of these of installations, now ranging in size from 1000 to 7000 km^2 (386–2700 mi^2), are home to numerous military facilities of all service branches. Since the end of the Cold War in 1990, the geo-strategic environment has become much more complex as threats to United States security can come from terrorism, regional instabilities and rogue governments from any number of hot-spots worldwide. The military must be able to effectively deal with these threats. Given that in many scenarios, the military tactical ground forces can effectively engage enemy targets at ranges of 60+ miles, the need for large areas for training have only increased (GlobalSecurity.Org 2011). The importance of large military installations in the desert southwestern United States allows the American military and its allies continue to train in state-of-the-art facilities for combat operations worldwide. It is unlikely that these large training centers, without staking a toe-hold in WWII, could have been developed into their current size and number in a more recent era of rapid population growth and the related environmental and land management issues.

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Preparing for War in the Desert Southwest; From the California—Arizona Maneuver Area to the Yuma Test Branch (and Beyond)

William J. Heidner

Abstract The history of the US Army Yuma Proving Ground (YPG) as the location for the scientific investigation of the natural environmental effects of desert climactic conditions on men and material of the United States Armed Forces, begins with the national response to our entry into World War II. As the Nation awoke to the terrible news of the Japanese attack on Pearl Harbor, we also awoke to the fact that as a Nation we were totally unprepared for war. The Desert southwest of North America was seen as an ideal location to take care of many of these issues of military preparedness that now faced the Nation. General Patton's Desert Training Center (DTC) was established to quickly get our forces ready for War in North Africa. The DTC would evolve to become so much more. War-time requirements undertaken in the Desert Southwest came with an extreme sense of urgency. In an effort to compress development time for the new and improved materials of war, Research, Development, Test & Evaluation (R, D,T&E) was conducted in the natural environment in order to more quickly derive results. The U.S. Army Quartermaster Corps, along with the Ordnance Corps would see the harsh environment and topography of Camp Seeley CA as offering ideal environmental conditions in which to test Army vehicles and their sub-systems. The U.S. Army Corps of Engineers would establish the Yuma Test Branch at the Imperial Dam, the ideal location to test tactical bridging equipment. In many cases, the Yuma Proving Ground occupies the same geography as these precursor facilities. In other cases it is the mission and heritage of those war-time entities that have continued to evolve at the Proving Ground. This paper covers this initial historic period, a period that covers from 1942 until 1950.

Keywords Desert Training Center/California—Arizona Maneuver Area (DTC/C-AMA Yuma Test Branch) · Desert Proving Ground · US Army Yuma Proving Ground

Although the World had been "officially" at war since 1 Sep 1939, America chose to maintain a stubborn pretense of neutrality. As the American people awoke on 7 December 1941 to the terrible news of the Japanese attack on Pearl Harbor, they

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also awoke to the fact that America was totally unprepared for war. This historical review will look at how the southwestern United States played a part in helping America become prepared for that war, while answering these questions; was the usefulness of this region tied directly to specific Theaters of War? How have the lessons learned from this experience shaped the use of this geographical area to date?

America's unpreparedness for war has historically been the rule, rather than the exception. There are many reasons for this. Among them was a defense paradigm that relied on the ocean(s) posing a natural obstacle with a strong Navy protecting our shores. There was also an aversion to a large standing army prevalent among our Founding Fathers. These views were codified within the U.S. Constitution. Teddy Roosevelt noted that this state of unpreparedness will always be the case, given the constitutional nature of the problem. He concluded that America would always face the same challenges in time of war; how do you equip, train the soldiers and prepare the leaders of the new army? America would find, in the Desert Southwest, a perfect location to address these issues. This paper will look at three facilities that were established to support the war effort. They became known as the Ordnance Desert Proving Ground, the Desert Training Center/ California—Arizona Maneuver Area (DTC/C-AMA), and the Yuma Test Branch (YTB).

The original impetus for what would become the Desert Proving Ground at Camp Seeley, California was that "…the plan for the African campaign was being formulated and the Allies were going to need 'desert-tested' equipment to match the armored strength of the mechanized Rommel" (Engler 1945). In a concurrent development, Army Ground Forces (AGF) "…realized the need for the testing of equipment under the conditions they were likely to face in combat situations. The Desert Warfare Board (DWB) was established for this task" (Bischoff 2000). The Desert Training Center (DTC) was tasked to accommodate this new organization.

The origins of the DTC were also linked to North Africa. Realizing that our first European campaign would be in North Africa, Lt. Gen. Leslie McNair, Chief of Staff, General Headquarters (GHQ), understood the Army's lack of experience with desert warfare. "McNair ordered that a location be found for a training center that would prepare soldiers for desert warfare. McNair placed Maj. Gen. Patton in charge of this project" (Bischoff 2000). Based on recommendations made to the War Department, and refined by GHQ, southeastern California and western Arizona became the location of a suitable site. Defined largely from a personal reconnaissance conducted by Patton, the DTC opened on 30 April 1942 and stretched from Yuma Arizona in the south, to Searchlight Nevada in the north, and Indio California in the west while the Colorado River initially formed the eastern boundary. Patton "claimed this to be probably the largest and the best training ground in the United States" (Meller 1946) (Fig. 1).

In addition to the vastness and remoteness of the area, the presence of water, and established rail and highway systems provided the infrastructure necessary to support the many activities. The purpose of the DTC was to be; "training in desert warfare. Equipment was to be tested, tactical doctrine applied, and the techniques and methods of training developed" (Meller 1946). GHQ established the Command structure. Maj. Gen. Patton, commander of the I Armored Corps, was to have

Fig. 1 MG George S. Patton Jr. takes a magnetic azimuth while standing next to his M3 Stuart Light Tank at the DTC. (Photo from Heritage Center of YPG)

concurrent command of the DTC. The Corps would occupy the DTC and conduct training on numerous missions and training objectives, culminating in a Corps level maneuver. “The I Armored Corps, whose total strength was less than a Division, arrived and trained under Spartan conditions” (Meller 1946).

Patton saw the harshness of the desert as a plus in hardening the men, and also to weed out weak leaders. “The first few weeks involved small-unit activities that emphasized teamwork and junior officer leadership. The last 2 weeks involved larger units and focused on vehicles, weapons and equipment” (Bischoff 2002). This exercise, consisting of approximately 225 vehicles and about 10,000 men was not the force-on-force maneuvers envisioned by AGF and Patton. Patton’s tenure at the DTC was short lived. “General Patton and the I Armored Corps were withdrawn suddenly. Their successors, Maj. Gen. Alvan C. Gillem Jr., and the II Armored Corps, encountered confused conditions because of his hasty withdrawal…” (Meller 1946).

Operation Torch, the amphibious landings of the U.S. Forces in North Africa, began in November 1942. Ironically, the units that fought in North Africa had not trained at the DTC because world events were moving faster than the Army’s training plan. Units in contact with the enemy learned deadly lessons, which were rapidly transferred to the DTC. Soon, the tide of battle began to turn in favor of the Allies. With the war in North Africa moving to a successful conclusion, there was less need for desert specific training. The mission of the DTC began to change. Initial growing pains had been overcome, yet there still existed difficulties in providing realistic training. "To overcome these difficulties and train units, under combat conditions, the concept was broadened. The center was established as a simulated Theater of Operations" (Meller 1946).

MG Walton Walker was placed in Command of the IV Armored Corps and oversaw the transition to a Theater of Operations early in 1943. Land expansion brought the training to Arizona. Camp Laguna was the first of the Arizona based Divisional Camps. Other Divisional camps in Arizona would soon follow. (The current footprint of Yuma Proving Ground (YPG) fits within the area of Camp Laguna, and includes some of the training and maneuver areas of the other Arizona camps.) McNair was pleased with the new direction. In a letter to Walker, he wrote; "I want to express my appreciation of all you have done, of the fine morale and spirit which prevails the place, and of course, above all, training progress achieved … I say this, of course, without criticism of Patton, who was the pioneer and who made a fine start" (Meller 1946).

In October the name of the DTC was officially changed to the California—Arizona Maneuver Area (C-AMA). McNair expressed the new direction in a straightforward manner; "Some officers and men have reached the wishful conclusion that the termination of the African Campaign has rendered desert training unnecessary. Desert training is merely an incident; the main objective is tough, realistic general training" (Meller 1946). Patton's view that the training should be tough, and lacking in all frills, stood the test of time. Walker, who had trained both a Division and a Corps in the Desert, saw the bigger picture; " It is our job to rehearse for war, to bring these units to that state of perfection that will be demanded of them by actual warfare, the perfection necessary to win battles" (W.E.B.S. 1984).

The operation of the DTC/C-AMA had always been plagued by a lack of service units. The switch to a more realistic form of organization forced the service and supply units to provide the necessary supply and service functions to their respective organizations under extremely harsh and realistic conditions. Later, under combat conditions, those units appreciated the training they had received in the desert. Increasingly, service units were being shipped out to overseas assignments. McNair recommended to the War Department that the C-AMA be closed (Meller 1946) and on 1 May 1944, it was. The success of the DTC/C-AMA may be summed up with comments made by members of the 3d Armored Division. "Desert Maneuvers of 1942 probably did more to toughen the 3rd and prepare it for ultimate combat than had all previous training" (Bischoff 2000).

Equipment testing had always been a part of the DTC/C-AMA. The Desert Warfare Board worked with the DTC/C-AMA to have equipment tested and evaluated (Fig. 2). Laboratory tests are by their nature, extremely controlled events. The process used is commonly known as the scientific method. In a natural environment, it is impossible to limit those variables caused by the naturally occurring geography and climate. While it is much harder to stay true to the scientific method while testing within a natural environment, results and conclusions so derived may be thought to be more akin to the real world.

Fig. 2 M3 Lee tank fitted with experimental blade at the DTC. (Photo from Heritage Center of YPG)

The Quartermaster Desert Test Command HQ's was established at Camp Seeley CA (near El Centro California). According to their first Commander, LTC J.E. Engler "No one knew how this job was going to develop. There were tents, the desert, its heat, and a great deal of room" (Engler 1945). The test range extended well to the east, encompassing most of the Imperial Sand Dunes and Yuma desert. While the testing at Camp Seeley started out as a means to answer questions regarding potential use in North Africa, it quickly became clear that the harsh environment of the desert was a place to bring about test results quickly. Initial tests "gave a good comparison picture rather than real scientific data" (Engler 1945).

Throughout the summer of 1942, cooperation with industry and the Quartermaster Corps would yield new designs and new test requirements. Desert testing became "more and more laboratorial in approach and in data produced." (Engler 1945). Subsequent testing would become more general, less specific to the operation of a given item in a desert environment. The desert terrain and environment were seen as a means of shortening development time by testing under the harshest of conditions, thus revealing material weaknesses more quickly.

The Ordnance Corps had been given the additional responsibility for all motor transport and for establishing standardized requirements across product lines. Tests for the octane rating of gasoline used in Army vehicles, tests of other petroleum, oils and lubricants, (POL) and vehicle cooling systems were assessed under these extreme conditions. In addition to the Army Transport vehicles, tanks became a mainstay of testing once Ordnance took over (Fig. 3).

The mobility of Army equipment was always a matter of concern. Water from nearby irrigation canals allowed for testing in muddy conditions. Local mountain chains or trips to the Yosemite National Park gave data for performance at altitude and at much colder temperatures.

By July of 1943, the Ordnance Desert Proving Ground was well established. Air cleaners were a large part of the testing. Dust courses were created to allow for the controlled production of dust. Test course grooming in order to assure consistent and valid data was introduced into the testing regimen. As testers became more proficient at their field of practice, the scientific method became more and more a part of their evaluation methodology.

Fig. 3 Stuart Light Tank undergoing testing at Camp Seeley. Note the side mounted racks with concrete blocks to increase test weight of vehicle. (Photo from Heritage Center of YPG)

Camp Seeley closed in February 1944. The personnel of the Desert Proving Ground went back to Aberdeen Maryland to receive training for their new job of gathering technical intelligence in Hitler's test facilities and proving grounds. Though closed, desert testing was not forgotten. The former test courses would play a part in the future of testing in Yuma.

While Camp Seeley may be the spiritual predecessor to YPG, the Yuma Test Branch is the physical predecessor. The Special Bridge Test Section of the Engineer Board occupied leased housing and about 13,798 acres near the Imperial Dam on the Colorado River. This activity was necessitated by a major problem with a new bridge the Army had adopted.

From the seventeenth century to the end of World War 1, little had changed in ponton bridge technology. Wooden boat hulls as pontons, wood stringers and flooring were still the standard for many ponton bridges. Pneumatic floats, previously unsuitable for use due to the rapid onset of dry-rot, were being used by the Germans in 1940. With improvements in rubber and rubberized fabrics, the American Army was ready to develop a ponton bridge utilizing pneumatic floats. Adapting the Steel Treadway Bridge, a design used to cross dry gaps, laid on top of these new floats, the M1 Steel Treadway Bridge showed great promise. Following a demonstration of capabilities at Fort Benning in 1941, the Armored Force adopted the M1 Bridge. Little did the Army realize that trouble was looming.

"The Storm broke in the fall of 1942; In the course of 5 weeks, four serious accidents occurred while tanks were crossing the bridge" (Coll et al. 1958). The first bridge accident occurred during training at the DTC as units used the Colorado River to practice tactical river crossings. Two incidents at Fort Benning were followed by one in Tennessee. The Engineers suspected a design problem. Armored Force Commanders thought it entirely a training issue. They urged the Engineers to leave the bridge system alone.

The Army Corps of Engineers blamed a lack of testing on the problems. "It underlines the fact that we have adopted a bridge that is essentially untested …" (Coll

Fig. 4 M-4 Sherman Tank in the midst of an M1 Steel Treadway bridge failure during testing on the Colorado River. (Photo courtesy of the U.S. Army Corps of Engineers)

et al. 1958). Without test data, the Engineers did not know the cause of the bridge failures. Was it training or design?

To answer this question testing was conducted just north of Yuma, near the Laguna Dam on the Colorado River (Fig. 4). During tests conducted in November of 1942, Lt. Col. Mullins determined "that stream velocities would be of tremendous concern whenever bridges with supports of this type were used" (Howard 1976). The pontons featured blunt ends and this was thought to contribute to the failures. "Hard upon this disaster came news that tanks would become both heavier and wider" (Coll et al. 1958). Many questions surrounded the decisions to modify bridges, adopt the British Bailey Bridge, or design a new system altogether. These were all tied to an as yet unknown set of requirements based on bigger, heavier loads. The recent bridge disasters were fresh in the minds of the engineers. The vital role of testing had been reinforced from the hard lessons learned.

The Laguna Dam trials had shown the benefit of being able to assess the floating bridges under realistic conditions. The ability to utilize the dam's equipage to regulate the conditions of the test was a huge advantage; however, the area around Laguna Dam was not suitable for developing a test facility. A new site was selected at the Imperial Dam "for the purpose of testing all floating equipment to be used by the engineer troops" (Howard 1976).

Colonel George W. Howard was the Chief of the Special Bridge Test Section. He arrived at the test site near the Imperial Dam on 20 January 1943. This location was a branch activity of the Engineer Board and quickly became known as the Yuma Test Branch (YTB). "For 2 years the Test Branch was one of the busiest places in the nation. Important results were achieved in a minimum of time" writes Howard (1976). Results from the Laguna Dam testing were used by the engineers to come up with two new designs. The bridges were shipped to Yuma for immediate testing. Working 16 h a day, 6 days a week, Howard's Test Branch "completed the development of the Steel Treadway Bridge, M-2, in less than 1 year" (Howard 1976).

Key to the unique testing afforded at the Imperial Dam was the Gila de-silting basin. Water from the Colorado River would enter the basin, and the silt would

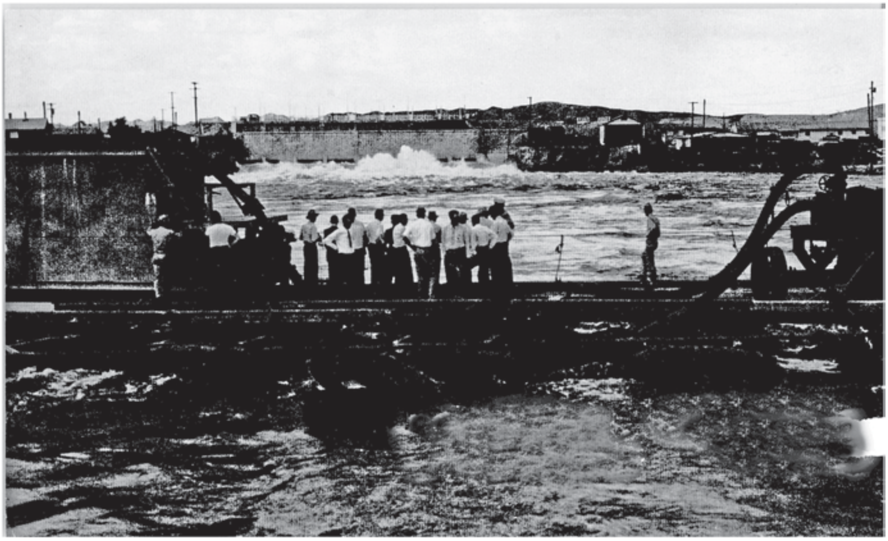

Fig. 5 Demonstration of a bridge test down-stream from the Gila de-silting basin (seen releasing water in the background) with metal container to vary weight loads seen on the left side and the irrigation pump to add or remove water from the load seen on the right. The presence of men dressed in neck ties indicates this was a demonstration for a group of VIP's. (Photo from the Heritage Center of YPG)

settle while relatively clean water was diverted into the Gila gravity canal. Occasionally the basin would be flushed by allowing the Colorado River to pass freely through the gates of the basin. This feature allowed the bridge testing engineers to analyze at a variety of stream velocities. Load weight on the bridges was easily varied using large metal containers that could be filled or emptied of water to achieve the appropriate amount of load for a given test (Fig. 5).

YTB would play a key role in the continuous testing of bridging materials, boats, rafts, ferries, trailers and well drilling equipment. Studies into how to quickly create a remote airfield may have resulted in the Laguna Army Airfield being built with experimental equipment in 1943. Like Camp Seeley, YTB's results confirmed the wisdom of conducting Test and Evaluation in a natural environmental setting. It drastically shortened the development time for their final products. Col. Howard estimated that during peace time, the development program for the M-2 Treadway Bridge would have taken ten times longer (Howard 1976). The Secretary of the Army's commendation to LTC Howard for his work on the M-2 Steel Treadway Bridge stated that "This floating bridge was the most important structure in that campaign, both to the United States and her Allies" (SEC Army Commendation Certificate 1946).

The war ended with the dropping of two atomic bombs on Japan in August 1945. The dreaded invasion of the Japanese homeland was averted and the Army set about to de-mobilize. In the following year many studies were conducted to review the lessons learned from the wartime experience. Organization, equipment, tactics and doctrinal reviews were held within each branch and technical service of the Army. MG G.M. Barnes, called the successful industrial mobilization of our country's resources "the greatest of all research and development programs", (Barnes 1947) and suggested that much had been learned in how to carry on in the post-war period. "We were fortunate in this war that time was available to develop and produce the necessary modern weapons. It can be readily imagined that, because of new technological development, a future emergency may arrive with such suddenness that time might not be available for putting carefully laid plans into operation. It will be necessary during peace not only to formulate these plans and designs, but very largely to execute them and be prepared to strike immediately" (Barnes 1947).

According to Barnes, the keys to this success had been the partnerships established between industry, academia, and the armed forces. The model was thus established; the armed forces understood best the material requirements and the conditions of use. Academia and other researchers understood best how to develop the newest findings from the fields of science and technology. Industry knew best how to produce the required materials. On the end of that process, it was the job of the armed forces to determine, through test and evaluation, if the materials met the requirements. While both Ordnance and Engineers had noted that their test facilities had been of great value to quickly meet the material needs of the Army, they also recognized that this capability had been hard to implement. One of the big lessons learned was that this capability to test in the natural environments should be sustained, if not expanded. In most cases, these recommendations were not taken up or funded in the post-war environment.

Much of the post-war review done in the Army focused on the tactical and operational levels of the Army's war-time experience. Major Robert A. Doughty notes the Army's problem in the new strategic environment;

> While the postwar strategic environment encouraged the reconsideration of doctrine, it also made the formulation of Army doctrine especially difficult. Since the American atomic monopoly seemed to have provided the perfect response to any threat, many Americans questioned the need for large ground forces. Many believed an act of aggression would result in all-out war which the United States would inevitably win with its atomic weapons. Given the Air Force monopoly over the delivery means, the Army's potential contribution seemed much less than in the past. Questions concerning its tactical doctrine also seemed less important. The introduction of atomic weapons seemed to forecast the demise of ground combat. (Doughty 1979)

The Army disagreed with this assessment, seeing a continuing need for ground combat capabilities, even in a strategically atomic environment. These capabilities, reinforced through the review of lessons learned during the war, were much the same capabilities that the Army had developed during the war. While atomic weapons and the strategic doctrine derived from their use was seen as revolutionary in nature, the Army contemplated evolutionary changes.

For YTB "the feverish pace of wartime activity was moderated" but not, the Engineers recognized, the "usefulness and value" of the facility (Howard 1976). Plans were put into effect to establish YTB as a permanent base. The viability of YTB was evident from the increasing work load and test schedule. In 1947 the Army Ground Forces and Board #2 sent Task Force (TF) Furnace to the Branch to determine the effects of the desert environment on ordnance equipment. Situated around the Laguna Army Airfield, men and equipment were tested in the extreme temperatures of the desert. It was also a busy year for the construction work on the new permanent installation being built southeast of the Imperial Dam site. Ground breaking ceremonies were held on 28 March 1947 and the new facilities were finished in 1948.

Problems with the Gila de-silting basin brought about mission ending change in 1949. Pressure build-up under the cement basin caused a major upheaval of the slabs, rendering the basin inoperable. This brought an effective end to the ability to test bridges downstream of the Gila sluiceway. Though some testing was attempted on the California side of the dam, bridge testing was finished as of 19 October 1949. Although the base was closed on 1 January 1950, the closure would be short-lived.

On 25 July 1950 the political division of the Korean Peninsula would come to a head when forces from the North invaded the South. American intervention was swift, but limited to troops available from the occupation forces in Japan. This was Task Force Smith, that "arrogant display of strength" (Garret 1999). The reasons for the failure of Task Force Smith are many and well studied. TF Smith is normally characterized as being under strength, poorly trained and ill-equipped. Much of the equipment they did have, especially munitions, failed to operate. TF Smith held for a mere 3 h, and their retreat south has been characterized as a rout. Subsequent defensive lines formed by elements of the 24th Division fared as badly, and for many of the same reasons. There were few good answers to the questions raised by these failures. One of the big questions was, of course, how did we go from having one of the best equipped armies in the World in 1945 to such a sad state of unpreparedness just 5 years later?

America had to once again create facilities and programs that had been successfully in place just a few years before. Among them was the need to find a facility capable of conducting the test and evaluation of Army materials and systems under a variety of natural environmental conditions and climactic extremes. Dr. Paul Siple was chosen to find a location for the conduct of testing in the desert climactic environment. Dr. Siple's official title was the Special Scientific Advisor, Army Research Office, Office of the Chief of Research and Development, Department of the Army. Dr. Siple was best known to America as the Boy Scout, who in 1936 accompanied Commodore Byrd on his first exploration to the Antarctica. Later he becomes known as a geographer and co-developer of the Wind Chill index (Heidorn 2002). In Dr. Siple's search for the new desert test facility, the choice came down to Yuma or another location in Nevada.

Yuma had several things going for it. Ordnance testers from Camp Seeley and TF Furnace had good things to say about the area around Yuma. The desert terrain was varied and analogous to many of the world's desert regions. In addition, the factors of vastness and remoteness, coupled with established infrastructure would make for an ideal test site. The icing on the cake was the recently closed Yuma Test Branch. Here was a fairly new military installation sitting in the midst of the ideal location for a desert test site (Swisher 2006).

The Yuma Test Station (YTS) was quickly established and an accelerated program of organization and construction was initiated to permit immediate use of the

Fig. 6 M65 "Atomic Canon" undergoing firing tests at YTS. (Photo from Heritage Center of YPG)

mothballed facilities. These would be used to conduct tests "in an environmental situation approximating conditions of actual use under controls comparable to those governing good laboratory practices (OTA 1952). Major Bill Swisher was the newly assigned Operations Officer who, along with Dr. Siple, worked with the members of the various test activities and boards to determine their needs. Their requirements served to determine the extent and nature of the new test ranges (Swisher 2006). In a memorandum dated 19 September 1951, permission for the transfer of the nearly 890,000 acres of land from the Department of the Interior to the Army was granted. YTS was host to six test activities and three Army development Boards. The Ordnance Test Activity was the largest and most frequent user of the test activities, while testers from the Corps of Engineers, Quartermaster, Signal, Chemical, Medical, and Transportation Corps, were also frequent tenants. Evaluation facilities included firing ranges, mobility courses, supporting laboratories, arms and ammunition labs (as well as manufacturing facilities), maintenance facilities, and machine shops in order to support full-scale climactic testing as envisioned by the Army. Summer, when conditions would be the hottest, was the prime time to test. Priority went to developing the firing front in order to support testing of the Army's 280 mm "Atomic Canon" (Swisher 2006) (Fig. 6).

Test programs at YTS were to;

> "… provide to the greatest extent possible, the establishment of clearly defined test objectives, the development and application of relatively precise and consistent methods and procedures, the complete and meticulous recording of data, the coordinated preparation of test reports to permit data comparison and correlation, and the impartial evaluation of the data thus derived… Such controlled technical tests, conducted in the field, provide basic data which can be used to formulate design criteria and permit most effective re-design or modification within the limits of good engineering practice and economy. Following the scientific method, YTS would provide complete information regarding the stresses and deficiencies that develop only under conditions of actual use." (OTA 1952)

During the winter months, testers from Yuma often found themselves in colder more arctic-like regions for testing. Some would go to Fort Churchill, in Manitoba Canada. Others would go to the site of the former Camp Hale, in Leadville Colorado.

The historical imperative to conduct such testing is deeply rooted in lessons learned from World War II and Korea. The Cold War provided a constant impetus for developing new capabilities while ensuring current capabilities met the needs of our national defense. We see over the period of our history at the U.S. Army Yuma Proving Ground (YPG) that a direct correlation between a particular geographical and climactic environment where our Armed Forces are committed, and a perceived need to test in a similar environment. These connections were made between the pending 1942 invasion of North Africa and the establishment of facilities in the Desert Southwest. We see it again as the extreme cold of Korea spurred on testing within the extreme conditions of the arctic. The war in Vietnam saw an increase in testing at our Tropic Regions Test Center. Even today, people point to our deployments to Iraq and Afghanistan and draw connections to the geography and climate of YPG. All of these connections make sense, and one can certainly find historical verification, though this is only part of the story.

During the period of operation of the Yuma Test Station (1951–1963) it was true that testing was seen to be most valid when items were tested during the high-heat conditions of the summer. During the winter months test teams were often sent to Fort Churchill in Manitoba Canada in order to conduct cold regions testing. Today, cold climate evaluations are done at Fort Greeley Alaska. This was completely in keeping with the focus on conducting RDT&E within a climactic and environmental extreme, but not necessarily a focus with any direct connection to ongoing hostilities. As we have often learned the hard way, when we wait to develop the means to operate within a particular environment until the materials, equipment and systems are required, we are probably too late. Too often we have sent our soldiers into harm's way with equipment that did not meet their needs. Historically this has led to degraded performance of our military forces with potentially dire consequences for our Nation. For soldiers in the field, the dire consequences are often immediate and fatal. Aside from issues of force effectiveness, we owe it to our soldiers to provide them equipment that will work wherever they may be sent. The best way to guarantee this is to expose the items to the most rigorous testing possible.

Patton's positive assessment of the DTC was due in large part to conditions not related to a specific Theater of Operation. It was the vastness, remoteness, and access to water and transportation that led General McNair to expand the Training Center while he declared "desert training is merely an incident" (Meller 1946). These same conditions have contributed to the success of the on-going RDT&E missions conducted at YPG.

Since 1964 the Yuma Proving Ground has been designated as a full-spectrum test center (Fig. 7). The 70's saw the skies above YPG fill with Air Force planes and the development of the equipment as the NAVSTAR—GPS system. Improvements in our ability to conduct RDT&E in general have ensured a steady stream of business at YPG. Several hundreds of miles of fiber optics link our ranges to sophisticated automated processing centers were data collection and data reduction come together

Fig. 7 M109 "Paladin" 155 mm Self Propelled Howitzer on purpose-built 60 % vertical slope at YPG. (Photo from Heritage Center of YPG)

in near real time. Our multiple capabilities to test for weapons systems, mobility systems, and air-based systems create a great deal of synergy within our nearly 860,000 acres of fully instrumented test ranges.

We like to point towards our higher command's motto of; "We Test for the Best". We do this while maintaining fealty to the scientific method. We do this while sustaining our test ranges and facilities so that they may continue to offer realistic and repeatable conditions. The natural environmental test setting of the Desert Southwest has served our Nation well. From those harrowing days following our unprepared entry into World War II until today, the desert has hosted a variety of activities that have allowed us to successfully prepare for war while we provide for the defense of our Nation.

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The Influence of Physical Geography on the Battle of Kasserine Pass, Tunisia 1943

Daniel A. Gilewitch and Jay D. Pellerin

Abstract The first significant WWII encounter between the American 1st Armored Division and German panzer divisions occurred at the Battle of Kasserine Pass in central Tunisia in February, 1943. The battle was a devastating defeat for the Americans and a significant blow to American morale and prestige. Axis forces handled the green American soldiers easily, defeating them in detail at Sidi Bou Zid and again at Sbietla; but as Allied reinforcements arrived and terrain turned more restrictive in the mountain passes around Kasserine, the Axis attack culminated. Eventually, the Allies gained the initiative and did not lose it again in the North African Theater. Both poor preparations for combat operations in the desert environment and an ill-conceived and poorly tested armor force doctrine contributed to the American defeat. This study examines the conduct of the engagements at Sidi Bou Zid, Sbietla and in the vicinity of Kasserine Pass itself. In the end, it was the restrictive terrain west of Kasserine Pass as much as the efforts of the Allied troops that forced Rommel's forces to culminate short of obtaining his objectives.

Keywords Kasserine Pass · North Africa · Desert warfare · Physical geography · Weather · Panzer · Operation TORCH

1 Introduction

Physical geography has always played a critical role in warfare. Terrain, vegetation, rivers and weather have at times been the decisive factor in success or defeat on the battlefield (Winters et al. 1998). This pattern repeated itself at Kasserine Pass, Tunisia in the winter of 1943. This series of engagements pitted the untried and relatively combat inexperienced American 1st Armored Division (1st AD) against

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German and Italian Panzer units that had been fighting in either the Eastern Front or in North Africa for months. The battle was initially a devastating defeat for the Americans and a significant blow to American morale and prestige, but the tide eventually turned and Axis forces were never able to regain the initiative in the North African Theater. This research investigates the conduct of the battle and the influence that terrain and weather had on its outcome in order to better understand the relationship between warfare and physical geography. Nascent American combined arms doctrine and a lack of training in desert warfare contributed significantly to defeat early in the battle, but a change in the battlefield environment that constricted maneuver as the Axis attack progressed, significantly contributed to the ultimate American victory.

2 The North African Campaign

The location and timing of American entry into WWII was a hotly debated topic amongst Allied planners in 1942 (Howe 1957). America had adopted the 'Germany First strategy' at the Arcadia Conference in Washington, D.C. in late 1941 despite the debacle in the Pacific at Pearl Harbor (Eisenhower 1948; Hastings 2010), but the decision as to where and when to deploy troops was not a foregone conclusion (Coggins 1980). The American War Department favored a cross-channel invasion as early as possible to get Americans on the European mainland, the most direct route to Germany, but British planners favored a landing in North Africa (Howe 1957). President Roosevelt insisted that American ground forces be committed somewhere in Europe during 1942 (USMA 1979). Because the buildup of a sufficient force to invade France was not possible that year, he felt that an invasion of northwest Africa would offer the Allies several advantages. It might provide some relief to the Russians by opening a second front. It would drive Field Marshall Rommel out of Africa, saving the Allies millions of tons of shipping annually by allowing a short trip through the Mediterranean to India, the Middle East and a land route to the Soviet Union via Iran, all under allied air cover. Also, it would strike at Germany without getting the inexperienced American forces within reach of the entire *Wehrmacht* (Coggins 1980; USMA 1979). The British clearly preferred this effort. With President Roosevelt's approval, Operation TORCH, the Allied invasion of North Africa, was launched in November 1942.

3 Operation TORCH

The Axis center of gravity on the African continent in October 1942 was the Panzer Army Africa (Eikmeier 2011). That Army, under General Erwin Rommel, had been fighting the British 8th Army in northern Egypt and Libya since March, 1941. On 5

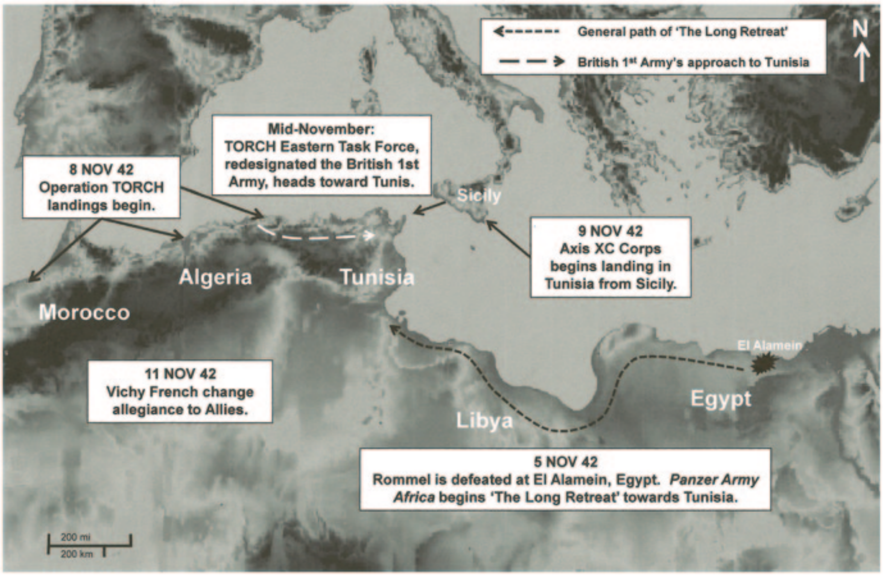

Fig. 1 The race for Tunisia, November, 1942. Following the nearly simultaneous defeat of Rommel's Panzer Army Africa at El Alamein and the successful TORCH landings in North Africa, both sides attempted to secure Tunisia

November 1942, the newly promoted Field Marshall Rommel was defeated by the British at El Alamein, Egypt, and began what became known as 'The Long Retreat' to Tunisia, a distance of over 2000 miles (Fig. 1).

Three days later, on 8 November 1942, Operation TORCH kicked off with American and British landings at Casablanca, Oran and Algiers. The ultimate objective of the operation was to set the stage for "the earliest possible occupation of Tunisia" (Headquarters 1942). Once the landings were secure and Vichy French forces in North Africa nullified, the Allies would capture the ports of Bizerte and Tunis in Northern Tunisia (Fig. 2), thus cutting off Rommel's escape route from the continent.

Almost simultaneously however, Axis forces began to land at both Bizerte and Tunis to reinforce Rommel. These forces arrived piecemeal, some 750 soldiers were airlifted in each day, and the first ships with tanks, guns, trucks and fuel arrived on 12 November (Coggins 1980). The newly formed German XC Corps was commanded by General Walther K. Nehring, and he wasted no time in ordering his troops westward to meet the new Allied threat moving east from the TORCH beaches. At the same time, Vichy French forces, who initially opposed the Allied landings, switched sides and began to fight for the Allies.

Thus, the stage was set for combat operations in northern Algeria and Tunisia. The Operation TORCH Eastern Task Force was designated the British 1st Army and pushed to Tebourba, Tunisia in an effort to split the German bridgeheads (Howe

Fig. 2 Leading up to the Battle of Kasserine Pass, January, 1943. In the *north*, the British 1st Army advanced on Tebourba in an effort to split the German Bridgeheads at Bizerte and Tunis. The 19th French Corps moved into central Tunisia and the American II Corps took up positions to the *south*

1957) (Fig. 2). A series of sharp battles occurred with American forces deeply involved, but the Allied offensive ended in late December 1942 without gaining the ports.

The now allied French 19th Corps eventually moved south of the British 1st Army to take passes through the Western Dorsal of central Tunisia and push to the Eastern Dorsal (Fig. 2). The American II Corps, under General Lloyd Fredendall, also moved south and established its headquarters and a large supply base in Tebessa. By the end of January 1943, the Americans were situated in defensive positions south of the French 19th Corps in the large desert plateau between the Dorsals, content to build combat power for a final attack towards Sfax on the coast that would split the Axis forces centered in Northern Tunisia from Rommel's approaching army in the south (Fig. 3). The Axis forces, however, were not content to wait.

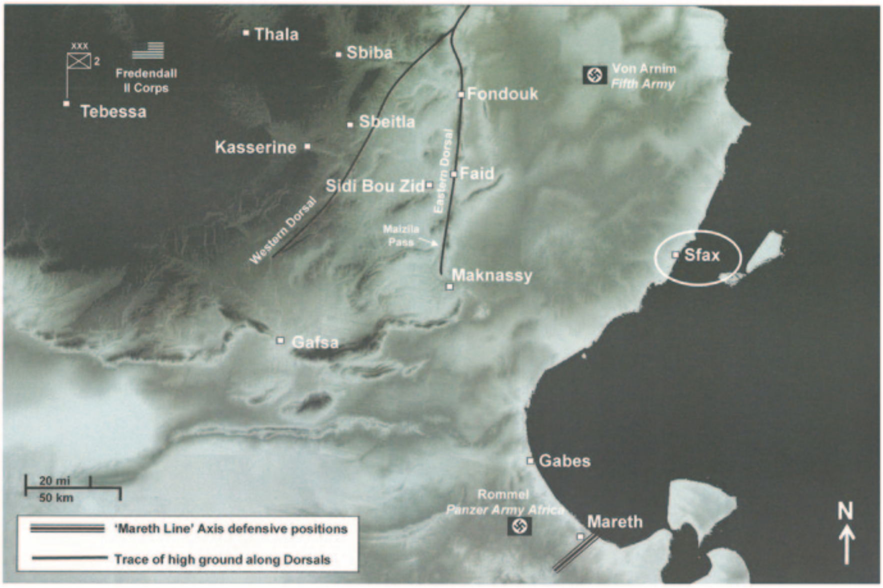

Fig. 3 Rommel's Panzer Army Africa closed on the Mareth line in late January, 1943 and prepared defensive positions against the British 8th Army approaching from the *southeast*. Axis leaders saw an opportunity to combine their forces and launch an offensive against the inexperienced American units before the British arrived. Meanwhile, the US II Corps commander was contemplating an offensive to take Sfax and split the two German Armies

4 Battlefield Geography

Unlike northern Tunisia's Mediterranean (Csa) climate, the region in central Tunisia where the Kasserine engagements were fought is a steppe (BSh) climate quite close to the arid (BWh) climate zone transition. The battle area in lower elevations is typical of desert regions marked by large, flat sandy valleys and rocky highlands. Higher elevations are covered with pine, cedar, and oak forests that give way to sparse xerophytic vegetation on the lower slopes due to altitudinal zonation. Terrain in the lower elevations is somewhat similar to the desert in northern Libya and Egypt, or the Southwestern United States.

Visibility is excellent on a clear day, but like most deserts, the terrain is deceiving with seemingly open areas crisscrossed by steep-sided wadis and with soft surfaces that bog down vehicles. Dust storms are common in the region and can last for hours, cutting visibility and noise detection significantly. Bedrock is exposed on most hills, causing troops difficulty in digging defensive positions and increasing the effectiveness of artillery as rock shards act as additional shrapnel. Like in most desert regions, the area of operations was much larger than the Americans had been accustomed to in either the United States or in northern Tunisia.

Central Tunisia is broken by the Aures Mountains that are divided into an inverted 'Y', with the stem in the north and the fork occurring near Djebel Fkirine

(988 m) (Fig. 2) (Coggins 1980). The eastern prong (Eastern Dorsal) runs south about 125 miles to Maknassy and the other (Western Dorsal) runs southwest towards the Algerian border. The Eastern Dorsal marked the farthest Allied advance by February 1943, and is split by several low lying passes that were key terrain in the early stages of the battle. There is a plateau between the Dorsals that is crossed by several ephemeral streams generally running west to east and is dotted with orchards, grain fields and cactus. The Western Dorsal marks a transition to the Aures Mountains, part of the Atlas Mountain Range. In the vicinity of Kasserine and farther west, hills and mountains dominate the landscape, making travel difficult and providing steep slopes and high elevations best suited to the defense. Average annual rainfall is 16 in. with a winter concentration (Coggins 1980).

5 The Context of US Armored Force Doctrine

American armored force doctrine applied by inexperienced troops at Kasserine proved to be inadequate against a seasoned force in the desert environment, setting the stage for initial failure in the battle. Emerging doctrine in 1941 was developed rapidly as a reaction to misconceptions of German "*blitzkrieg*" that was so successful in the takeover of Poland and France (Calhoun 1988), and again appeared successful for Field Marshall Rommel in North Africa. The popular idea that *blitzkrieg* entailed massed columns of tank-pure panzer formations breaking through static lines of defense and wreaking havoc in the rear areas, is simply not accurate. German tactical achievements were based on a combined arms doctrine that ensured tanks were closely supported by infantry, artillery, and close air support. Although Americans acknowledged the importance of combined arms, actually devising a workable doctrine and organization was a difficult task based by necessity on theory, not practice.

In an attempt to capitalize on the mobility and protection afforded by armor as demonstrated by the Germans, the Army reorganized on the eve of war into ad hoc combined arms teams in its tank divisions. These 'Combat Commands' (CCs) were brigade size forces that were temporarily task organized according to the current mission. While this reorganization increased the tank division's flexibility, it also tended to degrade cohesiveness because units were not necessarily accustomed to working together. Furthermore, if a tank division was divided into more than two CCs, its combat power was diluted substantially, making it nearly impossible to mass the division's tank force. The concept of CCs was overall successful and not abandoned by the Army until 1961, but at Kasserine, the idea was poorly executed.

Belief in the tank's offensive power led to a diminishing value associated with reconnaissance and the defense in American doctrine. "The swift advances made by the German Army in Poland, Norway, Belgium and France indicate that no time has been wasted in feeling out the enemy. Objectives are assigned and then attacked without prior reconnaissance. Reconnaissance is conducted at the same time as the attack," (HQs, IV Corps 1940, p. 39). This premise was not correct, but was adopted in the 1939 edition of US operational doctrine that employed tanks almost like heavy cavalry, massed at the right moment after the battle had already started. A failure to conduct reconnaissance played a critical role in the disastrous American counterattack at Kasserine.

Although the Army held some faulty ideas, it attempted to learn through experimentation. The Louisiana and Carolina Maneuvers were conducted in 1941 to test and refine doctrine. Often heralded as the most significant training event prior to U.S. entry into World War II, these exercises were held in the restrictive terrain and temperate climate of the Southeastern United States. Both Louisiana and the Carolinas are heavily forested, humid, and relatively wet (Cfa). Substantial vegetation, steep terrain, rivers, and mud characterized much of the maneuver area, limiting line of sight and reducing the tempo of battle significantly, quite the opposite of typical armored warfare in the desert. During the maneuvers, units were stuck in traffic jams along muddy roads, had to repeatedly wait for bridging equipment, and often ended up ‘lost in the woods’ (Gabel 1992). This experience poorly prepared 1st AD for Kasserine and tactics developed during the maneuvers, while adequate during the early fighting in the more humid environment of northern Tunisia, did not fit conditions encountered in central Tunisia.

Doctrine that emerged after the maneuvers did a fine job of assimilating both good and bad lessons learned. Not surprisingly however, it did not adequately address adapting that doctrine to the desert environment. The new operations manual produced after the maneuvers contained only one and a half pages devoted to desert combat (FM 100-5 1941). Moreover, units that fought at Kasserine did not have an earlier opportunity to work with the doctrine in a desert environment. Ironically, the Army established a highly successful Desert Training Center in California in 1941, but none of the units that fought at Kasserine trained there. Their only training and combat experiences prior to Kasserine were in the relatively humid environment of the southeastern US, or northern Tunisia. As a result, 1st AD was rather poorly prepared for desert operations.

6 Situation in Tunisia on the Eve of Battle

By the end of December 1942, Allied effort to take the ports of Tunis and Bizerte had culminated. Stiff German resistance, wet weather and extended supply lines forced the Allies to go to the defense and gather strength for future operations in the spring (Zaloga 2005). They established a defensive line that extended south along the Eastern Dorsal. After a series of small engagements, the US II Corps took up positions in central Tunisia along a 50 mile front from Fondouk Gap to Maizila Pass, protecting the French 19th Corps’ right flank. The main combat force in II Corps was the 1st AD.

Throughout January, the Germans conducted a series of attacks at several passes along the Eastern Dorsal and demonstrated to both sides that the French 19th Corps, holding the Allied center, was critically weak. The British 1st Army commander responded by detaching CCB from the 1st AD and placing it behind the French line, spreading the US II Corps dangerously thin. By the end of January, the Germans realized they had an opportunity to strike the inexperienced American forces prior to any offensive that could be conducted by Montgomery's Eighth Army that was approaching the Mareth Line from the south. The Axis therefore, planned an attack at Faid Pass and Gafsa that would be launched in mid-February. Meanwhile, Eisenhower and his staff also devised a plan to attack in central Tunisia to capture the coastal town of Gabes, then move north to take Sfax (Fig. 3). Operation SATIN would split Rommel's forces in the south from XC Corps in the north.

7 Operation FRUEHLINGSWIND

In early December, *General der Panzertruppen* Hans-Jürgen von Arnim took command of the XC Corps, redesignating it the 5th Panzer Army. Both Von Arnim and Rommel wanted to combine their forces and attack westward to throw the Allies into confusion, allowing more time to reconstitute and receive reinforcements. The Axis strategy however, was limited by competing ideas between Von Arnim and Rommel (Fig. 4). Von Arnim's focus was to expand the Tunis and Bizerte bridgeheads and Axis-held territory along the coastal plain. He wanted to take Sidi Bou Zid with his organic 10th Panzer Division and the 21st Panzer, which was attached to him from Rommel for reconstitution. Once Sidi Bou Zid fell, the 21st was to be chopped back to Rommel for his attack on Gafsa (Howe 1957; Whiting 1984).

Rommel favored a much more ambitious plan—a wide westward encirclement of the Allies from Gafsa to Tebessa that could potentially end on the coast at Bone and force the Allies completely out of Tunisia (Howe 1957; Messenger 1982). The problem was that Rommel needed units from the 5th Panzer Army to accomplish this (Messenger 1982; Zalonga 2005). While the issue remained unsettled, on 14 February 1943, Von Arnim launched Operation *FRUEHLINGSWIND* (Spring Wind) using the 10th and 21st Panzer Divisions to seize Sidi Bou Zid (Fifth Panzer Army 1943).

8 The Battle of Kasserine Pass

The Battle of Kasserine Pass is actually a series of engagements that took place at Sidi Bou Zid, Sbeitla, and in the vicinity of the Kasserine Pass itself. The American 1st AD, under Major General Orlando Ward, defended the open plateau between the dorsals, and in a clear break from emerging US doctrine, was divided into four Combat Commands (CCs) and a Division Reserve spread out over 80 miles (HQs, 1st AD 1943). CCD was the Corps reserve located in the vicinity of Bou Chebka on the Algerian border, about 55 miles west of Sidi Bou Zid. CCB had been detached to 1st Army and was located behind the French 19th Corps vicinity of Maktar, about 80 miles to the north of Sidi Bou Zid, and CCC was the Division reserve located near Hadjeb el Aioun some 13 miles north of Sidi Bou Zid. CCA at Sidi Bou Zid

Fig. 4 Rommel and Von Arnim had different plans for an offensive in February, 1943. Von Arnim wanted to expand the Tunis and Bizerte bridgeheads; Rommel favored a wide westward encirclement from Gafsa to Tebessa to Bone

consisted of two Armor Battalions (40 M4 Sherman Tanks), three battalions of infantry, two field artillery battalions and a tank destroyer company. The bulk of CCA's infantry had been poorly positioned on the high ground at Djebel Lessouda and Djebel Ksaira by the Corps commander himself, General Lloyd R. Fredendall, who made the dispositions from a map reconnaissance at his Headquarters in Tebessa, some 50 miles away or 70 miles by road (Atkinson 2002; HQs II Corps 1943; Zalonga 2005) (Figs. 4 and 5). These units were out of supporting distance from one another, covering a much larger front than doctrine dictated, and the inexperienced American infantry failed to dig in well in the rocky high ground, although they did string barbed wire and emplace protective minefields (HQs, 1st AD 1943). Ironically, General Eisenhower himself visited Sidi Bou Zid about 0100 h on the morning of the 14th, but did nothing to improve the American dispositions (Atkinson 2002).

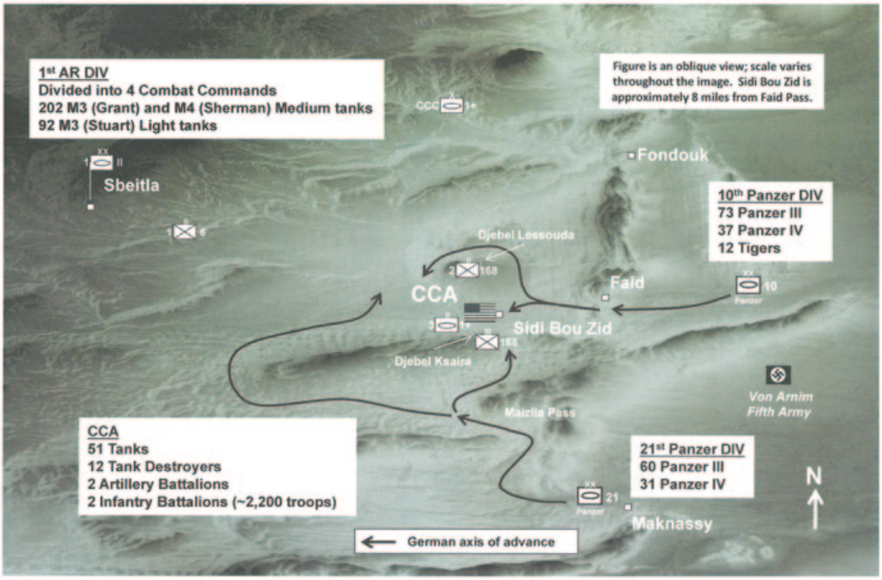

Fig. 5 Operation FRUEHLINGSWIND, 14 January, 1943. Under the cover of a sandstorm, General Von Arnim attacked the ill prepared Americans at Sidi Bou Zid; CCA was virtually destroyed

The Axis attack kicked off before dawn on Valentine's Day, 14 February (Fig. 5). It was a true *blitzkrieg* operation with tanks, closely supported by armored infantry, artillery, and Stukas, and conducted by the 10th Panzer Division, a veteran unit that had seen action in France and on the Eastern Front, and Rommel's veteran 21st Panzer Division, attached to Von Arnim, and probably the most experienced desert fighters on the planet at that time (Atkinson 2002).

9 The Influence of Physical Geography on the Conduct of the Battle

The desert environment had a significant effect on this battle, and magnified mistakes made by American Forces. During the night of 13 February, a strong northwest wind smothered sounds of the German 10th Panzer Division's approach toward Faid Pass. By 0400 in the morning, the wind had become a full-fledged dust storm. Forward elements of the American 2/168 Infantry Regiment, dug in at Djebel Lessouda, were supposed to provide early warning of an attack and call in a prepared artillery barrage, but they could not see or hear anything because of the storm. By 0630, the 10th Panzer had destroyed the battalion's observation posts and patrols near the pass, but the American main body on the hills was still unaware they were under attack (HQs, 1st AD 1943). By 0900, nearly 40 Panzer IV's had bypassed 2/168 Infantry on Djebel Lessouda to the north and the Stuka attacks began as soon as the dust storm cleared (Atkinson 2002; HQs, 1st AD 1943).

Meanwhile, the 21st Panzer Division made its way from the south, moving through Maizila Pass (Fig. 5). They hit a screening force near the pass and defeated it before warning of their approach could be made. The Panzers hit CCA from the south at 1345 h. It was a disaster. American units were either overrun or encircled. What was left began to retreat toward Sbeitla, leaving vehicles "stalled in soft sand or in wadis" (HQs, 1st AD 1943). The bulk of the 168th Infantry Regiment was trapped.

Because of the dust and confusion of battle, CCA never did identify the 10th Panzer Division as the attacking force (Howe 1957). This slowed Allied reaction to the assault because the leadership feared that it may be only a feint and the main attack would fall at Fondouk Pass to the north (Howe 1957). It was not until the next day, 15 February, that the 1st AD Commander, General Ward, eventually ordered his mobile reserve force, CCC (reinforced) to counterattack in order to restore the situation and rescue the 168th Infantry Regiment. Although doctrine suggested a dawn attack, CCC did not cross the Line of Departure until early afternoon and inexplicitly did not recon the route or objective. Initially, they moved across the level, open desert plain as if on parade, maintaining doctrinal distances until wadis and German artillery began to break the formation. It was a clear, dry and sunny day, typical of desert environments. Visibility was excellent. The two Panzer divisions had plenty of time to anticipate the attack and set up a combined arms ambush. Fighting lasted until 1740 h. CCC was enveloped and literally destroyed. II Corps was ordered to fall back to the western dorsal and exfiltrate its infantry from the high ground near Sidi Bou Zid (HQs, 1st AD 1943) (Fig. 6).

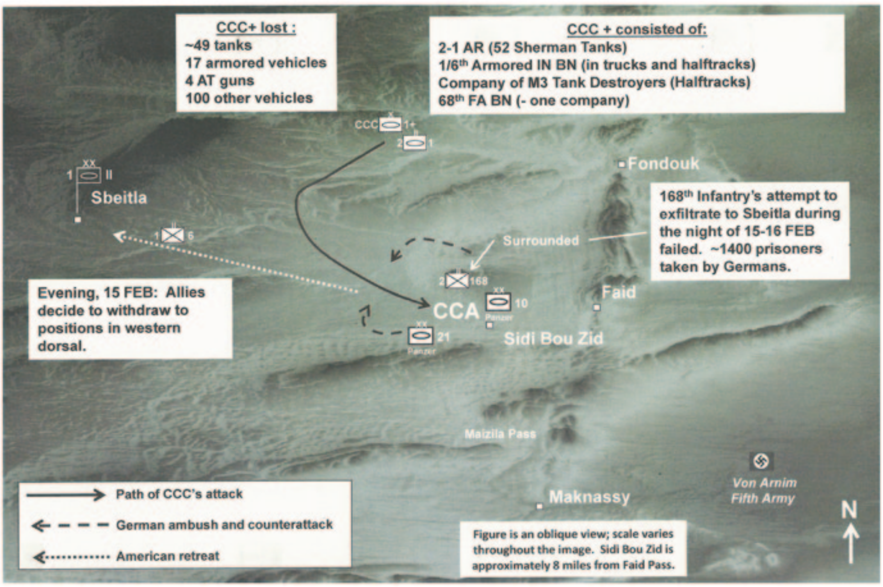

Fig. 6 On 15 January, CCC+ counterattacked toward Sidi Bou Zid. In accordance with doctrine that was tested in the temperate environment of Louisiana and Carolina, CCC launched without reconnaissance and was decimated by German forces

168th Infantry Regiment tried to escape that night, but because the distances were so great between defendable positions, they were caught in the open desert still moving toward Sbeitla at dawn. Almost everyone was captured, including the Regimental Commander and Colonel Waters, General Patton's son-in-law. American morale was shattered. A persistent rain that was to last 3 days began to fall.

The next day, 16 February, General Ward, reinforced now by the release of CCB from 1st Army, established his main line of resistance about 3 miles east of Sbeitla (Fig. 6). The terrain here was more broken and relatively unsuited for offensive tank warfare than that around Sidi Bou Zid. The persistent rain created slippery conditions that slowed movement across the uneven ground. The German attack came at about 1300 h on 17 February after significant probing and reconnaissance. Because of more favorable terrain, American tanks and anti-tank guns were well-placed in hull down positions in the wadis and Tank Destroyers were doctrinally sited on the flanks within supporting distance. The German attack was initially blunted, but American morale in 1st AD was in shambles after the beating they had taken earlier. By late that afternoon, defending American forces began to withdraw again, at a less-than-honorable pace in many cases (Atkinson 2002; Blumenson 1966). Sbeitla was lost. Then, the Americans got lucky.

9.1 The Axis Wastes a Day

Having obtained his objective, Von Arnim released the 21st Panzer to Rommel late on the 18th, but he retained the 10th Panzer Division, and sent it to Fondouk Pass to prepare to execute Von Arnim's follow-on operation, a plan separate from Rommel's (Howe 1957). Ironically, the Axis forces that had the initiative were dispersing and getting weaker, while the Allied forces that had been thinly spread, were attempting to consolidate. At this point, it was clear to the Allied leadership that the main attack was not going to be launched against the French 19th Corps to the north, but this attack was the major effort, and the 1st AD was hanging on by a thread. Eisenhower sent everything he could to the battle. It became a race between the Allies' ability to get reinforcements to the front and dig in along the higher ground near Kasserine Pass, and the German's ability to crush them with whatever forces were available.

Rommel arrived from Gafsa on 18 February with the *Deutsches Afrikakorps* (DAK) and the Italian *Centauro* Division with the intent to attack through Kasserine to capture the supply base at Tebessa (Fig. 4). Instead, he was ordered by Field Marshall Kesselring, Commander-in-Chief South, to make his main attack north to Sbiba (Howe 1957). Undaunted, he decided to try both routes with the intent to reinforce the one that had the most success. By now however, Allied reinforcements and replacement equipment were arriving in force.

Von Arnim finally released about half of the 10th Panzer to Rommel on the 19th of February, and now with sufficient forces, Rommel was able to launch his main attack toward Sbiba as instructed with the 21st Panzer Division. This unit was not used to fighting in mountainous terrain. The ground here was steep, broken by

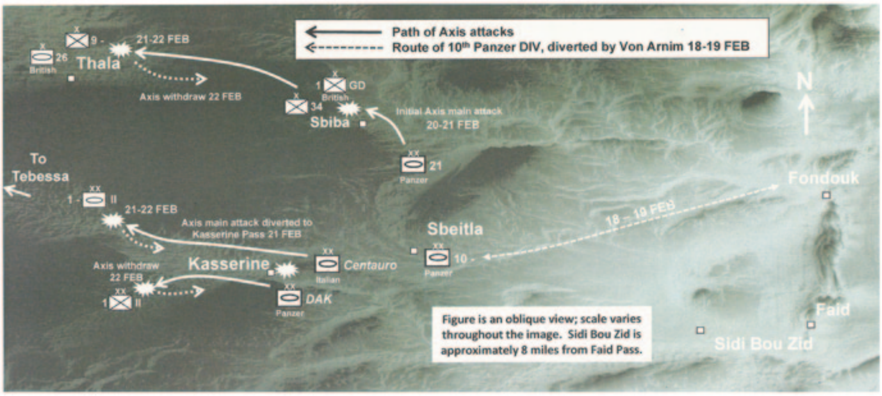

Fig. 7 Axis culmination. Rommel's forces become dispersed as they attacked in the steep terrain west of Kasserine, while Allied forces massed on the high ground. By 22 February, the German attack stalled and Rommel decided to withdraw

numerous wadis, and mud from the persistent rain greatly reduced trafficability and provided excellent cover and concealment. Distance from Axis airfields and the weather limited Stuka close air support. This combination of rough terrain, poor weather and Allied reinforcements slowed the 21st Panzer Division attack significantly. Rommel therefore, diverted his main attack through Kasserine Pass (Fig. 7).

9.2 Troubling Terrain

The pass near the village of Kasserine is only a mile wide at its narrowest point, and by now the Americans had time to place in-depth minefields and wire that, along with the wet silt and clay, restricted German vehicle movement largely to the roads. The difficult terrain and the prepared defenses should have been sufficient to stop the Axis attack and it did slow Rommel considerably. A major obstacle was the Hatab River that created the valley and forced Rommel to initially split his attack to both sides of the riverbed, violating his desire and need to mass. Once past the narrowest confines of Kasserine Pass, Rommel committed the 21st Panzer Division towards Thala in the north, trying to find a weakness in the hasty Allied defenses. Unfortunately, given the restrictive terrain, he could not recover the 21st Panzer in time to mass with what turned out to be the more successful movement eastward toward Tebessa (Fig. 7).

As Rommel's *Deutsches Afrikakorps* (DAK) and the Italian *Centauro* Division moved west, the terrain became more restrictive and provided the defending Allied forces with an opportunity to mass in a small area, dig in, and bring up artillery. Despite significant gains, within a few days it was clear that numerical superiority and the advantages of the defense in rugged terrain tipped the balance in favor of the Allies. Rommel's forces had in fact, been dispersed and the main effort was channelized into a relatively small area where it lost the ability to maneuver. Allied forces conversely, were able to mass their forces in a relatively small region in the defense aided by higher elevations and restrictive terrain. By the 22nd of February, unable to achieve his objectives, Rommel chose to withdraw.

10 Conclusions

The Battle of Kasserine Pass was initially an American disaster. US doctrine and training at the dawn of WWII poorly prepared American forces to fully appreciate the influence that the desert environment would have on combat in central Tunisia. Unproven doctrine based on misconceptions of *blitzkrieg* and tested in temperate environments did little to prepare green American forces to engage highly proficient Panzer Divisions in an open desert in good weather. CCA at Sidi Bou Zid for example, had units poorly positioned well out of supporting distance from one another. They failed to anticipate the German dawn attack that took advantage of a sandstorm. The CCC counterattack the next day was conducted without reconnaissance of the route or objective, leading to a combined arms ambush that shattered the force. Unit cohesiveness in the 1st AD was shaken. It was not until battlefield terrain became restrictive to maneuver later in the fight that American performance improved.

What tipped the balance in favor of the Allies was as much the rough, limiting terrain that allowed Allied commanders to concentrate their power in the defense and robbed the Axis of maneuver space, as it was the arrival of Allied reinforcements. Terrain and weather proved to be a significant advantage first for the Germans in the wide open desert plain near Sidi Bou Zid and Sbeitla; then for the Allies in the tight confines and deteriorating weather west of Kasserine Pass. Once again, physical geography played a decisive role in combat.

Field Marshal Rommel best summed up the influence that the desert environment had on his decision to cede the battle to the Allies with the following words:

> It appears futile to continue the attack in view of the constant reinforcing of the hostile forces, the unfavorable weather which renders the terrain impassable off the hard roads, and because of the increasing problems caused by the mountain terrain which is so unsuited to the employment of armored units. (Atkinson 2002, p. 386)

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The Influence of Geology and Geography on the Indian Wars in Eastern Washington Territory

Stephen W. Henderson and Michael M. Hamilton

Abstract It was a spring day in 1858 and Col. Edward Steptoe was riding north through the rolling grass prairie that covers the loess hills on the eastern side of the Columbia Basalt Plateau. His mission was to support settlers and miners in the northern part of Washington Territory with a show of force. A combined force of 1000 Plateau Indians of the Palouse, Walla Walla, Coeur d'Alene, and Spokane tribes stopped Steptoe at the Battle of Tohotonimme near Rosalia, Washington. The extensive loess "dune" fields allowed for concealed rapid movement of the mounted natives. The army dragoons were vastly outnumbered as they took a stand on a loess hilltop. Darkness, luckily, ended the battle and the troops fled south to Fort Walla Walla. It was a humiliating defeat for the army and quickly a better-equipped force under Col. George Wright was assembled to put an abrupt end to native resistance. In September, at the battles of Four Lakes and West Plains near Spokane, the army defeated the Plateau Indians. Wright positioned his troops armed with modern rifles and artillery on high ground created from basement rocks that rise above the flat basalt plains preferred by the mounted Indians. Both the Steptoe and Wright campaigns were significantly influenced by the geology and geography of eastern Washington. The juxtaposition of hills of older basement rock, a Miocene basalt plateau, and Pleistocene paraglacial loess fields and outburst flood deposits created topography with geomorphic features that were used advantageously by both sides in the conflict. The type locality of the geomorphic feature known as a steptoe is located just south of Rosalia, the site of Steptoe's defeat. These military campaigns of 1858 can be placed in the larger context involving the settlement of the Oregon country and the conflicting philosophies of land and water use of the Native Americans and the settlers. The Plateau Indians were traditional hunters, gatherers, and fishermen. With the coming of the Hudson's Bay Company, they were encouraged to trap beaver. Beginning in the 1840s, the Oregon Trail brought settlers from the eastern United States who began farming and mining, bringing

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Indians and settlers into conflict. In the 1850s a military road through the area further inflamed tensions. Although the Indian wars have long ended, conflict still exists in regards to land and water rights, involving fishing, hydroelectric power, and the honoring of past treaties.

Keywords Columbia basalt plateau · Pleistocene outburst floods · Loess · Indian wars

1 Introduction

The Plateau Indian War of the late 1850s in Washington Territory was strongly influenced by the terrain and underlying geology of the area. In this paper, the authors describe the ways in which the strategy and outcome of battles during this war were directly impacted by the geology. The geology has been studied for many years. Mangan et al. (1986) and Reidel et al. (1989) present extensive stratigraphic descriptions and correlations of the Miocene Columbia River Basalts of Washington, Oregon, and Idaho. The channeled scablands associated with the Lake Missoula floods and the loess deposits are interrelated, consisting of multiple floods and loess deposits. They can be related to the Pleistocene glacial advances of the Cordilleran ice sheet over the last 2 million years (McDonald et al. 2012). J Harlen Bretz (1923) first used the term "channeled scablands" as he developed his hypothesis that a cataclysmic flood had created the topography in this part of eastern Washington. Bretz's ideas of catastrophism appeared to run counter to Lyell's uniformitarianism, resulting in considerable controversy and general rejection of his theory. Bretz's extensive fieldwork built upon his initial conclusions (Bretz 1969) until there was final acceptance by the geologic community. A serious discussion of the role of catastrophes in geologic history and its connection to uniformitarianism resulted. Derek Ager (1993) wrote, "Geologists do not deny uniformitarianism in its true sense, that is to say, of interpreting the past by means of the processes that are seen going on at the present day, so long as we remember that the periodic catastrophe is one of those processes. Those periodic catastrophes make more showing in the stratigraphical record than we have hitherto assumed." Baker (2009) presents a good retrospective on the development of the channeled scablands, while Hanson et al. (2012) provide current knowledge on the Pleistocene flooding from glacial Lake Missoula. McDonald and Busacca (1992); Busacca and McDonald (1994); and Gaylord et al. (2003) represent some of the seminal papers on the formation of the loess and its association with the glacial outburst floods.

The 1858 military campaigns of the Plateau Indian War took place in eastern Washington Territory, including areas underlain by basalt that were eroded by the glacial Lake Missoula floods and were overlain by loess. The outcomes of the battles of Tohotonimme, Four Lakes, and West Plains were all strongly influenced by this geological terrain.

2 Geologic and Geographic Setting

The Columbia Plateau provides the name for the Plateau Indian War of the late 1850s (Fig. 1). The Plateau is a large intermontane plateau or basin. It is underlain by multiple flows of the Columbia River Basalt Group of Miocene age. Most of central and eastern Washington's terrain consists of open, rolling prairie or desert dissected by drainages that flow into the Spokane, Columbia, and Snake Rivers that encircle the basin. As an intermontane basin, the climate is semi-arid to arid, ranging from prevalent desert in the central part to steppe on the eastern side. The surrounding mountains catch enough rain and snow to supply ample water to the region's rivers. In addition, the Columbia River's connection to the Pacific Ocean supplied salmon to the native inhabitants. Elevations range from about 1700 feet above sea level on the Spokane River, to 2400 feet on the Columbia Plateau, to 3600 feet on the highest hills. The area is very seasonal in weather with severe winters and hot summers. Rainfall is mainly in the winter and spring; summers and falls are often long and dry. End of the summer wildfires are an annual event in this region.

The Columbia Plateau is floored by numerous basalt flows up to three miles in total thickness. The conflict area, being on the eastern side of the Plateau, is underlain by a much thinner section of basalt ranging in thickness from tens of feet to hundreds of feet. The basalt units in the conflict area range in age from 14

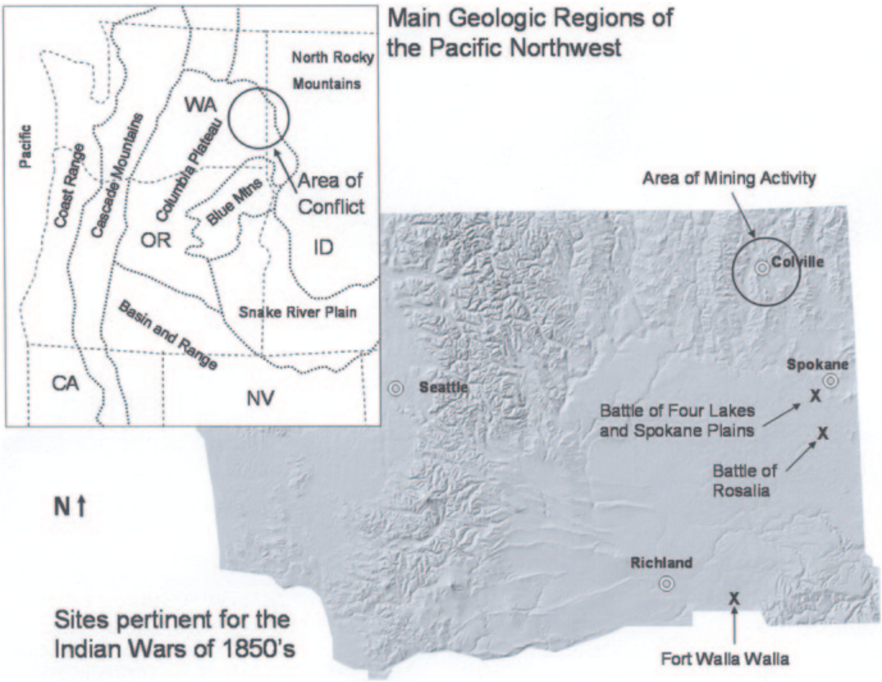

Fig. 1 Physiographic regions of the Pacific Northwest and Indian wars sites

to 15 million years old, and belong, for the most part, to the Wanapum and Grande Ronde Formations (Reidel et al. 1989). The basalt terrain tends to be flat, with steep, incised drainage cut into it near major rivers. The basalt ledges in rivers form waterfalls that provided major fisheries of migrating salmon for the native population, fisheries that were worth fighting for. The falls of the Spokane River are a good example.

The flat basalt terrain of eastern Washington is dotted with higher hills of older bedrock that stick up like islands through the basalt. These rocks range in age from Precambrian to lower Paleozoic, and consist of a variety of metamorphic units. The most notable of these hills is Steptoe Butte in central eastern Washington. The high mountains just to the east of the Columbia Plateau are part of the Northern Rocky Mountains of western North America. Native tribes in the conflict area frequented the mountains for their abundant game and wild berries. The topography of the area provided the local tribes with fish, game, and the mobility of the open plains.

The Plateau was well south of the continental glaciers of the Pleistocene Ice Age. The area did receive glacial outwash, glacial lake, and loess deposits. Most significant is the glacial loess. McDonald et al. (2012) found that the loess was derived from fine-grained flood deposits carried to the southwest by melt water then blown back to the northeast by the prevailing winds. These southwesterly winds represent the dominant wind direction at least for the last 50,000 years (McDonald et al. 2012). The extensive tracks of hills and dunes of loess that cover the central and southeastern sides of Washington are called the Palouse Hills. This topography played an important role in the battle near Rosalia.

The youngest of the geological events that shaped the landscape of the area were the glacial outburst floods of the Pleistocene. Multiple giant floods occurred when ice dams burst in northern Idaho and large glacial lakes in Montana drained rapidly to the Pacific Ocean. J Harlen Bretz developed the glacial flood model as he mapped the geology of central Washington in the 1920's, 30's and 40's. He found many very large, hydraulic landforms that could not be explained without having large amounts of water being rapidly released from the east. Today, this special topography associated with the glacial Lake Missoula floods has been well documented and described by a number of recent publications (Allen et al. 2009; Alt 2001; Bjornstad and Kiver 2012). Parts of eastern Washington were scoured into broad flood channels, slot canyons, and wide valleys. This area of eastern Washington has been referred to as the "channeled scablands". Extensive parts of the flood path were stripped of soil, leaving bare basalt outcrops that are full of pothole ponds, and are, in contrast to the prairies of the Palouse Hills, covered with ponderosa pine forest. This variation in ground cover figured prominently in the battle strategy of both the Native Americans and the U.S. Army.

3 Historical Background of Native American and Settler Conflict

The Plateau Indians of the eastern Washington Territory depended upon salmon as a major component of their diet. In addition they moved throughout the year to gather plants such as camas, bitterroot, wild strawberry, chokecherry, and huckleberry. Any destruction of this ecosystem or of the ability of the Native Americans to have access to it would severely limit their life style.

The first major incursion of European culture into the Pacific Northwest occurred when explorers realized the potential of the beaver fur trade in the area. The North West Company, combined with the Hudson's Bay Company established a number of trading posts as part of a fur trade network in the interior of the Pacific Northwest. In 1810 the North West Company built Spokane House at the confluence of the Spokane and Little Spokane Rivers, followed by Fort Nez Perce (later to become Fort Walla Walla) near the confluence of the Columbia and Walla Walla Rivers in 1818. The Hudson's Bay Company established Fort Vancouver on the Columbia River in 1824. With minimal disruption to their life style, the natives welcomed the trade goods and tolerated the European visitors.

As the fur trade faded in the late 1830's, it was followed by a system of missions that were built throughout the Northwest in an attempt to bring Christianity to the native population. Success was very limited, and conflicts between the Indians and the missionaries resulted in the slaughter of Dr. Marcus Whitman, his wife Narcissa, children, and workers, at Walla Walla in 1847 by a renegade band of the Cayuse tribe. The natives believed that Marcus Whitman was an evil shaman who killed the Indians with measles while the whites recovered from the disease. The Indians had no immunity to measles. The larger issue involved the flood of settlers that were arriving overland from the east by early wagon roads such as the Oregon Trail, which opened in 1843 (Wilma 2003).

The first Governor of Washington Territory and Superintendent of Indian Affairs for the region in 1853 was Isaac Stevens. In 1853 a survey for a northern transcontinental railroad route was made with Stevens in charge. During the winter of 1853 Lieutenant John Mullan was left in command to survey a road that would connect the headwaters of the Columbia River near Fort Walla Walla with the headwaters of the Missouri at Fort Benton. This is what would become the Mullan Military Road. The Plateau Indians were concerned that this route would bring miners and settlers on to land that had been set-aside for them in the treaties of 1855. They would be proved correct. Construction on the road began in 1859, after the Plateau Indians had been defeated, and was completed in 1862 (Graham 2005).

Through the use of force and intimidation, Governor Stevens coerced a number of the Plateau Native American tribes into signing treaties that ceded their land rights to the territorial government. Several tribes did not sign. In May 1855, he and Oregon Superintendent of Indian Affairs Joel Palmer invited the Nez Perce and other tribes to a great council in the Walla Walla Valley. Three treaties were signed at the Walla Walla Council. The tribal leaders did not want a separate reservation for their people. Their argument against a reservation invoked native law dealing with the sacred relationship between humans and the land. Cayuse Chief Stikus expressed it this way, "If your mothers were here in this country who gave you birth, suckled you and while you were sucking some person came and took your mother and left you alone and sold your mother, how would you feel then?" (Trafzer 2008). The Walla Walla, the Umatilla, and the Cayuse were forced to move from their 16,000 km^2 of land to a reservation in northwestern Oregon that was later reduced to 615 km^2 (Trafzer 2008). The second treaty resulted in fourteen tribes moving to the Yakama Indian Reservation and in the third treaty, the Nez Perce were confined to a reservation situated where Oregon, Washington, and Idaho converge. All told, under the three separate treaties, the combined tribes lost approximately 96,000 km^2 of their homelands (Nisbet 2008). The council concluded on 11 June 1855 and this soon followed with a 23 June 1855 newspaper article under Stevens' signature announcing that the Indian lands were open to settlement (Kip 1999). These treaties reserved the rights of the Indians to hunt, gather, and fish at usual and accustomed grounds and stations on and off the reservation. Soon, however, they were being told to move on to their reservations.

In a letter of 7 October 1855 dictated to Father Charles M. Pandosy, the Yakama leader Kamiakin said, "If the governor had told us, my children, I am asking you [for] a piece of land in each tribe for the Americans, but the land and your country is still yours, we would have given willingly what he would have asked us and we would have lived with all others as brothers. But he has taken us in number and thrown us out of our native country in a strange land among a people who is our enemy, for between us we are enemy, in a place where its people do not even have enough to eat for themselves" (Kip 1999, p. 151).

War broke out when the First Oregon Mounted Volunteers marched into the Walla Walla River Valley on 7 December 1855, engaging the Walla Wallas and allied tribes. The First Oregon Mounted Volunteers had been recruited in the fall of 1855 primarily from Portland and Dalles, Oregon Territory (Victor 1894). Prior to the battle, the Walla Walla chief, Peo-Peo-Mox-Mox was taken captive. On the first day of the battle, he and other hostages were killed. The Oregon volunteers defeated the Walla Walla in a 4-day running battle (Emerson 2008).

General John Wool figured prominently in the lead up to the Yakima Indian War. He was a hero of the War of 1812, having participated in the Battles of Queenston Heights and Plattsburgh. He was promoted Brigadier General in 1841 and was a leader in the Mexican War. After the war, he was posted to California and helped bring about an end to the Rogue River War in southern Oregon after the volunteer militias had committed many acts of genocide against the Indians (New York Times 1869).

General Wool was sympathetic to the Indians' plight. In his April 1856 letter to John Cunningham he wrote, "But for the Governor of Oregon and of Washington Territory, who are anxious for a long and expensive war, and the barbarous determination of the Oregonians to extermin[ate] its Indians, I would soon put an end to the Indian War. This practice of the Volunteers of killing friends as well as enemies has greatly increased the ranks of the hostiles." (Wool 1856).

Placer gold was discovered on the Colville and Columbia rivers in 1855, and there was a rush of miners to the area that ignored the recent treaty that reserved this area for the Yakama Indians. The placer resources were very limited and were associated with quartz veins in Paleozoic sedimentary and metamorphic rocks that were intruded by Mesozoic granite (Moen 1976; Battien 1989). These miners were soon to move north into Canada in pursuit of more lucrative discoveries. While the small trickle of miners into the area lacked the potential for a true gold rush, this new wave of strangers coming onto reservation land caused conflict. Angered by reports of trespassing miners stealing horses and abusing Indian women, the outraged natives killed eight miners. This lit the fuse on a powder keg that would lead to the Indian Wars of the 1850s.

In a letter dated 2 August 1856 from General Wool's Assistant Adjutant General, W. W. Mackall, relaying the orders from General Wool to Colonel George Wright, the mining activities at Colville are noted. "No emigrants or other whites, except the Hudson Bay Company, or persons having ceded rights from the Indians, will be permitted to settle or remain in the Indian country, or on lands not ceded by treaty, confirmed by the Senate and approved by the President of the United States. These orders are not however to apply to the miners engaged in collecting gold at the Colville mines. The miners will however be notified, that should they interfere with the Indians or their Squaws, they will be punished and sent out of the country." (Mackall 1856).

Colonel George Wright was a veteran of the Seminole Wars and the Mexican War and had been posted to command the District of Northern California in 1852. While in this position, he tried to keep the peace between the Native Americans and the whites and was criticized for favoring the natives. In 1855 he was promoted to command the Ninth Infantry, to be stationed in the Pacific Northwest (Hemphill and Cumbow 1992).

4 Plateau (or Yakima) Indian War

The Yakamas, led by Kamiakin, joined tribes to the east, including the Palouse, Walla Walla, Spokane, and Coeur d'Alene, who formed a loose alliance to resist the incursions by the whites.

Colonel Edward Steptoe rode out from Fort Walla Walla in the spring of 1858 with a force of 160 soldiers toward Fort Colville to investigate the killing of two miners that had been on their way to the mines. In addition, Steptoe planned to give the Indians a show of force. As he moved into the Palouse Hills, north of the Snake River, the combined alliance of tribes stopped him near present day Rosalia (Emerson 2006). "On Sunday morning the 16th, when near To-hoto-nim-me, in the Spokane Country, we found ourselves suddenly in presence of ten to twelve hundred Indians of various tribes—Spokanes, Pelouses, Coeur d'Alenes, Yakimas, and some others—all armed, painted, and defiant. I moved slowly on until just about to enter a ravine that wound along the bases of several hills, which were all crowned by the excited savages. Perceiving that it was their purpose to attack us in this dangerous place, I turned aside and encamped, the whole wild, frenzied mass moving parallel to us, and, by yells, taunts, and menaces, apparently trying to drive us to some initiatory act of violence." (Steptoe 1858, p. 346).

At about 8:00 a.m. on 17 May 1858, approximately 1000 Indians struck Steptoe at the Battle of Tohotonimme. "We labored under the great disadvantage of having to defend the pack-train while in motion and in a rolling country peculiarly favor able to the Indian mode of warfare." (Steptoe 1858, p. 346). The extensive loess "dune" fields of the Palouse Hills allowed for concealed rapid movement of the mounted Natives (Fig. 2). The fields of prairie-covered hills gave the mounted native warriors mobility and allowed for good communication between individual groups.

Drainage through the Palouse Hills is partially a remnant of the glacial flooding when surges of water moved north to southwest through the area. Rather than winding ridges and flat mesa areas, fields of individual hills commonly occurring in dune tracks typify the geomorphology of the Palouse (Alt 1995). The loess was derived from fine-grained flood deposits carried to the southwest by melt water then blown back to the northeast by the prevailing winds. These loess hills are linear features, deposited parallel to the wind direction. The hills are presumed to have been initiated as deposits in the lee of outcropping basalt knobs, which have subsequently grown through further loess deposition (McDonald et al. 2012). Colonel Steptoe followed the north trending valleys, the easy path through the region. This, however, greatly limited his awareness of the approaching native force and the ambush was successful for the native force with a better command of the topography.

Fig. 2 Loess hills of Tohotonimme Battlefield near Rosalia

The army dragoons were vastly outnumbered and outgunned as they took a stand on a loess hilltop. “About a half hour after this Captain Taylor was brought in mortally wounded; upon which I immediately took possession of a convenient height and halted. The fight continued here with unabated activity; the Indians occupying neighboring heights and working themselves along to pick off our men.” (Steptoe 1858, pp. 346–347).

Two of the dragoon companies had inaccurate smoothbore musketoons and the third had Model 1841 Mississippi rifles, too long to be muzzle-loaded while in the saddle. Some had 3rd Model Colt Dragoon revolvers (Emerson 2006). “Some of them were recruits but recently joined; two of the companies had musketoons, which were utterly worthless in our present condition; and, what was most alarming, only two or three rounds of cartridges remained to some of the men, and but few to any of them.” (Steptoe 1858, p. 347).

“Not an officer of the command doubted that we would be overwhelmed with the first rush of the enemy upon our position in the morning…it was therefore necessary to relieve ourselves of all encumbrances and to fly.” (Steptoe 1858, p. 347). Darkness, luckily, ended the battle and, after burying their howitzers, the troops fled south to Fort Walla Walla during the night.

Although this butte had nothing to do with the Battle of Tohotonimme, Colonel Steptoe’s name graces Steptoe Butte, which lies south of Rosalia in Whitman County, Washington. The butte consists of 500 million year old quartzite protruding out of the loess-covered basalt plateau of the Palouse Hills. Steptoe Butte has given rise to a geomorphic term. A steptoe is a hill or mountain that projects like an island above a surrounding lava field (Bates and Jackson 1987).

On 7 August 1858, in reprisal for Steptoe’s defeat, Colonel George Wright moved from Fort Walla Walla with a combined force of about 670 men from the 9th Infantry Regiment, 1st Dragoons, and 3rd Artillery, to subdue the Native Americans and put an end to the war with the Plateau Indians. By 18 August, they had reached the south bank of the Snake River at the mouth of Tucannon River. Captain Erasmus D. Keyes and an advance element of dragoons had built a small basalt fort, Fort Taylor, here to guard the Snake River crossing (McDermott and Grim 2002). “It stands at the mouth of a cañon, with high bluffs of basalt on each side, about eight hundred yards apart; one being two hundred and sixty, the other three hundred and ten feet high.” (Kip 1999, p. 42). In later years, Keyes rose through the ranks, becoming commanding general of the IV Corps of the Army of the Potomac during the Civil War. He resigned his commission in 1864 and went to California where he was involved with gold mining and wine making (Ballard 2004).

By August 27th Wright’s force was across the Snake and moving north. The Native Americans set the prairie ablaze in the arid climate, but the U.S. Army troops kept going. Wright was attacked on the banks of Medicine Lake on the afternoon of August 31st (McDermott and Grim 2002).

The next day, 1 September 1858, Wright’s force attacked at Four Lakes, about 15 miles southwest of Spokane Falls. In the battle, approximately 50 Native Americans were killed and many more wounded. None of the men under Wright’s command were killed (McDermott and Grimm 2002). Wright's victory at the Battle of Four Lakes can be subscribed to advantageous geographic position and superior firepower.

Colonel Wright's force had moved north to engage the hostile natives in the area of the Great Spokane Plains, an open prairie to the west and southwest of present day Spokane. His route north followed sections of the Cheney-Palouse Scabland glacial flood channel that offered relatively flat topography and the cover of the ponderosa pine forest that typifies the channel areas. In addition, the numerous pothole ponds that were scooped out by the massive glacial outburst floods were a convenient source of water for both the horses and the troops (Alt 2001). Initial contact between the two forces was near a large hill composed of Paleozoic metamorphic rocks that overlooks the surrounding flat topography of the Spokane Plains (Fig. 3).

The Battle of Four Lakes had begun. The high ground was soon commanded by Wright's troops with an accompanying howitzer battery. The native warrior horsemen chose the mobility of the flat plains. "After advancing about a mile and a half, we reached the hill and prepared to dislodge the enemy from it." "As soon as the dragoons reached the top of the hill, they dismounted,—one half holding the horses and the others acting as skirmishers. After exchanging a volley with the Indians, they drove them off the hill and held it until the foot soldiers arrived." (Kip 1999, p. 54).

"On the plain below us we saw the enemy. Every spot seemed alive with the wild warriors we had come so far to meet. They were in the pines on the edge of the lakes in the ravines and gullies, on the opposite hillsides, and swarming over the plain.

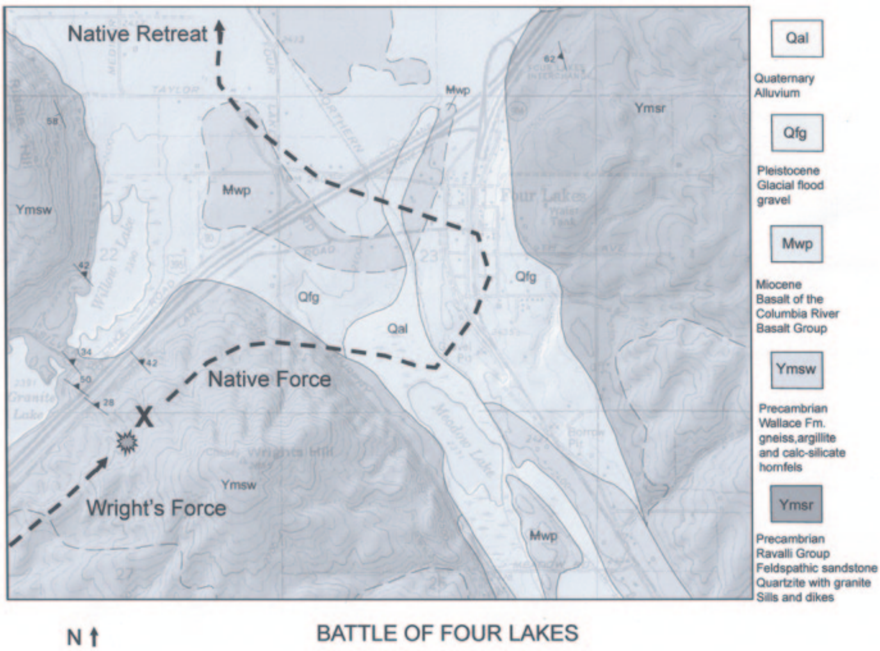

Fig. 3 Geology of the Battle of Four Lakes

Mounted on their fleet, hardy horses, the crowd swayed back and forth, brandishing their weapons, shouting their war cries, and keeping up a song of defiance. Most of them were armed with Hudson Bay muskets, while others had bows and arrows and long lances." (Kip 1999, p. 55). "But minnie balls and long range rifles were things with which now for the first time they were to be made acquainted." (Kip 1999, p. 56).

At the Battle of Spokane Plains (west southwest of Spokane Falls) on 5 September, the army met and defeated an estimated 500–700 Spokane, Coeur d'Alene, Palouse, and Pend d'Oreille warriors. "We had nearly reached the woods when they advanced in great force, and set fire to the dry grass of the prairie, so that the wind blowing high and against us, we were nearly enveloped by the flames. Under cover of the smoke, they formed round us in one-third of a circle, and poured in their fire upon us, apparently each one on his own account." (Kip 1999, p. 63).

"As soon as they took refuge in the timber, the howitzer under Lieutenant White opened upon them with its shells. Then the foot charged them again, driving them from cover to cover, from behind the trees and rocks, and through the ravines and cañons, till the woods for more than four miles, which lately seemed perfectly alive with their yelling and shouting, were entirely cleared." (Kip 1999, p. 64).

The Spokane Plains are an open area that was sheet-washed by the glacial floods that deposited thick layers of gravel and sand, filling and leveling the underlying topography. The flood sediments were deposited in a high-energy environment, resulting in poorly sorted deposits devoid of fine sediments. This material absorbs rainwater readily, resulting in the lack of surface drainage that would dissect the flat plains (Alt 2001).

The Native forces could not withstand the long-range effects of Wright's modern rifles and artillery, and choose a rapid, fighting retreat to escape (Fig. 4). This fighting retreat was the primary component of the Battle of Spokane Plains. It is thought that the native forces had hoped to draw the exhausted soldiers to the north off the plains and into the wooded ravines that lead to the Spokane River. Here they could have fought at closer quarters.

The Indians retreated into the pine forests at the edge of the plain and then down into the valley of the Spokane River and Latah Creek. Wright's force camped on a small plateau on the western side of the Spokane River. Near Liberty Lake they captured over 800 Indian horses. The Indians expected to be able to recapture the horses but Wright ordered the horses to be killed on 9 September 1858 at a spot along the Spokane River. The site, known as Horse Slaughter Camp, lies near the present day Idaho border (McDermott and Grim 2002). "We learned subsequently, that nothing we had done so much prostrated the Indians as this destruction of their horses" (Kip 1999, p. 75).

From Horse Slaughter Camp, Wright's force moved over the mountains to Cataldo (or Coeur d'Alene) Mission, arriving there on 13 September. After a council was held, a treaty was signed ending the Indian War on 17 September 1858. On his way back to Fort Walla Walla, Wright camped along Latah Creek. A Yakama chief, Qualchin, came into camp and was promptly tried for crimes against whites and summarily hung. The next day six more Native Americans were hung out of fifteen that were being held. Latah Creek has since been known as "Hangman's Creek"

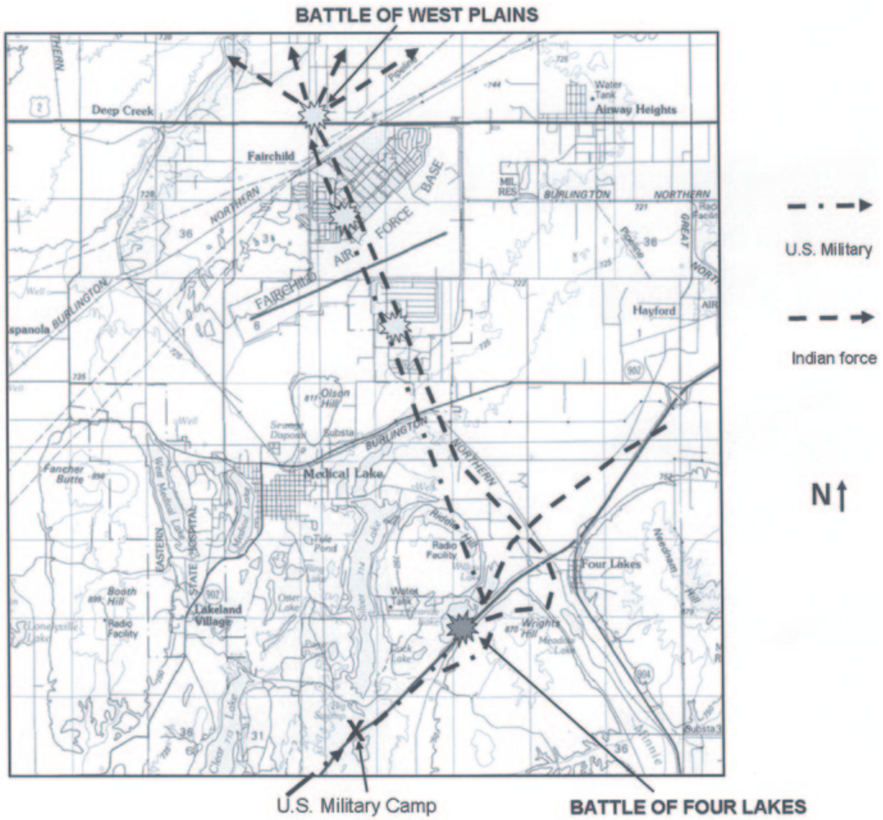

Fig. 4 Movement of forces from Battle of Four Lakes to Battle of Spokane Plains

(McDermott and Grim 2002). A number of other chiefs were either hanged or shot. Kamiakin fled north to British Columbia and the Yakama were removed to a reservation south of the present day city of Yakima.

"The Indian tribes, hitherto so troublesome and defiant, have been entirely subjected. They have been taught the power of the government, their worst chiefs have been cut off, and hostages given sufficient to keep them in obedience. Of their headmen who are hostile, none remain but Kamiakin, and Schroom, his brother. The former is reported to have fled into the Blackfeet country, and the latter is probably with him. They will certainly have no disposition to place themselves again in collision with the whites. It is probable, too, that among their own countrymen their influence and authority are gone. The tribes have suffered too much again to submit to their counsels. That immense tract of splendid country over which we marched, is now opened to the white man, and the time is not far distant when settlers will begin to occupy it, and the farmer will discover that he can reap his harvest, and the miner explore its ores, without danger from the former savage foe" (Kip 1999, pp. 127–128).

5 Aftermath of the Plateau Indian War

Settlers moved quickly into eastern Washington. The hills became ripe with wheat and small farming communities grew up in the area. The railroads were built to transport the agricultural products of the prosperous land. With the advent of statehood in 1889, the Native Americans were forgotten and the exploits of the Plateau Indian War were glorified in monuments and anniversary celebrations. The state continued to grow as more railroads were built and rivers were dammed for irrigation and electricity, limiting access by Native Americans to their areas guaranteed by the treaties of 1855 and destroying the salmon runs.

In 2010 the Yakama Nation sued the U.S. Department of Agriculture to block the planned shipment of waste from Hawaii to a private landfill adjacent to the Columbia River that would have involved movement across sacred Yakama land. The U.S.D.A. had certified the cargo as safe and had issued a permit to Hawaiian Waste Systems. Shortly after the suit was filed, the U.S.D.A. withdrew its permit to allow the Hawaiian company to ship the waste to the Washington landfill. According to the 1855 treaty, the Yakama retain the right to hunt, fish, and gather on the lands in question. According to the complaint filed by the Yakama Nation, "Yakama citizens gather huckleberries and chokecherries and roots like lammush and bitterroot and pick various flowers and plants from the lands surrounding the landfill—all for use as food or medicine." (Millman 2010).

In 2009 the first sockeye salmon were reintroduced to Lake Cle Elum after the species died out in the Yakima River drainage due to irrigation dams. Yakama Nation fisheries biologists have been working to restore the salmon and have a self-sustaining run of sockeye. In 2013 the first fish originally planted in Lake Cle Elum will return to the Yakama River. The project started when a lawsuit settled between the Yakama Nation and the Bureau of Land Reclamation resulted in this release system. A fish ladder is being tested that will be installed when funded. Brian Saluskin, Cle Elum fish passage biologist for the Yakama Nation said, "Our people will dry the sockeye, crush the meat into a powder and mix it with berries and other foods. It is an excellent source of protein" (Lester 2012).

6 Conclusions

In 1810, the North West Company built Spokane House for trading with the local native population (Fig. 5). With the movement of missionaries and settlers into the Pacific Northwest in the 1830s and 1840s, differences in cultures, combined with varying understandings of land ownership, set the stage for conflicts between the settlers and the Native Americans. In 1855 at the Walla Walla Council, when Governor Stevens of Washington Territory coerced a number of the Plateau Native American tribes into signing treaties that ceded their land rights and established Indian Reservations, conflict was inevitable.

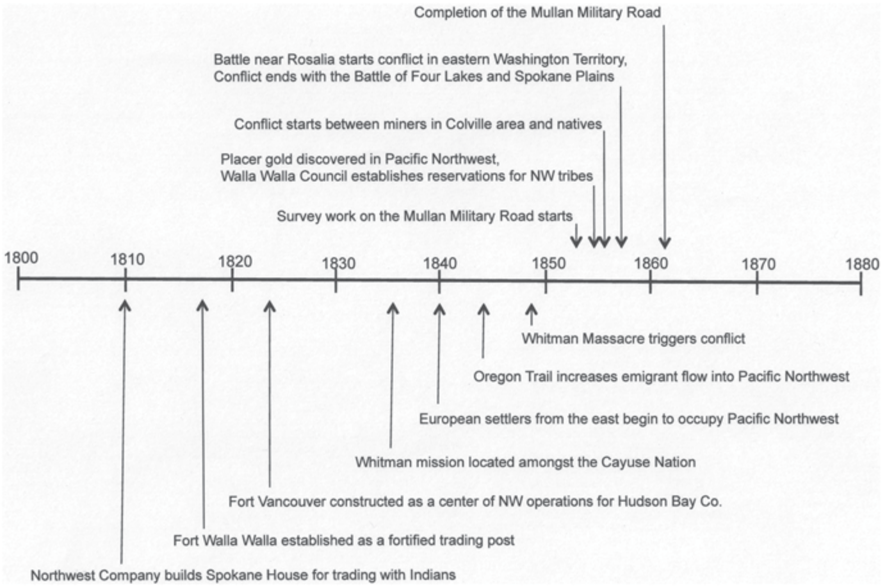

Fig. 5 Timeline of events in the Pacific Northwest, 1810–1862

In May of 1858, Colonel Steptoe met a combined force of Plateau Indians in the Palouse Hills at the Battle of Tohotonimme, near Rosalia, Washington. The prairie-covered loess hills proved to be advantageous to the Native Americans as they were ideal for concealing their movements. After Steptoe's defeat, U.S. Army forces under Colonel Wright moved out from Fort Walla Walla, attacking the Indians at the Battle of Four Lakes and subsequent Battle of Spokane Plains in September 1858. Wright's victory at these two battles was a direct result of his geographic advantages. At the Battle of Four Lakes, Wright was able to occupy the high ground created by Paleozoic metamorphic rocks, surrounded by the flat topography of the Spokane Plains. Although the Indians chose the mobility of the flat plains, they couldn't be concealed. The Spokane Plains were created when the glacial outburst floods deposited gravel and sand. The Plateau Indian War soon ended with the signing of a peace treaty at Cataldo Mission. Geography and the underlying geology of the area played a significant role in the cultures that came into conflict and the battles of the Plateau Indian War.

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Teaching Military Geoscience in the Twenty-first Century Classroom: Virtual Field Explorations of the Gettysburg Battlefield

W. Lee Beatty and Candace L. Kairies-Beatty

Abstract Access to the internet in today's classrooms has opened the door to a variety of new pedagogies that enhance learning in the geosciences while being easily adopted with minimal investment. Web-based virtual tours, explorable gigapixel panoramas, GIS and Google Fusion Tables allow users access to a wealth of information for conducting in-depth investigations and analyses of locations that are impractical to visit due to time or budgetary constraints. Several of these emerging techniques have been combined to bring field investigations of battlefield terrain into the classroom through virtual fieldwork. The Battle of Gettysburg, the largest ever fought in North America, was significantly influenced by the topography and geology of the farmland surrounding the small Pennsylvania town. This makes the battlefield an excellent venue for teaching the impacts of geology and landscapes on military operations. Several Gettysburg-based projects have been developed to introduce concepts of military geoscience to students and the public and integrate virtual fieldwork into the classroom. One virtual tour of the battlefield (https://sites.google.com/site/gettysburggeologyfieldguide/home) utilizes a traditional webpage platform to explore the effects of geology and topography on the fighting, while another (https://sites.google.com/site/gettysburgvirtualfieldwork/home) uses the unique interactive environment of Google Earth, with traverses, annotations, and immersive high-resolution panoramas that give the user a soldier's-eye view of the terrain. In-depth investigations of the battlefield can be conducted in the classroom with rock samples (both physical samples and 3D scans), topographic maps, explorable gigapixel petromicrographs, and geolocated GigaPan panoramas of the battlefield (www.gigapan.com). Students are provided samples representing the prominent rocks of the Gettysburg area and topographic maps with marked field stops. They orient themselves using Google Earth, make field observations (including locations of outcrops, weathering patterns of rocks, and topography), and identify rocks in outcrop. After compiling their data and creating a geologic map, they investigate how geology and topography affected the strategies of the Union and

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Confederate armies and the heavy casualties suffered by both sides. By creating interactive environments, these new tools promote learning through experience and exploration rather than memorization.

Keywords Gettysburg · GigaPan · Google earth · Virtual fieldwork · U.S. civil war · Battlefield geology

1 Introduction

Geology is an inherently visual science, but geoscientists often have few visual resources (e.g. single scale field photographs and hand samples) to record and present information about landscapes and outcrops. New technologies, including interactive maps and visualizations at multiple scales, have provided additional tools for collecting and sharing data. Incorporating these technologies into the classroom helps students to understand geological processes and builds problem-solving skills, especially when field work (which allows students to observe outcrops, landscape features, and geologic concepts and processes at a variety of scales) is difficult or impossible to accomplish, for both financial and logistical reasons.

We have incorporated these new technologies into virtual field experiences for diverse audiences that allow users to investigate geological features at scales ranging from landscape to microscopic. Using these interactive technologies is advantageous because they encourage users to explore and actively engage the subject matter. They are also well suited for open-ended, inquiry-based student exercises.

Using the military geology of the Gettysburg Battlefield as the subject for our proof-of-concept work, and the Pennsylvania DEP field guide "Geology of the Gettysburg Battlefield—How Mesozoic Events and Processes Impacted American History" (Cuffey et al. 2008), we have developed interactive tours and exercises for undergraduates that investigate how geology and terrain influence military operations. These incorporate dynamic maps, gigapixel panoramic images, and high-resolution photography of hand samples and petromicrographs to create virtual interactive field experiences for users.

2 The Gigapan System and Google Earth

Gigapixel images (high-resolution, scalable panoramas composed of at least one billion pixels) are created using the GigaPan robotic camera system. The GigaPan system (created by a team of researchers at NASA and Carnegie Mellon University) is actually a combination of several components: the GigaPan robot that captures the images used to create the panorama, the stitching software that combines individual images into a larger panorama, and the website (www.gigapan.com) that houses the completed panoramas and provides an interactive platform for users to interface with the panoramas. Using an off-the-shelf point-and-shoot camera, the robot captures a series of images by automatically adjusting the angle and tilt of the camera, capturing a hemispherical matrix of slightly overlapping images. Typical panoramas are composed of tens to hundreds of individual images. Stitching software aligns the adjacent images and transforms them into a larger two-dimensional panorama. Once the panorama is completed, it is uploaded to the GigaPan website.

GigaPan panoramas are fully explorable both on the GigaPan website and as embedded webpage objects. The resolution of GigaPan panoramas allows the user to move beyond traditional static viewing and truly explore an image at multiple scales, from a landscape view down to views of individual mineral grains. The snapshot feature allows users to select portions of the panorama that may be interesting to other users and annotate them. Annotated panoramas draw first-time viewers into the image and encourage their active exploration and participation in the investigative process.

The explorable, customizable mapping platform of Google Earth (earth.google.com/) is another tool that can be used to encourage exploration in the classroom. Along with topography and street views, Google Earth provides users the capability to annotate points of interest on the Earth's surface (at the time of this writing, these functions are also available for the Moon and Mars). GigaPan panoramas can be displayed as geolocated objects in Google Earth, allowing users to enter and explore the high resolution images at the location they were captured. Google Fusion Tables allow data to be incorporated into the Google Earth environment and displayed graphically. These capabilities provide users the opportunity to create virtual interactive learning environments and place historical and scientific information in geographical context.

3 Geology and the Battle of Gettysburg

The Battle of Gettysburg, the bloodiest battle of the American Civil War, was fought in and around the town of Gettysburg, Pennsylvania from July 1 to July 3, 1863. The battle was significantly influenced by the topography and underlying geology of the farmland surrounding the small Pennsylvania town, making this battlefield an excellent venue for teaching the impacts of geology and landscapes on military tactics. The details of the battle, the geology of the battlefield, and the relationship between the two have been thoroughly investigated over the last fifty years (Brown 1962; Doyle 2006; Inners et al. 2006; Cuffey et al. 2008) and will only be summarized briefly here.

The battlefield is primarily underlain by terrestrial red shales and mudstones deposited during the Triassic. These are intruded by dikes and sills of Jurassic diabase. At the margins of the igneous intrusions, mudstones have been altered to hornfels. The topographic high grounds are underlain by resistant diabase, but poor soil formation on the ridges would have made entrenching during the battle next to impossible. Fortifications in these areas were composed mostly of makeshift rock piles and repurposed farm fences. The inability of defending forces to dig in on the high grounds has been linked to the unusual number of casualties among Union soldiers (Brown 1962). Subtle landscape features, like the small rolling hills on the low ground between Seminary Ridge and Cemetery Ridge, also presumably affected the soldiers. It is easy to imagine the fatigue suffered by the Confederate soldiers participating in Pickett's charge as they marched over these hills in wool uniforms in the heat of the July sun on their way toward the Union line (Cuffey et al. 2008).

We adapted Cuffey et al. (2008) to create an interactive online field guide of the geology of the Gettysburg Battlefield (https://sites.google.com/site/gettysburggeologyfieldguide/home). GigaPan panoramas embedded into individual pages allow users to explore the battlefield at multiple scales while they read about the details of the local geology or open new windows to explore the panoramas with the full functionality of the GigaPan website. We also added many field images and petromicrographs to enhance the text and give users a better understanding of the links between the battle and the underlying geology.

4 Creating the Virtual Fieldwork Exercise

The immersive, interactive virtual fieldwork exercise for the Gettysburg Battlefield was initially developed for an Advanced Geomorphology class at Winona State University as one of a number of proof-of-concept tests for adopting this technology in the classroom (Kairies Beatty and Beatty 2009; Piatek et al. 2010). It not only gave the students additional experience with field techniques, but also highlighted the ways that geology and topography interact and influence human history. Our approach differed from the concept of a virtual field trip in that students were tasked to actively collect and analyze data rather than simply sightsee online. We have since expanded our original concept of virtual fieldwork, including the Gettysburg exercise, to be more interactive, employ additional technologies, and explore even more inaccessible field areas, such as the Moon (Beatty and Anderson 2011).

Using Cuffey et al. (2008) as a guide, field stops around the battlefield were selected to highlight areas with geologic, topographic, and historical importance. At each field stop, a high-resolution panorama was captured using a Canon PowerShot SX110 IS digital camera and a GigaPan Epic robotic camera mount (Fig. 1). Several hundred images were composited to create each high-resolution panorama. Hand samples representative of the three prominent rock units that underlie the battlefield were collected from an area outside the boundaries of Gettysburg National Military Park.

Once the panoramas were stitched, they were uploaded to the GigaPan website and georeferenced in Google Earth using latitude and longitude data collected in the field (Fig. 2). The full gallery of GigaPan panoramas created for this project can be viewed at http://www.gigapan.com/galleries/8823/gigapans or by searching www.gigapan.org for the keywords "ICMG" and "Gettysburg". A placemark was created for each of the field stops in Google Earth. Petrographic thin sections of the hand samples were created and photographed. Photographs of the hand samples and petromicrographs were then added as annotations to the appropriate field stops

Fig. 1 The GigaPan robotic camera system mounted on a tripod at the Longstreet Tower, Gettysburg National Military Park

(Fig. 3). Placemarks were also created to show the locations of additional rock units not readily observed in outcrop. Additional data such as field snapshots and historical photographs were added as annotations to specific field stops to enhance the interactive experience (Fig. 4). Using the image overly feature, maps outlining troop placement and movement for each of the three days of the battle were also added (Fig. 5).

The exercise instructions, a topographic map of the battlefield, links to the full resolution GigaPan panoramas and additional field photographs were incorporated into a virtual fieldwork website (https://sites.google.com/site/gettysburgvirtual-fieldwork/home). The virtual fieldwork website also contains a link to the Google Earth.kmz file for the exercise. This file allows all the georeferenced information used in the exercise to be viewed in Google Earth, and contains several layers of information that can be turned on or off as needed when completing the fieldwork. Field stops including immersive GigaPan panoramas and additional photographs of geologic features were marked with blue and gray placemarks, photographs and locations of rocks not present in outcrop were marked with green placemarks, and several other interesting (if not directly related) sites in the area, such as the sniper's nest at the Farnsworth house and the dinosaur footprints on the bridge that crosses Plum Run, were highlighted with red placemarks. Battlefield maps that can be projected directly onto the terrain were also included.

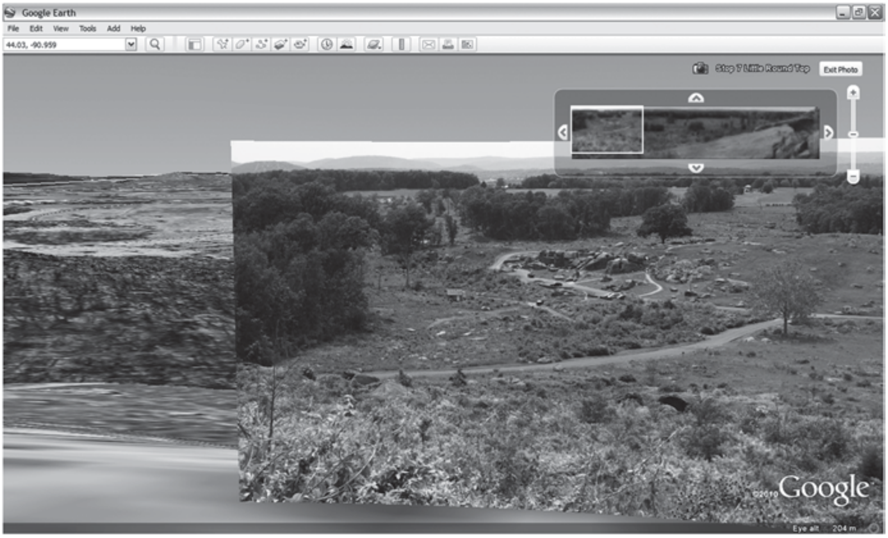

Fig. 2 A GigaPan panorama of the view from Little Round Top geolocated in Google Earth using latitude and longitude data collected in the field. These immersive panoramas give the user a soldier's-eye view of the battlefield, making the experience more interactive and helping to illustrate the relationships between outcrop-scale features and regional geology and geomorphology. By entering this panorama, users get a better sense of the spatial relationship between Little Round Top and Devil's Den than they can through satellite images or digital elevation models alone

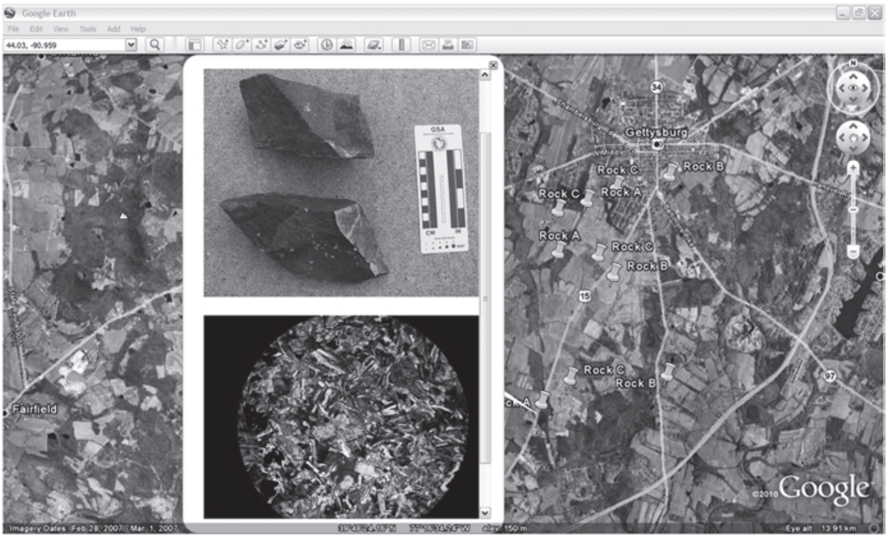

Fig. 3 Examples of geologic information that can be geolocated in Google Earth. Here, users can view hand samples and petromicrographs of the Rossville diabase that underlies Warfield Ridge. Markers show the locations of additional rock units not readily observed in outcrop. Students are asked to use this data, along with field observations collected from GigaPan panoramas, to create a geologic map of the battlefield

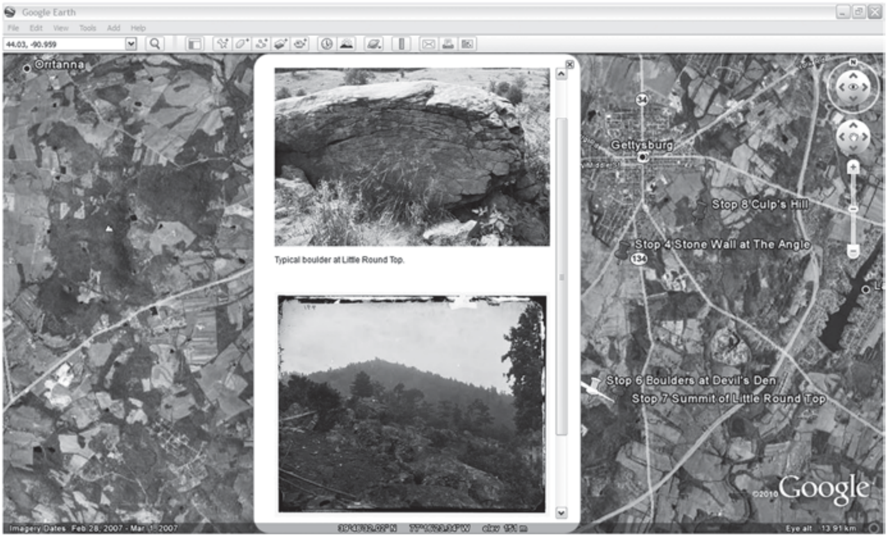

Fig. 4 Other types of information that can be geolocated in Google Earth. Field snapshots and historical photographs can enhance the interactive experience. Users can observe weathering patterns on Little Round Top to help identify rock types or view a photograph of hill taken just days after the battle for another perspective on how terrain influenced the fighting. Text, images, and video can all be geolocated in this manner. Historical Photograph: Timothy O'Sullivan, U.S. Library of Congress

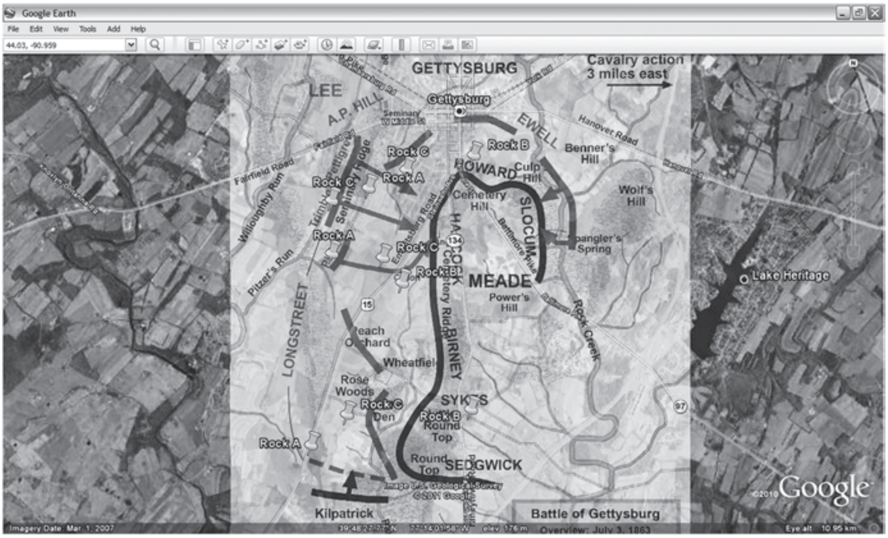

Fig. 5 Image overlays allow graphic data to be placed over the landscape in Google Earth. Geologic map overlays are useful in visualizing the relationships between geologic units and terrain. In the virtual fieldwork exercise, users can select to view maps outlining troop placement and movement during the battle to help them understand how these were related to the underlying geology. This is especially useful later in the exercise, when students are asked to analyze the effects of geology and topography on the battle. Map by Hal Jespersen, www.cwmaps.com

5 In the Classroom

The virtual field environment is best explored using a computer with high-speed internet access. Before completing the exercise, students should have some general knowledge of the battle (the WSU geomorphology students watched a documentary outlining the events of July 1–3, 1863). Students are directed to the virtual fieldwork website to begin the exercise. A student's first task is to identify and describe the hand samples. After identifying the rocks, the student can download a topographic map of the battlefield and the.kmz file to begin exploring the virtual field environment in Google Earth. At each of the seven field stops, students should orient themselves and find their location on the map, explore the associated panorama in both Google Earth and on the GigaPan website, make field observations (including locations of outcrops, weathering patterns of rocks and topography of the area) and identify rocks in outcrop based on their identification of the hand samples.

Students are encouraged to explore the panoramas on their own and make observations. They can also be directed to specific areas of the pan with the snapshot feature. The immersive geolocated panoramas allow students to establish a sense of place and get a soldier's eye view of the terrain, making the experience more interactive and helping to illustrate the relationships between outcrop-scale features and regional geology and geomorphology. By entering the panoramas, users get a better sense of the spatial relationships of landscape features than they can through satellite images or digital elevation models alone. Geolocated petromicrographs allow students to check their rock identifications based on observations of texture and weathering, and provide for a truly multi-tiered analysis of each site (from landscape to individual mineral grains). The overlay maps were especially useful later in the exercise, helping students to easily see the relationships between troop movement and terrain.

The student is then tasked with using their data to create a geologic map of the battlefield and analyze the relationships between geology, terrain, and tactics. The questions they are asked include:

- How did the underlying rocks influence the topography of the battlefield?
- What rock type was most common in the parts of the battlefield held by the Union forces? How did this provide the Union Army a tactical advantage?
- One of the axioms of infantry warfare is that an attacking army must expect significantly higher losses than a defending force, which ordinarily will be entrenched. When Union forces attacked well-entrenched Confederates at Fredericksburg (December 1862), and Spotsylvania (December 1864), they lost about twice as many men as the Confederates. But at Gettysburg, the defending Union Army suffered a disproportionately high number of casualties (23,000 compared to the Confederates' 28,000). Why was this so? (Brown 1962)
- Using the GigaPan panorama, carefully observe the field crossed by Confederate soldiers during Pickett's Charge. Describe the topography. How might the topography have affected the soldiers as they marched toward the Union line? Keep in mind that the soldiers' uniforms were wool, it was a hot July afternoon (almost 100° F), and they travelled on foot carrying all their equipment.

- Using the GigaPan panorama, describe the outcrop at Devil's Den. What processes are responsible for the outcrop pattern? Be as specific and descriptive as possible.

6 Conclusions

Although it is by no means a substitute for field experience, the type of virtual fieldwork made possible by integrating new technologies into existing courses grants students access to locations too remote to feasibly visit and opens the door to more inquiry-based learning. It also provides students with disabilities that prevent them from exploring field sites easily the opportunity to gain field skills. Student responses to these technologies have been positive. Many students have expressed their surprise at how interested they were to learn about a topic they thought they cared little for. In an interdisciplinary field such as geoscience, the opportunities for incorporating these technologies into the classroom are virtually limitless, and their use can open the eyes of students to previously unrealized connections, such as the connections between Civil War tactics and Mesozoic geology described here.

Appendix 1: Creating Your Own Virtual Field Experiences

Below are a few tips to get you started creating your own virtual field experiences as described above.

Creating GigaPan Panoramas
The GigaPan robotic camera system is available for purchase at www.gigapan.com. Stitching software is included. Authors of GigaPan panoramas are able to upload their pans, geolocate them in Google Earth and embed them in webpages using tools available on the GigaPan website. Visitors to the GigaPan website are able to create snapshots in any panoramas and embed selected panoramas into webpages.

Creating a Webpage
We set up several webpages to disseminate information for this project. Depending on your skill level, there are many options for creating your own webpage. We used Google Sites (https://www.sites.google.com/) which provides a free, easy-to-use platform for adding text and images to your webpage. It also allows users to directly edit the page's HTML code.

Creating the Virtual Field Environment in Google Earth
Google Earth provides much more functionality for creating virtual field experiences than can be discussed here. Those who wish to explore virtual field experiences further should start with "An Illustrated Guide to Creating Virtual Field Trips Using Google Services" (ATEEC 2007).

- To create a virtual field environment in Google Earth, first download the latest version of the free software (http://www.google.com/earth/index.html). If you are not already familiar with navigating in the Google Earth environment, take a few minutes to familiarize yourself with the controls by working through the product tutorials available on the website.
- Click on the "Add" menu at the top of the Google Earth window to add a folder. Give this folder a project name—all your project materials will be housed inside this folder. Once it is added, you will see the folder in your "Places" panel. Be sure that your new folder is inside the "My Places" folder and not inside the "Temporary" folder—simply drag and drop to rearrange the folders.
- Once you have found a feature you would like to mark with a placemark, click on the yellow tack icon at the top of the window (or Add → Placemark) to add a placemark to your folder.
  - Position the placemark (by dragging the yellow box) so that it is centered over the feature you are marking.
  - In the "New Placemark" window, you can name the placemark, type a description of the feature you are marking, insert a link, or add HTML content. If you already have content on a webpage that you would like to add as an annotation to the placemark, simply copy the HTML code from the part of the webpage you would like to use and paste it into the "Description" tab in the "New Placemark" window. The content you have added will appear when users click on the placemark.
  - Clicking on the yellow tack in the upper right corner of the "New Placemark" window will allow you to choose a new icon for your placemark.
  - To finish your placemark, click OK.
  - Note that your new placemark has appeared inside your folder in the "Places" panel. If not, drag and drop until it does.
  - You can edit the placemark by right-clicking on the placemark and selecting "Properties."
- To add an image overlay to your project (useful for projecting geologic maps or battle maps onto the terrain) click the "Image Overlay" button at the top of the window (or Add → Image Overlay).
  - The image overlay can be scaled by dragging the green edges of the image.
  - Transparency is controlled by a slider in the "Image Overlay" window.
  - Location and rotation of the overlay are controlled in the "Location" tab in the "Image Overlay" window.
- The panel on the left side of the window allows you to turn placemarks and other layers on and off by checking or unchecking the boxes.

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Fort Fisher, NC Past and Present: A Geospatial Analysis using LiDAR and GIS

Michael J. Starek, Russell S. Harmon and Helena Mitasova

Abstract Fort Fisher was constructed in 1861–1863 by the Confederacy at the mouth of the Cape Fear River in North Carolina to protect the vital trading routes of the seaport at Wilmington. The largest Confederate fort, Ft. Fisher was constructed as an L-shaped fortification consisting of 30 ft (9 m) thick earthen mounds capable of absorbing the shock of a heavy bombardment. In its prime, this fortification consisted of an approximately 1800 ft (550 m) long land face and a mile-long (1.6 km) sea face bounded by two larger 45 ft (14 m) and 60 ft (18 m) high mounds on the southern end. Today, Ft. Fisher is a mere remnant of its former self, with only about one-tenth of the original structure remaining. The region where the fort was constructed is a highly dynamic section of coastline that has undergone extensive shoreline retreat over the past century, resulting in the loss of the majority of the original fortification. Light detection and ranging (LiDAR) survey data and historical maps were used to generate past and present 3-D digital elevation models (DEMs) for both the terrain and fort. The historical shorelines, aerial imagery, bathymetric data and fort models were then integrated and compared within a geographic information system (GIS) to analyze and to model the evolution of the coastline from past to present. Results provide insight into the geographic advantages behind Ft. Fisher's original layout for defense of the inlet compared to the present day geomorphology of the region.

Keywords LiDAR · Coastal erosion · Civil war · Spatial modeling

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1 Introduction

Following the War of 1812, which saw British forces sail into Chesapeake Bay in 1814 and then occupy and burn Washington, the U.S. Congress appropriated funds in 1816 for an ambitious system of seacoast defenses that was known as the "Third System" (Weaver 2001). The Board of Engineers for Fortifications recommended that forts be built at 50 sites, but by 1850 nearly 200 sites had been suggested. Ultimately, forts were built at 42 of these sites, with several additional sites containing towers or batteries. The main defensive works of these forts were often large structures, based on combining the Montalembert concept of many guns concentrated in tall thick masonry walls and the Vauban concept of a layered series of low protected-masonry walls (Weaver 2001).

Fort Fisher in North Carolina was not a part of the US coastal fortification system, but instead was a fort constructed in 1861–1863 by the Confederacy at the mouth of the Cape Fear River to protect the vital trading routes of the port at Wilmington. The largest Confederate fort, Ft. Fisher was constructed as an L-shaped fortification consisting of 30 ft (9 m) thick earthen mounds capable of absorbing the shock of a heavy bombardment (Fig. 1). The mounds of both lines shared an underground network that was impenetrable to artillery and joined at the Northeast Bastion. The 1800 ft (550 m) long land face sat behind a 9 ft (3 m) high palisade stake fence and was equipped with 25 guns distributed among its 15 mounds. The mile-long (1.6 km) sea face consisted of 25 guns at a series of 12 ft (3.7 m) high batteries and was bounded on the south end at Mound Battery by two larger 45 (14 m) and 60 ft (18 m) high mounds (Moore 1999).

Today, Ft. Fisher is but a mere shadow of its former self with only about one-tenth of the original structure remaining (Fig. 2). Federal Point (Fig. 1b), where the fort was constructed, is a highly dynamic section of coastline that has undergone extensive shoreline retreat over the past century resulting in the loss of the majority of the fortifications. In this study, a geospatial analysis was performed to better understand the rationale behind the fort's original construction relative to the present day terrain. Data sets from disparate sources including airborne light detection and ranging (LiDAR), aerial imaging, and historical shoreline maps were integrated and compared using geographic information system (GIS) analysis tools to model the evolution of the region from its former self to the present day.

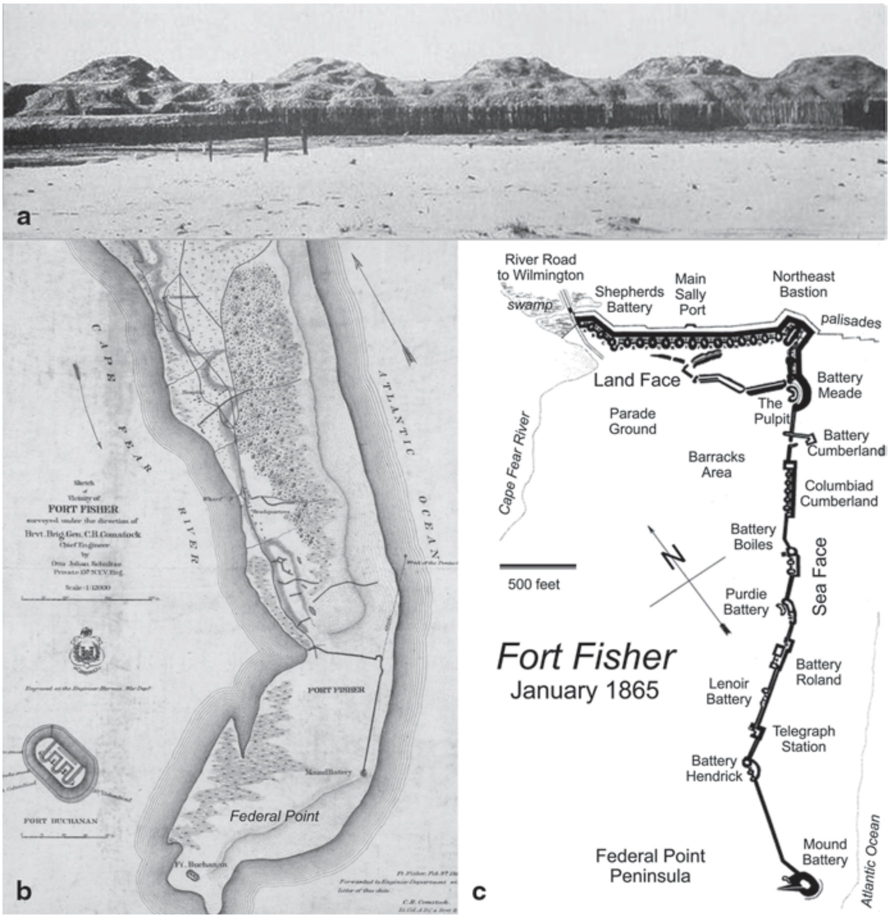

Fig. 1 **a** Historic image of Fort Fisher, NC showing the earthen mound construction and palisade fence along a portion of the fort's sea face. Image from Miller and Lanier (2011). **b** Historical chart showing the L-shaped layout of Fort Fisher, and its location along Federal Point. Image from NOAA (2011). **c** Map of Ft. Fisher in 1865 (Moore 1999)

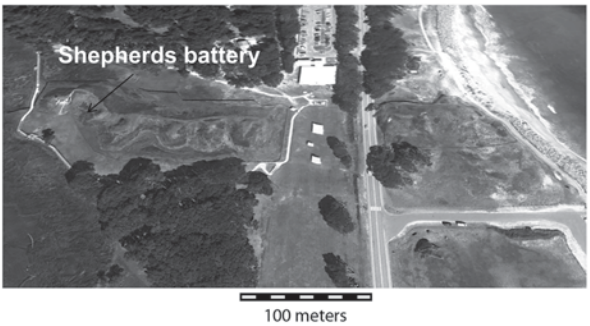

Fig. 2 Aerial image showing the remnants of Fort Fisher. Image acquired from Google Earth

2 Geospatial Modeling

Airborne LiDAR data acquired over the region were used to generate a 1 m digital elevation model (DEM) of the terrain to represent the present-day state of the fort and surrounding coastal landscape. The LiDAR point cloud data, downloaded from the NOAA Coastal Services Center online distribution site (NOAA 2011), were acquired during a 2005 survey conducted by the USACE Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) using an Optech SHOALS LiDAR system. Published vertical accuracy is better than ± 0.3 m at 2σ with a point density of approximately 1.3 pts/m (NOAA 2011). The raw data consists of an irregularly spaced x, y,z point cloud that was then interpolated into the 1 m elevation grid using a regularized spline under tension routine within the open-source GRASS GIS (Mitasova et al. 2005; Neteler and Mitasova 2008). Figure 3 shows the present day state of the terrain and fort (see Fig. 2) as represented by the LiDAR-derived DEM.

For comparative purposes, a 3-D digital model of the historical fort was constructed using the computer aided 3-D design tool Google SketchUp (Google 2010). The model was scaled to approximate the dimensions of the 1865 construction (Fig. 1c) and georeferenced by aligning it to the LiDAR-derived DEM and airborne imagery of the region. This enabled the 3-D model to be imported into a GIS system to assess the historical layout of the fort relative to the present day coastline. Figure 4 shows the extent of the historical fort relative to the present day terrain within Google Earth. Referring back to Fig. 3, approximately half the land face and the entire sea face of the fort have been lost over the past century and a half due to coastal erosion and inundation. Shepherds battery and the remaining earthen mounds on the western side of the road that now cuts through the historic fort have fared much better compared to the remnants on the eastern side of the road facing the sea.

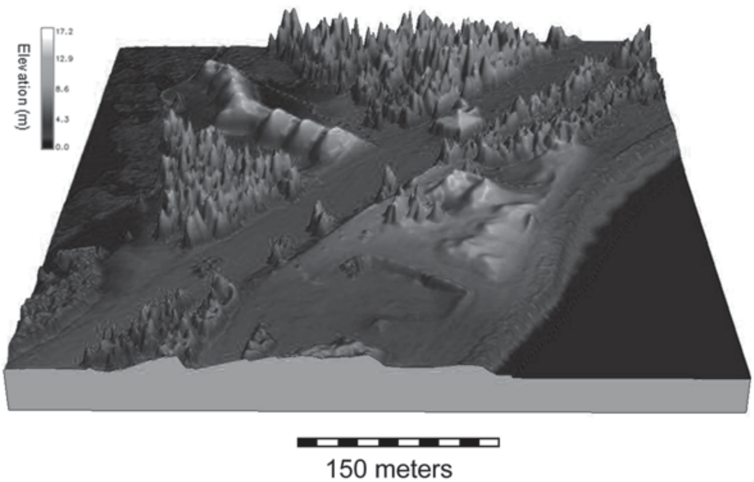

Fig. 3 LiDAR-derived 1 m DEM showing the present day state of the fort and terrain

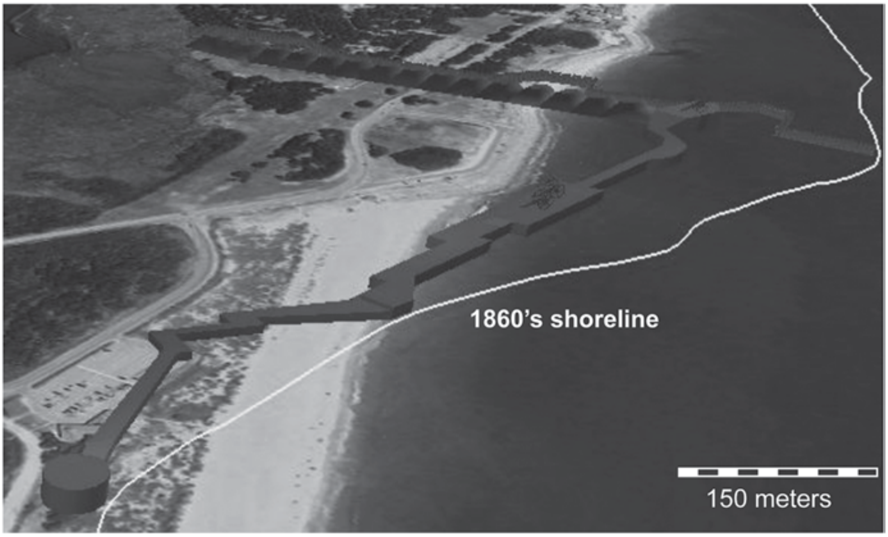

Fig. 4 3D model of historical fort showing its layout relative to the present day coastline. Model developed from historical maps using Google SketchUp. The USGS historical shoreline vector data for the region were downloaded from the NOAA shoreline website (USGS 2011)

3 Coastline Evolution

The Fort Fisher shoreline is characterized by erosion resistant coquina limestone (calcarenite) that underlies Pleistocene humate sandstone and outcrops along the intertidal beach. The shape and evolution of the shoreface in the region is directly linked to the outcropping and underlying Pleistocene geologic units (Swain and Cleary 1992; Riggs et al. 1995; Cleary et al. 1996). In the early part of the 20th century, major sections of the coquina that crops out on the beach area were removed for construction materials. This coupled with the closure of an inlet south of the fort, discussed below, ultimately contributed to a shoreline erosion rate exceeding 17 m/year between 1926 and 1931 (Cleary 2008; Beach Erosion Board 1931).

This region of the North Carolina coast is also prone to storm impact and coastal flooding, which further amplify the shoreline retreat. Major hurricanes that have impacted this area include Hurricane Hazel in 1954 and Hurricane Fran in 1996, each of which stripped away the sand prism and exposed the underlying headlands platform. In the aftermath of Hurricane Fran in 1996, the U.S. Army Corps of Engineers replenished an approximately 5500 m long segment of beach including the Fort Fisher shoreline reach (Cleary 2008).

To gain a better understanding of how the coastline has evolved since the time of Fort Fisher's construction in the early 1860's, historical maps and shorelines of the region were compared to aerial imagery of the present day coastline. Figure 5a is a Confederate survey map showing the 1860's coastline. Evident in the map is the strategic location of Ft. Fisher along Federal Point at the mouth of New Inlet. New Inlet was the primary entry point for the Port of Wilmington. This offered

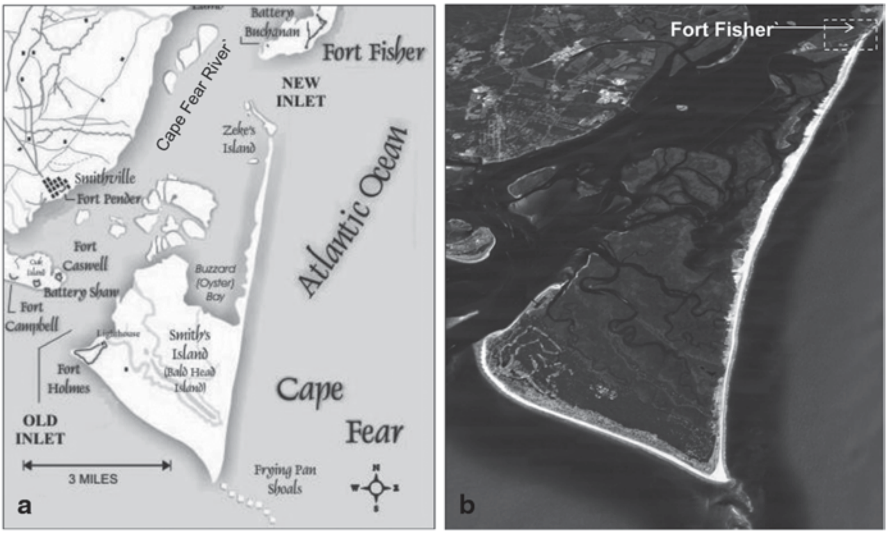

Fig. 5 **a** Coastline in the 1860's showing the strategic location of Fort Fisher at the mouth of New Inlet. Image adapted from Moore (1999). **b** Aerial imagery acquired from Google Earth showing the present day coastline. New Inlet has since filled in

ships a short cut to the harbor, so defense of that point by Confederate forces was crucial. For comparison, Fig. 5b shows aerial imagery of the present-day coastline. As clearly shown in the figure, New Inlet has since closed. In the late 19th century, a long rock jetty called "The Rocks" was built west of Ft. Fisher to aid navigation by stopping shoaling in the Cape Fear River (NC State Parks 2014). Completed in 1881, the massive jetty effectively cut off tidal exchange between the Cape Fear River and the inlet estuary thereby resulting in the closure of New Inlet. This blockage in tidal exchange led to an increase in the Cape Fear River Inlet tidal prism and a subsequent increase in the bar channel water depths (Cleary 2008).

Closure of New Inlet set the stage for the excessive shoreline retreat observed along the updrift shoreline segment at Ft. Fisher. Prior to inlet closure in 1881, a large asymmetric ebb shoal containing a minimum of approximately 38 million m^3 of material fronted the Ft. Fisher shoreline (Swain and Cleary 1992). The highly skewed ebb delta acted as a natural breakwater to incoming wave energy and protected the updrift shoreline against direct wave attack. Closure of the inlet prompted the collapse of the ebb shoal, as the tidal prism of the inlet was drastically reduced. Since closure, the oceanfront has retreated by as much as 250 m (Cleary 2008). Figure 6 shows USGS historical shoreline vectors (USGS 2011) and the 3-D model of Ft. Fisher overlaid on aerial imagery of the present day coastline along Federal Point. The 1860's shoreline follows the northern boundary of the former New Inlet that was defended by the fort. By 1930, the shoreline had already started to cut through the eastern sea face of the fort. This erosive trend continued over the past century as evidenced by the successive landward retreat of the 1980 and 2000 shorelines resulting in as much as 200 meters of shoreline loss measured relative to the 1930 shoreline position.

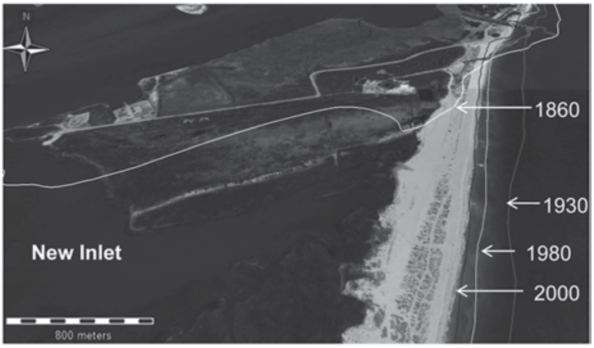

Fig. 6 Historical shorelines from USGS (2011) overlaid on present day aerial imagery in Google Earth showing the massive retreat in shoreline resulting in the loss of the majority of fortifications. The 1860 shoreline outlines the northern boundary of the former New Inlet that was closed in 1881 by construction of a dam

Closure of New Inlet and the removal of the coquina were major anthropogenic events that have had a significant and long-lasting impact on this portion of the coast (Cleary 2008) as evidenced by the extensive shoreline retreat. In order to mitigate the rapid shoreline retreat in the region, a beach erosion control project was authorized in 1976 to protect Fort Fisher's remaining earthen-mound fortifications. After obtaining a variance from the State, the project was initiated in 1995. It consisted of a 930 m long rock revetment with crest elevations of 3–5 m, a base width of 21 m, and an armored toe consisting of five-ton interlocking concrete Sta-Pod units (Dennis 1996). The project was completed in the spring of 1996 and stands as a last defense against the encroaching sea.

4 Sea Level Rise Simulation

Sea level rise in the region has a mean rate of approximately 2.5 mm/year based on a NOAA tidal gauge in Wilmington, NC (NOAA TIDES 2011). To determine if there any interesting submerged landscape features that may be vestiges of the historic fortifications, a 30 ft resolution (~9 m) topo-bathymetric DEM of the region generated from airborne LiDAR and sonar data was acquired from RENCI (2011). The DEM was then used to simulate the difference in sea level between the present day and the time of Ft. Fisher's prominence in the 1860's. Figure 7a shows the topo-bathymetric DEM referenced to the North American Vertical Datum of 1988 (NAVD88). The present day remnants of Ft. Fisher and New Inlet are observed in the DEM.

Mean sea level (MSL) in the region is approximately −0.2 m referenced to NAVD88 based on a localized NOAA tidal gauge (NOAA TIDES 2011). This elevation was used to generate a MSL flood simulation on the topo-bathymetric DEM using the r.lake module in GRASS GIS (Neteler and Mitasova 2008). Figure 7b shows the present day MSL flood simulation overlain on the DEM. MSL at the time of Ft. Fisher's construction in 1860 was estimated to be −0.6 m NAVD88 by assuming a 2.5 mm/year MSL rate for the past 150 years. Figure 7c shows the 1860 MSL flood simulation overlaid on the DEM. Given a difference in MSL of only

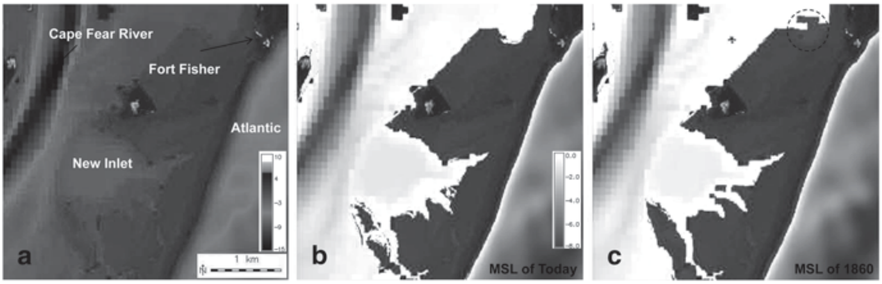

Fig. 7 **a** 30 ft resolution topo-bathymetric DEM of the region showing the terrain and bathymetry elevation in NAVD88 meters. **b** Flood simulation showing the present day mean sea level *(MSL)* overlaid on the DEM. Grayscale bar shows water depth in NAVD88 meters. **c** Flood simulation showing 1860 MSL overlaid on the DEM. The circle shows a zone of exposed topography to the west of Fort Fisher

about 0.4 m in elevation between 1860 and the present day, the overall differences in exposed topography between Fig. 7b and c are minor except for the region directly west of Ft. Fisher (Fig. 7c). In 1860, this was a swampy region consisting of inundated and exposed terrain with tree coverage that bordered a transit road along the river from the fort to Wilmington (Moore 1999). Today, this region consists solely of inundated marshland, demonstrating further how much the landscape has evolved since the time of Fort Fisher's original construction.

5 Conclusions

Fort Fisher has played a unique role in United States history. Up until the last months just preceding the Civil War, the fort provided protection for the Port of Wilmington to blockade runners supplying vital goods to Confederate armies inland. By 1865, the supply line through Wilmington was the last remaining route open to GEN R.E. Lee's Army of Northern Virginia. When Ft. Fisher fell after a massive Federal amphibious assault on 15 January 1865, its defeat helped seal the fate of the Confederacy by cutting off this vital supply link.

In this study, a geospatial analysis was conducted to examine the extent to which Ft. Fisher and the surrounding coastline have evolved since its original construction as a defensive fortification for the former New Inlet. By generating a 3-D model of the fort just after its construction in 1865, the spatial layout of the fort relative to the present day terrain could be visualized. Closure of New Inlet in 1881, and the subsequent removal of coquina rock in the adjacent coastal area are two human activities that impacted long-term coastal processes in the region. As documented by the shoreline analysis, these events, coupled with climatic forcing leading to relative sea level rise and coastal inundation plus the effects of two hurricanes in the mid-twentieth century, have resulted in extensive shoreline retreat and a loss of the majority of fortifications such that only about ten percent of the original structure remains.

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Part II
Military and Defense Interests and the Environment

There's Uranium in Them Hills: The Archaeology of Nevada's Uranium Boom

Jonah S. Blustain

Abstract The central role of the atomic bomb in geopolitical conflict during the mid-twentieth century has been extensively documented by historians, economists, and political scientists. However, as it has only recently passed into the realm of history, little work has been conducted within the archaeological realm regarding the uranium used to make these weapons, in particular its prospection and mining. Spurred on by the policies of the United States government, particularly the Atomic Energy Commission, the uranium boom of the 1950s and 1960s inspired a significant wave of exploration for uranium within the continental United States. The State of Nevada, while more well-known for its gold, silver, and copper reserves, was the focal point of substantial uranium prospecting and mining between 1951 and 1968. This paper uses data from Nevada's uranium boom to create a model for the archaeological investigation of uranium-related mining sites as well as attempts to draw attention to the uranium mine and its ancillary features as a legitimate object of archaeological interest and an area of much-needed cultural resource management.

Keywords Uranium · Mining · Archaeology · Cultural resource management

1 Uranium: Discovery and Early Applications

Uranium (U) is a very dense, silvery-white metallic element which has the second highest atomic weight of the naturally occurring elements. The metal occurs naturally in very low concentrations averaging a few parts per million, but can be found in much higher concentrations in select geologic contexts. The metal was first described in 1789 by Martin Klaporth, a German pharmacist who was experimenting with *pechblende*, a greasy mineral found in association with the rich silver deposits of the Bohemian region (Baroch 1965). *Pechblende*, translating loosely as "bad-luck rock", was at that time known to be an amalgam of lead and some other unknown element and was not only a sign to the eighteenth century miners that they

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had reached the end of their silver vein, but was a portent of oncoming sickness, later identified as radiation poisoning (Zoellner 2009). After separating an unknown silvery substance from the lead, Klaporth named the purified metal Uranium, after the newly-discovered planet Uranus.

Very quickly, uranium became the target of study in multiple fields. Late nineteenth and early twentieth century European scientists experimented with the largest-known atom, looking for applications. It was hypothesized that if a neutron was fired into a single uranium nucleus, a chain reaction would take place resulting in the splitting of more atoms, thereby creating a source of energy thought impossible at the time (Zoellner 2009). This idea eventually came to the attention of Leo Szilard, a physicist at Columbia University who, with physicist Albert Einstein, wrote a letter to be hand-delivered directly to the United States' President Franklin D. Roosevelt on October 11, 1939 (Zoellner 2009). The letter outlined the potential of such a power source and insinuated at potential military applications of such a chain reaction, including weaponization as a bomb. Most importantly, the letter observes that in relation to other areas, the United States has few known sources of high quality uranium ore (Zoellner 2009).

Szilard and Einstein further advised President Roosevelt to entrust an advisor or friend with the unofficial task of acting as a liaison between the President himself and those sectors of the academic community actively working on uranium fission. The President acted on the advice and immediately created The Uranium Commission, an ad hoc committee with an initial budget of only $6000.

On-going research into splitting the nucleus of an atom of uranium revealed there to be two isotopes of the element, one lighter and one heavier. Experiments showed that while the isotope U-235 was significantly more unstable than the heavier U-238, it was also more rare. Without a massive industrial facility, it was impossible to economically distill the U-235 from the more common U-238. Foreseeing dire global consequences if Nazi Germany created an atomic bomb first, the United States government authorized the director of the federal Office of Scientific Research and Development to create the S-1 Project, also known as the Manhattan Engineer District (Baroch 1965; Zoellner 2009). The creation of the Manhattan Project in 1942 coincided with a total media blackout regarding U-235.

1.1 World War II and Uranium Weaponization

The Manhattan Project created the first atomic bomb out of the last 141 pounds of U-235 available at the time in America. The parent ores came primarily from the Belgian Congo, but included ores from other areas including a shipment meant for Imperial Japan that was captured in a U-Boat at the end of the European Theatre (Zoellner 2009). As the war ended, the Manhattan Project had served its purpose and was no longer needed. In 1947, President Truman signed the Atomic Energy Act of 1946 which created a new government agency, the Atomic Energy Commission (AEC), to oversee the peacetime development of the United States' atomic energy program.

Under the Atomic Energy Act, the AEC was tasked with the oversight of the powerful new energy source and was responsible for creating useful applications for atomic energy while stockpiling uranium for military use (Buck 1983, p. 1). From the start, the Commission had a complicated mission. On one hand, it had to promote the benefits of atomic energy for the greater public and its potential to improve the free market system; while on the other hand, it also dealt with State secrets and the military applications of the atomic program. As a result, the first AEC was structured to be unique from other governmental agencies. AEC employees were not bound by the Civil Service system, and the results of their work would be under direct AEC control, outside of the mainstream patent system. In addition, the United States Government initially retained tight control over all of the AEC's facilities, thereby ensuring operational security.

In the aftermath of the explosions in Hiroshima and Nagasaki, the American public became aware of the power of the atomic bomb, and uranium fever was born. The public love affair with the dangerous metal was expressed in multiple, often differing ways. Some thought that it should be used as a universal currency, much as the dollar was backed by a theoretical amount of gold (Zoellner 2009, p. 77). Others saw the potential for unlimited power sources that would usher in new utopias. The AEC's first director, David Lilienthal, traveled across the country making speeches and giving presentations regarding the new power source. Acting as boosters for uranium and atomic power, Lilienthal and the AEC encouraged the American fascination with all things related to the fission bomb. This atomic age was marked by a love of all things associated with nuclear power. The word itself was ascribed to anything and everything seen as powerful and exotic (Zoellner 2009, p. 92). One of the more grand expositions of the power of the atom was Man and the Atom, a large exhibition in New York City's Central Park featuring demonstrations by the AEC and large government contractors.

1.2 Developing Military and Civilian Applications of Atomic Power

The optimism of the post-war atomic future was tempered by the uneasy geopolitical situation between the United States and its allies, and the growing power of the Union of Soviet Socialist Republics (USSR). In September of 1949, the USSR successfully carried out their own test of an atomic device in the Pacific Ocean, effectively ending the monopoly the United States had on thermonuclear technologies (Buck 1983, pp. 1–2). The official announcement by the USSR confirming their successful test was met with fear by the Commissioners of the AEC. On 31 January 1950, President Truman made the construction of thermonuclear devices the main priority for the AEC as they were "essential to the security of the United States" (Buck 1983, p. 2).

After the executive decision to shift the focus of the AEC away from the peaceful applications of atomic power, to one that was more heavily influenced by foreign policy and military doctrine, Lilienthal resigned. With the beginning of the conflict in Korea that same year, and continuous saber-rattling of the USSR, the AEC began an extensive renovation to its production facilities. The major outcomes of the production expansion were two-fold: (1) over $3 billion in Federal money went to increasing and modernizing gaseous-diffusion plants for the purification of uranium-235; and (2) the AEC quickly realized that there was a significant need for a range on which to test the new nuclear devices that were being made (Buck 1983, pp. 2–3).

With the success of the on-going program to weaponize atomic power, attention once again shifted back to the civilian and commercial application of nuclear power (Buck 1983, pp. 2–4). A small amount of electrical power suitable for public consumption was produced by an AEC reactor in Idaho on 20 December 1951, followed by a much more successful test in a nuclear submarine in June of the following year. Public interest in nuclear power for non-military applications rose, and was reflected in Congress. The culmination of this increase in interest was the passage of the 1954 Atomic Energy Act.

By the early 1950s the United States had an ample supply of nuclear material and began to invest more heavily in the peaceful applications of nuclear power. In early December 1953, President Dwight D. Eisenhower delivered his well-known "Atoms for Peace" speech in which he laid out his idea of atomic energy as a beneficial force that could ensure international peace (Buck 1983, p. 3). If the President's vision was to occur, there would have to be a fundamental policy change regarding the use of atomic resources. Under the Atomic Energy Act of 1946, the vast majority of the country's nuclear infrastructure was owned by the United States Government and most of the work was performed by AEC employees. In addition, all nuclear material was nationalized. Such an arrangement was less than ideal for private industry.

With the passage of the Atomic Energy Act of 1954, private industry, expertise, and capital were tapped to explore the civilian applications of nuclear energy. Construction of a series of five experimental reactors was planned from 1954 through 1959 (Buck 1983, p. 3). In addition, private industry was also allowed to build its own power stations using fissionable material that could now be leased from the government. Three years after the passage of the 1954 Atomic Energy Act, the AEC owned seven experimental reactors and was partnering with private capital in several more. The net capacity of these new power plants exceeded 79,000 kW (Buck 1983, p. 3).

During this period, while government and industry investigated the peaceful uses of atomic power, the United States military continued to explore the weaponization of uranium. With the increased weapons testing in the Pacific as well as Nevada, public apprehension surrounding the effects of radioactive fallout grew. Higher-than-background radiation levels, which had previously been indicative of potential uranium ore, now conjured up images of radioactive fallout (Buck 1983, p. 4). In part due to the public concern the United States, as well as the USSR, began a moratorium on nuclear weapons testing in October 1958. This test ban would only last 3 years before the USSR backed out. A second moratorium was agreed upon in August 1963 (Buck 1983, p. 4). This agreement specifically precluded any weapons testing underwater or in the atmosphere, but allowed for limited testing underground.

Following the ban on weapons testing, there was renewed confidence that atomic power could be harnessed for peaceful purposes (Buck 1983, p. 5). In 1962, President Kennedy again made nuclear power a priority for the AEC which was tasked with the goal of nuclear power being competitive with traditional fuels by 1968. A year later, President Johnson further demonstrated the United States' belief in the peaceful applications of nuclear power by cutting back the production of enriched uranium by 25 % (Buck 1983, p. 5). The goal of competitive nuclear power was realized in December 1963, when a New Jersey nuclear power plant operated by the Jersey Central Power and Light Company produced enough electricity in a sufficiently efficient manner to be competitive with other plants that relied on traditional fuels. The nuclear materials that were used in the power plant had to have been leased from the government, representing a major impediment for power expansion.

As the civilian applications for nuclear power became more and more prominent, the private industries actively working on making such applications a profitable reality were increasingly hampered by the government ownership of all nuclear materials since 1946. In August of 1964, President Johnson signed the Private Ownership of Special Nuclear Materials Act which allowed for private businesses to acquire, store, and own nuclear materials (Buck 1983, p. 5). An additional clause of the bill included a planned transfer of all nuclear materials from Federal to private hands by mid-1973. As the infrastructure to collect and process uranium was still held by the AEC, many of the Commission's technical briefs were declassified, and their ore beneficiation services were offered to American and foreign customers. With the passage of the Act, the stage was set for full privatization of the civilian nuclear power industry.

While electricity production from nuclear power had always been a main goal of the AEC since 1946, no one could have anticipated the efficiency and capacity such reactors would reach. Initial expectations of nuclear power generation were capped at approximately 5000 MW by 1970; however with the inclusion of private industry, those expectations were increased twice. By 1966, the AEC was allocating approximately half of its yearly funds to civilian uses for nuclear materials such as uranium (Buck 1983, pp. 5–6).

1.3 Decline of the Uranium Mining Industry

By the beginning of the 1970s, the nation's priorities regarding nuclear power and uranium resources had changed. The United States was suffering from a power crisis caused by the 1973 OPEC oil embargo, insufficient domestic oil and gas production, and concerns over the environmental impacts of coal-fired power plants (Buck 1983, p. 7). To add to this dearth of readily-available energy, the AEC simply did not have the resources or infrastructure to support and regulate the massive amounts of nuclear plants that were demanded. While the AEC's military programs were once one of the primary means of ensuring the country's safety, it very quickly became clear to members of the government that the Commission was having difficulty switching gears and efficiently regulating the United States' nuclear power industry (Buck 1983, pp. 3–8).

In October of 1974, President Ford signed the Energy Reorganization Act which effectively ended the Atomic Energy Commission's stewardship of the country's uranium reserves. Under the Energy Reorganization Act of 1974, the AEC was divided into two discrete bureaucracies. All of the Commission's resources relating to the research and development of new nuclear technologies was subsumed by the Energy Research and Development Administration, while the regulatory functions were given to the Nuclear Regulatory Commission (Buck 1983, p. 8). The nation's use of uranium for civilian and military purposes continued; however the large-scale exploration and exploitation of the Continental United States' uranium resources dropped significantly as existing stockpiles were exploited.

2 Uranium Mining in Nevada

Unbeknownst to many, even the miners themselves, uranium has been continuously mined in the United States since the last quarter of the nineteenth century (Hahne 1990). Between 1871 and c.1905, miners extracted small amounts of uranium ore from the Colorado Plateau to fuel demand on the world market. The ore was often used for scientific experiments, to color glazes for ceramics, or as a glass colorant (Hahne 1990). Later in the 1920s, it was discovered that these small uranium deposits contained significant amounts of vanadium, a metal used in the production of high-strength steel. Immediately, vanadium mining boomed, and with it, uranium.

2.1 The Vanadium Rush

Between 1925 and 1945, the United States was a major producer of vanadium. As vanadium was often found in areas that contained significant quantities of uranium ore, old uranium mines were reworked for their vanadium content. In 1942, the United States Geological Survey dispatched geologists to the western United States to evaluate the potential of the country's primary vanadium deposits. The ores examined by the geologists assayed well at approximately 1.5 % vanadium and 0.25 % uranium (Hahne 1990). It was around this time that uranium ores were mined solely for their vanadium content. The uranium content extracted from the ores during the milling process was discharged from the mill as tailings (Hahne 1990).

2.2 *Uranium in Nevada*

As of 2012, little scholarly research has been conducted into Nevada's uranium mining industry, as it has been overshadowed by the Comstock boom of the late nineteenth century and the subsequent gold, silver, and copper booms of the early twentieth century. In Nevada, there are at least 442 known occurrences of uranium spread across the state. Like the more-extensively studied precious metals deposits more familiar to archaeologists, uranium rarely occurs in single isolated deposits, but instead is clustered in localities that have a common origin. Often uranium was first observed in negligible concentrations in association with precious or industrial metals, or in prospecting features positioned adjacent to producing districts. A smaller percentage of known occurrence clusters are associated with sites or rocks that, because of some natural phenomena, proved more susceptible for uranium deposition than other contexts (Garside 1973).

The low natural concentrations of uranium in the natural environment, coupled with the uncertain depositional environment, made locating and exploiting natural uranium ores difficult. Historic miners had to first locate the deposit, ensure that it was of a concentration that was economic to exploit, and plan mine operations such that the majority of the ores were extracted efficiently. Of these 442 known deposits, only 28 have been economically exploited, producing approximately 68 tons of uranium oxide (U_3O_4) between 1951 and 1968 (Garside 1973) (Fig. 1). The vast majority of the uranium was shipped to AEC purchasing stations in Utah.

Like in the rest of the Intermountain West, the majority of the surficial uranium deposits were located during the prospecting boom of the late-1940s to 1960s (Garside 1973). These prospectors left behind a large amount of cultural material in the form of archaeological sites, mining equipment, and other artifacts that can still be observed on the landscape. Neither the material culture of the prospectors nor the remains of the uranium mines have been systematically studied by archaeologists, leaving a significant period of local, state, and national history uninvestigated. Without further study, these cultural resources cannot be managed properly, leaving them open to destruction. The sections that follow place uranium mining within the broader framework of American cultural resource management.

3 Archaeological Investigation of Uranium-Related Resources

The proper identification of cultural resources related to uranium mining is critical to their evaluation and management. Extensive research has been conducted into the identification and evaluation of historic precious metals and industrial minerals mining resources (e.g. Francaviglia 1997; California Department of Transportation 2008; Hardesty 1990, 2010; National Park Service (NPS) 1997), and similar amounts of scholarship has been conducted as to their preservation and interpretation

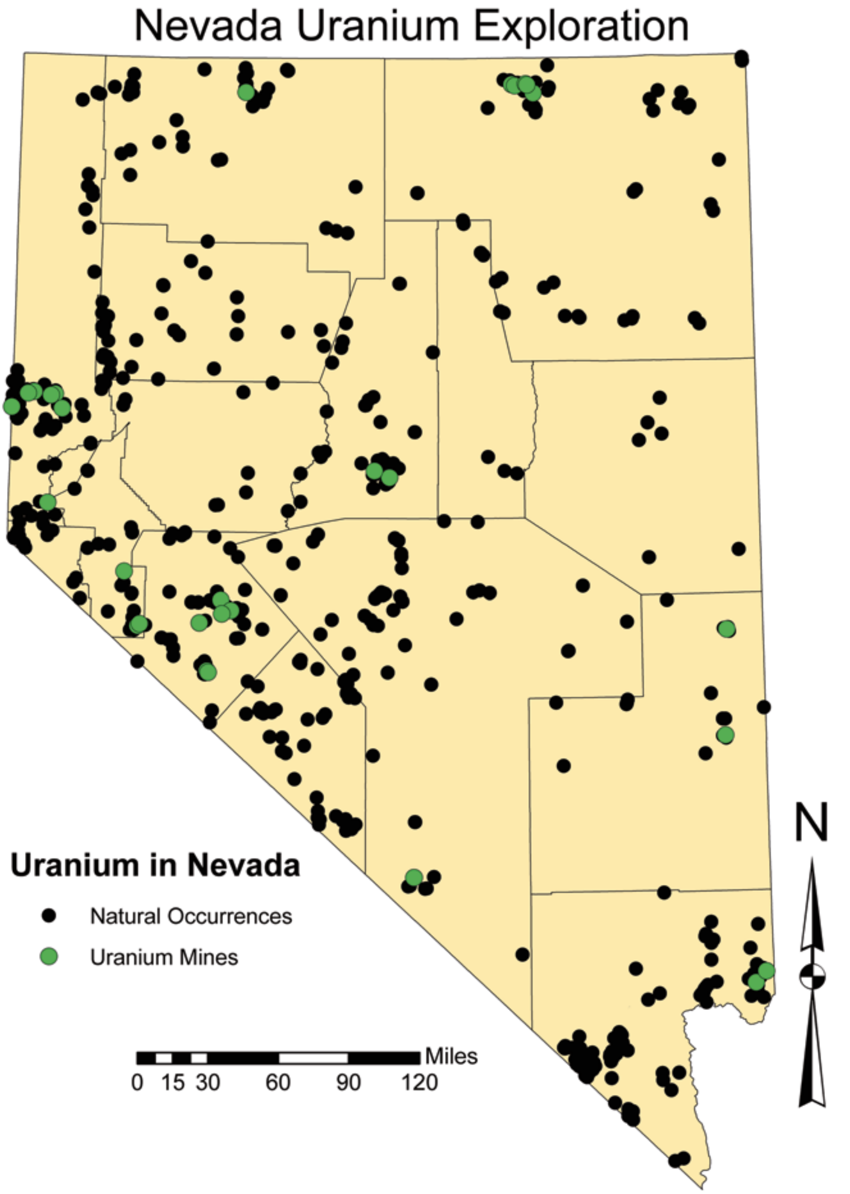

Fig. 1 The location of all known uranium occurrences and dedicated uranium mines in the state of Nevada. (Data from Garside 1973)

(e.g. Hardesty 2010; Hardesty and Little 2009). It appears, however, that little work has been done as to the proper identification, management, and evaluation of modern and sub-modern uranium-related mining.

The initial positive identification of an archaeological resource as related to uranium mining rests upon two conditions: that (1) the archaeologist recognizes the site as a center of prospecting or extractive industry, and (2) that the archaeologist associates the mining resource with uranium exploration or mining. Failure in one or more of these conditions may cause an incorrect identification of the resource, potentially leading to the destruction of a building, structure, district, site, or object with substantial cultural and historical significance. Without a positive identification of a resource as being related to the uranium boom, proper management cannot proceed. The sections that follow outline both phases of uranium mining, prospecting and extraction, which occurred in Nevada. As all uranium ores could only be sent to AEC processing facilities, and there were no such facilities in Nevada, there is no discussion of milling or beneficiation (Baroch 1965).

3.1 Uranium Prospecting

In the early years of the uranium boom, prospecting was a simple affair marked by simple tools and a simpler understanding of the geological processes which concentrated uranium ore into amounts economical for extraction. Prospectors mostly sought to exploit areas that, while now barren desert, formed under warmer, moister conditions accompanied by dense vegetation during the Jurassic Period. Following subsequent burial, the geochemistry of oxidizing groundwater leached uranium from overlying deposits and precipitated uranium in locally reducing environments associated with the carbonaceous deposits. Eventual erosion of overlying deposits left many of these deposits close to the surface and easily-exploitable; these types of deposits were often of low quality. Another source of uranium was uraninite, the same material the eighteenth century miners called *pechblende*. Uraninite was a much higher quality ore, but was more difficult to extract as it exists in largely subterranean veins which require substantially more capital to exploit.

Early prospectors, along with many avocational uranium hunters, most likely sought the surficial, easily exploited deposits. Amateur prospectors equipped themselves with tools of the trade similar to those the professional would use, however, unlike the full-time professional prospector, avocationalists often bought their equipment in kits produced by large supply companies based in Chicago and Los Angeles (Feininger 1955). If the potential uranium millionaire was not within an easy drive of these areas, similar kits were available mail-order from Sears, Roebuck & Co. and Montgomery Ward.

Uranium mining kits, at their very minimum were often composed of simple Geiger-Mueller counters (Geiger counters) and equipment essential to hiking or camping in the desert. One kit advertised in *Life* magazine in 1955 included a Geiger counter, a canteen for water, ore sacks, location papers, a compass, hand tools, and a snakebite kit for just under $100 (Feininger 1955). More complete kits included army-surplus survival equipment, an electric hoist, maps, and other accoutrement for approximately $3500. The range of kits available enabled the majority of Americans to afford at least the basics if they sought to prospect for uranium. At the very least, prospectors on a tight budget could conduct a basic ground survey looking for any dark mineral that could be pitchblende. Once found, a simple roll of unexposed film left over the suspected vein would cloud in a few days as a result of the natural radioactivity of the ore (Anonymous 1949). The returning prospector would unroll the film and examine it. If there was evidence of clouding, he or she could stake a claim according to local mineral laws.

Regardless of the form of ore the prospector sought, the basic equipment a prospector would need was a pick, shovel, a Geiger counter, and some form of transportation (Zoellner 2009). The introduction of the scintillation counter in 1944, which measured radioactivity like the Geiger counter, but was substantially more sensitive, further improved the prospector's ability to locate buried or distant deposits of radioactive material. While the historical imagery of the lone, grizzled prospector riding a faithful burro to and from his claims was considered by some to be the ideal, many uranium prospectors availed themselves of jeeps or other off-road vehicles (United States Atomic Energy Commission 1949, 1954).

The use of jeeps or other automobiles for use in survey applications was not limited to the uranium rush. Cars have been used in mining contexts since the early twentieth century as easy transportation, shelter, and as the basis for bare-bones mining equipment (see Miller 1998), but it was only during the uranium rush that their full potential was realized. The car-traverse method of prospecting for uranium was first developed in 1945 by the United States Geological Survey (Nelson 1953). The automobile, often a jeep or panel truck if the terrain was amenable, would be fitted with a Geiger counter or a scintillator which would register any radioactivity in the area. The vehicle would drive through the area, registering any radioactivity which might correlate to a uranium deposit. The Geiger counter or the scintillator was wired to an alarm that could be programed to sound when the vehicle was passing through a radioactive field of desired size. Based upon empirical observations, the USGS suggests that the car-traverse method allowed the prospector to sample up to 200 linear miles per day driving at speeds approaching 50 miles/h (Nelson 1953). In addition to its utility in exploring previously untested areas, the car-traverse method could be used to estimate the boundaries of a known deposit in advance of increased mining. Once a promising deposit was located, the prospector would often build a road to the site to allow for the use of heavy machinery. These roads crisscrossed much of the Mining West, and remains can still be observed today. While these roads are often indistinguishable from similar roads created for other purposes, their identification is important as they are part of the greater uranium mining system.

In addition, another common prospecting tool was the ultraviolet (UV) lamp. Many uranium bearing minerals, including uraninite, fluoresced under a black light. Prospectors brought such lamps with them as both as a method of field assaying potential ores, but also as a method for surveying large areas. Entering a promising area at night, the prospector would shine a powerful UV lamp around the area and place a flag or stake next to samples that fluoresced. The next day, the prospector could return and take advantage of the daylight to investigate the nature of the fluorescence. While pieces of broken UV lights in archaeological contexts are not necessarily diagnostic of uranium prospecting, they do serve as important circumstantial evidence that can be used to indicate the possibility of uranium exploration and exploitation.

Helicopters were also used with other methods described here to prospect large areas for uranium ores. Often the aircraft were outfitted with extremely sensitive Geiger counters, scintillators, or UV lights and promising positions were marked by either a point plotted on a map or some form of mark on the surface. One prospector used to throw bags of flour of lime out of the helicopter to mark locations which should be examined on foot (Zoellner 2009).

3.2 Uranium Mining

Like prospecting activities, uranium mining also leaves a significant mark on the landscape. Depending upon the nature of the deposit, miners would extract uranium either from traditional shafts and tunnels or via an open pit (Baroch 1965). Both methods would have required substantial initial capital investment in infrastructure and materials. The sections below describe each mining system and briefly describe the material culture that would remain in the archaeological record.

If the uranium ore is locked in veins deep underground or is irregular in its distribution, mining would typically be carried out underground (Baroch 1965). Depending upon the size of the ore body, miners would sink shafts and excavate the ores out using a variety of stoping methods—such as room-and-pillar and longwall retreat. None of these methods would be visible from the surface; however because uranium ore is often found in association with substantial amounts of radon, a health hazard, such mines may have required some form of ventilation (Baroch 1965). Remains of these ventilation systems could be observed on the surface and the size, location, and layout of such features could be used to infer the size and extent of the mine. If, however, the miner has limited access to large-scale earth-moving equipment, he or she could follow the vein into the bedrock, extracting only the richest material. This system would appear in the archaeological record identical to the rathole mining utilized throughout the western U.S. since the 1860s.

Uranium in regular concentrations or in lenses was often exploited through the use of open pits. These pits were often cheaper than shafts and tunnels to sink and maintain, but often required large earth-moving equipment such as haul trucks and draglines (Baroch 1965). Although open-pit mining does leave a very distinctive mark on the landscape, without knowledge of the geology of the area it would be difficult to determine precisely what material was being mined. In Nevada where open-pit gold and copper mines are common, knowledge of the geology or a documentary research are required in order to determine if a pit was indeed used for uranium mining.

Both lode and open-pit mining methods leave recognizable traces on the landscape that are indicative of mineral exploitation. These physical manifestations of past human activity not only inform on past events and systems, but also represent important parts of our shared history and therefore speak to Nevada's mining heritage.

4 Uranium Mining and Cultural Resource Management

The National Register of Historic Places (NRHP) is the United States' Government's official list of the culturally and historically significant properties. Instituted by the National Historic Preservation Act of 1966, the NRHP aims to identify, evaluate, and preserve notable historic and archeological resources. To this end, the NPS developed standards by which such properties are evaluated. Known as the National Register Criteria for Evaluation, these guidelines provided in the National Register Bulletin 15 (NPS 2000) stipulate that properties must, as a rule, be at least 50 years old at the time of evaluation and are required to meet at least one of the following criteria for listing on the NRHP:

Criterion A: Association with major events significant in U.S., Nevada, local history, or traditional cultural values; or
Criterion B: Association with persons important in the past; or
Criterion C: Representative of the distinctive characteristics of a particular type, period, or method of construction; of the works of a master; of high artistic values; or of a significant and distinguishable entity whose components may lack individual distinctions; or
Criterion D: Have the potential to yield important information to understanding prehistory or history

Once significance is established, the integrity of a property, how and whether it can convey its significance, is evaluated. Integrity comprises seven aspects: location, design, setting, materials, workmanship, feeling, and association. These aspects are defined as:

Location is the construction place of the historic property or place where the historic event occurred. Location helps in understanding the "why" of a construction or event.
Design is the result of the conception and planning that create the form, plan, space, structure, technology, scale, materials, functions, aesthetics, and style of a property.
Setting is the character of the physical environment of an historic property. Setting, or how the property is situated, includes geology, topographic features, vegetation, cultural features, relationships between features, and open space.
Materials are the combination of physical elements that were used to create a historic property during a particular period of time in a particular pattern. The property must retain actual historic resources dating from the period of its significance.
Workmanship is the evidence of artisans' labor and skill of a particular culture or people in creating a property during any given period in history or prehistory.
Feeling is the presence of physical features that express the aesthetic or historic sense of a particular period of time.
Association is the direct link between an important historic event or person and an historic property.

As Nevada's uranium mining infrastructure, and the materials made from the extracted ores is rapidly reaching the 50 year mark for significance under NRHP guidelines, they can be evaluated under NRHP's criteria to determine significance.

The majority of Nevada's uranium cultural resources are archaeological sites, and as such it is tempting to simply evaluate them as such (i.e. California Department of Transportation 2008). However, because these resources are significant aspects of the American collective past, they can also be evaluated based upon other criteria.

Historic uranium mines and prospecting areas can be considered categorically eligible to the NRHP under Criteria A as they are associated with the Cold War and the Atomic Age, a defining period in American history. Such resources may also be eligible under Criteria B, as they are associated with famous uranium miners. If determined eligible under Criteria A or B, the sites must display substantial preservation of features, artifacts, and systems in order to convey important associations with events or persons.

Similarly, under Criteria C, uranium-related properties must retain the majority of their components to illustrate a site type, time period, method of construction, or work of a master. An example of a property eligible under Criteria C would be a mining or milling facility designed by a prominent mining engineer or specifically designed to overcome a specific metallurgical problem.

A site's general condition is less important under Criterion D, in which integrity is based on the property's data potential for cultural resource managers, particularly archaeologists and architectural historians. Properties related to the uranium boom that are eligible under Criteria D include archaeological sites that could inform upon the lives of uranium miners, contain specific information about poorly-understood extractive metallurgical techniques, etc.

Additional guidelines for assessing a mining site's significance and eligibility are provided in the *National Register Bulletin 42: Guidelines for Identifying, Evaluating and Registering Historic Mining Sites* (NPS 1997), and *National Register Bulletin 36: Guidelines for Evaluating and Registering Archaeological Properties* (NPS 2000). These bulletins are invaluable for designing proper investigations of uranium-related cultural resources.

4.1 Cultural Resource Management in Practice

The need for the proper management of America's uranium-related cultural resources is becoming progressively important. As of May 2001, the advancing age of the properties, environmental concerns, and increased interest in cultural resources related to the Cold War have put the remains of the country's uranium mining heritage in a national spotlight. While Nevada was not the foremost producer of uranium during the boom, it still contains significant cultural resources that require attention.

As indicated earlier, Nevada's uranium mining boom occurred between 1951 and 1968. As of 2001, many of the uranium-related resources in Nevada have achieved the National Register's 50-year criteria for eligibility, and all uranium sites in Nevada will meet the NRHP threshold by 2018. At this point, all uranium-related mining sites in the state can be considered potentially eligible to the NRHP under Criteria A. Because they may be eligible, they require increased attention on the part of land managing government agencies, cultural resource managers, as well as the public. Furthermore, any potential adverse effects to such eligible resources would most likely have to be mitigated; however as there has been little holistic study of Nevada uranium sites, preservation and interpretation efforts could be negatively impacted.

Finally, in 2009, the Secretary of the Interior formed the Presidential Advisory Committee on the Cold War Theme Study, which was charged with identifying cultural resources that were significant during the course of the Cold War. The committee, consisting mostly of historians and architects, developed an initial list that consisted solely of existing defense-related properties. Little acknowledgement was given to the source of the uranium used during the Cold War, nor was the benefits of archaeology in relation to heritage and public outreach discussed. These issues were brought to the attention of Ron James, Nevada State Historic Preservation Officer and chairman of the National Historic Landmarks Committee. Mr. James successfully petitioned for the inclusion of historic uranium mining into the theme study. As of June 2011, Mr. James and the author are working on a small appendix to the final report detailing AEC policies towards uranium procurement and its effects on national uranium extraction.

5 Conclusion

While a significant amount of research has been conducted into the weaponization of atomic power, scholars have paid relatively little attention to the governmental policies that spawned a nationwide rush for uranium. Between the late 1940s and 1960s, uranium was a highly-sought after commodity, with avocational prospectors and professional geologists seeking to make their fortunes. While more famous for its other precious and industrial metals, Nevada was the focal point of substantial uranium prospecting and mining between 1951 and 1968. This paper proposed a model for the archaeological investigation of uranium-related mining sites as well as highlighted the uranium mine and its ancillary features as a legitimate object of archaeological interest and an area of much-needed cultural resource management. Hopefully, by the time Nevada's entire uranium infrastructure reaches the 50-year criteria for eligibility in 2018 a framework will exist which allows for proper management and interpretation of these important aspects of our industrial heritage.

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Military Development and Geographic Change on San Diego Bay

Andy Yatsko

Abstract Interest in military geosciences spans a range of issues, including the role of terrains in past and modern warfare, management of military lands in different climatic regions, and the impact of local environmental conditions on military operations. Military geosciences can also seek to ascertain the degree to which past operational or facilities-related military activities themselves affected the associated environments; however, such evidence is often transient and dwarfed by the scale of surrounding natural landscapes. This is not the case at the maritime margin of the American desert southwest, where some military development has significantly altered the coastal geographies along which it occurred. This paper provides a historical overview of geographic change resulting from the development of Navy and Marine Corps installations around the margins of San Diego Bay during the first half of the twentieth Century. The consequences of this change continue to challenge the military's current and future use of San Diego Bay.

Keywords Navy · Land management · Coastal environment · Holocene · History · Marine

1 Introduction

The overarching themes of the 9th International Conference on Military Geosciences (ICMG) in Las Vegas were the role of deserts in past and modern warfare, management of military lands in desert regions, and the impact of desert environmental conditions on military operations. But also within the reach of military geosciences inquiry is how past operational or facilities-related military activities may themselves have affected their geographical environments.

In the American Desert Southwest, such effects are sometimes dramatic. This was certainly evident during the 9th ICMG's field trip to the Nevada National Security Site with the dramatic changes to the landscape from atomic testing between

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1951 and 1992. But more often effects are ephemeral, transient or dwarfed by the scale of surrounding natural landscapes. This was seen during the post-conference field trip to the World War II Desert Training Center (DTC) created in the central Mojave Desert by General George Patton in 1942. The scars from training on the DTC landscape are now progressively subject to degradation by slow, but persistent, desert environmental processes, as well as increasing human recreational use of the landscape (BLM 2012).

By contrast, along the Desert Southwest's maritime margins in Southern California, past military development of installation infrastructures has also significantly, and permanently, altered coastal geographies through the filling of adjacent bays and estuaries. The 9th ICMG's post-conference field trip concluded with two days in San Diego touring selected Navy installations, for which the author provided access and indoctrination on their histories. The post-conference field trip saw, as all visitors to San Diego see, a setting around San Diego Bay that is much changed from that experienced by the Spanish and American immigrants that settled San Diego in the eighteenth and nineteenth centuries. But how much of this history of change on San Diego Bay is commonly known or recognized, even by local residents, is uncertain.

From the late nineteenth century to into the mid-twentieth century, Army, Navy and Marine Corps installations around the margins of San Diego Bay have been progressively developed to include facilities required to variously support harbor defense, early stages of naval aviation and carrier warfare, basic training of generations of sailors and Marines, and maintenance and supply of the U.S. Pacific Fleet. In an effort to provide for additional buildable land in response to these expanding installation infrastructure requirements, parts of these development histories include punctuated periods of artificial filling in portions of the adjacent San Diego Bay. The scale of geographic change resulting from these filling activities significantly changed the original configuration and marine environment of San Diego Bay and their histories provides dramatic evidence for the scale of this change. This paper provides an expanded discussion from the author's short, introductory overview at the 9th ICMG that preceded the post-conference field trip on the scale of geographic change associated with military development around San Diego Bay.

Punctuated periods of military development around San Diego Bay were directly influenced by larger historic patterns of conflict and economic change. The establishment or expansion of military installations on the bay mirrored great events at the time, including the Spanish American War, World War I, the Great Depression, and World War II. These influences, as well as parallel political and economic forces, frame the following discussion.

While the development of Army, Navy and Marine Corps facilities on San Diego Bay affected significant segments of the bay's margins, local civilian government and industrial development to support civic and commercial needs also contributed significantly to the change. Broadly, the scale of even just the bay-wide military-influenced changes is beyond the reach of this paper. Accordingly, the focus here is generally limited geographically to military installations clustered around the northern end of San Diego Bay. These include: former U.S. Army Fort Rosecrans (now Naval Base (NB) Point Loma) at the southern end of Point Loma west of the

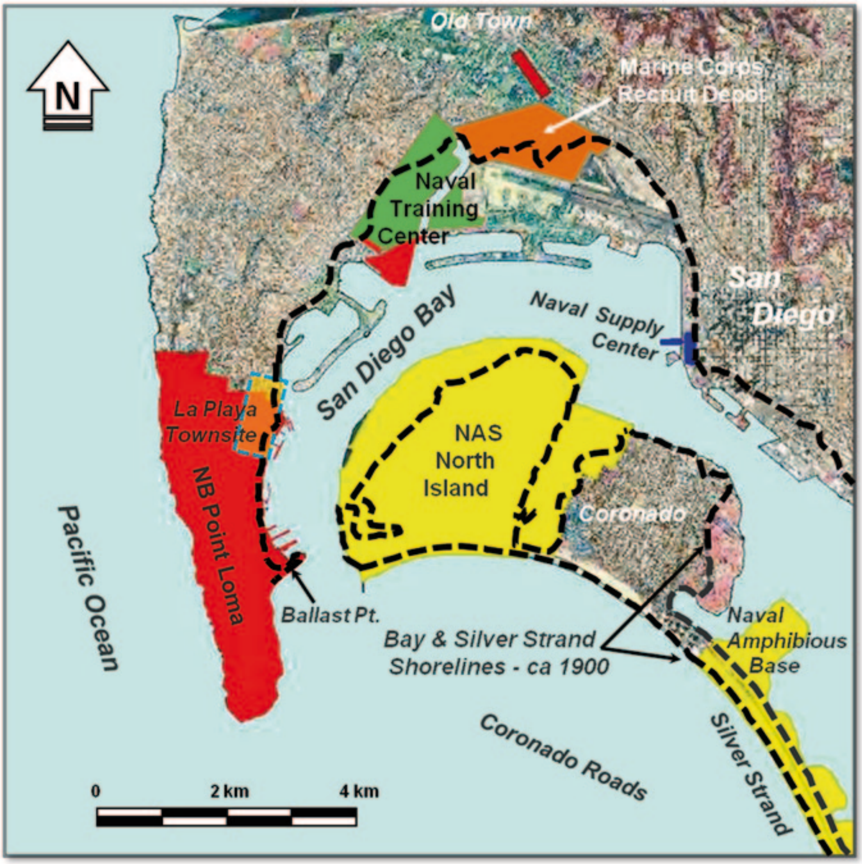

Fig. 1 Navy and Marine Corps installations on northern San Diego Bay, 2012, with ca. 1900 shorelines

entrance to the bay; Naval Air Station (NAS) North Island (now Naval Base Coronado) east of Point Loma across the bay entrance; and former Naval Training Center (NTC) San Diego (closed and privatized for commercial and residential use as Liberty Station in 1997 under the Base Realignment and Closure (BRAC) process) located further into the northern part of the bay (Fig. 1). But any discussion of change to San Diego Bay first requires a description of its natural geographic setting.

2 The Geography of San Diego Bay

At the time of first European entry into San Diego Bay with Juan Cabrillo's landing on Point Loma in1542, the configuration of its shorelines, bathymetry and onshore topography had been shaped by the combination of rising sea level and regional tectonics influencing sedimentation and erosion processes over the last 18,000 years (Masters 1988). The geology and geomorphology surrounding and underlying San Diego Bay is generally comprised of flat-lying Cretaceous, Tertiary and Quaternary sedimentary strata. These range from Cretaceous submarine fan sandstones and conglomerates that characterize Point Loma to Pleistocene non-marine and marine sandstones, representing deposition sea within shoreline and brackish estuarine back-bay environments during fluctuating sea levels, at lower elevations along the eastern margin of the bay, on North Island and Coronado near the bay mouth, as well as at the bay's southern extreme (Abbott 1999; Masters 1988). The margins of the bay including the prominent northwest-trending spit (Silver Strand) are composed mostly of Holocene-aged sandy beach sediments (and now artificial fill) (Fig. 1).

The configuration of San Diego Bay derives from the dynamic interaction between late Pleistocene into the middle Holocene rising sea level, general mechanisms of sediment transport and shore evolution responding to rising sea level, and topographic highs like Point Loma (Inman 1983; Masters 1988). The Point Loma peninsula bounds the northwestern margin of San Diego Bay. This upland results from active tectonic tension accommodated by northwest-directed strike-slip movement along the Rose Canyon fault zone that bisects northern San Diego Bay.

During the last glacial maximum toward the end of the late Pleistocene (~ 18,000 years ago), sea level was approximately 120 m below present sea level (mbpsl) (Fig. 2a). Rivers and streams that presently flow into San Diego Bay from the east (San Diego River, Chollas Creek, Sweetwater River and Otay River) flowed directly west and eroded deep channels across the exposed continental shelf before reaching the paleo-shoreline, then located 6 km west of Point Loma's present coastline (Masters 1988) (Fig. 2b). This paleo-shoreline was essentially straight, with Point Loma forming a massif above the exposed continental shelf. By 10,000 B.P., sea level rose and the coastline advanced to the east to a stand at approximately 20 mbpsl, forming a small embayment within a wave shadow created by the Point Loma upland. As the sea level rise slowed around 6000 B.P., the coastline north of the mouth of the Tijuana River formed within the Point Loma embayment, developing a strong, north-flowing reverse eddy. A sand spit grew north of the Tijuana River as the transport path for a portion of its sediments shifted with this eddy (Fig. 2c). This spit bridged the channels of Chollas Creek, Sweetwater River and Otay River, forming a tombolo that connected terraces north of the Tijuana River with the Coronado and North Island lowlands, creating the nascent San Diego Bay. At this time, all the eastern drainages flowed to the ocean through the San Diego River channel between Point Loma and North Island. By 3500 B.P., sea level stood within 1–2 mbpsl. Accompanied by dune building along its length, the tombolo and spit had also migrated east to its present position to become the Silver Strand (Fig. 2d).

Most tidal lagoons, and certainly those in the region north of San Diego Bay, are described as passive and dissipative, with their tidal ranges decreasing with distance from their openings. According to Masters (1988, after Redfield 1950), however, the length of San Diego Bay is responsible for the tidal body within the bay behaving as a partial quarter wave resonator. This characterizes a tidal flushing process more intense than would be typically the case in tidal lagoons. This holds profound

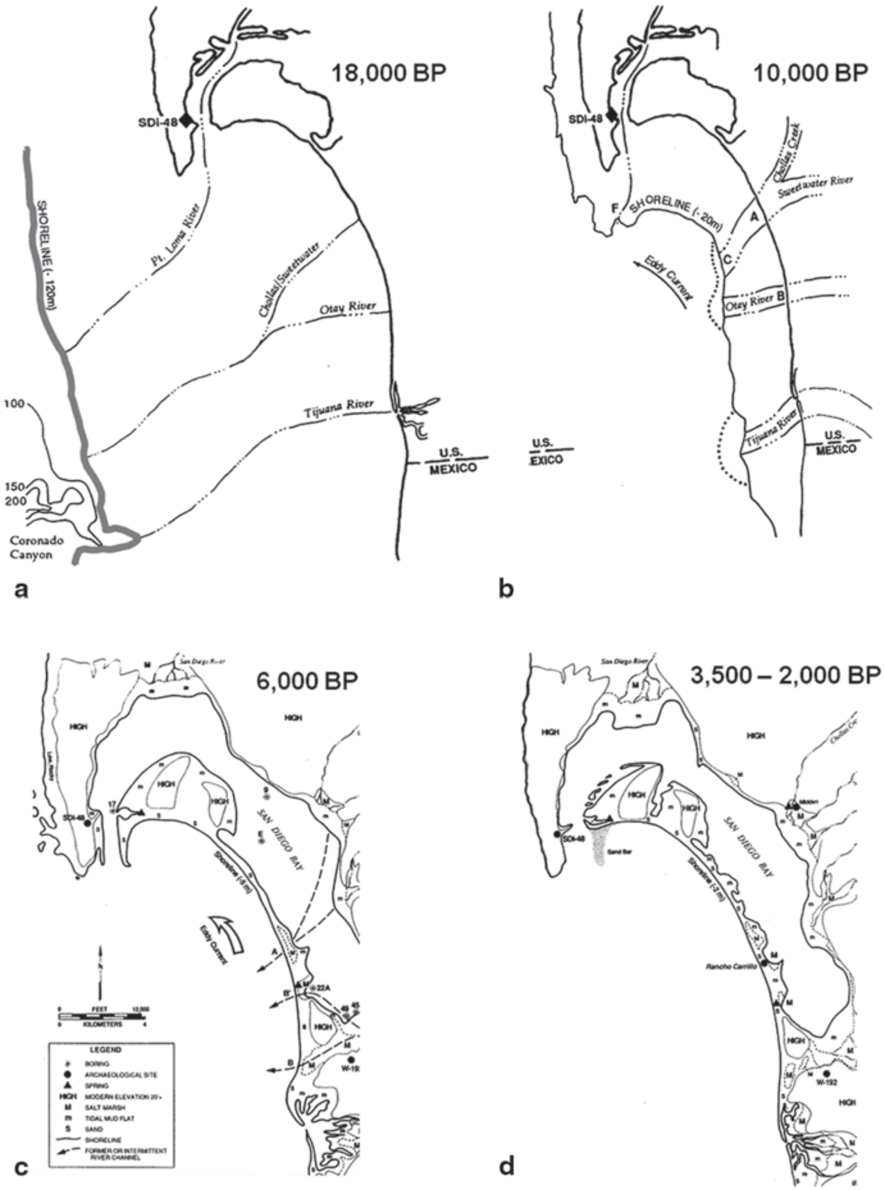

Fig. 2 Late Pleistocene—Middle Holocene evolution of San Diego Bay (from Masters 1988, Figs. 4.5 and 4.6)

inferences for the formation of San Diego Bay, implying the bay developed as a unit of nearly its present length, without land divisions like deltas intruding across its axis. This supports the general reconstruction of the bay having developed within a relatively brief time period prior to 6000 B.P. In its natural state, the bay has always been well-mixed, with tidal currents strong enough to maintain a scour channel through to the entrance.

During formation of the bay, the various rivers and creeks emptying into it were building deltas as tidal flats and salt marshes, with these wetlands expanding rapidly around the protected bay margins. Prevailing winds from the northwest and west also created sandy beach environments along the east shore. Countering these natural filling processes, the bay's tidal currents were strong enough to flush much of these stream sediments out through the entrance channel, maintaining a clear, if shallow, channel running deep into the bay, closely encroached on by tidal flats and salt marshes (Fig. 3). This is the estuarine environment that was first encountered by Juan Cabrillo in 1542, and on the shores of which the Spanish first colonized Alta California in 1769.

3 Historic Use of San Diego Bay

3.1 Spanish-Mexican Period

When the Spanish came to San Diego Bay in 1769, they established their first settlement with a strategic defensive intent by building a presidio (fort) on a ridge overlooking the mouth of Mission Valley. Located in what is now Old Town San Diego, this is where the San Diego River exited from its confined, channel across a series of elevated marine terraces that comprise the inland terrain and turned south into that bay. From here, the nearest bay shore was 3 km south. However, this bay shoreline opened onto wide and soft tidal mud flats unsuitable for travel and landing or shipping goods by sea. The nearest suitable sandy shoreline was at a place named La Playa, located 8 km to the southwest on the bayside of Point Loma near the entrance to San Diego Bay. This became the port for Spanish Colonial, and eventually Mexican, San Diego. La Playa was the local port of call for the international hide and tallow trade that characterized and sustained Spanish Colonial California's economy in the early nineteenth century. And La Playa is where American naval forces landed in 1846 to take possession of San Diego during the Mexican War.

3.2 Early American Period

More than the local Spanish-Mexican inhabitants, the first American colonizers after the Mexican War understood the importance of developing bay-front residence and infrastructure for the purpose of expanding maritime commerce and increasing the economic benefits of San Diego Bay. With that in mind, La Playa was the first location for the townsite mapped out by the Americans in San Diego. It's significant that a resulting 1849 townsite plat already indicated an early intent to artificially fill

Fig. 3 1857 U.S. Coastal Survey Map of San Diego Bay showing mudflats, sand bars and tidal scour channel through bay

adjacent, firm bottomed bay shallows to create buildable land. While La Playa continued to function as the port of San Diego through the 1860s, the actual economics and expense of filling any significant portion of the bay front precluded affecting this goal.

Early in the American period, however, as land speculators established New Town San Diego further east along the bay's shore at another sandy beach and firm bay bottom opposite Coronado, the focus of the bay's economic development shifted away from La Playa. But even at New Town, filling the bay margin to create new land was considered a prohibitively expensive enterprise. Maritime commerce was instead supported and encouraged through the construction of numerous commercial piers along New Town's water front (Heilbron 1987). Substantial bay filling in the interest of increasing maritime commerce continued to be an important goal of New Town developers, the emerging San Diego Chamber of Commerce, and local and federal politicians (Jensen 1965; Linder 2001, 2003). All these interests understood that an important catalyst for accomplishing this economic impetus would best be found in establishing a permanent U.S. Navy presence on San Diego Bay.

3.3 U.S. Military on San Diego Bay

Through the late nineteenth century, the U.S. Navy was only an intermittent and transient presence on San Diego Bay. The Gold Rush had firmly established San Francisco Bay as the economic and population hub of the state. In 1854, coincidental to the United States' effort to extend its naval power into the Pacific Ocean around the time of California statehood, the Navy established the first permanent installation on the Pacific Coast at Mare Island north of the San Francisco Bay. For the remainder of the nineteenth century and into the early twentieth century prior to World War I, Mare Island and San Francisco Bay were the home base for the Pacific Fleet. Elements of the Pacific Fleet on patrol along the West Coast treated San Diego only as an occasional port of call. But the common Navy wisdom was that San Diego Bay's narrow, shallow channel and encroaching sand bars made it unsuitable for basing naval vessels. This perspective began to change with the advent of the Spanish American War and the resulting shift in American interests in the Pacific.

3.3.1 Spanish American War Era

In 1852 shortly after California statehood, the southern half of Point Loma had been reserved by the United States as a military reservation in support of harbor defense, as it had been under the Mexican government. However, the Army only began to take an interest in developing defenses there in the 1870s, when it expelled squatters and began construction of a battery. That battery was still incomplete in 1896 when new construction of four batteries on Ballast Point was directed, with plans for barracks and associated buildings nearby. With the beginning of the Spanish-American War in April 1898, there was a fresh sense of urgency to provide additional defenses on all coasts, including construction of three new batteries at the San Diego harbor entrance, which was completed by 1900 (Thompson 1991). This early coastal defense development, and in fact nearly all such Army development up to World War II, did not result in artificial filling of adjacent bay.

The Spanish American War also stimulated the Navy's interest in developing logistical support facilities in San Diego Bay. In 1901, the Navy segregated 360 acres along the San Diego Bay shoreline of Fort Rosecrans at the former La Playa

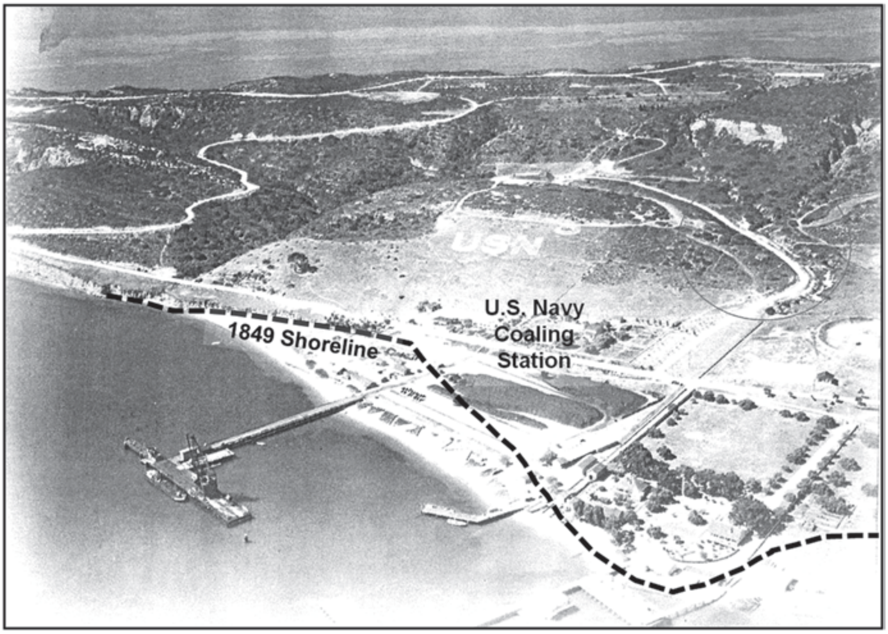

Fig. 4 Navy La Playa Coaling Station on Point Loma in 1920s, showing extent of ca 1903 filling

townsite to develop a coaling station (Schmidt and Byrd 2004). The La Playa Coaling Station facility was commissioned in 1904. Its construction involved the first instance of military-related filling of a portion of San Diego Bay. In this case, the filling process involved borrowing from adjacent upland areas, with the natural, gradually-sloped terrain leveled and the borrowed spoil graded out into the San Diego Bay shallows, partially realizing the original vision of the 1849 townsite plat (Fig. 4).

As dramatic as the Army's response to the Spanish American War was in its expansion of coastal defense facilities on Point Loma, the La Playa coaling station represented the only real Navy infrastructure investment on San Diego Bay until 1917. Even the Navy's Bureau of Yards and Docks reporting in 1898 that San Diego was the preferred site in southern California for a naval repair base and dockyard, in addition to a 1900 Navy survey of the bay, which identified it as "the only good harbor south of San Francisco," didn't spark interest within a Navy Department that "lacked a West Coast vision" (Linder 2003, p. 6). It would take the run-up to World War I to awaken a wider Navy interest in the bay.

3.3.2 World War I and the 1920s

Bruce Linder (2003, p. 5), a retired Navy captain and well-respected chronicler of San Diego's naval history (Linder 2001), has suggested that the period between

1917 and 1922 was the most consequential to establishing a significant Navy presence on San Diego Bay. Over those years, the bay changed from an infrequently visited naval logistics stop to the permanent homeport for over 100 warships. The naval presence expanded dramatically from minor and disconnected facilities into an integrated, bay-wide naval complex. According to Linder (2003, p. 5), by 1922 the Navy's presence on San Diego Bay had reached a "critical mass," the point where it became self-sustaining and virtually assured ongoing naval investment.

The catalyst for this Navy growth, and its interconnected influence on the local growth of a Marine Corps presence, was a convergence of increased naval requirements in response to World War I and local San Diego economic politics. Among San Diego City fathers, there had been disagreement on whether to pursue the Los Angeles model for encouraging new industries, manufacturing and development, or to guide the city towards an economy based on tourism, agriculture and commerce. Coming out of a mayoral election of early 1917, the Navy emerged as the perfect compromise "industry," representing economic progress without the smokestacks (Linder 2003, p. 7).

The consequence of World War I was an expansion of Navy and Marine Corps facilities, including docks, repair yards, training centers, supply depots and a naval air station. Because the bay's shoreline still consisted largely of undeveloped mud flats, this immediately began a new, military-driven, and now federally-funded, initiative to fill submerged tidelands to created buildable land. These included: development of the Marine Corps Recruit Depot (MCRD; 1918), built partially on artificial fill placed on the Dutch Flats tidelands at the northeast of the bay; the U.S. Destroyer Base (1921) at the mouth of Chollas Creek on the east shoreline south of the city, which involved an early use of dredge spoils as fill; the Naval Supply Center at the foot of Broadway in downtown San Diego, also built on dredge spoils; and westerly adjacent to MCRD, the Naval Training Center (NTC; 1922–1923), which was laid out on the eastern slope of Point Loma and adjacent tidal flats using artificial fill from nearby sources.

Naval Air Station (NAS) San Diego (now NAS North Island) had also been established in 1917. Into the 1930s, the air station jointly occupied North Island with the Army's Rockwell Field, the first permanent Army air field, originally a Signal Corps aviation school established there in 1913. Both the Army and Navy expanded facilities through World War I and into the early 1920s, with North Island initially providing sufficient space to preclude the need to fill additional areas in the bay.

NAS San Diego was originally designed as a seaplane base, reflecting the early, pre-World War I philosophy about the nature of naval aviation. However, lessons learned during World War I rapidly redirected Navy strategic aviation thinking toward the use of aircraft carriers. In November1924, the first Navy carrier, the USS Langley (CV-1), a converted collier, arrived at North Island. This began the air station's eventual preeminent role in defining carrier warfare strategies that would later serve the Navy successfully during World War II.

The mid-1920s San Diego Bay still represented a relatively shallow, narrow-channeled anchorage; requiring all ships above the size of a destroyer to anchor in the naturally scoured channel, with no ability anywhere on the bay to tie up at a pier. The "controlling depth" for the majority of the navigable portions of bay was between 32 and 35 ft. This was considerably less than the 40–45 ft which the safe navigation of capital ships at the time required, eventually including the Navy's new carriers (Shragge 2003). A solution lay in extensive dredging of the bay to deepen and widen the channel and its margins. The challenge was finding the necessary funding. This was difficult to find in the best of times, but assumed even harder with the onset of the Great Depression in 1929.

3.3.3 The Great Depression and the 1930s

In 1930, the economic consequences of the Great Depression already pressed hard on the San Diego region. But in an early attempt to hold back the national economic slide, the Hoover administration proposed broad federal public works projects as an economic stimulus (Shragge 2003). Congress examined San Diego harbor to determine how dredging there might be part of this program. Congress directed $10,250,000 ($500,000,000 in 2010 dollars) to San Diego Bay, over 80% earmarked for its naval bases. Under Franklin Roosevelt's New Deal in 1933, the federal government pledged another $8,750,000 ($400,000,000 today) for additional public works around San Diego Bay, most again directed at its naval operating base. By 1940, Congress would appropriate an additional $6,500,000 ($250,000,000 today) toward further harbor dredging.

These dredging funds passed from the federal Public Works Administration (PWA) to the War Department, which applied it to deepening and widening the harbor entrance (Shragge 2003). From the beginning, the dredging generated millions of cubic yards of sandy spoils. Access to San Diego Bay for aircraft carriers involved shore-side berthing and maintenance facilities, and space to construct these. Accordingly, NAS North Island used dredge spoils to expand approximately 550 acres along the bay margin for carrier facilities (Fig. 5). Other naval installations also benefitted from the sedimentary largess. Through the late 1930s, NTC added an additional 240 acres. Further down the bay at Naval Station San Diego (former U.S. Destroyer Base), 120 acres of tidal flats and salt marsh were also filled.

3.3.4 World War II

Notwithstanding the incremental, but substantial military development around San Diego Bay preceding 1941, the onset of World War II represented a new watershed event that caused exponential expansion and intensification of the military's presence in the San Diego region. As the Navy, Marine Corps and Army established numerous new installations across the wider region, those around San Diego Bay received new pressure to expand buildable land. This was again accommodated using dredge spoils from the continued widening and deepening of the bay's navigation channel and anchorages to support increasing numbers of Navy ships, particularly the new, deeper-draft Essex-class aircraft carriers (Shragge 2003).

At Fort Rosecrans on Point Loma, the Army, which had not previously had need to fill their bay margins, filled in the cove behind Ballast Point at the harbor's en-

Fig. 5 Filling bay adjacent to NAS North Island in 1936. Viewed east toward downtown San Diego. City of Coronado is to the right, separated from North Island by the Spanish Bight

trance, the very place where Juan Cabrillo had anchored in 1542. This provided for barracks space to accommodate additional Army coastal artillery personnel required to man the new coastal defense batteries in construction at Fort Rosecrans between 1941 and 1944.

The Navy further expanded the NTC, adding another 160 acres out into the bay to increase the training center's capacity for training the personnel demands of the Pacific Fleet. Concurrent with this filling, the City of San Diego filled the remaining in-shore portion of the Dutch Flats tidal area to become what is now the San Diego International Airport.

On North Island, the naval air station expanded by 450 acres with the filling of the Spanish Bight, the shallow tidal embayment that had separated North Island from Coronado. On Coronado's opposite shore, the Navy filled 40 acres of the bay to provide for construction of housing for Navy families. And south of Coronado on the Silver Strand, the Navy filled 210 acres of bay to create the Naval Amphibious Base, which used the adjacent beaches and offshore Coronado Roads to train Navy and Marine Corps forces for the island-hopping campaign that characterized the war in the Pacific. In southern San Diego Bay, a collective 500 acres of bay and salt marsh were also filled in building out Naval Station San Diego and other facilities.

World War II represented a high water mark in the artificial filling of San Diego Bay's margins. Substantially all post-war filling was by municipalities bordering the bay and by a newly created port district, in the interest of expanding both commerce and tourism. The rate of filling slowed progressively through the 1950s and 1960s, and effectively ceased after 1970.

4 San Diego Bay Today

In the early twenty-first century, the U.S. armed forces continue to play an important role in the San Diego region, both as a presence and as an economic engine. The military generates $18.3 billion for the local economy, amounting to 13.68% of economic activity in the region (Hamsik and Moore 2007). The Navy accounts for about 65% of this and the Marine Corps for 23%, with 150,000 military personnel in the region. San Diego Bay continues to be an essential focus of the Navy on the West Coast, with the BRAC process since the late 1980s concentrating all California-based ships in San Diego. But the processes of simply filling in more bay to accommodate growth is a thing of the past, with especially the Navy facing challenges growing out of what have come to be viewed as its sins of the past.

4.1 Long-Term Environmental Consequences of Bay Filling

Immediate consequences of the filling of San Diego Bay's margins from the 1920s into the late 1960s were certainly initially perceived by both the military and the civilian community as beneficial. However, as late twentieth century political processes have progressively focused on effects to the environment by human activities, these original economic and operational benefits have increasingly come into a different balance with concerns now defined under environmental laws and regulations.

4.1.1 Habitat Loss and Restoration

It is objectively the case that the civic and military activities that created new land around San Diego Bay caused significant losses to natural estuarine and adjacent upland habitats. The Navy and Marine Corps alone filled more than 2500 acres of former tidal wetlands and open bay. Together, military, civic and private filling activities over the past 125 years have resulted in the loss of 42% of San Diego Bay's historic shallow sub-tidal habitat, 84% of its intertidal mudflat habitat, and 70% of its salt marsh habitat (USFWS 2012). Most adjacent wetland/upland transition and native upland habitats have also been lost to development.

Since the early 1970s, evolving environmental laws and regulations, especially "no net loss" policies associated with the Clean Water Act, have increasingly negated the option to fill wetlands without substantial mitigation. Mitigation usually involves setting aside existing wetlands, rehabilitating damaged wetland habitats, and creating or recreating wetlands or open bay around San Diego Bay and other regional estuary systems. One consequence of this evolved regulatory sensitivity is increased public scrutiny of processes affecting San Diego Bay and wider recognition of the need to protect and restore the bay's historic coastal habitats. Instances of this have directly linked with ongoing Navy requirements for berthing space.

In the late 1990s, NAS North Island needed to fill 17 acres of open, previously-dredged bay bottom along its northeastern margin to construct new berthing facilities sufficient to support three Nimitz-class aircraft carriers, which was directed by Congress to be their home port by the early 2000s. The mitigation for this planned filling required the Navy to restore tidal wetland and bay bottom habitats on the northern margin of North Island near the bay entrance by removing 25 acres of fill previously placed there in the 1930s.

In a similar instance, the Navy loaned the ex-USS Midway (CV-41) to a San Diego non-profit organization in 2003 to become an aircraft carrier museum. Its permanent berthing at the former Naval Supply Center's pier created environmental effects requiring wetland mitigation elsewhere on the bay. The 4-acres of permanently shaded bay bottom created by the Midway adversely affecting essential fish habitat, requiring mitigation through rehabilitation of a small tidal marsh originally isolated by earlier shore development. While the non-profit organization bore the expense of this mitigation, this again reflects the regulatory sensitivity on estuarine habitat issues around San Diego Bay.

4.1.2 Seismic Risk

As noted earlier, the Rose Canyon Fault Zone (RCFZ) directly underlies many filled areas around San Diego Bay, particularly at the bay's northern extreme where the fault zone parallels Point Loma. San Diego County does not have the history of earthquakes common to the rest of southern California, and the RCFZ is the only major earthquake fault in the urban San Diego area (SCEC 2012). But even though the RCFZ has not produced a major earthquake since long before European settlers arrived in the area, it is still considered seismically active by the State of California for having had a history of generating large magnitude earthquakes in the last 11,000 years. And certainly other parts of the fault zone (i.e., Newport-Englewood fault zone) north of San Diego into Los Angeles County have been subject to historic seismic activity (Grant and Shearer 2004). But by any account, a major earthquake along the RCFZ beneath these artificially and non-engineered fill areas composed of variable mixtures of loose and saturated silty to sandy sediments over bay muds could have devastating consequences to buildings and infrastructure due to amplified shaking and potential liquefaction. This risk is further exacerbated with the understanding that nearly all permanent construction from before the late1930s at places like NAS North Island, MCRD and NTC is comprised largely of unreinforced masonry and shallow foundations. This remains a known, but an unresolved, concern for the Navy and Marine Corps in San Diego.

5 Conclusions

This discussion on the consequences of geographic change from the development of Navy and Marine Corps installations around San Diego Bay is presented as a contrasted alternative area for military geosciences inquiry. But the San Diego Bay example is also contrasted in being somewhat an exception where the local civilian community was very much a willing partner, and frequently the political instigator, in seeking federal aid to expand military, and not coincidentally civilian, facilities through significant modifications to the natural geographic conditions of San Diego Bay. A more common experience for military land use in the American desert southwest has been through temporary or permanent withdrawal of public lands, often including the expropriation of private in holdings, during periods of historic duress to provide for the reservation of large scale landscapes for military needs. General Patton's World War II DTC is an early example in California's Mojave Desert, with examples still persisting in places like the Marine Corps Air Ground Combat Center Twentynine Palms, the Army's Fort Irwin National Training Center, and the Cold war-era-driven Nevada National Security Site in Nevada.

The early military-civilian collaboration discussed in this chapter was clearly of critical importance for the local community in the placing San Diego Bay as a significant node in evolving U.S. geopolitical and strategic interests in the Pacific. This will certainly continue with a renewed national policy focus on "the Pacific Rim." But as is also pointed out, even these good military and economic benefits have evolved to have an environmental price to pay as well. This continues to be the challenge for the military and civilian partnership that uses San Diego Bay. Although this ongoing use can no longer involve further encroachment on the bay by artificial fill, it will continue to develop or redevelop on land this historical process created around San Diego Bay. And because of the local geomorphology over which the artificial fill was created, a geosciences perspective will increasingly need to be applied in the planning for this ongoing use and reuse.

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High Density Metal Contaminant Transport in Arid Region Ephemeral Channels

Julianne J. Miller, David S. Shafer, Charalambos Papelis, Craig A. Refosco and Nathan A. Krzyaniak

Abstract Depleted uranium (DU) particles and DU oxides are present at military test and training ranges in the southwestern United States (U.S.) because of its use in military munitions and for armored shielding. Also, since approximately 1990, DU particles and DU oxides also occur in similar arid region military theatres throughout the world. At a study area in the northern Mojave Desert in the U.S., soil sampling and ground and aerial gamma-ray screening had suggested that DU particles and DU oxides had not migrated by surface water transport significant distances from their original location near a target area. However, no predictive models had been developed to forecast how far the particles would move with time. A flow and transport model was developed using the FLO-2D model to study the unconfined flow conditions over the complex alluvial fan topography in the study area watershed. The Zeller-Fullerton sediment transport equation was selected because of its ability to model sediment transport when a substantial portion is expected to be by bedload, an assumption warranted because of the density of DU and DU oxides (19.20 and 4.80 g/cm^3, respectively). Modeling results indicate that a local 100-year storm could cause transport of both DU particles and DU oxides, primarily

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along well-defined channels, although transport could occur across alluvial surfaces as well. However, the transport distance of DU particles and DU oxides was limited to approximately 120 and 150 m, respectively. The modeling approach used in this study could be used as a predictive tool for transport on military testing ranges to address environmental compliance issues and protect military personnel during training exercises from potential unnecessary exposure by better delineating the eventual area where DU particles and DU oxides may occur. The predictive modeling also could be applied in military theatres where DU munitions were used to better understand the dispersal of DU particles and DU oxides over time by fluvial transport to help protect military and civilian populations from coming in contact with the high density metals.

Keywords Depleted uranium · Contaminant transport · Hydraulic modeling · Sediment transport · FLO-2D · Arid environment · Alluvial fan · Radiological risk · Flooding · Fluvial transport

1 Introduction

Depleted Uranium (DU) munitions have been tested on U.S. Department of Defense test and training ranges in the southwest United States (U.S.), and have been used in similar arid region military theatres throughout the world. Beyond munitions, military uses of DU include having it serve as counterweights in aircraft, and for defensive armor plating and armor-piercing ordnance (WHO 2003). Oxidation of DU occurs under natural conditions, leading to the formation of uranyl oxide hydrate minerals that form on DU surfaces (Buck et al. 2004; Lind et al. 2009). This oxide is visible on the ground, particularly after precipitation events, when bright yellow hydrous "DU oxides" form on the surface of DU particles (Fig. 1). The DU oxides eventually slough off the DU particles, forming a separate phase in the environment.

In a study area in the northern Mojave Desert in the U.S., soil sampling and gamma surveys had indicated that DU particles and DU oxide had been fluvially transported from a target area, particularly in ephemeral channels (Abell 2004). However, there was no predictive tool to forecast how far the contaminants would potentially move over time. To assess the potential for surficial water transport of high density metals at the study area, a flow and transport model was developed using the FLO-2D hydraulic model (O'Brien et al. 2009) to study the unconfined flow conditions over the complex alluvial fan topography in the study watershed where channelized and overland flow had been observed to occur (Miller et al. 2011; Shafer et al. 2010). In addition to addressing environmental compliance issues, the approach used in this study could be used to evaluate the eventual area where DU particles and DU oxides could be fluvially transported in military theatres, leading to better protection of military and civilian populations from inadvertent exposures.

Although DU is regulated by the Nuclear Regulatory Commission in the U.S. as "source material," DU is only weakly radioactive because of the preferential

Fig. 1 The growth of DU oxides on the surface of the DU projectile (*circled*) results in a stippled appearance of the projectile. The DU oxides that have been eroded from the projectile surface are scattered on the surrounding ground

removal of the U-235 isotope (Christensen 2011). Human and ecological health concerns with DU particles and DU oxides are primarily associated with their toxicity, particularly to the kidneys, when they are in soluble forms. Inhalation of insoluble U compounds (e.g., UO_2 and U_3O_8) presents a pulmonary injury hazard due to the physiochemical nature of the compounds, as well as some evidence of increased risk of internal radiologically-induced cancers from alpha particle emissions (ATSDR 2011). Overall though, the National Resource Council (NRC) has concluded that in general U poses a low-risk of cancer to people. A more significant radiological risk from DU is the beta emissions associated with a U daughter product, protactimium-234 m, particularly when the material is in close contact to skin (NRC 2008). Thus, limiting exposure of military and civilian populations to these high density metals is important.

2 Methods and Modeling

The study area lies within the northern-most part of the Mojave Desert (Shafer et al. 2010). Precipitation at the closest continuous meteorological monitoring station (Indian Springs, 19 km southwest of the study area), averaged 89.5 mm per year between 2000 and 2010 (Shafer and Hartwell 2011). However, the temporal distribution of precipitation in the Mojave Desert is the highest of the deserts of North

America. Precipitation events vary between isolated, short-duration, high-intensity convective events in the summer and regional scale, long-duration, low-intensity frontal events in the winter (Hereford et al. 2004). Channel and unconfined overland flow in the study has been observed during El Niño precipitation events (Abell 2004) as well as from winter regional storms in 2009 and observed by the authors.

2.1 Mapping and Field Characterization

A geomorphic map was developed as an integrated predictive tool for forecasting runoff potential, based on unique, predictable relations that exist between landscape position, soils, and geology. Nine distinct landform types were mapped within the project area, although only six landform types were characterized as contributing runoff to contaminated sites: alluvial fans (Qf1/Qf2, Qf3/Qf3m, Qf4/Qf4m); alluvial plains (Qp1/Qp2, Qp1m, Qp3, Qp3m); active washes (Qf6); alluvial terraces (Qf5/Qf5m); pediment (Qfp); and bedrock (Bx) (Fig. 2). Paired particle size distribution (PSD) and bulk density (BD) measurements were made on 54 soil samples collected for characterization of geomorphic units, and an additional 71 samples collected as part of field soil hydraulic measurements.

2.2 Flow and Particle Transport Modeling

Flow and transport models, such as FLO-2D (O'Brien et al. 2009), are used to estimate flood volumes and particle transport capacities within ungaged watersheds. The model predicts the area and depth of inundation, the flow velocity, the particle transport capacity, and the erosion and deposition across the study area. In this study, a FLO-2D model was constructed to study the unconfined flow conditions over the complex alluvial fan topography in the DU-contaminated study area watershed.

Topographic data used to create the 30.5 m × 30.5 m grid system of nodes were developed from a 10-m digital elevation model of the watershed also used for the geomorphic mapping studies, which produced a GIS shapefile consisting of the geomorphic units within the watershed (Fig. 2). This shapefile was used in the development of the FLO-2D model to differentiate soil hydraulic parameters, such as the precipitation loss parameters and hydraulic conductivity measurements obtained in field tests, respectively, throughout the computational domain of the model.

In this study, the regulatory storm (100-year) was analyzed, although the flow and transport model can analyze any design storm. Standard hydrologic parameters were input, including point precipitation values that were selected for the watershed centroid coordinates through the NOAA Atlas 14 website (www.hdsc.nws.noaa.gov; retrieved 02/04/2009); a 6-h duration was assumed per local flood control drainage design guidance. The point precipitation values were reduced by the

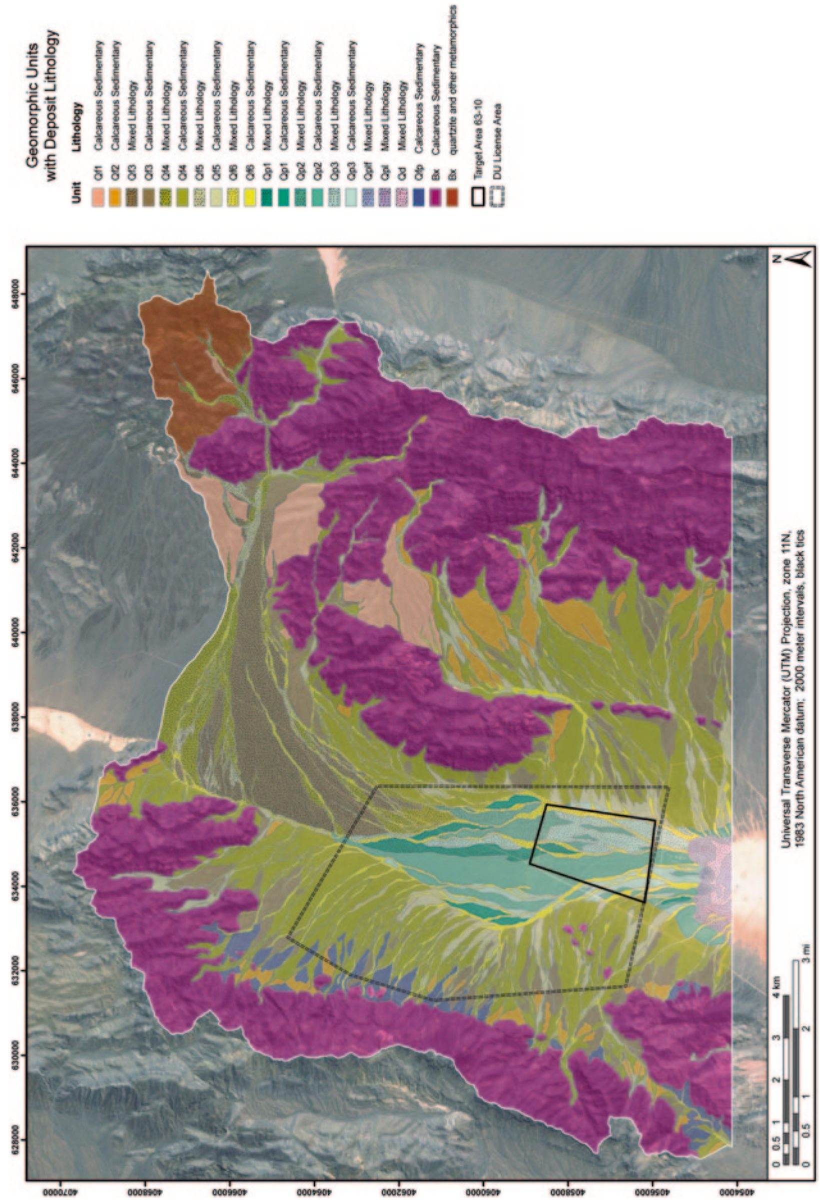

Fig. 2 Geomorphic map of the study area showing the coalescing alluvial fans along the valley margins, the central axial drainage through the valley, the central alluvial plain emanating from the axial drainage, and the boundary of the DU-contaminated area within the valley

appropriate depth-area reduction factors for the watershed area, as it is unlikely that a storm would occur equally over an entire drainage basin, and an appropriate storm distribution for the watershed area was used to develop the hyetographs.

2.3 Geochemical Parameterization

For estimating the potential mechanical transport of DU oxides by surface flows, it is important to identify the U oxide phases present so that estimates for physical properties, particularly density, could be used as inputs to the flow and transport model. Geochemical analysis of soil samples concluded that the U phase is likely dehydrated schoepite ($UO_3 \times H_2O$, where $0.75 \leq \times \leq 1$). Although reported densities of schoepite were fairly consistent, there was some variation (Buck et al. 2004; Lind et al. 2009); however, for the purposes of transport modeling, a density of 4.8 g/cm^3 was used to represent DU oxides in general. Because the exact isotopic composition of DU can vary, there is no one specific density value for DU; however, because the density of naturally occurring U is 19.06 g/cm^3 and is composed of 99.27 % U-238, a DU density value of 19.2 g/cm^3 was calculated and used in the contaminant transport modeling performed in this study.

2.4 Soil Runoff Potential and Hydraulic Conductivity

Standard statistical methods to determine flood discharges are not applicable to a majority of watersheds in the southwest U.S. because most watersheds are ungaged or have short periods of record with many years of no flow. Therefore, flow and transport models, such as the FLO-2D model (O'Brien et al. 2009), are based on adapting and using design precipitation events with specified return periods to estimate peak flow and hydrographs. For this study, input values included field tests of soil hydraulic properties, including rainfall simulation tests (RFS) used to calculate precipitation loss values, and measurements of soil hydraulic conductivity (Ks) using a mini disk tension infiltrometer (MDTI). Laboratory inputs included examination of particle size distributions and bulk densities of soil samples collected in the field from different geomorphic surfaces.

Locations for RFS and MDTI tests were chosen to obtain data representative of the mapped geomorphic surfaces. More tests were conducted on those surfaces that covered a larger percentage of the watershed. However, because only existing roads were used to reach locations for RFS and MDTI tests, the locations of test sites are not equally distributed across the watershed. Nevertheless, RFS and MDTI tests were conducted on alluvial fan (Qf1/Qf2, Qf3/Qf3m, Qf4/Qf4m); alluvial plain (Qp1/Qp2, Qp1m, Qp3, Qp3m); and alluvial terrace (Qf5/Qf5m) surfaces (Fig. 2). The remaining surfaces were not tested as they represented a small percentage of the overall study area (e.g., pediments—Qfp), and would not contribute significant runoff to the watershed.

3 Predictive Modeling Results

Both clearwater (no particle transport) and particle transport models were developed for the 100-year storm over the study area. The clearwater model was used to establish baseline runoff conditions for the watershed; no particle transport was considered. Figure 3 shows areas and depths of inundation across the study area where clearwater runoff occurs during the storm; channelized flowpaths are clearly delineated. Baseline particle transport models were also developed for the 100-year storm, using the matrix soils data collected in the field. This analysis demonstrated the matrix soil (sediment) transport capacity through the study area, with areas of erosion and deposition of the matrix soils across the study area shown on Fig. 4.

The FLO-2D model allows the user to select from several different commonly used particle transport equations (O'Brien et al. 2009). The Zeller-Fullerton equation (Zeller and Fullerton 1983) was selected for use in this study because of its ability to model a range of channel bed and alluvial floodplain conditions when most of the particle movement is expected to be transported by bedload rather than suspended within the flow. This is especially important when the particles are relatively heavy, such as DU particles and DU oxides, which are both unlikely to move as suspended particles.

The FLO-2D model, however, does not allow specific sediment data to be input into each grid node. Rather, the model relies on information from a single particle size distribution (PSD) to be input for the entire study area. Because the primary area of interest is the DU-contaminated area, a weighted PSD for fine-grained sands through coarse gravels for the alluvial plain (Qp surfaces) and channel (Qf6) geomorphic units was developed from the PSD values obtained from the soil sampling. Information from this distribution was used as input to the Zeller-Fullerton equation (Zeller and Fullerton 1983) for analysis of the matrix soils transport throughout the entire study area. Although assuming that the PSD data from a limited area are representative for the entire watershed is not ideal, using the finer-grained particles found in the alluvial plain and channel surfaces within the DU-contaminated area results in more conservative values of erosion across the entire watershed (i.e., using finer-grained particles results in a potential to over- rather than under predict erosion).

During the 100-year storm, as expected, most of the erosion and subsequent deposition occurs along the channelized flowpaths (Fig. 4) that are clearly delineated by the greater clearwater flow depths within the unconfined (shallower) flows across the alluvial plain surfaces (Fig. 3). Although the 100-year matrix soil transport analysis (Fig. 4) shows some areas of erosion and deposition within the DU-contaminated area, the flow hydraulics, slope, and matrix soil particle sizes make

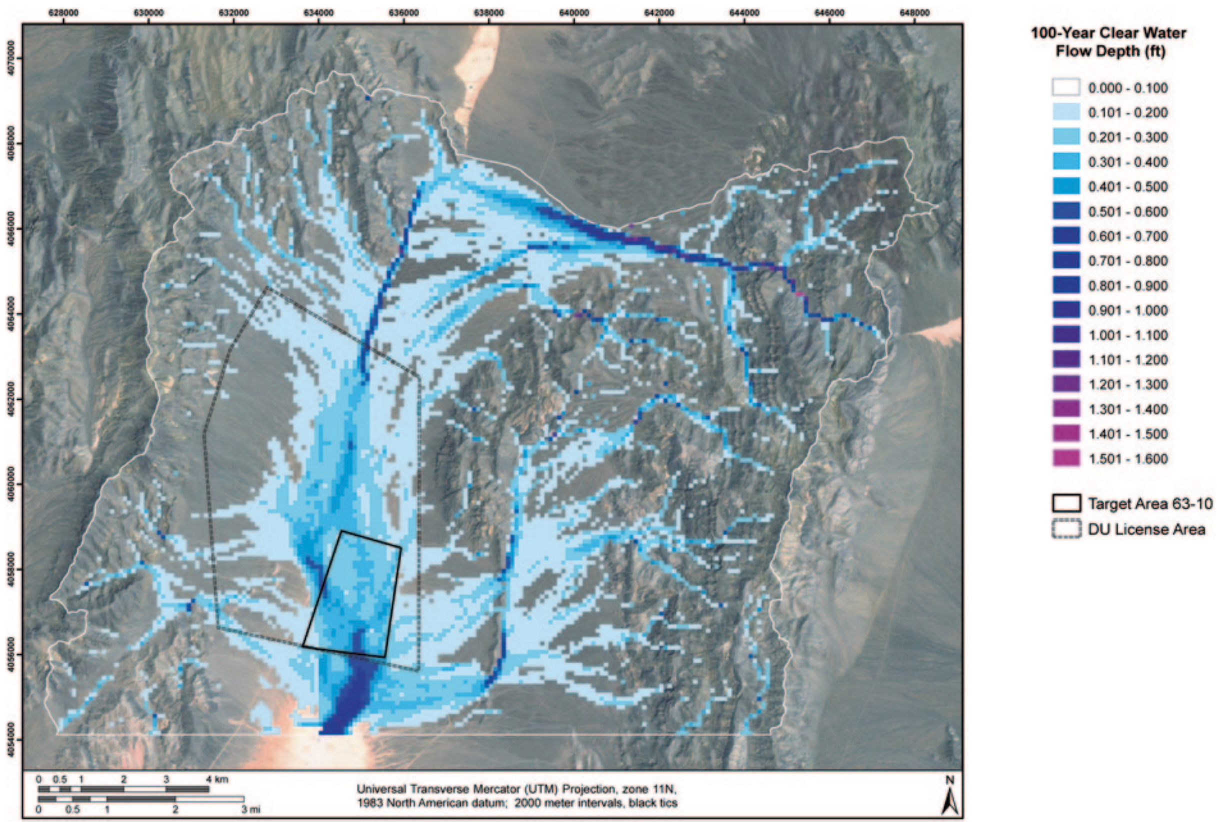

Fig. 3 100-year storm baseline clearwater flow model output, showing areas and depths of inundation within the DU-contaminated study area watershed

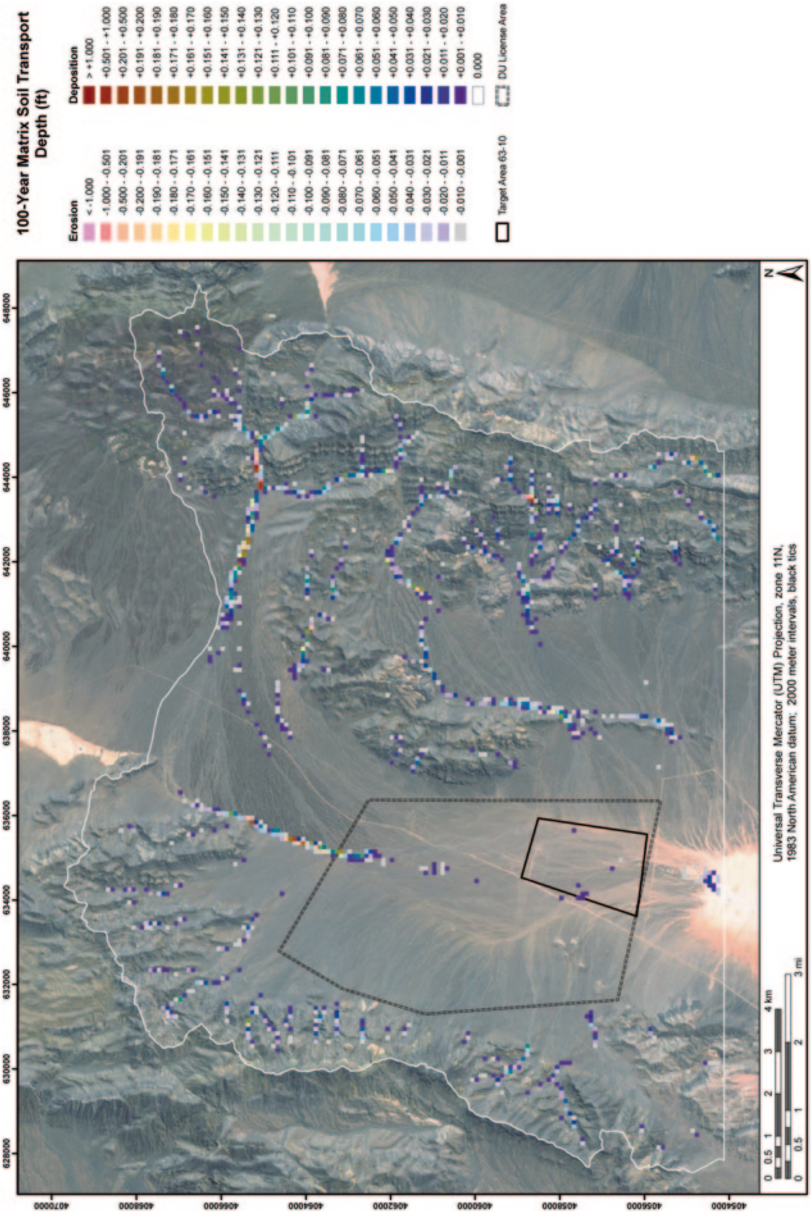

Fig. 4 100-year storm baseline matrix soils transport model output, showing depths of erosion and deposition within the DU-contaminated study area watershed

sediment transport beyond a few hundred meters unlikely on the alluvial plain (Qp) surfaces within the DU-contaminated area.

For the analyses of the DU particle and DU oxide transport, a modification was made to the procedure used for the soil matrix analyses to account for the significant densities of the contaminant particles. No standard particle transport equations are appropriate or accurate for materials such as DU particles and DU oxide with densities of 19.2 and 4.8 g/cm^3, respectively. Therefore, it was assumed that the contaminant materials both had densities of 2.65 g/cm^3 (matrix soil), but the median particle size (D50) value (where 50 % of the particles are larger and 50 % are smaller within the overall PSD), of both contaminants were modified to represent the specific weight of each contaminant. The revised D50 values, scaled to represent the heavier DU particles and DU oxides, were used as input to the DU particle and DU oxide transport models developed in FLO-2D. The potential areas of erosion and deposition of DU particles and DU oxides during the modeled 100-year storm are shown in Figs. 5 and 6, respectively.

During the 100-year storm, any erosion and subsequent deposition of materials with the specific weight of the DU particles and DU oxides occurs along the channelized flowpaths that are clearly delineated by the greater clearwater flow depths across the alluvial plain surfaces (Fig. 3). The 100-year DU particle transport analysis indicates that the 100-year storm can cause some transport of DU particles within the DU-contaminated area, but that transport distances are limited (Fig. 5). The maximum potential movement within the DU-contaminated area is less than approximately 120 m, and mostly occurs within the channelized flowpath near the upper portion of the DU-contaminated area. The 100-year storm DU oxide transport model is shown in Fig. 6. The 100-year DU oxide transport analysis shows the maximum potential movement within the DU-contaminated area is less than approximately 150 m, and mostly occurs in the same area as the DU transport.

Although there are isolated areas of deposition within the DU-contaminated area, because of the flow hydraulics, the shallow slope, the high Ks values (and thus high infiltration rates) of the alluvial plain (Qp) soils, and the density and the sizes of the DU particles and DU oxides, it is unlikely that transport of either contaminant would occur beyond the DU-contaminated area boundaries.

4 Conclusions

Hydraulic predictive modeling forecast the transport distances of DU particle and DU oxide downstream from a target area in the Mojave Desert, confirming previous soil sampling and ground and aerial gamma surveys (Abell 2004) of the contaminant distributions within the contaminated area boundaries. At the study area, DU particles are periodically removed from the area and disposed as radioactive waste. In channels there is a higher frequency of wetting and drying cycles, both from precipitation events as well as flow events, which create DU oxide development on DU particles. Removal of the DU particles from the channels is a simple but important mitigation strategy to both limiting the formation of the DU oxides in the

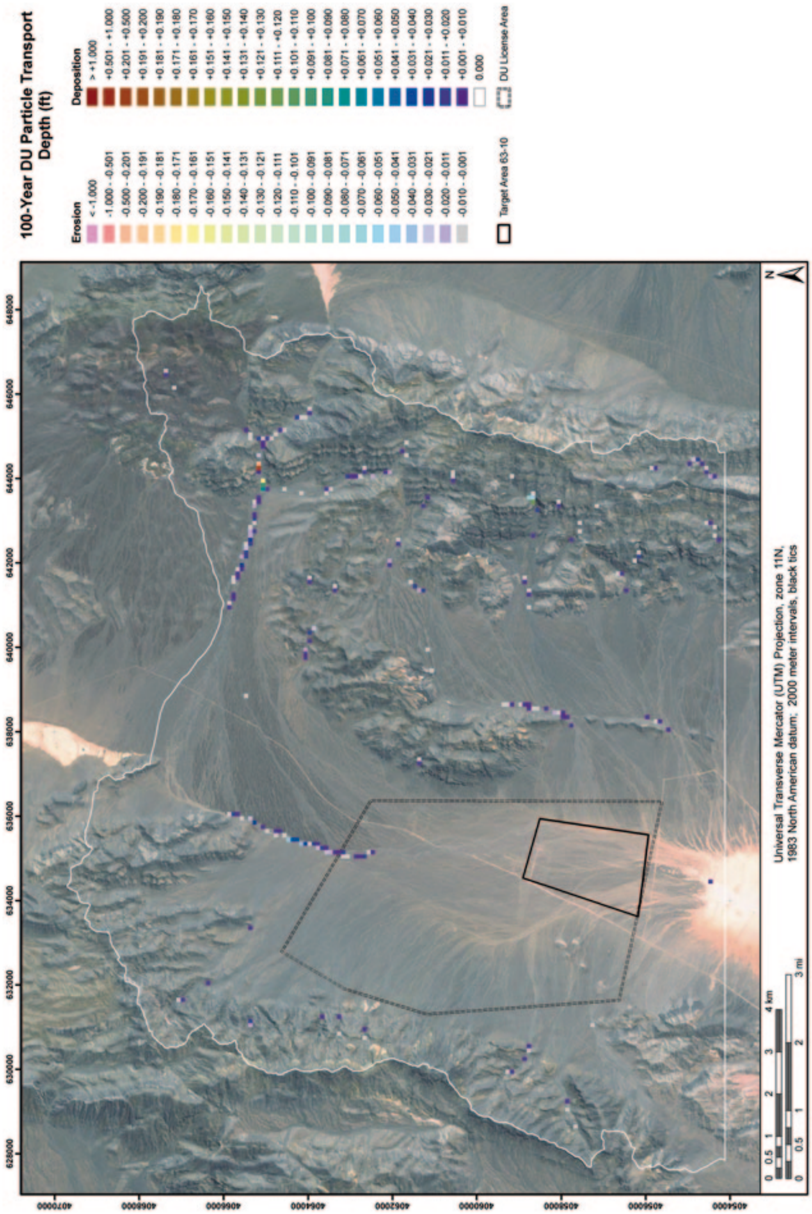

Fig. 5 100-year storm DU particle transport model output, showing potential depths of erosion and deposition within the DU-contaminated study area watershed

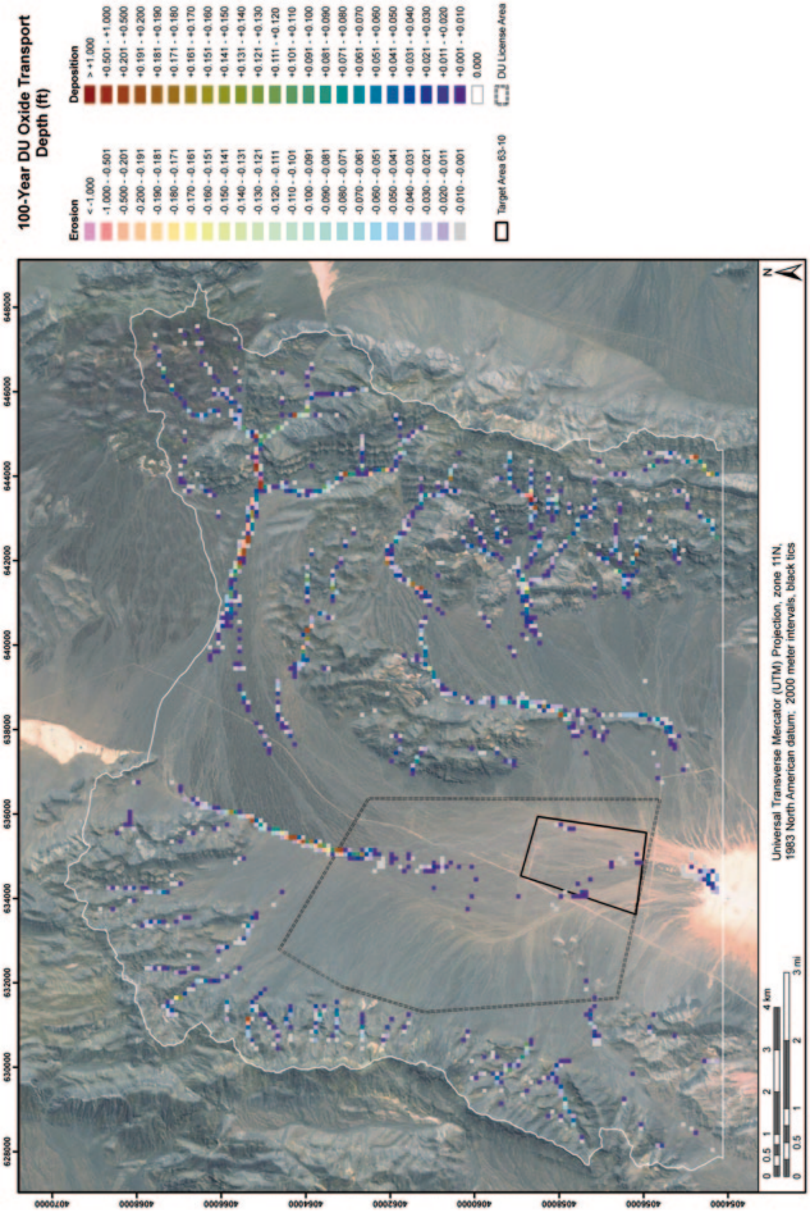

Fig. 6 100-year storm DU oxide transport model output, showing potential depths of erosion and deposition within the DU-contaminated study area watershed

environment as well as minimizing contaminant transport distances. The successful modeling of the transport distances of DU particles and DU oxides demonstrated in this study provides a means of estimating potential areas that could be impacted by contaminants over time because of fluvial transport. In arid military theatres where DU munitions have been used, the ability to model potential transport of DU particles and DU oxides provides a means of predicting the distribution of contaminants over time, an effective step in limiting military as well as civilian population contact with the high density metals (IAEA 2009).

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Comparing Playa Inundation Estimates from Landsat and LiDAR Data to a Doppler Radar-Based Hydrologic Model

Mary E. Cablk, Julianne J. Miller and Steve A. Mizell

Abstract Although water is a contentious resource in terms of human use and consumption, particularly in the southwestern United States (U.S.), its presence is not always considered valuable or welcome. Where water accumulates on the flat, hard surfaces of desert playas used for the military mission, ephemeral conflict with nature occurs; conflict present only so long as standing water persists into scheduled use for training and testing. Flood occurrences on playas where runways and flightlines are established may incur added financial burden due to unanticipated scheduling changes in training and testing, or damage to infrastructure. The ability to better estimate and predict flooding events including duration and frequency of inundation, which could affect use of playas with infrastructure, may present range managers with a means to avert potential conflicts. For this reason examining the current model that incorporates watershed parameters and Doppler-radar precipitation measurements to estimate runoff onto Rogers (Dry) Lake at Edwards Air Force Base (EAFB), U.S.A. was done. Satellite imagery and digital elevation model data are spatially explicit (associated with a geographic location) and present that advantage both for planning and to provide comparison of model estimates. The degree to which either or both approaches reflect ground condition following storm events was quantified. Pre- and post-standing water extent for the two significant rainfall-runoff events was mapped from Landsat satellite imagery and standing water volume on the playa was then calculated using a high spatial resolution LiDAR–derived digital elevation model (DEM). These results were compared to the runoff volume estimates made from a model that extrapolated precipitation from Doppler-radar and meteorological stations within the Rogers Lake watershed. The results showed both over- and under-estimated playa inundations when compared.

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1 Introduction

Water is arguably one of the most controversial topics in terms of availability, quality, quantity, distribution and use, among others, and is recognized as a limited resource in arid and semi-arid lands. The southwestern United States has been a battle ground for what is termed “water wars” about which volumes have been written (e.g., Walton 1994) in both popular media (Nash 2005) and scientific literature (Pannu 2012). But not all water is for consumptive use and not all wars involve force on force. Water affects infrastructure and transportation, causes property damage, and changes the natural environment when heavy precipitation events lead to flooding. In the southwestern U.S. the military mission and in particular military training, is affected by rainfall and runoff events that result in flooding. For example, at Edwards Air Force Base (EAFB) in southern California, U.S.A., Rogers Lake hosts active runways and when water ponds on the playa, flight activities are restricted; in some cases flight line infrastructure has been flooded.

Dry lake beds are common geomorphic features in arid and semi-arid regions. Commonly called playas, they are prominent and definitive features of hydrologically closed watersheds (Lichvar et al. 2008). Because of their hard, flat surfaces, playas have seen use as high-speed race tracks (Rea 2012; SCTA 2012) and other recreational use including kite buggying and archery (Bureau of Land Management 2012a), and for rocket launching and experimental use (Bureau of Land Management 2012b). Military use of playas for landing strips, airfields and the associated infrastructure demonstrates their importance as useful, natural features (Freeman 2011; EAFB 2009). The fact that they accumulate water from precipitation events directly, in the form of rain or snow, and indirectly, as a catchment of runoff from the surrounding watershed, creates an interesting juxtaposition. Playas are characterized by physical properties of hardness and flatness, which is the value to military operations. Add water and they spring to life; literally soften. Their ability to catch and retain standing water in desert regions makes playas short-lived refugia for biological diversity arising from and supported by intermittent bursts of life (Adams and Sada 2010). Yet the simple physical presence of standing water subjects the military and its partnering agencies to potential operational limitations, as well as to wildlife incursions and aircraft strike hazards from birds.

1.1 Relevance to the Military

Locating runways and flight line infrastructure on playas where standing water occurs may present economic, construction, and operational issues, as has been suggested at EAFB. Edwards Air Force Base lies in the western Mojave within the Antelope Valley, a large closed hydrologic basin. It is home to the U.S. Air Force Flight Test Center (AFFTC), the National Aeronautics and Space Administration (NASA) Dryden Flight Research Center, and hosts the Air Force Research Laboratory. The AFFTC mission is to conduct and support research, development, test, and evaluate manned and unmanned aerospace systems (Cablk et al. 2007). Home to the US Air Force Test Pilot School and 412th Test Wing, airfield operations on the lakebed are an essential part of training and testing missions. Here both the US Air Force and the NASA Dryden Flight Research Center use Rogers Lake for pilot training and flight test operations. In April of 1981 NASA's Space Shuttle Columbia landed safely on Rogers Dry Lake, making history as the first orbiting space vehicle to launch with rocket power but return to earth as an aircraft (EAFB 2009). Although the main runway is somewhat elevated relative to the lakebed surface, several active runways are located directly on the lakebed, and lakebed flooding may restrict or prohibit airfield operations for significant time periods, which can translate into human and equipment risks and increased operational costs.

Just how often the Rogers Lake playa is flooded, to what depth and the duration standing water persists, is not well documented. Motts and Carpenter (1970) noted that water stood on Rogers Lake and adjacent playas for five months during the winter of 1965–1966. In later investigations Dinehart and McPherson (1998) observed playa flooding events on Rogers Lake in 1991, 1992, 1995, and 1996. Validated models to estimate playa flooding are a critical component of managing activities involving lakebed facilities, and provide the US Department of Defense (DOD) with a useful tool to support the US Army's "Expedient Airfield Construction" program. With the availability of a decades-rich archive of Landsat satellite imagery, questions about the temporal nature and spatial extent of playa flooding can be addressed. Accurately estimating playa inundation to include surface extent, volume and depth with geospatial reference provides improved capability towards this end for DOD military installations.

1.2 Study Area—Rogers Lake

Rogers Lake is an endorheic desert salt pan, a hard lake bed with a surface area of approximately 118 km^2 (46 mi^2) and a mean elevation of 692 m (2270 ft). The surrounding Rogers Lake watershed encompasses an area approximating 1,821 km^2 (703 mi^2) with an elevation range from 2,862 m (9390 ft) in the mountains down to 691 m (2267 ft) on the playa in the north (Fig. 1). The climate at EAFB is continental desert and is semi-arid to arid. Temperatures may dip as low as −16 °C (34 °F) in winter months and summer maximum temperatures may exceed 43 °C (109 °F). Precipitation occurs almost entirely between November and April as long-duration winter frontal events across a regional scale. These winter events typically result in Rogers Lake inundation. Mean annual precipitation in the surrounding Antelope Valley and EAFB is 127 mm (5 in). Although there are no natural perennial water

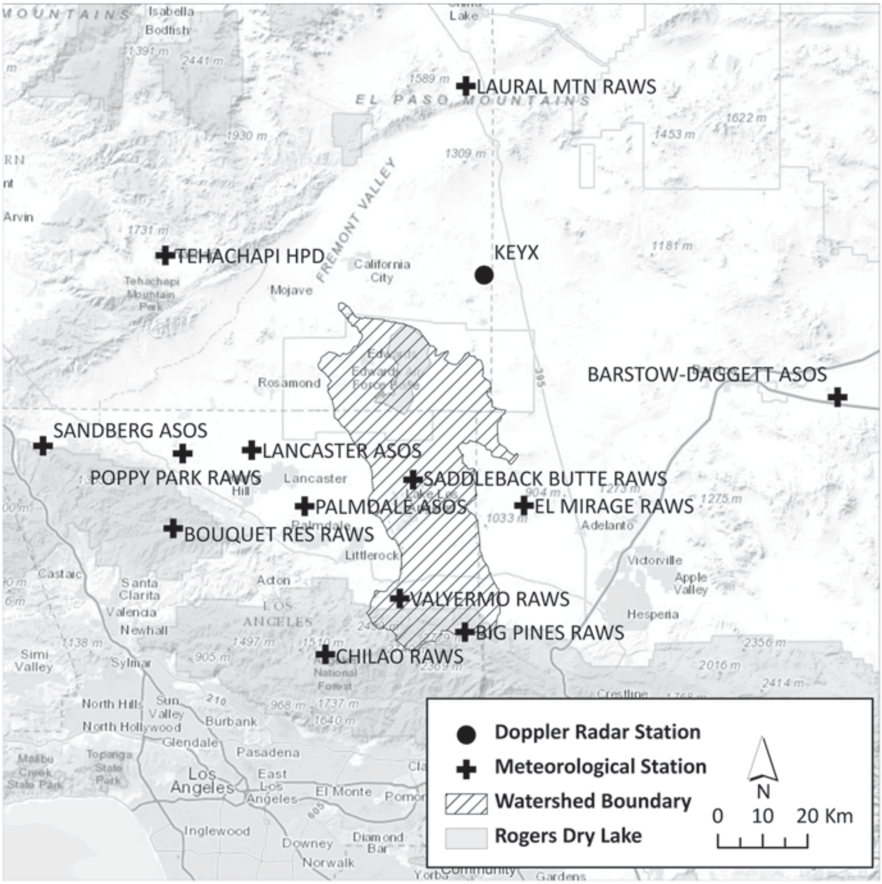

Fig. 1 Location of Rogers Lake watershed in the Western California Mojave desert and sites where meteorological and Doppler radar data were obtained. The extent of Rogers Lake within the watershed is also shown

bodies within the valley, there are a number of artificial water sources including ponds and wastewater effluent (Cablk et al. 2007). When precipitation events occur, Rogers Lake receives water as runoff from within the watershed and direct rainfall onto the lakebed; the accumulated water may persist for weeks or months.

For this reason the use of hydrologic, spatially explicit models is critical to maintain and plan mission operations. Traditionally this is accomplished using hydrologic models which may or may not be spatially explicit. With respect to EAFB and the surrounding region, hydrologic modeling approaches have undergone refinements to address spatial variability of precipitation. French et al. (2005) estimated the 100-year regulatory floodplain on nearby Rosamond Dry Lake (California, USA) conservatively assuming that while precipitation varies with elevation, the distribution of precipitation is otherwise uniform over the entire contributing watershed.

Precipitation patterns in deserts are understood to be spatially heterogeneous across scales (Milewski et al. 2009; Huxman et al. 2004). Miller (2009) refined this approach by incorporating spatially varied precipitation threshold values. The 100-year floodplain that was established for Rogers Lake by Miller (2009) used the cascading model of Miller (1998) and French et al. (2003), and radar-measured storm events. A follow-on study was conducted to address the spatial variability of precipitation across a regional (watershed) scale using Doppler radar precipitation to incorporate the spatial variability of rainfall, and to validate the approach for the Rogers Lake watershed (Miller et al. 2011). The ability to accurately display and assess standing water on the playa following precipitation events, contributed to by the surrounding watershed, is the natural scientific advancement. Satellite imagery presents an opportunity to contribute towards this goal.

1.3 Using Satellite Imagery to Estimate Surface Water Extent

Natural and anthropogenic features are identified and mapped with satellite imagery based on surface or near-surface reflectance properties of those features. In terms of mapping water, both surface and near-surface characteristics can be identified because visible light can penetrate water to relatively shallow depths, while infrared light is almost completely absorbed (Bastawesy et al. 2008). The spectral response in the visible and infrared part of the electromagnetic spectrum of a surface of standing water is distinguishable from a dry surface for this reason. Saturated surfaces, and particularly saturated soils, present processing challenges because the reflectance response is a mixture of both light-absorbing properties of water and soil reflectance.

Identifying water on earth surfaces with satellite imagery typically involves using the ratio of bands in the shortwave and near infrared (Lillesand et al. 2004; Doxaran et al. 2005; Jensen 2008). In arid regions identifying standing water from unsaturated soil can be straightforward due to the physics of light, although albedo and anisotropic reflectance of particularly bright surfaces can create significant problems using spectral-based image analysis (Bulley et al. 2013). This can be problematic where the spatial extent of a water feature is physically small compared to the albedo response ("bleeding") across the data array. Margins of saturated soils present additional challenges in classification. The point at which a surface becomes inundated with standing water must be defined and then measurable; for example, determining when a soil is fully saturated and differentiable from having a film of water, from a centimeter depth of water, or greater inundation. The effect of standing water at any depth has implications for the use of its surface, particularly airfields on playas.

The problem with the current approach of using simple band ratios lies primarily with the existence of image-to-image variability demanding subjective interpretation. This variability is multiply sourced due to registration error, atmospheric conditions, sensor position or parameters at time of acquisition, and radiometric differences, among others (Radke et al. 2005). In addition to scene to scene variability, the quality of the water affects the spectral response in terms of reflected and absorbed light, thus having an effect on the return response captured by a satellite sensor (Jensen 2008; Lillesand et al. 2004). The responses of clear deep water compared to clear shallow water differ due to light penetration depth—as will clear shallow water bodies with differing bottom substrates—and differs to water with algae or sediment. Therefore (i) there is no means to set a standard threshold value(s) using a band ratio approach; (ii) each scene must be manually interpreted; and (iii) the interpretation is entirely subjective. With subjective interpretation, the ability to conduct retrospective mapping lacks adequate rigorousness and repeatability. Confidence in the output from this approach is low, and thus analyses relying on unvalidated, subjective methods are considered to have unknown accuracy.

Time series assessments using Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) contribute valuable data and have provided scientific advancement towards understanding changing landscapes, including aquatic and marine environments. The Landsat satellite program, conceived in the mid-1960's and made operational with the launch of Landsat 1 less than a decade later, provides a foundation spaceborne imagery data set in and for the U.S. For 40 years Landsat data has been reliable, providing seamless geographic coverage with a relatively high spatial resolution (30 m), broadly applicable spectral bands, and is free of charge. Both NASA and the United States Geological Survey (USGS), which operate the Landsat Program, are committed to the Landsat Data Continuity Mission, the future of Landsat satellites. Landsat 8, which was successfully launched on February 11, 2013, is the new platform. Its Operational Land Imager (OLI) will have two new spectral bands in addition to the existing complement on board Landsat 7, will maintain the nominal spatial resolution of ~30 m, and will have a higher repeat frequency, returning 400 scenes per day compared with the 250 acquired from Landsat 7. The addition of current data, to be archived, will continue. Thus the approach presented in this study, which is Landsat-based, will be achievable in the foreseeable future with the launch of OLI.

2 Methods

The objective was to compare standing water volume estimates generated using two different methods for Rogers Lake: a hydrologic model and satellite image interpretation. The hydrologic model was a Doppler radar-based rainfall–runoff model which produced non-spatial volumetric estimates, and the image interpretation used Landsat satellite imagery and a high resolution LiDAR-derived DEM (Fig. 2). The output volumetric water estimation was for the extent of Rogers Lake.

Two storms of interest were evaluated, 11–13 February 2003 and 13–15 April 2003. The 11–13 February 2003 storm was selected for analysis because it produced the largest single-day precipitation total of 54.1 mm (2.13 in) for EAFB during the time for which both Doppler radar precipitation data and Landsat imagery were available. The 13–15 April 2003 storm was selected for analysis because it pro-

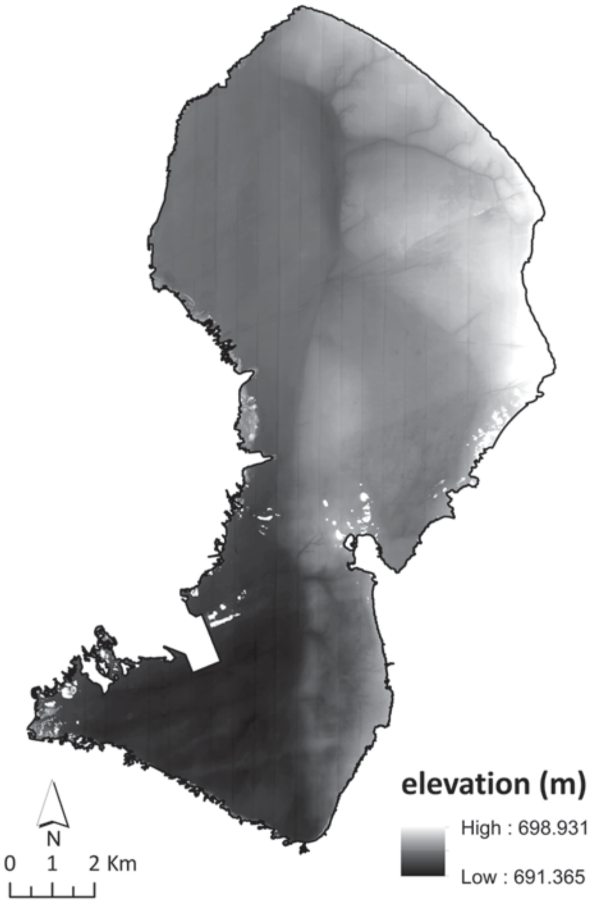

Fig. 2 Standing water volume was calculated using the LiDAR-derived DEM underlying the extent of water identified in the imagery. Elevation ranges from ~691 to ~699 m for the lake bed

duced significant precipitation at EAFB and cloud-free Landsat imagery was available 5 days before and the day following the storm event.

2.1 Image Analysis of Water Extent on the Playa

The Tasseled Cap Transformation (TCT) is an orthogonal transformation and is a type of principal component analysis (PCA). These are linear transformations of intensity and are used to transform a multispectral image into a different intensity space prior to conducting a change analysis (Radke et al. 2005). Unlike PCA, the TCT uses a known set of algorithms into which the original bands of data are transformed, resulting in a consistent resulting transformed intensity space (Crist and Cicone 1984).

In addition to transformation of the data against known axes, this process reduces data volume and allows for an expected universal interpretation of the output components. The first three output component bands are labeled as semantic descriptors of the information contained within each: 'brightness', 'greenness,' and 'wetness' (Jin and Sader 2005; Cohen and Spies 1992). The resulting TCT bands are used to optimize characterization of three basic elements, namely vegetation, soil, and water. Playas represent unique features in terms of differentiating water from non-water because depth can be in the millimeter range and because soil can be saturated without having measurable water on the surface. This is a very different scenario from differentiating a river from its riparian vegetation or a shoreline along a coast, for example. An advantage, therefore, of using the TCT is that regardless of where in the world the Landsat scene was acquired, the location of pixels plotted in a 2-dimensional graph representing water, dry soil, green vegetation, etc. remains consistent. For this reason, identifying standing water with the TCT can be done more objectively than subjectively setting thresholds based on simple band ratios. Because each scene being evaluated is the same path and row, covering the same geographic location of the earth, threshold values of TCT transformed images can be applied consistently across each date of imagery.

2.2 Image Interpretation and Volumetric Calculations

Four dates of cloud-free Landsat imagery were acquired for the study area in 2003 surrounding two identified storm events: 3 February (ETM+), 7 March (ETM+), 8 April (ETM+), and 16 April (TM). The images were subset and masked to the playa extent for data compression and the TCT was applied to each scene individually. Standing water on the playa was then identified in each resulting transformed image with a threshold value of ≥ 0 applied to the third component ('wetness'). This produced a binary, spatially explicit output where pixels with values greater than or equal to this threshold were assigned a value of '1' (standing water) and all other pixels were assigned '0' (not standing water). The results of this analysis for each of the four dates analyzed are provided in Fig. 3.

The binary raster images were exported to vector file formats and intersected with a LiDAR-derived DEM to digitally extract the elevation statistics for the perimeter of each standing water body, which were attributed back to the shape. The nominal spatial resolution of the DEM was 2 m with a z-value increment of ~ 0.5 m (Fig. 3). The mean perimeter elevation of the binary standing water extent was used to determine the height of the plane of water; the volume was thus calculated for each individual water polygon using the DEM surface underlying the corresponding surface water plane. Total water for each date was calculated by summing the volume across all polygons within the playa.

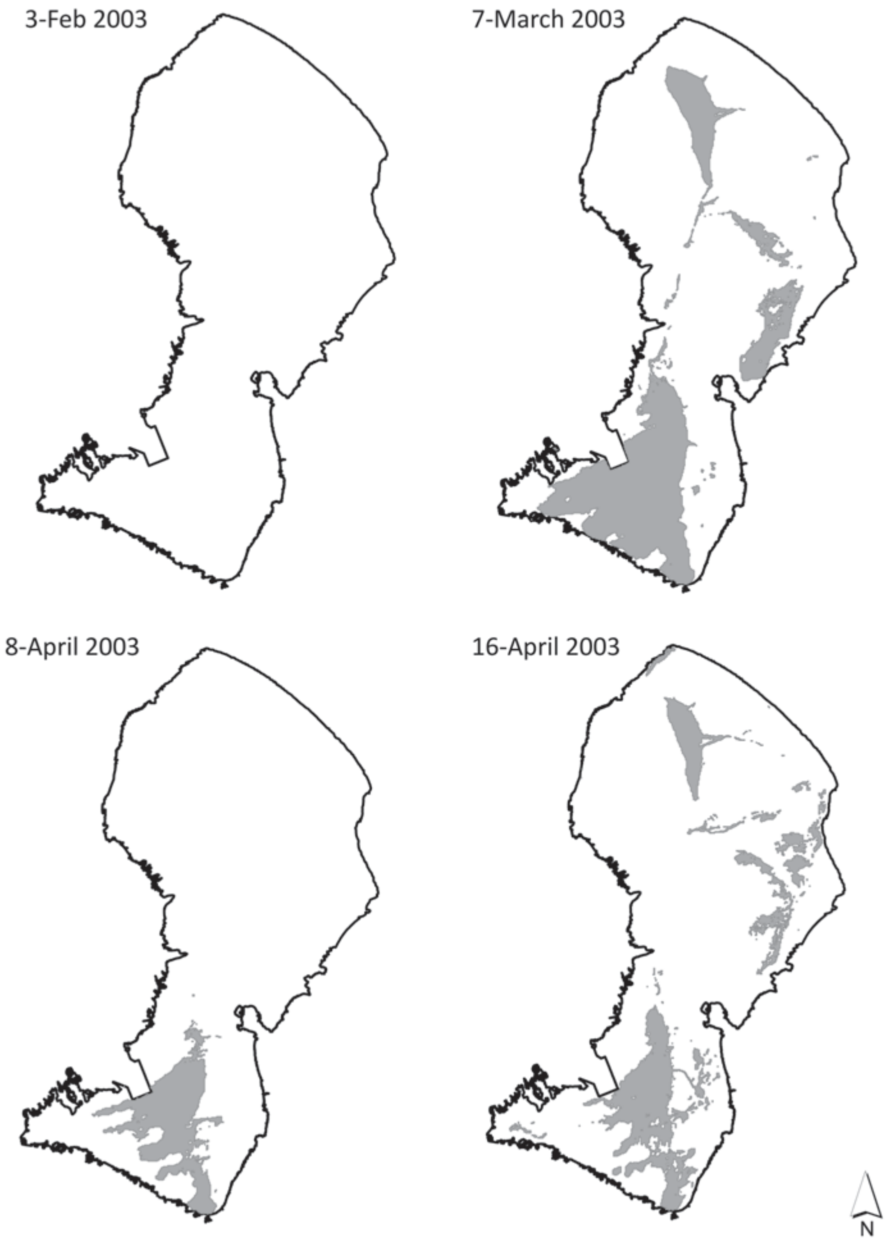

Fig. 3 Results showing standing water (*gray*) on Rogers Lake (*outlined*) for each of four different dates. The geographic extent of standing water as mapped from the wetness component of the Tasseled Cap transformed imagery. Reprinted with permission from ASCE

2.3 Precipitation Runoff Modeling

A detailed description of the watershed runoff model is provided by French *et al.* (2003) and Miller (2009). To summarize the approach, the assessment of playa flooding using the watershed runoff model was performed using Doppler radar-derived storm total precipitation data. Although use of the storm total precipitation estimates from the radar data neglects the temporal patterns of the storm it does retain the spatial resolution of the radar data. The model estimates runoff for and within elevation-defined intervals, which occurs as 'excess precipitation'. Excess precipitation is the difference between Doppler-based precipitation estimates and a site-specific determined threshold precipitation value, which is related to the hydrologic curve number based on soil type and land use for a given elevation interval. It is considered a cascading model because the excess precipitation (i.e., runoff) in each elevation interval, plus run-on from the adjacent higher elevation interval decreased by the Channel Loss Reduction Factor (Mockus 1972), produces the estimated volume of water available for release to the next lower elevation interval. Complete details of the modeling conducted for comparison with the image-based analysis presented here are provided in Miller et al. (2011).

Precipitation input for the watershed runoff model was obtained from the US National Climate Data Center (NCDC) that maintains precipitation data developed from Weather Surveillance Radar-1988 Doppler (WSR-88D) measurements. The WSR-88D station "KEYX" is located about 35 km (22 mi) northeast of Edwards AFB in the Roger Lake watershed (Fig. 1). Both precipitation data and spatial registration information were downloaded from the KEYX records on the NCDC website (http://www.ncdc.noaa.gov/nexradinv/) to enable processing in a geographic information system (GIS).

3 Comparing Model Output with Satellite Imagery

The spatial extent of standing water as mapped with Landsat imagery is shown in Fig. 4. Table 1 summarizes the results for both methods. Prior to the 11–13 February 2003 storm event the imagery acquired 3 February 2003 showed no standing water on the playa, establishing a dry condition baseline. During the subsequent 11–13 February 2003 storm event the Doppler-based model estimated an accumulation of 2,659,676 m^3 (93,925,577 ft^3) of water on the playa due to run-on and direct precipitation. Analysis of the 7 March 2003 image yielded a spatial extent of standing water to be greater than 25 million m^2 (272 million ft^2) of surface extent of standing water totaling nearly 4 million m^3 (131 million ft^3) in volume. The spatial distribution of this water spanned the entire playa north to south (Fig. 3). The DEM-based volume estimate for the 7 March image, captured nearly 3 weeks after the February storm, was 1.4 times more volume of standing water than the model estimated.

Examining the extent and location of standing water on the playa relative to runways and infrastructure is an advantage of mapping extent from imagery. Figure 4

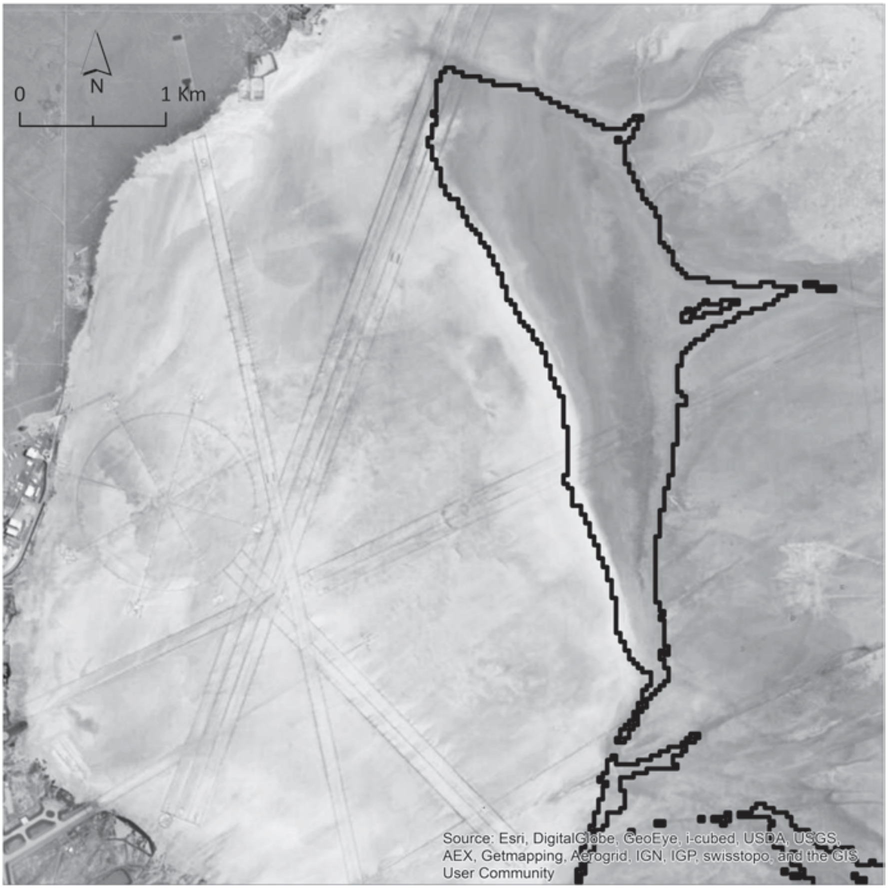

Fig. 4 Runways and surface water extent mapped from the 7 March 2003 imagery ingested in Google Earth Pro (© 2012 Google, © 2012 TerraMetrics) over the northwestern extent of Rogers Lake. This illustrates the utility of assessing where water, outlined in black, covered parts of runways following the February 2003 storm event and could be used in predictive modeling

Table 1 Surface area and volume of standing water post-storm event on the playa as estimated with imagery and LiDAR-derived DEM data. The change in volume (Δ volume) accounts for prior inundation from pre-existing conditions where some water was present prior to the storm event assessed. Also presented is water volume estimated for the playa based on the Doppler-radar modeling

	Image date (2003 for all images)				Model estimate	
	Feb 3	March 7	April 8	April 16	11–13 Feb	13–15 April
Area extent (ft^2)	0	272,819,938	92,141,339	161,597,521	–	–
Area extent (m^2)	0	25,345,800	8,560,210	15,012,900	–	–
Volume (ft^3)	0	131,103,755	29,304,414	62,627,730	93,925,577	68,011,313
Volume (m^3)	0	3,712,444	829,808	1,773,419	2,659,676	1,925,866
Δ volume (ft^3)	–	131,103,755	–	33,323,316	–	–
Δ volume (m^3)	–	3,712,444	–	943,611	–	–

shows the standing water extent derived from the 7 March 2003 Landsat image ingested into Google Earth Pro. This figure shows where runways in the northwestern part of the playa were inundated and where standing water was not present following the February 2003 storm. Combining the standing water polygon areas with digital data for the lakebed in a GIS is a simple exercise that can yield valuable insight over time as to persistence of standing water in space, and be paired with storm events. Further analyses into image-based prediction may prove valuable to the military and others who utilize dry lake beds for similar purposes.

Prior to the second storm event that occurred 13–15 April 2003, approximately 0.83 million m^3 (29 million ft^3) of water remained on the southern extent of the playa at its lowest elevations based on analysis of 8 April 2003 imagery (Fig. 3). As evident from the image, some water remained from and subsequent to the 13–15 April storm event, and is thus assumed to have contributed to the approximately 1.77 million m^3 (62.6 million ft^3) of water estimated from analysis of the post storm image (16 April). Therefore the net change in volume was calculated to be approximately 0.94 million m^3 (33.3 million ft^3). As evident in Fig. 3, areas of inundation across Rogers Lake were relatively consistent over time, with the lowest area of the basin being at the southern end (Fig. 2) and where standing water persisted. Runoff to the lakebed estimated by the model using Doppler radar precipitation data yielded an accumulated 1,925,866 m^3 (68,011,313 ft^3) of standing water. The volume of water on the playa attributed to the April storm by the runoff model was more than twice the volume difference estimated from the imagery, which was 943,612 m^3 (33,323,346 ft^3); this was calculated based on the estimated differences for the 8 April and 16 April images when standing water was observed and identified.

4 Discussion and Conclusions

The over- and under-estimation vector differences between modeled and image-based water inundation was inconsistent for the two storm events. Following the February storm, the model estimated less water on the playa than was calculated from imagery and DEM data, whereas for the April storm the model yielded a greater inundation estimate. There are several contributing factors that may explain these differences. Modeling approaches operate on assumptions that may or may not represent ground condition, or do so consistently, over all events being examined. In any quantitative analysis errors exist in data and are propagated through the course of calculation.

The model assumes that all excess precipitation collects in the lowest areas of the playa, ignoring the natural distribution and re-distribution of water that does occur. The model also does not account for wind effects on the water surface. Wind effects can include superelevation where the surface plane of the water extent is not level, or by physically pushing water upgradient against gravitational pull. Landsat imagery records a snapshot in time of the natural distribution of water as it flows onto and is then re-distributed across the playa. Images acquired towards the end of a storm may depict a larger area of inundation because water on the playa resulting from a widely distributed precipitation pattern will not yet have drained to the lowest parts of the playa surface. In addition, topographic variations in the playa surface exist and water can be moved across the lake bed by the wind. The image analysis produces an area extent of water surface, but cannot be used to estimate water volume without an underlying surface such as a DEM. Imagery alone does not produce data on water depth, movement, or underlying surface elevations. The Doppler based model estimates volume but is not spatially explicit and thus does not provide inundation area. Thus, wind effects may be a contributing factor to the differences between model- and image-based volumetric estimates. Wind effects were not accounted for in this analysis because lakebed-specific data were not available.

Other possible reasons for the output differences produced from the watershed runoff model are those associated with determining the precipitation input to the model, estimating hydraulic parameters of the model, and quantifying the area of inundation of the model estimate of water volume on the playa. Doppler precipitation estimates and ground station gage measurements do not always correlate well (Hartzell et al. 2001; Hardegree et al. 2008) and these differences may be explained partly by operational limits and interferences of the radar system. Preliminary comparison of the Doppler precipitation estimates for the 11–13 February storm with ground measured precipitation at 13 stations scattered throughout the western Mojave Desert and surrounding mountains indicated that the Doppler data underestimate the ground measured precipitation. Further work into the possible reasons for the differences may improve these issues. Validated models to estimate playa flooding are critical to manage activities involving lakebed facilities and provide the military with useful and accurate tools to support the use of playas for training and testing activities. There is also a need for spatially-explicit representation of water distribution over the playa surface. Preventative measures based on accurate predictions about lake bed flooding risk and hazard can have direct impacts on safety and costs.

Landsat data, enabled an objective quantitative approach to mapping standing water on Rogers Lake and would be expected to produce similar results on other desert playas. Beyond the military applications related to predicting playa flood events to avert scheduling conflicts and maintain mission continuity, the approach presented here offers potential application in other fields of study. The application of the TCT to archived satellite imagery would yield a database with a wealth of data relevant to collection of precipitation as standing water on valley floors in time and space. The spatial pattern of standing water and its persistence over time may provide insight into past patterns of precipitation in both time and space, possibly reflecting climate change. The data in this manner provide a baseline, and baseline variability in these patterns that would be valuable for future projections.

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Environmental Security and Trans-Boundary Water Resources

Francis A. Galgano

Abstract Environmental security refers to a range of security issues triggered by environmental factors such as climate change, resource shortages, demographic factors, environmental change, and non-sustainable practices. Water resources are a particularly problematic area because water is an essential resource for which there is no substitute, and the amount of fresh water is finite and not equitably distributed in a spatial sense. From a geopolitical perspective, the world's largest river systems are shared by multiple states and the potential for conflict is high. However, historically water resource conflict has been resolved by cooperative means and states have relied on technology, trade, and diplomatic solutions. This research argues that the security landscape has changed profoundly, and the history of cooperative water-conflict resolution is no longer a reliable guide to the future. This paper suggests that continued peaceful resolution of interstate water conflicts is inconsistent with the realities of the emerging national security landscape: climate change is already affecting the distribution of water in many critical water basins, and the proliferation of failing states has reduced the potential for diplomatic resolutions. This paper examines linkages between environmental stress, regional instability, water availability, and conflict and uses the Middle East as a case study to highlight these points. The analysis suggests that the region is now more vulnerable to environmental stress and water-related conflict. Given these circumstances, it is plausible that we will witness a surge in three modes of conflict, driven by water demand: ethnic/racial warfare enabled by environmental stress and demographic trends; civil warfare prompted by environmental stress and economic collapse; and limited-scale interstate wars.

Keywords Environmental security · Water resources · Watersheds · Military geography

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1 Introduction

Since the end of the Cold War, linkages between the environment and conflict—that is, environmental security—have become an important paradigm in national security planning. Kaplan (2000) suggests that water and other environmental factors represent the core foreign policy challenge in this century. In his 2010 *National Security Strategy*, President Obama reinforced this notion when he listed environmental factors and resource scarcity as important features of the national security landscape. He indicated that wars driven by ideology might give way to conflict triggered by demographic and environmental factors (Obama 2010). Thus, national security affairs may no longer be about armies and weapons; but instead, climate, resources, and demographics may now be viewed as being equally important as traditional elements of national power (Butts 2010).

Environmental security refers to a broad range of security issues exacerbated by environmental factors and suggests that environmental stress has the potential to destabilize states and trigger violent conflict (Galgano and Krakowka 2011). Water is a particularly challenging factor in the environmental security milieu because it is an essential resource, and the fresh water supply problem only promises to intensify in a greenhouse world. Growing global population and its attendant economic demands means that the pressure placed on fresh water resources will grow inexorably. Today, about 1 billion people lack access to safe drinking water, and this number is likely to grow to nearly 3 billion by 2050 (Gleick 2012). In places that are conflict-prone and vulnerable to water shortages, such as the Middle East, climate change could seriously affect regional stability (Trondalen 2009).

To further complicate this problem, 60 % of the world's population lives in crowded water basins shared by multiple states—many of whom are failing, congenital enemies, or both (Postel and Wolf 2001). This is a compelling problem from a military geography perspective because most of the world's largest river systems are shared by multiple states. Thus, the possibility of water wars resonates throughout contemporary national security literature (Diehl and Gleditsch 2001; Gray 2009).

The U.S. National Intelligence Council warns that the likelihood of water-related conflict will increase in the coming decades (Conca 2006). Nevertheless, many water scholars dismiss this estimation as exaggerated, and history appears to support their position. An examination of some 1000 international water-related events during the past 50 years suggests that two-thirds were resolved by cooperative means. This implies that water disputes are not likely to lead to warfare; rather, states tend to resolve these disputes through economic agreements, and diplomacy (Fagan 2011). However, this study argues that the security landscape has changed profoundly, and the history of cooperative water-conflict resolution is no longer a reliable guide to the future. The public's perception of the relationship between water and conflict is clearly gaining momentum, and a number of experts now acknowledge that water wars are certainly plausible; especially if we persist in denying the seriousness of the water crisis in key regions (Soffer 1999; Pearce 2006; Trondalen 2009).

This paper suggests that continued peaceful resolution of interstate water conflicts is inconsistent with the realities of the emerging national security landscape. First, climate change is already affecting the distribution of water in many critical water basins. Second, the proliferation of failing states has singularly reduced the potential for diplomatic resolution in many regions, and that we can no longer continue to rely on quasi-peaceful means using established diplomatic and international protocols to resolve conflicts (Rosenthal 2004). Finally, water is an essential resource; however, since 1950, the renewable supply of water per person has fallen by 58% (Fagan 2011).

Water shortages will likely provide a tipping point for regions already on the brink of conflict, such as the Middle East. States in this region border highly contested water basins and they are facing chronic water shortages combined with the world's fastest growing population. These factors combine to intensify latent ethnic/religious conflicts and decades of distrust and territorial disputes. Population growth and climate change are fueling a dangerous nexus of water shortages, political instability, and economic stagnation, which are eroding an already unstable situation. This paper examines linkages between international watersheds and potential conflict. This analysis suggests that states that border international water basins are more vulnerable to violence. Hence, we may witness a surge in three modes of violent conflict: (1) ethnic warfare enabled by environmental stress and demographic trends; (2) civil warfare prompted by environmental stress and economic collapse; and (3) limited-scale interstate wars.

2 The Emergent National Security Landscape

The security implications of water vulnerability in the Middle East could be severe and represent a departure from the traditional view of security. The Cold War strategic partition of the world dominated the security landscape for more than four decades following the Second World War. Today, however, the potential for violent conflict triggered by environmental stress looms over society, which is much different from the traditional Cold War concept of security (Myers 1989). Thus, a major shift has occurred: during the Cold War, divisions were created and alliances formed along ideological lines; but now security officials have begun to pay greater attention to problems arising from intensified competition over essential resources (Butts 1997).

Barnett (2004) developed a national security paradigm that attempted to incorporate emerging post-Cold War dynamics—that is economic competition, environmental stress, and failing states. In Barnett's view, these factors are destabilizing large segments of the world because globalization, and the expansion of the global economy that followed, did not lead to an era of integration and world peace. Rather, the unbalanced nature of economic prosperity generated pervasive instability in much of the developing world (Barnett 2004). This suggests a major shift in the security landscape because Barnett's map (Fig. 1) presents a world that is segregated

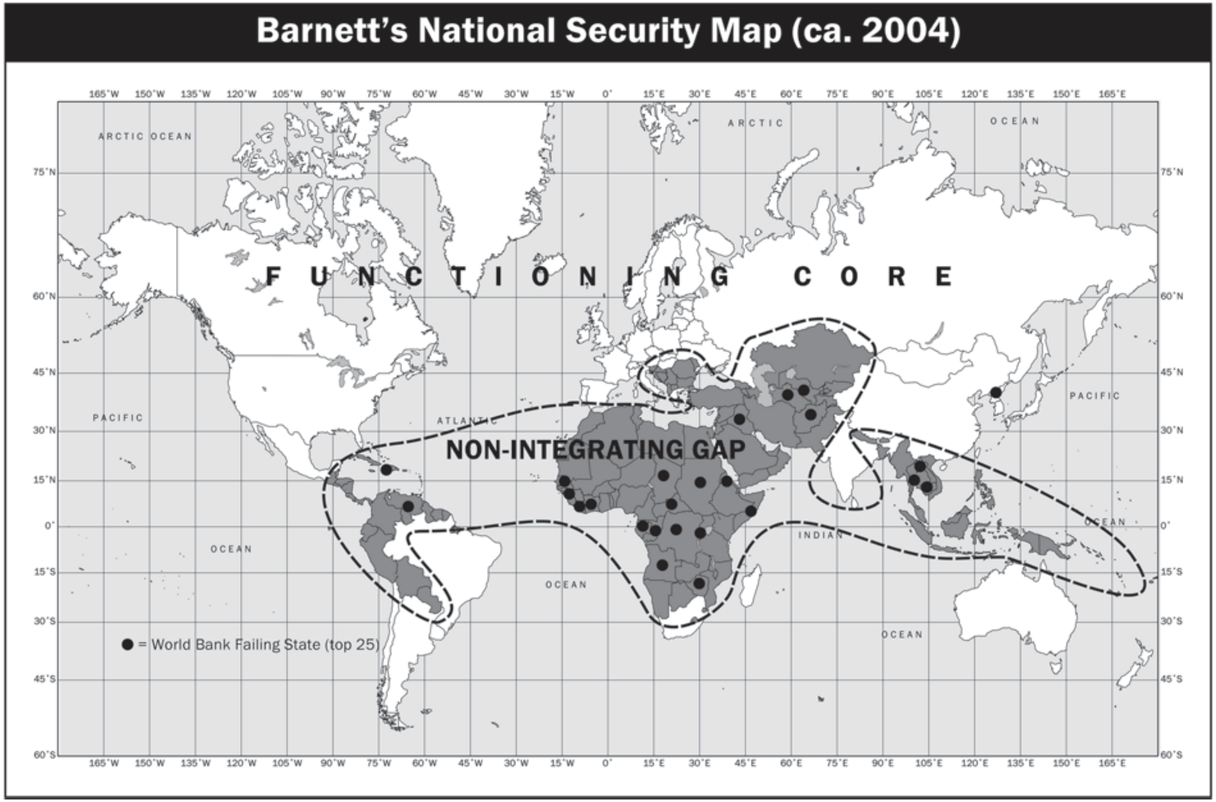

Fig. 1 Evolution of the post-Cold War security landscape. Barnett's (2004) map illustrates the separation of the *non-integrating gap* from the rest of the world. *Black dots* on the map indicate the 25 least effectively governed states in the world according to World Bank Governance data (Kaufmann et al 2008). Cartography by the author

into one that it integrating itself into a so-called *Functioning Core*, and one that is trapped in a *Non-Integrating Gap* (Barnett 2004). The *Non-Integrating Gap* is essentially disconnected from the rest of the world; but more importantly, it is inherently unstable and susceptible to environmentally triggered violence (Galgano and Krakowka 2011).

Klare (2002) suggested a national security geography to explain the evolving spatial dynamics of conflict following the Cold War—this one driven by competition over vital resources. Klare argues that conflict during early 1990s in the former Yugoslavia and Central America compelled the world community to concentrate on preventing intercommunal warfare rather than focusing on potential violence triggered by economic inequities and resource competition (Klare 2002).

Klare's geography of conflict (Fig. 2) integrates tensions in the new international system, and attempts to predict conflict by viewing international relations through the lens of the world's contested resources. Thus, Klare's map indicates major deposits of oil and natural gas lying in contested areas along with disputed water resource areas—especially the Nile, Jordan, Tigris, Euphrates, and Indus River basins (Klare 2001).

U.S. policymakers have long acknowledged the destabilizing imbalance of natural resource supply and demand, and its profound consequences for its security interests (Butts 1997). The Arab oil embargoes of the early 1970's quadrupled gasoline prices and clearly pointed out that the global economy depends on highly concentrated deposits of increasingly scarce resources. Although we understand oil as an instigator of conflict, water poses a different and potentially more difficult dilemma because it is a problem that cannot be easily managed (Klare 2001).

3 Water and Environmental Security

Water is becoming one of the seminal environmental security factors of the emergent national security landscape because it is an essential resource for which there is no substitute (Butts 1997). Renewable freshwater is fundamental to human society; however, contemporary water demands are approaching the limits of a finite supply (Hensel and Brochmann 2007). Only 0.036% of the world's supply is renewable freshwater; and by 2015, some 3 billion people (about 40% of the global population) will live in regions that are unable to provide sufficient freshwater to meet basic needs (Gleick 1993a; Postel and Wolf 2001). Hence, inequities in freshwater supplies will continue to be a source of friction. In fact, 25% of all water-related disputes during the past 50-years have resulted in some form of hostilities—37 have resulted in recorded incidents violence or military action (Gleick 1998; Postel and Wolf 2001).

Globalization has reduced the friction of distance and created expectations of economic growth in the developing world, thus escalating the disparity between developed and developing states (Butts 2010). In the context of environmental stress and resource competition, the crux of the matter is that global economic output

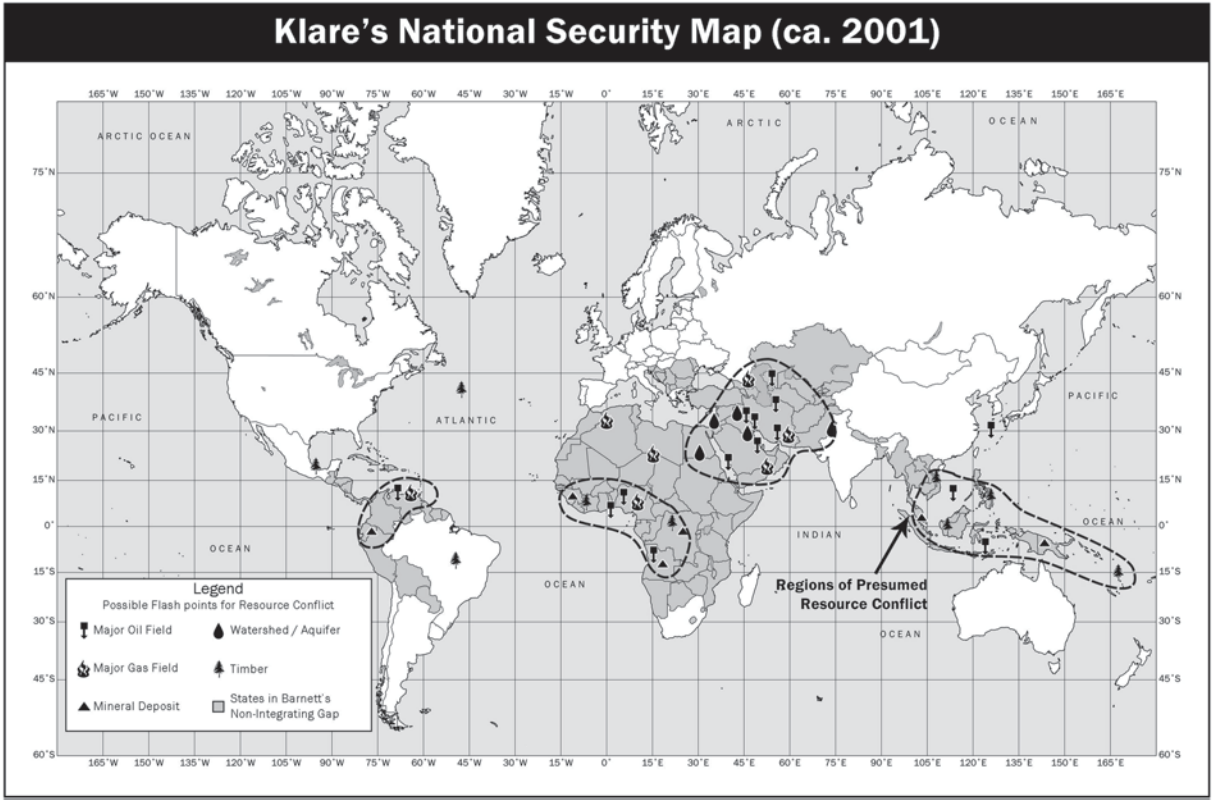

Fig. 2 Klare's (2002) national security map, which views post-Cold War conflict through the lens of contested resources. This map overlays Klare's presumed areas of potential conflict over Barnett's (2004) non-integrating gap. Cartography by the author

quadrupled after 1950 and during that period, population grew by 3 billion. However, the problem that looms is that we expect global population to approach 9 billion by 2050, and to keep pace, economic output will have to quintuple, which will place greater demands on global freshwater resources (Homer-Dixon 1999). Thus, water may become an environmental tipping point that triggers violent conflict as greater economic aspirations and human population accelerates demands on the freshwater supply, while at the same time climate change makes supply more uncertain (Gleick 1993b).

Recent statistics indicate that global water demand for irrigation, domestic, and industrial use will increase faster than the rate of population growth (Fagan 2011). Furthermore, freshwater supplies are, geographically, highly variable and are not equitably distributed in a spatial sense; nor does its spatial distribution match population distribution. The water scarcity problem is further complicated because water does not lend itself to international trade and it is not practical to transport from surplus areas to places of acute scarcity (Pearce 2006). Water supply is often diminished by water quality issues. Increasing populations require more irrigation and dams, both of which can adversely affect water quality. Thus, water passed to downstream users, even in water-rich regions, is typically contaminated (Butts 1997).

The geo-political implications of water supply are challenging as well. From a strategic perspective, upstream states have an advantage in the control of water; downstream states generally remain vulnerable to the political decisions of those upstream. This presents a vexing geopolitical dilemma: according to the United Nations (U.N.), there are roughly 214 international rivers: 150 are shared by two states, and the remainder are shared by three to ten (U.N. 1978). It does not help that coincidentally, many of these same river systems are located in the most unstable places on the planet, and unfortunately, in the international legal setting, water law is not effective in settling conflict (Gleick 1993b; Soffer 1999). Thus, the method of determining sovereignty over trans-boundary rivers remains contentious; and in the context of places with increased population pressure and severe water stress the potential for conflict is high (Butts 1997).

Demographically driven increases in water demand during the past 50-years have been unprecedented and forced the Middle East into an acute water deficit. To put this into practical terms, on an annual basis, each individual needs about a cubic meter of water for consumption, about 100 cubic meters for other personal needs, and 1,000 cubic meters to grow food (Darwish 1994). Thus, the annual minimum basic need is about 1,100 cubic meters: a country with less than 1,700 m^3 per capita is regarded as water stressed, while less than 1,000 m^3 is considered water scarce (SIWI 2009). Fig. 3 illustrates the geographic distribution of water stressed and water scarce states and it confirms the chronic problem that exists in the Middle East. The U.N. (2009) now considers 13 states to be water scarce, and four of them—Israel, the Palestinian Authority, Saudi Arabia, and Jordan—are located in this region. U.N. projections suggest that another 10 states will be added to this list by 2025, to include Egypt, Ethiopia, Iran, and Syria: in other words, one third of the world's water scarce states are located in the Middle East. Clearly, population is the crucial variable because every additional person essentially requires 1,100 cubic meters of

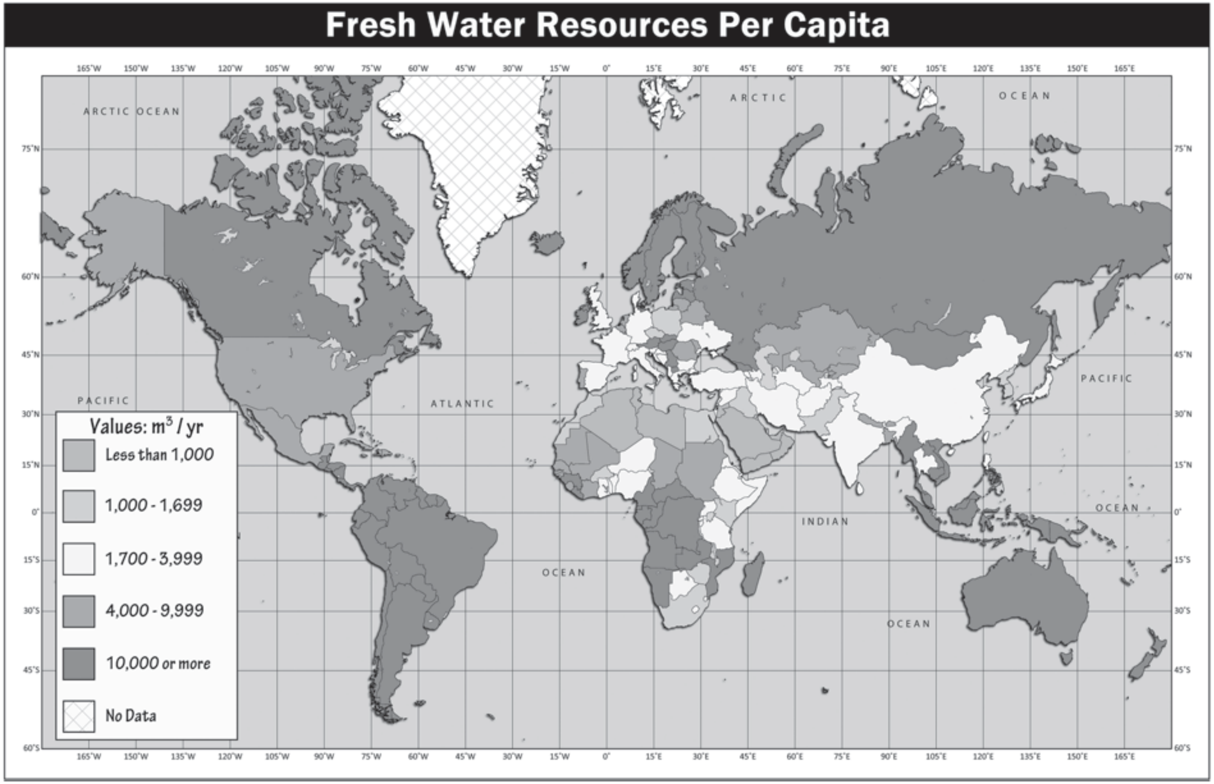

Fig. 3 Water scarcity and stress. After Gleick (1993b). Cartography by the author

additional water resources every year and the region's associated agricultural water needs present a near impossible challenge for Middle Eastern economies (U.N. 2009).

In the context of environmental security, water has two important characteristics that make it a potential source of inter-state warfare: (1) its degree of scarcity, which is being affected in the Middle East by climate change and demographic factors; and (2) the degree to which a water basin is shared between multiple states; a problem that is being exacerbated by poor governance (Gleick 1993b; Smith and Vivekananda 2007).

3.1 Climate Change and Future Water Supply: The Middle East

Climate change is expected to have a significant adverse effect on water vulnerable areas that are already conflict-prone (Trondalen 2009). Recent data from the Intergovernmental Panel on Climate Change (IPCC) suggests that temperatures in the Middle East increased by approximately 2–3°C during the last century. The IPCC (2012) model projects a decrease of 15–25 % in rainfall over large areas of the Middle East, thus causing extreme drought and increased competition for increasingly scarce water supplies.

The implications of the various climate models are clear: diminished rainfall, less surface water, lower soil moisture, reduce aquifer recharge, and higher water demand for crops and humans. Yet, it is important to note that there is a degree of spatial variation in temperature and precipitation in the region, and the seasonality of rainfall makes change models and generalizations for the Middle East somewhat speculative. Although there is uniformity among temperature predictions, those of precipitation are inconsistent (Trondalen 2009). This is because standard resolution climate models have difficulty representing precipitation in the Middle East, which is modified by complicated topography, inland bodies of water, and proximity of the Mediterranean Sea (Black et al. 2010). While there is variability between climate models, it is nevertheless clear that the Middle East is the world's most water-stressed region, and all projections suggest that climate change will play a role in significantly reducing water availably (Krichak and Alpert 2005; Sappenfield 2007; Black et al. 2010; IPCC 2012).

An analysis of relevant climate models suggests that water vulnerability in the Middle East could be severe. The IPCC (2008) analysis outlines a series of general climate-related problems that are relevant to the Middle East, all of which predict the region will be subjected to prolonged drought and extreme water deficits in the coming decades. Zhang et al. (2005) suggest that the overarching driver of this problem is the statistically significant and spatially coherent trends in indices that suggest a considerable elevation of temperatures throughout the region. However, Zhang et al. (2005) indicate that trends in precipitation indices are less consistent. Notwithstanding this variability, models suggest statistically significant reductions in rainfall through the end of the century (Trondalen 2009).

Alpert et al. (2008) examined a series of climate models for the Middle East. Their analysis indicates that temperatures in the region increased by 1.5–4°C during the past 100-years, and that regional temperatures are expected to increase by 4–6 degrees Celsius by 2100. Simultaneously, precipitation data from the region indicate a dominant negative trend since 1950 (Alpert et al. 2008). Ragab and Prudhomme (2000) developed a monthly climate model for the Middle East, which was developed to predict changes in rainfall from contemporary monthly mean values. Their model suggests that by 2050, most of the region will experience reduced rainfall amounts up to 20–25 % lower.

Ragab and Prudhomme (2000) developed a water exploitation index based on the results of their model, which predicts subsequent water demand as a percentage of renewable annual water resources. Their analysis paints a dire picture for the Middle East. For example in the Jordan Valley, it is expected that Israel will exploit 140 % and the West Bank/Gaza 169 % of the renewable water supply by the end of the century. Kitoh's et al. (2008) analysis of climate models suggests a decrease in the Jordan River's annual flow by as much as 73 %. Finally, Weib et al. (2007) suggest that droughts will be 10 times more frequent along with a 15 % decrease in rainfall over the next 100 years.

3.2 Governance Matters

Contemporary research indicates that countries that are poorly governed and have ineffective institutions will be hardest hit by climate change and water shortages. Water scarcity will clearly intensify the strain under which those societies already exist (Smith and Vivekananda 2007). However, environmental stress alone does not, inevitably, trigger warfare. Evidence suggests that it enables or intensifies violent conflict when it combines with weak governance and social division, along with economic inequities to affect a spiral of violence, typically along ethnic and political divisions (Galgano 2007). For example, this problem is evident in the Darfur region of Sudan, and was one of the triggers for the Ogaden War in the Horn of Africa during the late 1970s (Myers 1989). Contemporary trends indicate that environmentally driven violence has been concentrated in the developing world because it exhibits extreme social fragmentation and stratification (Homer-Dixon 1999). Developing states are more susceptible to environmentally triggered conflict because they are, characteristically, more dependent on the environment for their economic productivity; and lack the resiliency to overcome these challenges because they have weak economies and small capital reserves, shortages of scientists and engineers, and poor distribution infrastructure (Galgano 2007).

Political instability and weak governance make it problematical for some states to adapt to the physical effects of climate change and water scarcity. Regrettably, governance is a considerable and emergent crisis in the developing world, and since 1990, the number of failing states has grown. The World Bank (i.e., Kaufmann et al. 2003, 2008) examined governance by indexing six key metrics as a means to quantify state stability (i.e., voice and accountability of the government; political stability and absence of violence; government effectiveness; regulatory quality; rule of law; and control of corruption). Their 2003 findings indicate that of 187 countries examined, 92 (i.e., 49 % of all states) exhibited high levels of instability and could be considered failed or failing states (Kaufmann et al. 2003). Their 2008 findings suggest a deepening of this troubling trend. First, government stability and effectiveness in developing regions such as Sub-Saharan Africa, South America, the Middle East, and Asia is growing weaker. Second, the rift between the developed and developing world is growing. Finally, the 2008 World Bank data indicate that, while overall governance scores have marginally improved, the number of failed or failing states has increased. Of 212 state entities examined, 122 exhibit significant levels of instability—i.e., 57 % of all states (Kaufmann et al. 2008).

Figure 4 illustrates the extent of the governance problem within the three key river basins in the Middle East. This graph uses the U.N. Human Development Index (HDI) (U.N. 2010) and the World Bank combined governance index (WBGI) to portray the level of stability and government effectiveness in these countries as compared to the world's 25 most effectively governed states (according to the World Bank and U.N.). The WBGI (i.e., Kaufmann et al. 2008) assigns positive and negative values to states. More positive values suggest more effective governance

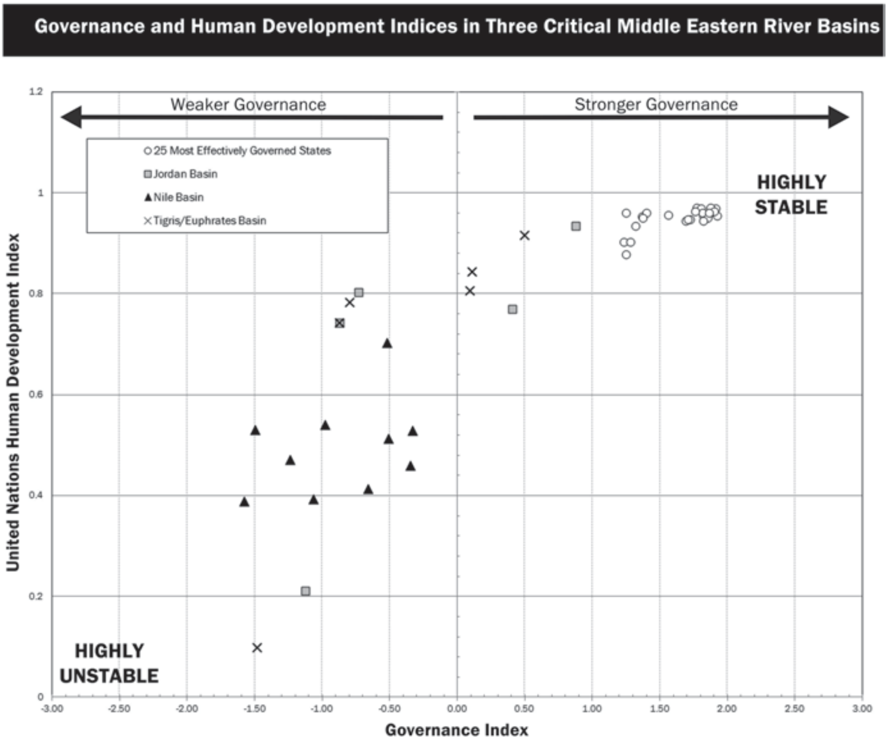

Fig. 4 Governance and development in the Middle Eastern river basins. The graph indicates development levels and governance indicators of states within the regions three large river basins. (Sources: U.N. 2010 and Kaufmann et al. 2008)

and negative values equate to failing states. The U.N. (2010) developed the HDI as a means of measuring development by merging indicators of human health, education, economic development, and quality of governance into a composite index that can serve as a frame of reference for the overall level of development within a state. The HDI sets a minimum and a maximum with zero equating to low development and one equating to very high development (U.N. 2010). Thus, the data given in Fig. 4 suggest that with minor exceptions, most of the states within the Middle East's three principal river basins exhibit low development (i.e., HDI score <0.5) and weak governance (i.e., WBGI score <0.0). In fact, the data in Fig. 4 suggest that most of these countries are failing states.

Failing states are troubling because they have large areas that are outside of effective government control and thus, can be affected severely by humanitarian disasters, environmental stress, and ethnic conflict (Galgano 2007). Failing states are more vulnerable to environmental stress and suffer from four fundamental causally related effects: (1) reduced agricultural production; (2) economic decline; (3) population displacement; and (4) civil disruption (Homer-Dixon 1991). These effects fundamentally determine the vulnerability and adaptability of the society and raise the complexity of the problem for governments as well as non-governmental organizations and intergovernmental bodies as they attempt to develop relief strategies (Galgano 2007).

The London based non-profit group International Alert published a study (Smith and Vivekananda 2007) that examined the nexus of climate change and failing states. Their analysis outlines the scope of the problem of environmentally triggered violence in a greenhouse world. Smith and Vivekananda (2007) indicate that there are 46 states within which the effects of climate change, coupled with weak governance, will create a high risk of violent conflict (Fig. 5). These states, which have a combined population of 2.7 billion, coincidently, incorporate the world's most contested river basins. Their analysis further suggests that a second set of 56 states will experience significant destabilization from climate change because of chronically ineffective government institutions (Fig. 5).

The International Alert study is compelling because it attempts to illustrate the geographic scope of the nexus of water scarcity and poor governance. History indicates that water conflicts were typically resolved in a peaceful fashion. In many cases, leaders of government and non-governmental organizations were able to remedy the problems presented by contested water resources using conventional diplomatic and international protocols. In such cases, well-established doctrine is reasonable as it imparts normative guidance (Rosenthal 2004). However, those same well-established diplomatic protocols and international doctrines and the principles they engender must be now considered in light of the new national security landscape, which is being significantly altered by the double edged-problem of climate change and failing states.

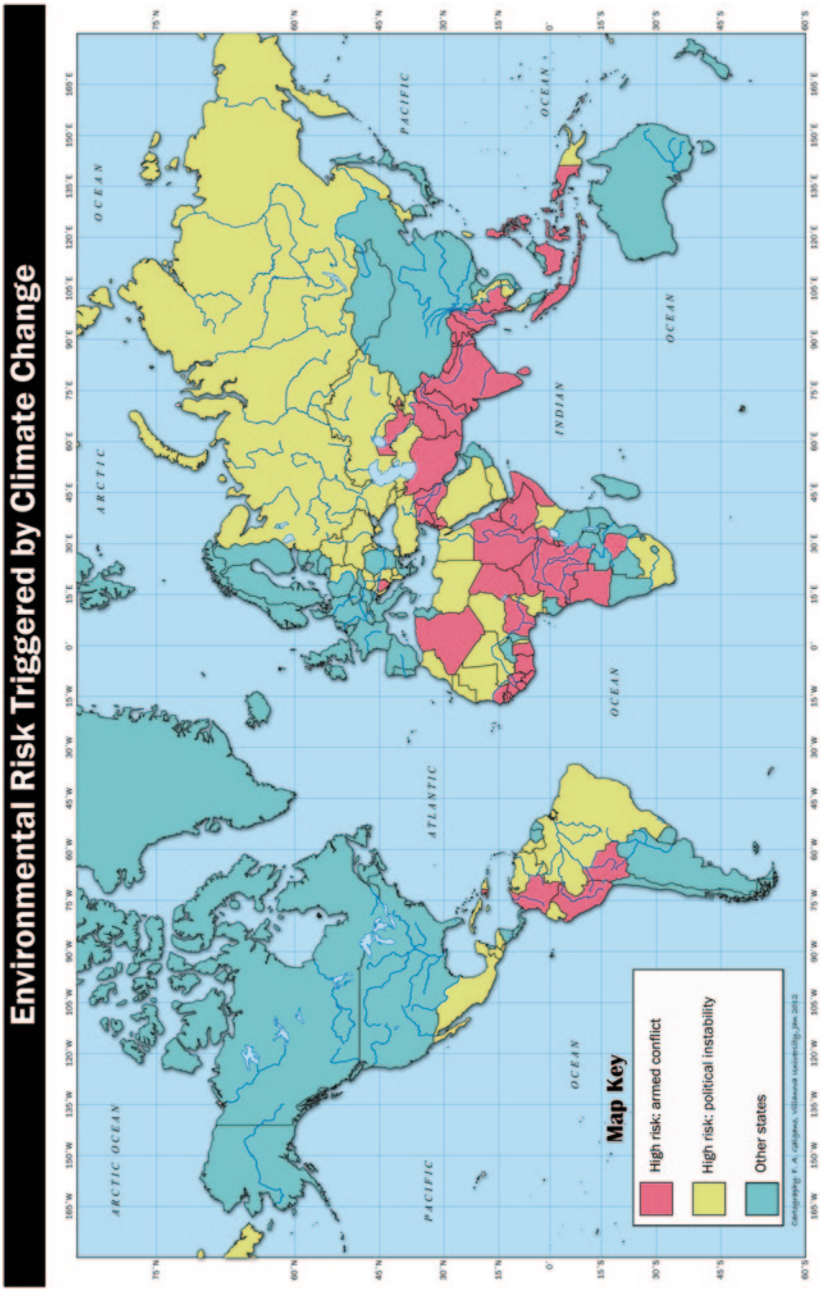

Fig. 5 Environmental risk and potential violent conflict triggered by climate change and weak governance (Smith and Vivekananda 2007). Cartography by the author

3.3 Water Supply, Demand, and Potential Conflict in the Middle East

Dynamics between population, environmental stress, and conflict are complex, but are not a deterministic recipe. The outcome of a potential environmental security scenario is influenced strongly by government policy, social structure, technology, and infrastructure (Dalby 2002). The critical problem is defining the tipping point between a highly degraded and stressed environment, and those societies and governments that can adapt. The insufficiency of water has, in the past, led to conflict, and it is currently the source of tension in the Middle East; however, we should not assume that water shortage would inevitably lead to war (Amery 2002). Technology, diplomacy, and policy changes can potentially alter the prescription for conflict. However, given rapid population growth, changes in climate, and the imbalance of water, combined with regional political instability, it is reasonable to assume that conflict is a possible outcome. The real problem is that in the Middle East, like the rest of the developing world, the capacity to adapt is declining (Hensel and Brochmann 2007).

The Middle East (Fig. 6) includes three large, transboundary river basins (i.e., Jordan, Nile, and Tigris-Euphrates). The demand for water placed on these three river basins is dictated largely by the region's population, and projections leave little room for optimism. The Middle East manifests some of the fastest growing and urbanizing population in the world, and it also a region within which the withdrawal of water resources are among the highest (Fig. 6), while the renewal rate is the slowest (SIWI 2009). Hence, Middle Eastern states are worrying today about how they will provide drinking water for the extra millions born each year, not to mention agriculture, the primary cause of depleting water resources in the region. In raw population numbers (Table 1), the region is expected to exceed 700 million by 2050—an increase of some 65 % during the next 40 years (PRB 2011). The data also indicate that the global rate of natural increase is 1.2 % with a mean of 1.7 % for the entire developing world. However, by comparison, rates of natural increase for the Middle East are striking: the mean rate for the region is 2.23 %. Even more noteworthy are the doubling times illustrated for each state, and the region's doubling time of 31 years, which is nearly half that of the global rate (PRB 2011). These data (Table 1) are problematical, and given projected population growth, changes in climate, and the imbalance of water supply and demand, water continues to be a source of tension. Across the region, *per capita* availability is already the lowest in the world; and Middle Eastern states are already exploiting nearly all of their renewable water resources (Amery 2002).

As a representative example, the level of the problem for the Jordan River basin is given in Fig. 7. The data illustrate the precipitous decline of water resources and suggest that by 2010, four of the five states in the basin were experiencing severe water scarcity and could not meet the needs of their population from internal, renewable water resources. By 2025, all of the states will be experiencing water scarcity (Aquastat 2012; SIWI 2009), and considering the anticipated increases in

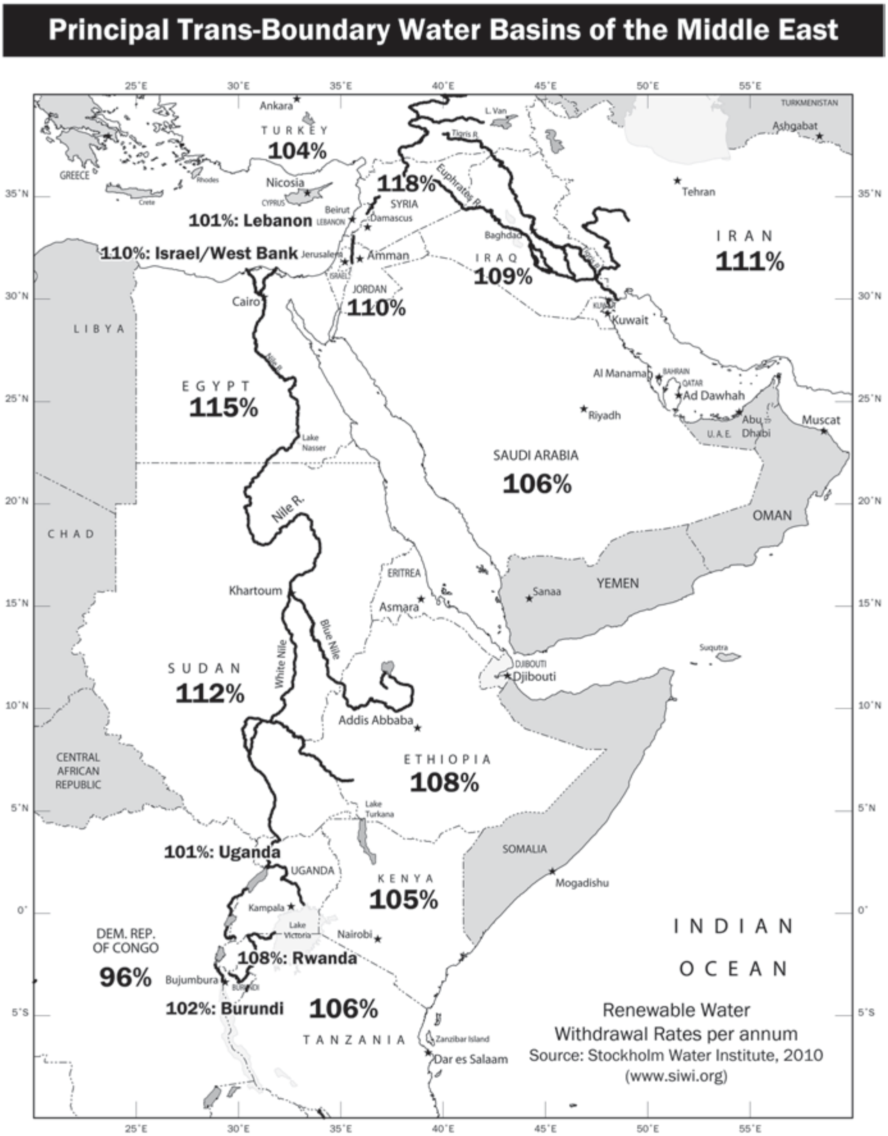

Fig. 6 Map of the three major river basins in the Middle East. The map also indicates the percentage of annual withdrawals of renewable water resources for each state. (Source: Aquastat 2012). Cartography by the author

the region's population (Table 1), potential scenarios are not encouraging given the region's pervasive instability. The data for the Jordan River basin are particularly discouraging given the highly contested nature of the region's space and the ongoing hostilities that already exist (Gleick 1993b).

Table 1 Comparison of principal states adjacent to major transboundary, Middle Eastern rivers to global population trends

State	Rate of natural increase (%)	Doubling time (years)	2010 population (millions)	2025 population (millions)	2050 population (millions)
Egypt	2.1	33	80.4	103.6	137.7
Ethiopia	2.7	25	85	119.8	173.8
Iran	2.6	2.6	75.1	87.1	97
Iraq	2.6	26	31.5	44.7	64
Israel	1.6	43	7.6	9.4	11.5
Jordan	2.6	27	6.5	8.5	11.8
Kuwait	2	35	3.1	4.1	5.4
Lebanon	1.5	47	4.3	4.7	5.4
West Bank/Gaza	2.8	25	4	6	9.4
Saudi Arabia	2.6	27	29.2	35.7	49.8
Sudan	2.2	32	43.2	56.7	75.9
Syria	2.5	28	22.5	28.6	36.9
Turkey	1.2	58	73.6	85	94.7
Regional mean/total	2.25	31	466	593.9	772.8
Summary					
Global	1.2	58	6829	8108	9485
MDS[a]	0.2	350	1237	1290	1326
LDS[b]	1.7	41	4318	5343	6722

[a]More developed states (see PRB 2011)
[b]Less developed states (see PRB 2011)

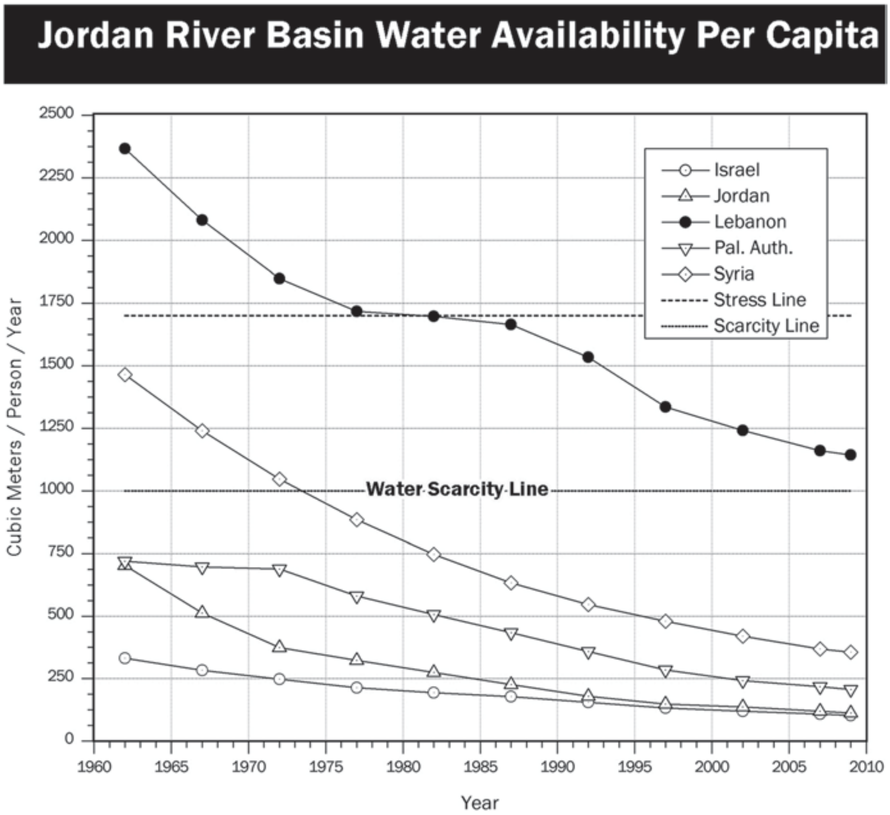

Fig. 7 The extent of the water shortage crisis in the Jordan Valley is illustrated on this chart. These data suggest that most of the states in the basin, with the exception of Lebanon, are below the *water scarcity line*. This line is based on the idea that each person requires about 1000 m^3 of water each year. (Source: Aquastat 2012)

4 Discussion

Oil has always been the expected trigger for warfare in the Middle East. However, water is now a critical variable because these states depend on three great river systems, or vast underground aquifers (which we have not mentioned), which are already being exploited beyond a sustainable level (Amery 2002). Water has already played an intrinsic role in fostering conflict, altering policies, and changing alliances in the region. During the 1960s, cross border raids against water-related infrastructure were common between Israel, Syria, and Jordan culminating in the 1967 Six-Day War. During the 1964 Arab summit in Amman, Jordan, it was decided to redirect the headwaters of the Jordan River, thus depriving Israel of its most important water supply. General Ariel Sharon placed this into context with this quote, *“People generally regard 5 June 1967 as the day the Six-day war began,”* he said.

"That is the official date. But, in reality, it started two-and-a-half years earlier, on the day Israel decided to act against the diversion of the Jordan River." (Darwish 1994, p. 3)

More recently, Turkey seized an opportunity to exhibit its ability to control the flow of the two great rivers of the Fertile Crescent that emanate from its hinterland. In January 1990, it stopped the flow of the Euphrates. Officially, the disruption was needed to fill the massive lake in front of the new Ataturk Dam; in fact, it was a demonstration to Syria of what might happen if it continued aiding Kurdish rebels in southeast Anatolia (Soffer 1999). Halting the flow of the Euphrates into Syria also brought water shortages in Iraq as well, thus bringing about a remarkable alliance between two bitter enemies (Darwish 1994). More importantly, however, Turkey's actions during this episode demonstrate the strategic advantage of an upstream state within a transboundary watershed, and the potential for such activity instigate full-scale military confrontation.

There are short-term solutions to mitigate the effects of water scarcity, such as food imports (e.g., virtual water), desalinization, and international water law practices. However, these are not a panacea, and are typically only short-term solutions, at best. Remarkably, Middle East governments have been able to forestall the seemingly predestined consequences of their escalating water deficits. In the 1970s, water demands in the Middle East could be met from within the region. However, population growth has forced the region into an acute water deficit; and yet, surprisingly, there has been no water war since 1967. Many think that the answer lies in so-called *virtual water*, which is the water contained in imported food (Allen 1998). In fact, more water flows into the region annually as virtual water than flows along the Nile (Darwish 1994). Virtual water has enabled the region to augment its water resources with grain imports and devote scarce water resources to domestic use rather than irrigation, which has reduced tensions and raised the threshold for conflict (Allen 1998). However, it is not an enduring solution because virtual water is heavily subsidized. Given the status of the global economy and the fact that droughts are producing food shortages worldwide, continued reliance on virtual water is on shaky ground (Allen 1998). Today, water scarce states account for 26% of grain imports, yet as an additional billion people are added to these water-stressed basins during the next 15 years, and more states join the ranks of food importers, the demand for international grain will exceed supply, thus unbalancing the virtual water flow into the Middle East (Postel and Wolf 2001).

Desalinization is often presented as a popular solution to chronic water shortages and it is being used extensively in localized situations. Nevertheless, desalinization is enormously expensive and cannot meet long-term water demands in the Middle East (Amery 2002). In 2005, more than 13 million m^3 of fresh water were produced from desalinization each day; nonetheless this represents just under one hundredth of fresh water consumption per day in the Middle East (Conca 2006). Desalination can only be viewed as a short-term solution to resolve or mitigate a very localized water shortage scenario (Gleick 1993b).

If warfare over water is to be avoided, steps must be taken to enable an equitable distribution of water in a basin and permit a fair resolution of conflicts (Soffer

1999). International agreements and treaties are certainly desirable, but international law is not very robust. Water law in the U.S. and other parts of the world is well developed and backed by many precedents, and thus conflict resolution can typically rely on well-established doctrine (Butts 1997). For example, in many regions, the legal distribution of water is based on *riparian rights*. This doctrine works well in places where there is a considerable renewable water supply. However, in arid regions, *appropriations doctrine* is more accepted, and under this doctrine, priority is given to the first user of the water (Darwish 1994).

Other doctrines may be appropriate for trans-boundary water basins. For example, the principle of *equitable apportionment* has been initiated in some regions and appears to be a practicable solution in the Middle East as well (Darwish 1994). Equitable apportionment calls for a sharing of water benefits equally among states in the watershed on a sustainable basis, regardless of claims to sovereignty. Fortuitously, equitable apportionment is congruent with *Shari'a Law*. For example, under this religious principle people who dig a well maintain rights to first use, but cannot refuse its use for drinking to others. Thus, a state would have full possession of only the amount of water it needs at a precise moment, thus leaving sufficient water for its downstream neighbors (Darwish 1994).

5 Summary and Conclusions

International law is, unfortunately, not robust or clear in settling water conflicts. The alternative doctrine of equitable apportioned is attractive, but predictably, in the context of the Anatolia Dam water conflict, Turkey maintains the position that it has complete sovereignty over the basin because it is the upstream state. However, Iraq and Syria clearly support the doctrine of equitable apportionment, insisting on a reasonable distribution of water based on need and historical use. Noticeably absent, however, and a guarantee that international water law will remain inadequate, is an enforcement mechanism.

In the past, the resolution of water-related conflicts was typically achieved through diplomacy, economic cooperation, and technology. However, the emerging security landscape is far more complex and is being affected by the growing inequities between developed and developing states, and the pervasiveness of failing states. Globalization of the economy and population growth, combined with greater expectations of increased economic affluence are going to place greater demands on resources and exacerbate the problems of resource supply and demand—certainly the world's renewable freshwater resources will be strained beyond sustainable levels and may become a tipping point for environmentally triggered violent conflict. This would be difficult enough, however the security situation will be intensified by climate change, which may dramatically reduce rainfall and river discharges in the world's most populated and water-stressed regions.

Water resource scarcity is an environmental security issue that currently exercises considerable influence on regional stability. Projected trends in population growth, water demand, and climate change could make water scarcity far more prominent on the geopolitical and security landscape. Although the role of water as a possible trigger for violent conflict on an inter-state scale remains a hypothetical exercise, water issues will continue to be a strategically important variable on the national security landscape, and they should be used as an indicator of impending regional instability and a persistent reminder of the significance of geographical variables to military security affairs.

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Environmental Reporting in the South African Department of Defense and Military Veterans

H. A. P. Smit and T. J. Mokiri

Abstract During the past few decades the spotlight of international concern for the environment humans live and work in has been extended to include military activities. In South Africa, concern for the way the military operate in the environment led to numerous activities and institutional policies geared towards securing sound and sustainable utilization of the vast tracts of land entrusted to the South African Department of Defense and Military Veterans (DODMV). An unanswered question and the research question this paper strives to investigate is: Have these activities and policies indeed secured general environmental awareness and debate amongst the personnel of the DODMV? One of the ways of assessing the level of environmental awareness and debate within a society or organization is to analyze media content to assess the reporting of environmental issues. Content analysis of the DODMV official, printed public media for the period 1994 to 2011 was performed in this study in order to observe and record trends and patterns of environmental reporting in the DODMV, and to gain understanding of the representation of news concerning environmental issues. The results obtained from the study indicate that the debate on military environmental issues in the DODMV is not as consistent and in-depth as can be expected. However, the positive tone of most of the articles analyzed indicated a general positive attitude towards military environmental issues. These findings can inform DODMV leadership of their member's largely positive attitude towards military environmental issues, and should act as a springboard towards building a credible, environmentally conscious DODMV.

Keywords Content analysis · Defense · Environment · Environmental awareness · Environmental debate · Environmental management · Environmental reporting · Military · Military environmental management · *Salut* · South African Department of Defence and Military Veterans (DODMV) · South African Soldier

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1 Introduction

1.1 Environment and the Military

> Defense activities, by their very nature, have the potential to do significant environmental damage if not responsibly managed. *On the other hand, good environmental management contributes to the sustainable, flexible and cost-effective use of assets.* (Bevis 1996, p. 3)

The past few decades have been characterized by a worldwide upsurge of environmental awareness, with new concepts and principles, such as sustainable development and environmental management becoming household words. Governments, industries and citizens around the globe have become increasingly aware of environmental issues and the need to manage these issues effectively.

As this growing environmental awareness gathered momentum, it became clear that militaries will be held accountable for the management of the areas under their control as well (Potgieter 2000; Shrivastava 2001; Mosher et al. 2008). In South Africa, the first official instruction to care for the military environment was issued in 1977 (Godschalk 1998). Since then various initiatives regarding the management and use of the South African military environment emerged.

Following the 1994 integration of the different defense forces into the South African National Defence Force (SANDF), the Environmental function became a fully integrated support function of the DODMV. The adoption of Military Integrated Environmental Management (MIEM) encapsulated by the phrase *"Green Soldiering"* has as its aim to "ensure the environmental sustainable management of facilities and activities" (Godschalk 1998, p. 2), implying that all activities are to be conducted with sustainable environmental management principles integrated into the planning, practice, and execution thereof.

The National Environmental Management Act (NEMA) No 107 of 1998 obligates all scheduled organs of the state with functions that affect the environment to develop an Environmental Implementation Plan (EIP) (RSA 1998). In 2001 the EIP for Defence was formulated and became part of South African subordinate law after publication in the Government Gazette (RSA 2001). Since then a second edition EIP was published (RSA 2008), and the DODMV designed an Environmental Management System (EMS) for Defense (Smit 2011). This EMS for Defense was piloted in a few units, but has not yet been implemented (Liebenberg 2011). The DODMV is thus externally mandated by the South African Constitution, and more specifically NEMA, and internally committed through the EIPs, and the Environmental Management System for Defense, to effective environmental management.

An unanswered question is whether management activities increased general environmental awareness and debate amongst the personnel of the DODMV. In other words, did the management initiatives make the DODMV personnel more environmentally aware?

One of the ways of assessing the level of environmental awareness and debate within a society or organization is to analyze the media of such an organization or society to assess the reporting of these issues (Taylor-Clark et al. 2007). Kim et al.

(2000) argue that the mass media play an important role in building public awareness about the environment, a sentiment that is echoed by Henderson et al. (2000). At the same time they also reflect the public's thoughts on environmental issues because most people have access to environmental information through the mass media. Kim et al. (2000), concludes that the rise in the number of public complaints about environmentally related problems and the increase in media coverage of environmental issues will suggest an increase in environmental awareness.

1.2 Investigating Environmental Reporting in the South African Department of Defense and Military Veterans

To investigate the debate about environmental issues in the DODMV, a content analysis was conducted on all environmental coverage that appeared in the official, public media of the DODMV. Copies of the *South African Soldier* and its predecessor, *Salut*, for the period 1994 to 2011, were used for this purpose. This provided an easily accessible, rapid, and cost effective way to establish trends and patterns in the level of reporting and debate about environmental issues since the first democratic elections in South Africa in 1994.

According to Hasan (2007), content analysis has been marked by a diversity of purpose, subject matter, and technique and has been widely used by social scientists and humanities scholars, particularly in mass communication and linguistic studies. Content analysis is used by social scientists to investigate the content of mass media, although it has application across a wider range of spheres. Content analysis is the objective, systematic, and quantitative description of the content of documents, including print media and broadcast media coverage. This involves selecting the unit of analysis, defining categories, sampling, and coding (Hsieh and Shannon 2005).

According to Elo and Kyngäs (2007), p. 107, "The objectives of content analysis are to identify, categorize, and quantify terms, phrases, and expressions in the text that represent the concepts of interest for a given investigation." Content analysis helps to build a picture of the pattern of how certain issues are presented or covered in media that is usually hidden away from the view of the ordinary readers (Graneheim and Lundman 2004; Riffe et al. 2005; Elo and Kyngäs 2007).

Hasan (2007) used content analysis to do a comparative study of the Malaysian and New Zealand press to determine the representation of environmental news by the two countries. Hasan (2007) suggests that content analysis has proven to be an important study method in the examination of magazine or newspaper content, and can provide new insights and increased understanding of a particular phenomenon. According to Kalof (1998), most environmental media research has used traditional content analysis to assess the importance of environmental issues in the print media, such as counting articles, measuring columns, counting the frequency of specific words, and measuring trends in coverage of environmental issues.

2 Methods

2.1 Using Content Analysis to Collect and Analyze Environmental Reporting in the DODMV

The objective of content analysis, as used in this study, is to understand the reporting of environmental news in the official, public media of the DODMV. The rationale for using content analysis as the analytical method for this research is the widespread acceptance of this technique in previous research, which has similarities to this study, as well as the fact that it provided a rapid, cost effective way to execute the study. The first step of the content analysis was to define the scope of analysis and select the media sources. For this study, content analysis was conducted on all the articles in the DODMV magazines (*South African Soldier* and its predecessor, *Salut*) over the period January 1994 to December 2011. The total number of magazine editions covering the period January 1994 to December 2011 numbered 209. Because the manageable number of editions made it possible to analyze all the copies, there was no need for sampling, and all the copies covering the period of study were used.

During the second step, the unit of analysis or key words for this study were derived from the literature and identified as common environmental issues faced by defense organizations all over the world. These were augmented by key words identified during the process of coding. Thus, for the purpose of this study, environmental stories or environmental news reporting is defined as content that deals with the natural, social, and cultural environment in which the military operates. This definition included reporting on a wide variety of topics such as global warming, wildlife, flooding, energy use, erosion, preservation of heritage buildings, pollution, waste management and recycling, environmental destruction, oil spill management, and environment management on DODMV properties. Phrases such as environmental management, environmental implementation plans, military integrated environmental management, environmental awards, environmental management system, and integrated training area management, were also utilized in the process to identify articles addressing environmental coverage in the DODMV. The key words and phrases derived from the definitions were then employed to identify articles and letters to the editor pertaining to these environmental issues. During the whole process key words and phrases were constantly identified and added to the list. This is consistent with the method of content analysis as described by Hsieh and Shannon (2005). After all the copies of *South African Soldier* and *Salut* were investigated in this manner, the complete list of keywords and phrases was again used to work through the 209 journal editions to make sure that all articles adhering to the criteria were identified. This ensured that all articles that met the search criteria were identified for coding and those irrelevant ones were sifted out. Altogether 110 (i.e., $n=110$) articles from *Salut* and *South African Soldier* were identified for further analysis.

During the third step, all the identified pages of the magazine were manually analyzed and coded based on the coding categorization that was adapted and reformulated from Robinson (2006) and Hasan (2007). Each article was coded in terms of general characteristics of the article (e.g., month/year of publication, volume), topic, length, content tone (e.g., negative, neutral, or positive), number of articles dealing with environmental issues per time period, and source (This identifies the authors of the articles analyzed, for example, Environmental Services personnel, journalists from *Salut* or *South African Soldier*, or other members of the DODMV). This was done in order to establish the most dominant news source in the DODMV magazines. In other words, from where did the environmental reporting in *Salut* and *South African Soldier* originate?

Finally, the prominence of environmental issues in each time period studied was analyzed. The change in frequency of articles that address any issues pertaining to environmental management was calculated. The frequency of environmental articles within each 2-year segment was also compared to important environmental events that took place in South Africa, both within the DODMV, as well as in civil society. This was done to determine the effect of environmental events on environmental reporting.

Data were analyzed and represented using graphs and tables. All the coded environmental stories were analyzed for the period January 1994 to December 2011.

All of the above will indicate and explain the trends and patterns in environmental reporting in the DODMV media over the period of study.

3 Results

3.1 Understanding Environmental Reporting in the South African Department of Defence and Military Veterans

This section will address, in order: (i) the general characteristics of the environmental reporting, (ii) the most common topics, (iii) the length of the articles analyzed, (iv) the tone (positive or negative) of the articles, (v) the frequency of articles dealing with environmental issues over the period of the study, in 2-year segments, and (vi) the author or source of articles.

3.2 General Characteristics of the Environmental Reporting

The total number of magazine editions covering the period January 1994 to December 2011 numbered 209. Because this was seen as a manageable number of editions, there was no need for sampling, and all copies covering the period of study could be analyzed. On average each magazine had 43 items of reported news. A total number of 110 articles dealing with environmental issues were identified for further analysis. Of these, 26 appeared in *Salut* between 1994 and 1999, while 84 articles were published in the *South African Soldier* between 2000 and 2011.

One of the observed trends during the period of study is that most of the environmental articles are written in the final quarter of the year, and the month of October registered the most activity. A possible explanation for this might be that most of the annual environmental activities, such as environmental competitions take place in September, and are thus reported on later in the year.

Another trend is that there has been an increase from January 1994 through December 2011 in the number of articles written by ordinary members of the DODMV. The change in this regard happened when *Salut* was replaced by the *South African Soldier*. This might indicate an increase in interest and awareness of environmental concerns amongst ordinary members, coupled with a fresh editorial approach by the editorial staff of the *South African Soldier*. There is, however, much room for improvement in this regard.

Finally, it must be noted that most of the articles are reports on environmental events and issues, and that almost no debate about the issues takes place. No indication of people either questioning the policies and activities regarding the military environment, or urging the DODMV to expand/change these activities, could be found amongst the analyzed articles.

3.3 Environmental Topics Reported

Table 1 shows a large spread in article topics over the 18-year period covered by this study. It was found that 30 % of environmental topics in the DODMV media are concerned with four main categories of institutional activities such as the Environmental Implementation Plans for Defence (EIP), Military Integrated Environmental Management (MIEM), Environmental Management System for Defence (EMS), and the Military Environmental awards. Other important categories are concerned with conservation and restoration (i.e., 20 %), and environmental management (i.e., 19 %). Topics covering waste management and recycling totaled 12 %, while 8 % of the articles address oil spillage and development impact on the environment. About 3 % of the articles are devoted to less-reported issues such as energy and fresh water resources, 1 % cover natural disasters, and another 1 % is devoted to air quality and pollution.

The remaining 6 % covers a variety of other topics, such as individual achievements in terms of military environmental management, or a military unit's achievements in terms of sustainable environmental management practices.

The four main categories account for more than 80 % of the articles. The articles address institutional activities, conservation and restoration, environmental management, waste management and recycling. These issues dominated the debate within the DODMV for the period of the study. It should be emphasized that articles

Table 1 The most important environmental topics reported

Topics	Frequency (Expressed as a percentage)
Institutional activities such as EIPs, MIEM, Environmental awards, etc.	30
Conservation and restoration	20
Environmental management and environmental awards	19
Waste management and recycling	12
Oil spillage and developmental impact on the environment	8
Energy and freshwater resources	3
Natural disasters like floods, droughts, landslides and fire	1
Air quality and pollution	1
People playing an important role in environmental management, and their achievements, various other topics	6
Total	100

reporting on EIPs, MIEM, EMS and Environmental Awards are regarded as institutional efforts. Management activities such as EIPs, MIEM, EMS, and the annual Environmental Awards, where individuals and units are recognized for military environmental efforts, indicate the intentions of the DODMV in terms of military environmental issues. However, these activities do not necessarily indicate what the DODMV does or how it is assimilated by DODMV personnel. The data indicate that most of the articles in the *Salut* and *South African Soldier* magazine are dedicated to institutional activities, and as such, they might not accurately reflect the situation at ground level. Important issues, such as campaigns to increase environmental awareness and environmental degradation within training areas are not adequately addressed. More importantly, debate on reported issues does not form a prominent part of the environmental news content. This might indicate a lack of depth in the environmental knowledge within the DODMV, or perhaps it suggests a lack of interest about environmental issues amongst ordinary members of the DODMV.

3.4 Length of the Environmental Articles

Analysis of the length of environmental articles indicates that most are rather short, which is something that might hinder the effective conveyance of the environmental message. However, the length of environmental articles is greater than the average length of all articles in the two magazines.

Figure 1 demonstrates the length of environmental content in the DODMV media. The category of environmental reporting of half to a full page in length accounts for 41 % of the environmental content. When the category more than one page (i.e., 37 %) is added, it becomes clear that these two categories account for more than 78 % of environmental reporting. When compared to the length of all

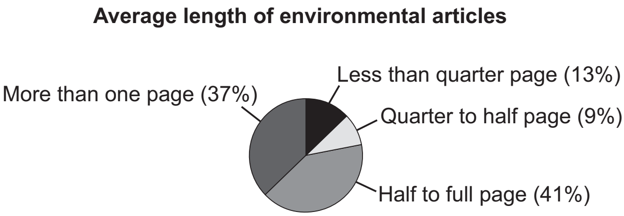


Fig. 1 Average length of environmental articles in the DODMV official public media

articles in the two magazines (Fig. 2), it was found that only 47 % of all articles fall into these two categories. This indicates that, in terms of the scope of general reporting in the DODMV media, environmental content gets adequate coverage in terms of the length of articles.

3.5 Tone of Environmental Reporting

The tone of the articles was clearly positive with respect to environmental issues. About 86 % of the articles analyzed falling in the positive category, 9 % in the neutral category, and only 5 % being negative (Fig. 3). This is an important indicator of the generally positive attitude towards environmental issues that exist in the DODMV, at least amongst contributors towards the environmental debate.

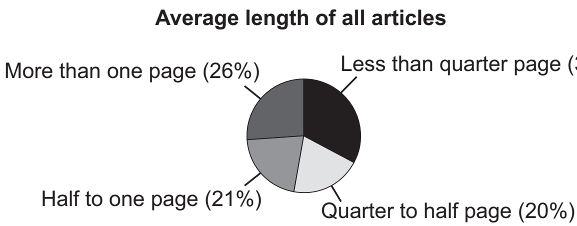
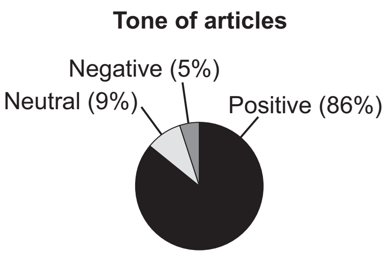


Fig. 2 Average length of all articles in the DODMV official public media

Fig. 3 Tone of environmental articles



3.6 Frequency of Articles per Time Period

Figure 4 illustrates the change in total frequency of articles per unit of analysis over the period of study, whereas Table 2 gives an overview of important environmental events that might have influenced the environmental coverage in the DODMV media.

The frequency of environmental coverage for the period 1994–1995 was only 6 articles. The promulgation of the Republic of South Africa's Constitution in 1996 as the supreme law in the country paved the way for a new look at environmental management in South Africa. It seems as if this might have given impetus to a surge in environmental coverage in the DODMV media during the 1996–1997 period, with 17 articles related to environmental issues being published.

The 1998–1999 period saw a sharp drop in the frequency of articles. The five articles from this period were followed by seven during the 2000–2001 period. This accounted for the lowest frequency of articles during two consecutive periods. Important environmental events during these periods, like the promulgation of the National Environmental Management Act of 1998, the signing of the Memorandum of Agreement regarding Co-operation on Military Environmental Matters between the U.S. and South Africa, the promulgation of the First Edition EIP for Defence, the presentation of the Mobile Military Integrated Range Management Courses, and the promulgation of the Corporate Environmental Policy Statement for Defence, provided the impetus for the second most productive period, the period 2002–2003. Important environmental events during the 2002–2003 period, such as the World Summit on Sustainable Development in Johannesburg (WSSD), in 2002, and the International Conference on Military Integrated Environmental Management (MIEM), in 2003, gave added momentum and resulted in 19 articles being published in this period.

After this highly productive period, a drop in reporting occurred during the 2004–2005 period, with only 9 articles published. Despite this drop in reporting, an important environmental event took place within the DODMV. It was during this period that the EMS for the Department of Defence was developed. Ironically, it is possible that all of this activity could have tied up the attention of Environmental Services personnel, preventing them from writing more about these events. The

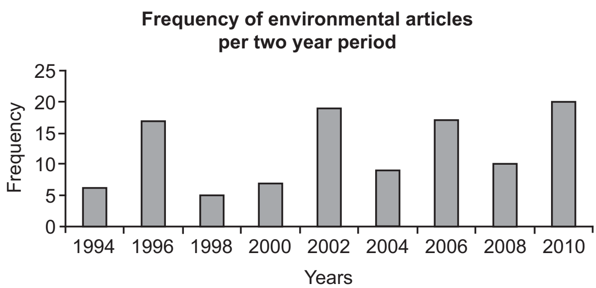


Fig. 4 Frequency of articles per 2-year period

Table 2 Important environmental events in South Africa and the DODMV

Environmental event	Date of event	Category period	Frequency
		1994–1995	6
Constitution of Republic of South Africa 1996 (Chapter 2, Section (24) of the Bill of Rights)	1996	1996–1997	17
Defence Committee (DEFCOM) established	1997		
National Environmental Management Act No 107 of 1998	1998	1998–1999	
Signing of Memorandum of Agreement regarding Co-operation on Military Environmental Matters between USA and RSA	1999		5
Environmental Implementation Plan (EIP) First Draft	2001	2000–2001	
Mobile Military Integrated Range Management Course Presented	2001		7
Promulgation of the Corporate Environmental Policy Statement	2001		
World Summit on Sustainable Development in Johannesburg (WSSD)	2002	2002–2003	
International Conference on Military Integrated Environmental Management (MIEM)	2003		19
Environmental Management System (EMS) for Defence based on ISO 1400 principles developed	2004	2004–2005	9
Departure of Colonel Seakle Godschalk, SSO Environmental Services, after more than 30 years of service in the Environmental Services	2006	2006–2007	17
Second Draft Environmental Implementation Plan (EIP)			
Capt (SAN) Adri Liebenberg appointment as new SSO Environmental Services	2009	2008–2009	10
		2010–2011	20

2006–2007 period saw another sharp increase in publication with 17 environmental articles being published. This was again followed by a period of less activity (i.e., 10 articles), possibly coupled to the departure of Col. S. Godschalk, Senior Staff Officer (SSO) Environmental Services, after a distinguished career of more than 30 years. The absence of experienced leadership might have inhibited environmental reporting during this period. In 2009 a new SSO Environmental Services, Captain (SAN) Adri Liebenberg was appointed. This change in leadership was accompanied by an increase in the number of articles. The 2010–2011 period was the most productive of the study periods, with not less than 20 articles being published. This amounted to 1.8 articles per issue.

In conclusion, it can be suggested that the frequency of articles dealing with environmental issues fluctuated during the period of the study. This fluctuation can be explained by the frequency and timing of important environmental events in the DODMV, and in South Africa in general, and gives an indication of how environmental reporting has evolved from January 1994 to December 2011.

3.7 The Authors or Sources of Environmental Content

Based on Fig. 5, it can be concluded that most of the environmental news reported in *Salut* magazine was reported by DODMV journalists. This type of reporting was categorized as editorial, and constitutes 54 % of the articles identified. The remaining 46 % was reported by Environmental Services personnel.

An analysis of the *South African Soldier* magazine (Fig. 6), reveals a different trend, with most of their environmental content written by Environmental Service personnel (i.e., 70 %), while editorial content accounted for only 19 %. The remaining 11 % was dedicated to commentary, letters, or reports by ordinary members of the DODMV. Although this is a small contribution, it suggests an important shift in environmental reporting when compared to the articles in *Salut* that had no contribution by ordinary members.

When environmental reporting over the whole period of the study is analyzed, it is clear that Environmental Services (i.e., professionals) is the most prominent voice in the reporting of environmental issues. They were responsible for 65 % of the articles analyzed, whereas editorials (including letters to the editor), were responsible for 27 % of all sources mentioned in the period of study. Ordinary members of the DODMV contributed 8 % of articles published. Although a small positive change took place for content written by ordinary members when comparing *Salut* with *South African Soldier*, it is clear that the debate on environmental issues in the DODMV is not driven by ordinary soldiers and personnel within the DODMV, possibly indicating a lack of environmental awareness amongst DODMV personnel at grassroots level.

Fig. 5 Sources of environmental articles in *Salut*

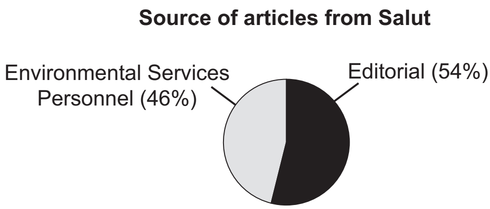
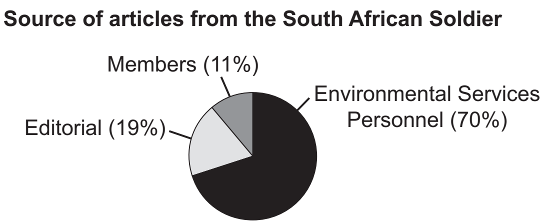


Fig. 6 Sources of environmental articles in *South African Soldier*



4 Summary and Conclusions

This study identified 110 articles dealing with environmental issues in 209 editions of *Salut* and *South African Soldier* magazines, using content analysis. These monthly magazines represent the official, public media of the DODMV. These articles were further analyzed in terms of their general characteristics, most common topics, length, tone, frequency of articles, and source.

Topics in the DODMV media are mainly related to institutional activities, along with conservation and restoration, and environmental management being the other important categories. A wide variety of other topics are less frequently being reported. Furthermore, this analysis indicated that the lengths of the articles are generally longer than non-environmental articles. This suggests that environmental content gets adequate coverage in terms of length of articles.

The tone of environmental articles was overwhelmingly positive, with 86 % falling in the positive category. This is an indicator that the contributors to the debate deem environmental issues important in the DODMV public media.

Environmental reporting in the DODMV exhibits a fluctuating pattern: some periods manifest high levels of activity interspersed by periods of relatively low publication activity. These periods can be linked to important events such as the acceptance of the new constitution of the Republic of South Africa in 1996, the World Summit on Sustainable Development, held in Johannesburg in 2002, and the International Conference on Military Integrated Environmental Management, held in Pretoria in 2003. An encouraging trend is the fact that 42.7 % of all the reporting had been done during the last 6 years, indicating an upwards trend in environmental reporting.

As far as the source of articles is concerned, it is clear that most articles (65 %) originate from professionals such as personnel from the Environmental Services. This rate increases to 70 % if only the *South African Soldier*, the present magazine, is taken into account. The increase from 0 to 11 % in the contribution by ordinary soldiers and personnel is another positive and important trend that emanates from the research. There is, however, still a need for investigative journalism that can stimulate debate and determine the awareness of the members of the DODMV when it comes to environmental issues. It is also clear that important environmental events taking place in South Africa and the DODMV boost the number of articles published by the DODMV media. This holds true for both an annual and long-term analysis.

The institutional effort to increase awareness and environmentally responsible conduct in the DODMV are in place and driven by committed and experienced professional military environmental officers. This can be seen in the positive tone of the vast majority of the articles analyzed, as well as the significant contribution of environmental officers to the debate.

Most of the environmental reports are descriptive in nature, aimed at informing the reader of recent events or what is envisaged by the DODMV. What is lacking is an argumentative approach in order to engage the reader in making up their mind on a wide range of environmental issues. The challenge lies in widening the debate to ensure the involvement of a more representative group of stakeholders, and in deepening it to also include critical discussion and not only reporting of environmental issues.

This research added to the body of knowledge about military environmental issues in general and South African military environmental issues in particular. Hopefully it will help to stimulate the very debate it investigated.

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Operation Iraqi Freedom (OIF) and the Use of Forwarding Operating Bases (FOBs)

Eugene J. Palka

Abstract Global military operations can complicate matters for the U.S. Army as it strives to ensure continuous maintenance, transportation, logistics, medical, and personnel support for its deployed forces. Since World War I, the Army's deployed units have relied on Allied bases or U.S. bases established in host countries. A major paradigm shift occurred shortly after the onset of the Global War on Terror (GWOT), as Army units had to establish forward operating bases (FOBs) in order to function at great distances from their home bases, under austere conditions, and on non-linear battlefields. A forward operating base (FOB) is a relatively secure position that is located forward in a hostile or austere area and can be used to support tactical operations. FOBs vary in terms of their size, composition, and the activities that they support. At the outset of Operation Iraqi Freedom (OIF) in March 2003, most U.S. Army units staged from Kuwait. As OIF unfolded, however, and units displaced north of the Kuwait-Iraqi border into all parts of Iraq, FOBs were established at various locations to house, protect, and sustain the force and to ensure continuous support of military and humanitarian assistance missions. FOBs were not uniformly located throughout the country, but exhibited a geographic pattern that correlated with military missions, levels of insurgent activity, the locations of former Iraqi bases, major population centers, economic hubs, and transportation infrastructure. FOBs played a fundamental role during the course of OIF from 2003 to 2011, enabling the U.S. Army to transition from combat to stability and support, and eventually, full spectrum operations. As the U.S. military commitment approached its conclusion, some FOBs were closed; others were converted to different uses, and some continue to function as part of a vital support network for the Iraqi government. Superimposed during the course of OIF, some FOBs have become an enduring, if not integral, part of Iraq's cultural landscape.

Keywords Forward operating base (FOB) · Iraq · Operation Iraqi Freedom (OIF) · Military geography

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1 Introduction

It is often impractical for the U.S. Army to reach back directly to the Continental U.S. for continuous maintenance, transportation, logistics, medical, and personnel support during the course of conflict or contingency operations abroad. Historically, the Army has drawn support from activities situated on Allied bases or from U.S. bases established in host countries. For the past 11 years, the Army has had to establish and rely on forward operating bases to support the Global War on Terror (GWOT). A relatively secure position that is located forward in a hostile or austere area and can be used to support tactical operations, a forward operating base (FOB) can also have operational and strategic implications. FOBs vary in size, composition, and the activities they host.

At the outset of Operation Iraqi Freedom (OIF), most U.S. Army units staged from locations within Kuwait. As OIF unfolded, units were displaced throughout the country. FOBs were subsequently established to house, protect, and sustain the force and to ensure continuous support of military and humanitarian assistance missions. The resulting network of FOBs exhibited a geographic pattern that correlated with military missions, the locations of former Iraqi bases, major population centers, transportation infrastructure, and levels of insurgent activity. Consequently, while one could explain the rational for each individual FOB, the "FOBscape" was extremely dynamic during the course of OIF. The network of FOBs constituted a new imprint that was superimposed upon Iraq's cultural landscape during an eight year timeframe.

This chapter begins with a brief chronicle of OIF in order to recall the sequence of events leading up to the establishment of a network of FOBs throughout Iraq. The emergence of the country's FOBscape is described in terms of the locations and distributions of individual base camps. I subsequently explain the tactical, social, and economic impacts of FOBs on the surrounding communities and ultimately review the process of deconstructing the FOBscape during the course of the U.S. drawdown and eventual withdrawal from Iraq.

2 Historical Background of OIF

To understand the morphology of FOB construction throughout the Iraqi landscape, it is necessary to briefly review how Operation Iraqi Freedom unfolded. Unlike the situation during Operation Desert Shield in 1991, when the U.S.-led coalition assembled nearly 500,000 troops in Saudi Arabia, the political climate was much different in 2003, and Saudi Arabia did not permit their territory to be used as a staging base for an incursion into Iraq (Palka et al. 2011). Alternatively, Kuwait became the major staging area for U.S.-led forces. Camp Arifjan and Ali al-Salem airbase, along with a number of camps in the sparsely populated northern portion of the country supported the build-up and enabled units to prepare to cross the border into Iraq.

OIF began on 21 March 2003. The specific objectives included: (1) ending Saddam Hussein's regime; (2) identifying, isolating and eliminating Iraq's weapons of mass destruction; (3) capturing and driving out terrorists harbored in Iraq; (4) collecting intelligence related to terrorist networks in Iraq and beyond; (5) delivering humanitarian relief to Iraqi citizens; (6) securing Iraq's oil fields and resources; and (7) helping the Iraqi people to create a representative self-government (DoD 2003).

The U.S. plan consisted of a two-pronged attack featuring V Corps and its equivalent of three divisions attacking west of the Euphrates River from Kuwait towards Baghdad, moving rapidly through the desert and bypassing most of the populated areas. Meanwhile, the 1st Marine Expeditionary Force (I MEF), which included the 1st Marine Division and the British 1st Armored Division, attacked simultaneously from Kuwait through central Iraq. The U.S. 3d Infantry Division (V Corps) would eventually attack Baghdad from the west while the I MEF attacked Baghdad from the east (Murray and Scales 2003). Additionally, the British 1st Armored Division secured southern Iraq by seizing the port cities of Basra and Umm Qasr (UK MOD 2003).

Allied special operations forces complemented the main attacks by entering Iraq from Jordan to eliminate the threat of Iraq using SCUD missiles to draw Israel into the war (Palka et al. 2011). Special Forces troops also linked up with Kurdish Peshmerga, and operated in conjunction with the U.S. 173rd Airborne Brigade to secure northern Iraq.

The ground war was short and decisive, and on 1 May 2003, President Bush declared an end to major combat operations. Many perceived that the mission was complete and anticipated that the Coalition would bring the troops home as it had done in the first Gulf War (Woodward 2008). However, with the ensuing political and social chaos and a badly damaged economic infrastructure, Iraq was not in a position to restore order without the Coalition's assistance. By June 2003, a growing insurgency emerged as multiple groups, each with their own agenda, found common cause in resisting the Coalition occupation (Clark 2004). The U.N. authorized the occupation in October 2003, while calling for an early transfer of sovereignty. The U.S. Army Corps of Engineers and various private contractors began work to establish FOBs to house the occupational force, while a massive rebuilding effort was undertaken to restore critical services and to address the devastation from 30 years of neglect and the post-war looting of the country by Iraqis (Palka et al. 2005).

As the Iraqi Study Group would later conclude, the nature of the violence was complex and multi-faceted and involved a Sunni Arab insurgency, Shi'ite militias, al Qaeda, widespread criminality, and sectarian conflicts (Baker and Hamilton 2006). In the Sunni Triangle, a combination of Ba'athist Hussein supporters, Iraqi nationalists, and foreign terrorist elements conducted relentless attacks against U.S. forces. In Shia areas to the south, uprisings were led by Moqtada al-Sadr, a radical Islamic cleric who sought to dispel the Coalition and enhance his own position. The opportunity to fight the Americans attracted foreign fighters, Jihadists, and opportunists from outside of Iraq. Many of these fighters joined the ranks of the Jordanian militant, Abu Mussab al-Zarqawi, who was later killed during a U.S. airstrike (Woodward 2008).

The Coalition responded to this complex scenario politically and militarily. By mid-2004, Iraqi security forces were being rebuilt, an Iraqi interim government under Prime Minister Iyad Allawi was installed in June 2004, and plans were made for nationwide elections of a new government on 30 January 2005 (Palka et al. 2011). Meanwhile, various insurgent groups launched campaigns to intimidate the civilian population and newly recruited Iraqi military and police, to disrupt the elections, and to hinder the efforts to unify the country (Palka et al. 2011).

Unprecedented democratic elections occurred in 2005, but the multi-faceted insurgency gained momentum throughout Iraq. During late 2006 and early 2007, a "surge" of U.S. ground forces and a comprehensive counter-insurgency campaign were employed to address the increased instability caused by multiple insurgent groups and sectarian violence (Woodward 2008). General Odierno (commander of U.S. Forces in Iraq) characterized the threat environment as four interacting conflicts: counter-occupation, terrorism, insurgency, and a struggle for power and survival (Andrade 2010). Within this context, U.S. units operated from FOBs throughout the country and conducted daily patrols and various missions into the major urban areas in an effort to protect the civilian population, while facilitating the reconstruction and nation-building effort. The increased military presence, civil works projects, persistent support to Iraqi political and military institutions, and a range of economic development initiatives yielded dramatic improvements throughout the country during 2008 and 2009 (Palka et al. 2011). However, the highly contentious national elections of 2010, unresolved Kurd-Arab tensions over disputed territories, renewed sectarian violence, and U.S. troop withdrawals throughout 2010 and 2011, presented uncertainties through the final stages of OIF and opening phase of Operation New Dawn. In the aftermath of the U.S. withdrawal, 2012 proved to be a turbulent year and peace and stability continue to be elusive.

3 Establishing FOBs

3.1 The Fundamental Purpose

Unlike the high intensity operations in the wide-open desert, which characterized actions during Desert Storm and at the outset of OIF, most military operations since May 2003 have focused on providing security, stability, and support, although units have been required to conduct full spectrum operations throughout the period. Within this operational context, FOBs were established to house and sustain U.S. Forces as the nature of the U.S. mission in Iraq evolved in response to political objectives and as U.S forces assumed the role of an occupational Army.

Initially focused on war-fighting in March of 2003, the U.S. military emphasis shifted to stability and support operations by May of the same year. With subsequent emphasis on counter-insurgency and nation-building, FOBs provided the means to distribute U.S. forces among the Iraqi population. Rather than being arrayed on

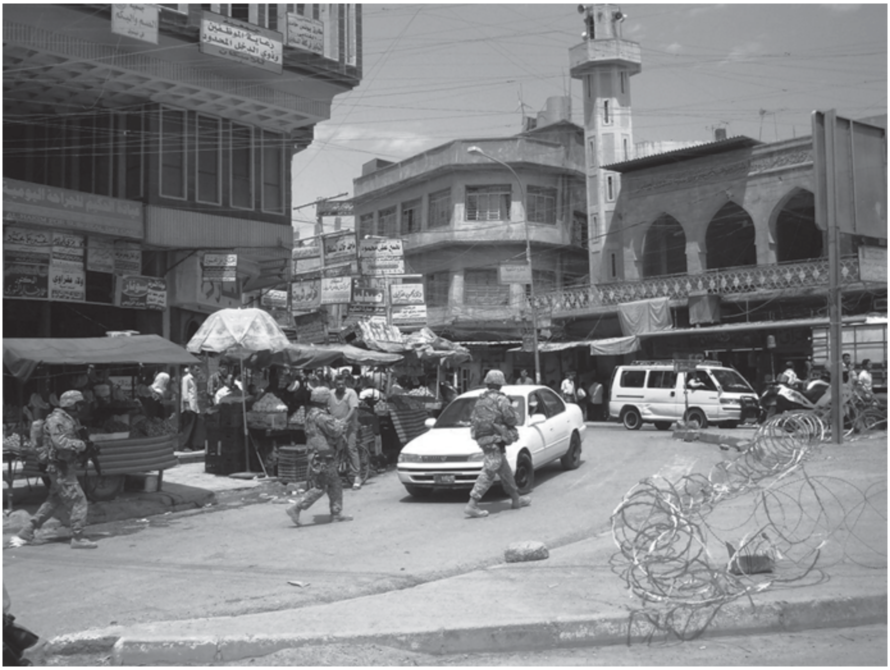

Fig. 1 A U.S. patrol in the "old town" sector of Mosul enables a local market place to conduct business, although the combat troops and concertina wire are indicative of tense, if not dangerous, conditions (author photo, 2009)

isolated battlefields awaiting an organized and recognizable enemy that would never appear, U.S. troops were charged with protecting the population from a range of insurgent and extremist groups, while facilitating an international reconstruction effort. These missions called for a constant presence within the neighborhoods of the major cities and surveillance of the infrastructure that provided essential services, such as power, fuel, trash-removal, and water (Fig. 1).

3.2 The Morphology of the Iraqi FOBscape

Given the requirement to house an occupational Army, the Department of Defense signed a $200 million contract in June of 2003 with the Kellogg, Brown, and Root (KBR) subsidiary of Halliburton to build barracks for 100,000 troops in Iraq in as many as 20 locations (Global Security 2010). Hundreds of similar contracts would follow with KBR and dozens of other private military companies (PMCs). By mid-2004, U.S. occupation forces were deployed to an estimated fifty locations throughout the country, and by May 2005, U.S. forces occupied a total of 106 bases (Global Security 2010). The number of FOBs peaked during the surge, and by some counts,

Fig. 2 A living support area (LSA) on COB Speicher comes complete with protective "T-walls," containerized housing units (CHUs), and community showers and latrines. (Photo courtesy of LTC Joseph P. Henderson, 2010)

was estimated to be more than 300 during 2008 (Gilbert 2010). Others contend that at its zenith, the American military deployed 180,000 troops and occupied approximately 480 bases and facilities across Iraq (Fontaine 2010).

In a general sense, FOBs provided the framework for the U.S. military presence and its operations in Iraq, housing logistics and support areas where munitions and supplies were stored, vehicles were repaired or maintained, headquarters elements were based, mail was transferred, medical care was provided, and showers, sleeping quarters, dining facilities, and recreation centers relieved the stress of deployment and missions "outside the wire" (Washington Times 2008; Fig. 2). Not all FOBs, however, were designed to have the same capabilities. Some included airfields, and elaborate support infrastructure, while others were much more rudimentary, depending upon the type and size of the unit that was housed, its specific missions, and the anticipated duration of operations within the area.

3.3 Locations and Distribution

FOBs were not spread uniformly throughout Iraq. The geographic distribution related to the nature of U.S. military missions, the locations of former Iraqi bases (Fig. 3), major population centers, transportation infrastructure, and insurgent activity (Fig. 4). Because the nature of operations and levels of insurgent activity evolved or changed over time, so did the numbers and locations of FOBs. While many were short lived after serving their initial purpose, others were envisioned as strategic hubs for the foreseeable future. Populations on some bases surpassed more than 20,000, with thousands of contractors and third-country citizens to sustain them (Santora 2009).

Since most FOBs were designed to bring units into daily contact with the civilian population, FOBs were logically scattered throughout the most populated areas

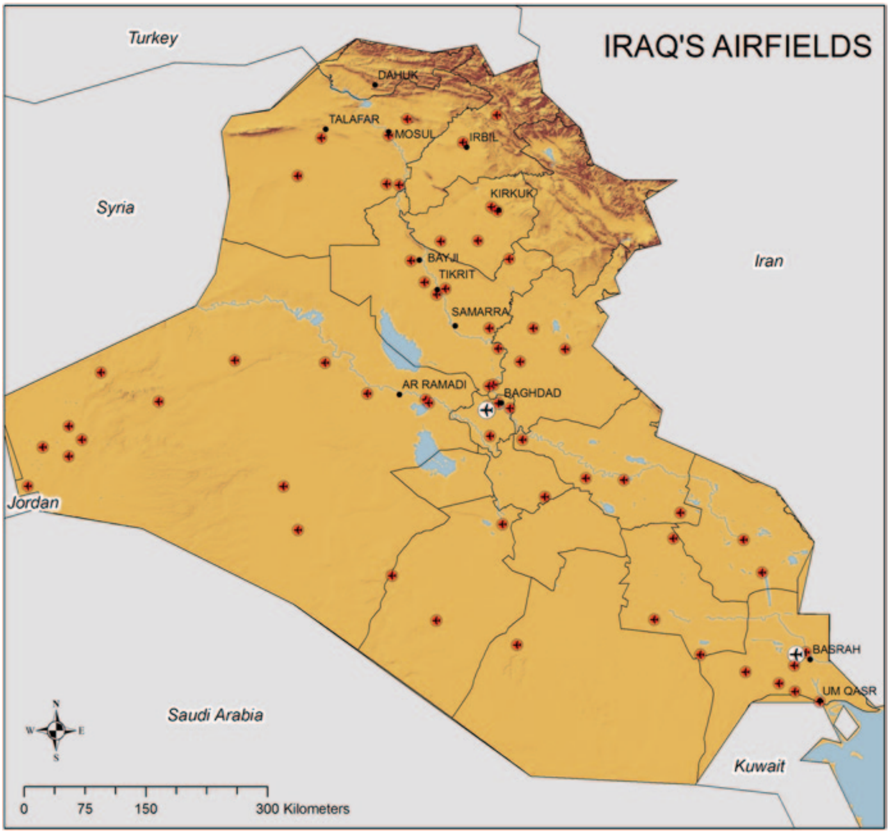

Fig. 3 Iraqi airfields and former bases (adapted from ESRI data, 2008). Bases were not "terrain oriented," but were located near population centers, along major roads, and near border crossings. Isolated air bases were also located in sparsely populated western provinces to provide regional security

of the country, generally along the Tigris and Euphrates Rivers (and in between), near the coast, and in and around the major cities (Baghdad, Basara, Mosul, Kirkuk, etc.). Given the concern with the porosity of Iraq's borders, FOBs were also positioned near major crossing routes. With Baghdad serving as the country's primate city, the development of the "Green Zone" became a massive undertaking necessary to provide a protected sanctuary for U.S., Iraqi, and other Coalition government organizations and facilities, as well as military forces (Fig. 5). Given the territorial extent of the Green Zone and the need to house numerous units engaged in Baghdad, FOBs were concentrated in great numbers throughout the capital region and within the Green Zone itself.

Some FOBs that were built around former Iraqi Air Force bases, such as Al-Asad (100 miles west of Baghdad), Balad (about 45 miles north of the capital), and Speicher (outside of Saddam's hometown of Tikrit), were vast complexes, with

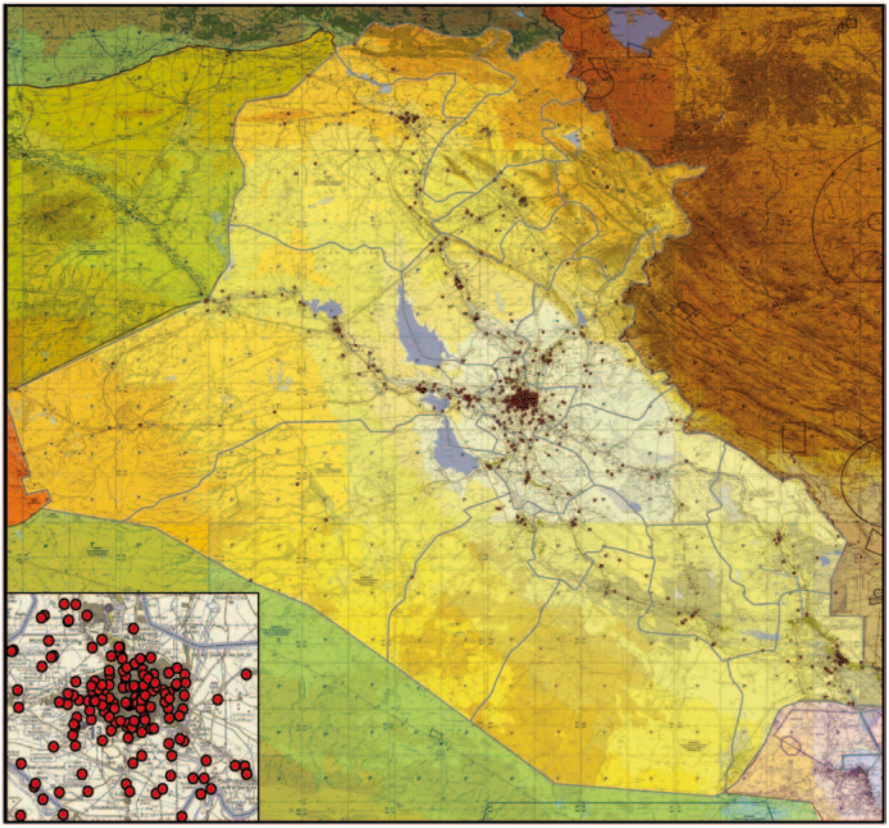

Fig. 4 This dot density map depicts more than 400 FOBs that were located throughout Iraq (ARCENT OPS ENG Environmental/GIS Office 2011). The inset attempts to capture the significant clustering within Baghdad. Major FOBs and base camps correlate well with previously existing Iraqi Army and Air Force bases. Major FOBs were not “terrain oriented,” but sought to take advantage of existing facilities on former Iraqi bases, and so were clustered in the most populated parts of the country and near major border crossings. Smaller and often short-lived FOBs emerged in response to insurgent activity, sectarian violence, or other dynamic security conditions

runways in excess of 13,000 ft (Tompkins 2009; Fig. 6). These “super FOBs” were in essence small cities, as were the massive complexes such as Camp Victory (on the edge of Baghdad), Tillil (just to the south), and Qayyarah (to the north), and because of their capacity and projected use, they were designated as “contingency operating bases” (COBs) in February 2005 (Global Security 2010).

3.4 *The Tactical Impact of FOBs*

FOBs played a vital role when the U.S. surged an additional 30,000 troops into Iraq in mid to late 2007 to quell insurgent and extremist violence (Tomkins 2009). The

Fig. 5 The International Zone (IZ) is a sprawling urban complex located in the heart of Baghdad. The IZ housed several FOBs (the headquarters of each are identified), a wide range of logistics activities, and numerous government and international agencies (U.S. Army Corps of Engineers, Gulf Region Division 2004)

operating bases provided a more permanent U.S. presence and enabled continuous patrolling, which resulted in increased interdiction and deterrence of insurgent activity, and improved security and stability (Tomkins 2009). In most cases, the presence also enabled the fostering of rapport with local residents and leaders and was a huge step towards winning the hearts and minds of the citizens, while facilitating the rebuilding effort (Tomkins 2009).

It was during the surge period that the employment of combat outposts (COPs) also came into widespread use, further complicating any attempt to accurately count the number of operating bases within the country. Located in parts of large cities and situated miles from a supporting FOB, COPs were often established in abandoned buildings with protective barriers added and included the most basic of facilities, such as "porta-potties" or latrines using burnable waste bags (The Washington Times 2008; Fig. 7). COPs were normally occupied by platoon size elements for brief periods of time (often 1 week) and units constantly rotated back and forth between the COP and the supporting FOB. The advantage of a COP was a constant presence, increased familiarity with the local area, and a significant decrease in movement between the FOB and the area of responsibility, thus reducing soldier vulnerability, as well as convoys of mine resistant ambush protected (MRAP)

Fig. 6 COB Speicher (located adjacent to Saddam Hussein's hometown of Tikrit) was a major Iraqi military base that included an extensive runway and both Air Force and Army facilities. Established initially as a FOB, the base was further developed to serve as a COB and housed the headquarters for the Multi-National Division-North (author photo, 2009)

Fig. 7 COP Power, formerly located on the east side of Mosul, was occupied by a platoon sized element (30–40 personnel). Like most COPs, the facilities were protective, but living conditions were "Spartan," requiring platoons to rotate in and out of the outpost on a weekly basis (author photo, 2009)

Fig. 8 A convoy of mine resistant ambush protected (MRAP) vehicles encounter a herd of livestock crossing a street in Mosul. Armored vehicle convoys were an absolute necessity, but often interfered with local traffic, commerce, and the way of life. Vehicle modifications were also necessary to negotiate narrow streets and low hanging wires. (Photo courtesy of CPT Gene W. Palka 2009)

vehicles, which often disrupted commerce or neighborhood activity (Fig. 8). Living conditions within COPs were "Spartan" at best, but soldiers could pace themselves knowing that after a week or so they would return briefly to the FOB for a shower, laundry, equipment exchange, and rest.

3.5 Economic and Social Impacts

In many areas, FOBs served as growth poles where the local and neighborhood economy had become stagnant. Neighborhood grants and contracts extended to Iraqi vendors enabled some FOBs to bolster the local economy. Meanwhile, the areas in close proximity to the FOBs became relatively secure, enabling neighborhood businesses to regroup.

FOBs also served as staging bases for a vast number of projects funded by the Commander's Emergency Response Program (CERP), which was designed to win the hearts and minds of the Iraqi people by improving the Iraqi infrastructure and quality of life (CALL 2009; Lee 2010). Efforts focused on providing essential services (the provision of water, power generation, and trash removal) on a consistent basis, improving roads and transportation networks, reconstruction of urban areas, and employing thousands of otherwise unemployed Iraqi citizens (CALL 2009; Martins 2005). Oversight and resources for many of these types of projects were

Fig. 9 A joint neighborhood patrol in Mosul during the spring of 2009 was the continuation of an effort to win the hearts and minds of local citizens by establishing a presence that would enable the restoration of essential services and activities in the area. The joint nature of the patrols was essential for enhancing communications and fostering cooperation and was a logical approach to transitioning the responsibility for security and stability to Iraqi forces and police (author photo, 2009)

provided by the nearest FOBs, which also served as coordination centers. During the course of OIF, billions of dollars were spent on thousands of CERP projects, which provided significant local and regional economic benefits to Iraq's depleted infrastructure and struggling economy. For example, during the timeframe from fiscal years 2004 through 2007, more than $2.26 billion was spent on more than 22,000 projects (GAO 2008).

The social impacts were perhaps more advantageous in that FOBs brought U.S. troops into neighborhoods on a daily basis. Improved communications fostered trust, rapport and greater understanding. Patrols were gradually conducted jointly with Iraqi units and police (Fig. 9), and by 30 June 2009 (in accordance with the Security Agreement), all U.S. troops withdrew from the cities and villages and remained on the FOBs until requested by the Iraqi military or security forces. All along, the goal had been to provide the security and support necessary to enable a sense of normalcy to return to the neighborhoods as soon as possible.

4 Deconstructing the FOBscape

The "drawdown" in Iraq had been projected for many years. As such, the U.S. military had consolidated bases around the country as it drew down forces (Santana 2010). FOB Qayyarahh West (better known as Q-West) was one of the FOBs that was used to consolidate vehicles, equipment, and shipping containers full of items that were destined to be either shipped directly to Afghanistan or back to the U.S.

(Gilbert 2010). A sprawling FOB of about 20 km^2, Q-West was a major transfer point and a key hub during the drawdown and was transferred to Iraqi control in the fall of 2010 (Gilbert 2010).

The Security Agreement signed by Iraq and the U.S. in late 2008, and President Obama's speech at Camp Lejeune on February 27, 2009, added further impetus to deconstructing Iraq's FOBscape. Some FOBs and COPs were handed over to the Iraqi Army or Police for use as bases or training facilities, while others were converted to different uses as requested by the Iraqis, and some were bulldozed to the ground and the landscape reclaimed until other land-use decisions could be made. During the course of 2009, the U.S. closed or turned over 142 bases to the Government of Iraq (GOI) (Cordesman 2009). By the end of 2011, the only U.S. base remaining was COB Adder, located about 185 miles south of Baghdad (Logan 2011).

The last of the U.S. Brigade Combat Teams (BCT) left Iraq on 18 August 2010, leaving only about 50,000 troops remaining in country. The remaining units, comprised of support personnel and six Advise and Assist Brigades (AABs), were projected to be gone by December 31, 2011. Adhering to the scheduled plan, the last convoy of U.S. soldiers withdrew from Iraq on December 18, 2011 (Logan 2011). Under the Provisions of Operation New Dawn, the remaining U.S. military personnel constitute a transitional force designed to carry out three distinct functions: training, equipping, and advising Iraqi Security Forces (Cochrane Sullivan 2010). These troops have continued to operate from the remaining U.S. FOB or operate jointly from those that have already been turned over to the Iraqi Army.

Ironically, as many FOBs were closed, converted to other uses, or transferred to Iraqi control, the USA Corps of Engineers and other private military companies (PMCs) continued to construct new FOBs for the Iraqi Army (Aziz 2007). Seen as the ideal model for basing units, maintaining security, and integrating military facilities within the cultural landscape, new multi-million dollar construction projects continued to spring up around the country during the drawdown (Aziz 2007).

5 Conclusion

FOBs played a fundamental role in enabling the U.S. Army to transition from combat to stability and support operations. As the U.S. military commitment drew to a close, the remaining FOBs were closed down and the land reclaimed or converted to other uses. Some FOBs, however, were transferred to Iraqi control and will continue to function as a vital support network for the Iraqi government, as well as the U.S. transitional forces who are charged with advising and assisting the Iraqi Army.

FOB warfare has also prompted doctrinal changes and revisions to tactics and techniques employed by Army units. The National Training Center at Fort Irwin, California, has been transformed from training units to operate in high-intensity battles against mechanized and armor forces in the Fulda Gap and elsewhere, to preparing units to operate from FOBs to conduct light and decentralized missions against insurgent threats within urban areas (Miles 2007). Summer training scenarios at the U.S. Military Academy at West Point and within ROTC programs have also been revamped to familiarize cadets with operating from FOBs, and each of the Army's branch schools and training centers have integrated FOB operations into their respective programs of instruction.

The FOB concept perfected in Iraq is now well established in Afghanistan. Moreover, it has also been adopted for use along the U.S.-Mexico border, where in many places members of the National Guard and Border Patrol are housed in a series of austere locations astride the extensive international border (Miles 2006).

In hindsight, the use of FOBs to house an occupational Army and to provide a framework for launching and sustaining a counterinsurgency campaign seemed to be a logical and effective approach to addressing the complex scenario in Iraq. In many respects, FOBs will continue to play a critical role for the Iraqi government, and particularly, its military and police forces as the latter collectively strive for security, stability, and peace within the country.

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U.S. Army Agriculture Development Teams, Afghanistan: The Role of the Geoscientist

Alexander K. Stewart

Abstract In the spring of 2008, the National Guard Bureau and the U.S. Army began employing a new counterinsurgency tool in Afghanistan—Agriculture Development Teams (ADT). These specialized, egalitarian U.S. Army teams, consisting of 12 soldier-expert hybrids, work directly with Afghanistan officials and farmers to support their agricultural needs. ADTs provide agriculture-related education, training and sustainable projects, which are U.S. funded and locally operated and maintained.

For the Texas ADT, geoscientists are generalists working in three areas: (a) Hydrology, (b) Education and (c) Geology. Hydrologically speaking, control, conservation and management of spring snowmelt from the Hindu Kush is vital to farming and livestock management, so delay-action dams, gabion structures and irrigation projects were developed. In response to village concerns, a dam assessment and hazard-mitigation program was developed and implemented. Team geoscientists also helped in watershed delineation and the selection of dam emplacement locations. With respect to education, university- and high-school-level support and training projects are also developed and implemented. Genuine geology-based projects were atypical due to overall security and time constraints; however, Texas ADT geoscientists completed remote sensing of chromite mineral resources in their area of operation.

Overall, ADT geoscientists are essential for mission success because of their flexible approach to problem solving, which is paramount in an ever-changing battle space where data and observations are limited to time, space and support. The role of a geoscientist in these teams varies depending on the unit's deployed location and their commander's intent. The success of an ADT geoscientist, however, is contingent upon the commander's understanding of what a geoscientist IS and DOES!

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Keywords Afghanistan · U.S. Army · Geoscience · Agriculture · Hydrology · Hindu Kush

1 Introduction

The military and the geosciences have been loosely connected since the dawn of warfare (Guth 1998) where a commander's better understanding of the terrain led to successful action against the enemy (e.g., Kiersch and Underwood 1998; Winters et al. 1998; Hippensteel 2011). After the two World Wars, the U.S. military formally recognized the need for routine input of terrain analysis and developed "Terrain Analysis" teams that were included at the division and corps level (ATRRS 2013). These teams still survive, albeit in an updated capacity as computer-savvy geospatial engineers and analysts (ATRRS 2013). Guth (1998) recognized the military's continued need for geoscientists, not terrain analysts, by summarizing his abstract with, "the classic dilemma for military geology has been whether support can best be provided by civilian technical-matter experts or by uniformed soldiers who routinely work with combat units." This pre-War on Terror statement has been answered by the U.S. Army, not as an either/or, but as a hybrid of both expert and soldier. Civilian technical-matter experts, who are Army National Guard soldiers, are currently being selected to support the War on Terror as uniformed soldiers in a specialized, counterinsurgency (COIN) unit. This hybrid solider-expert, working as a ground troop in a platoon-sized combat unit, is unique in the history of warfare and is being typified in the U.S. Army's Agriculture Development Teams (ADTs) (CALL 2009; Stewart 2010, 2011, 2012; Turner 2010).

Despite the existence of geospatial military occupational specialties (MOS), the development and proper implementation of the ADT concept requires real-world experience associated with the agricultural field in order to maximize the product. This use of real-world experience is not new to the military, for they commonly use civilian expertise in those skills that directly influence logistics and welfare. For example, whether at war in Afghanistan or on a humanitarian mission in Nicaragua, soldiers who have civilian skill sets, such as a plumber or electrician, will most likely support a unit's needs in these areas. This commonsense use of real-world expertise, as opposed to a technical, MOS-trained, limited-experience use (even in plumbing or electrical work), is ingrained in the military, which adapts and overcomes with the resources at hand.

As a result, the use of geo-related, MOS-trained technicians is not the answer to supporting a specialized, COIN team. State National Guard units are selecting from within their ranks (from Specialist, E-4 to Lieutenant Colonel, O-5) civilian-educated, real-world-trained workers in agriculture-related/supporting fields (e.g., agricultural science, engineering). The qualifications of any particular soldier range from having a high school diploma and a life on the farm (for a "farm manager/maintenance" position), to the preferred qualification of a college degree, or, rarely, even a graduate degree in an agriculture-related specialty.

Using this logic, the U.S. Army and the National Guard jointly deployed ADTs for Afghanistan. For most ADTs, the most prevalent members of the teams are geoscientists who can make up 25 % of the team's expertise. Redundancy in the geosciences is critical for the success of an ADT, for the geoscientist is a traditionally trained, quantitative describer of observations who is well versed in critical-thinking skills (Kastens et al. 2009). The training and experience of a geoscientist, moreover, is key because of their flexible approach to problem solving; geoscientists typically approach problems with an intellectual toolbox that contains a variety of tools selected as appropriate to the job at hand (Frodeman 1995). This "toolbox" approach to problem solving is becoming more and more important on the battlefield where a soldier is required to solve problems with limited time and resources (Frodeman 1995; Powell and Leveson 2004).

2 Agriculture Development Teams

During early 2008, the U.S. Army, in conjunction with the Army National Guard, developed and began employing ADTs to Afghanistan. These specialized U.S. Army teams comprise 12 hand-selected, soldier-expert hybrids in the agriculture field; supported by an organic security team and a headquarters element. As an egalitarian team, these soldiers work directly with both regional and local Afghanistan government officials and farmers to support their agricultural needs. ADTs provide agriculture-related education, training and sustainable projects, which are US funded and locally operated and maintained. As of the spring of 2012, 12 states have supported the ADT mission (Fig. 1) providing a total, thus far, of 34 teams that operated in 15 provinces and contributed over 595 agriculture-related projects, which generated over $35 million in economic impacts for the people of Afghanistan (USA 2012).

Of these 12 agriculture-related experts, geoscientists can make up to 25 % of their strength. The civilian and military planners who implemented these teams in 2008 were correct by including geoscientists who are traditionally trained in quantitative observation and critical thinking. Geoscientists in these ADTs typically work as civilian geoscientists. Due to the flexibility of the geoscientist's mindset and training, they are currently undertaking a variety of missions that challenge the limits of their traditional expertise, while doing so with ease and success. Typical projects run by geoscientists range from delay-action dam planning and emplacement to mineral-resource reconnaissance to environmental protection projects and general agricultural projects such as animal husbandry, irrigation and infrastructure support. Geoscientists thrive in this environment requiring functionality beyond their formal training.

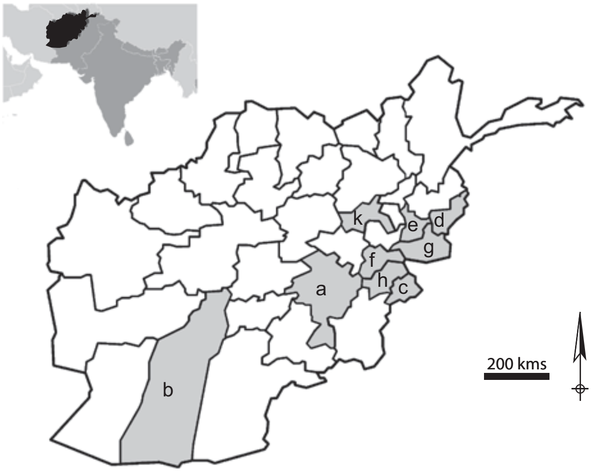

Fig. 1 Map of Afghanistan showing provincial boundaries and locations of ADT efforts (*gray* shading). Note the focus of ADT efforts in the east-central portion of Afghanistan, linked to population and the cross-border influx of Taliban from Pakistan (and poppy-dominated Helmand Province "b". List of annotated provinces/ADT-sponsoring state: *a* Ghazni/Texas, *b* Helmand/South Carolina, *c* Khost/Indiana, *d* Kunar/Illinois, Iowa and California, *e* Laghman/Kansas, *f* Logar/Georgia and North Carolina, *g* Nangarhar/Missouri, *h* Paktia/Nebraska and *k* Parwan/Kentucky. For clarity, "i" and "j" are not used. Map modified from cia.gov)

2.1 *Soldier Always, Geoscientist Sometimes*

These technical-matter experts must be proficient soldiers, yet work as if they are civilian professionals in a non-military-styled, egalitarian team. Team members typically excel both as soldiers and civilians, so the fusion may appear simple; however, it can be a constant struggle to work inside the limits of the battlefield. For example, depending on the location, times on target (data-collection location) may be as short as 10–15 min for counter-sniper procedures, which means the soldier-expert needs to be able to survey the situation, collect the appropriate data and be sure that the mission is complete because returning may not be an option. In addition to time limits on the battlefield, there is also a spatial limit—both general location (e.g., is it accessible) and site maneuverability. Working inside a security bubble adds another dimension to the site survey and data collection. The freedom to work and wander as one would in the non-battle environment is not an option. Inside this temporal-spatial context, the soldier-expert has to also adapt to the socio-political environment. The soldier-expert must master this anthropocentric environment in order to maximize the effectiveness of a particular mission and the ADT as a whole. The local population is the primary source of information regarding the area and their expectations and needs (CALL 2009; Fig. 2).

While tackling these soldier-expert duties, whether it's being a member of a district's *shura* determining the fate of a particular project or scouting out the location

Fig. 2 Four generations of Hazara from Malistan District, Ghazni Province. Unlike the Pashtun found in Ghazni city and along the Kabul-Kandahar road, the Hazara are more western thinking; notice the matriarch *left of center* who allowed us to take photographs. The *left* column represents the Texas ADT's message card, which were distributed to locals to help initiate and foster a friendly, working relationship. (Message card modified from CALL, 2009; photograph by author)

of a new slaughterhouse, the soldier-expert is always a soldier first. The primacy of the rifleman in U.S. Army is not lost on these soldier experts. They, like their security teammates, are battle hardened, carrying the same weapons and munitions (e.g., rifle, pistol, grenades, ammunition) and with the same situational awareness; however, they must skillfully juggle their soldierly duties with the expectations of their civilian specialty.

2.2 Mission Statement and Selected Mission Assignments Involving a Geoscientist

The mission statement of the ADTs in general, is simple: to provide basic agricultural education and services for the people of a particular province (Fig. 1) in order to support the legitimacy of the Government of the Islamic Republic of Afghanistan (GIRoA). Due to the general nature of this mission statement, "agricultural education and services" is broadly defined. Working to support the national Ministry of

Table 1 Examples of Texas ADT projects in Ghazni province, 2009–2010

District	Theme	Title
Ghazni	Agriculture	Agriculture extension agent training
	Agriculture	Agriculture centers and veterinary clinics
	Agriculture	Demonstration farm upgrades
	Agriculture	Farmer's market assay and upgrades
	Power	Demonstration farm wind and solar power
	Animal Husbandry	Livestock husbandry training
	Animal Husbandry	Poultry training
	Animal Husbandry	Refugee village poultry training
	Animal Husbandry	Para-veterinary training
	Animal Husbandry	Slaughter facility extension
	Govt. Agency	Environmental conservancy park
Jaghori	Agriculture	Demonstration farm
	Power	Demonstration farm wind and solar power
	Animal Husbandry	Slaughter facility
	Irrigation	Crop irrigation
	Irrigation	Earthen, delay-action dam
Malistan	Agriculture	Demonstration farm
	Animal Husbandry	Livestock husbandry training
	Animal Husbandry	Poultry training
	Animal Husbandry	Aquaculture assessment
	Irrigation	Earthen, delay-action dam
Nawur	Agriculture	Demonstration farm
	Agriculture	Wheat planting and processing
	Power	Demo. Farm wind and solar power
	Animal Husbandry	Poultry education
	Animal Husbandry	General husbandry education
Deh Yak	Agriculture	Fruit and vegetable processing
	Animal Husbandry	Livestock husbandry training
	Animal Husbandry	Poultry training
Gelan	Animal Husbandry	Livestock husbandry training
	Animal Husbandry	Poultry training
Jaghatu	Animal Husbandry	Poultry training

Irrigation, Agriculture and Livestock, ADTs co-ordinate with their respective Provincial Directors of Irrigation, Agriculture and Livestock (DAIL) and district elders to develop and implement sustainable, Afghan-run, U.S.-funded projects supporting GIRoA and COIN (Table 1).

The following are examples of projects that the author developed and implemented as a soldier-geoscientist:

2.2.1 Hydrology

Dam Assessment

The March 2005 failure of the Band-e Soltan dam in Ghazni City killed 14 people, displaced thousands (Nasrat and Sharifzad 2005) and renewed villagers' interest and concern about their local dams (Fig. 3). The anxiety generated from this failed dam and the addition of U.S. forces into Ghazni Province prompted village elders to seek assistance in assessing the stability and usability of their dams. Most dams in Afghanistan are small, earthen, delayed-action dams and present little hazard to the communities associated with them. There are, however, several masonry dams on the decameter scale, which are a cause for concern. Because of the Taliban influence in Ghazni Province, the Texas ADT realized dams were neglected and went without appropriate management and maintenance. According to village elders, the addition of the Texas ADT into the province and its ability to operate in a hostile environment gave them an outlet for their concern.

The Texas ADT geoscientists only observed those portions of the dam that could be measured (e.g., dimensions, composition, sections, type) with unseen sections

Fig. 3 Okaak village elders (Nawur District of Ghazni Province) discussing the results of their Texas ADT dam assessment. *Inset* shows author taking oral notes on a locally devised wing-wall extension to the larger, Okaak dam. At previous inspection, the Texas ADT recommended no action; however, the locals moved forward with this wing wall, despite our recommendations. (Photographs by author)

(e.g., internal workings or internal damage) not interpreted (Fig. 3 inset). As an observational scientist, the geoscientist was able to approach these dams with a keen, trained eye, without being a dam engineer. These data, results and summaries were relayed to the local elders (Fig. 3) and were summarized in a series of Dam Assessment Reports and submitted to the Joint Task Force Command, provincial authorities and, for the Band-e Soltan assessment, to U.S. and Afghanistan national authorities.

Band-e Soltan Dam

The Band-e Soltan dam, located approximately 23 km north of Ghazni City, is a curved gravity dam with portions of it dating to the tenth century. The original structure, the oldest in Afghanistan, worked until the early part of the twentieth century when a new dam was partially built upon the same footing (Ezzat 2001; Fig. 4a, b). The Band-e Soltan reservoir currently has an approximate maximum capacity of 2.0×10^7 m^3 and is fed by an approximately 1200-km^2 basin ranging in elevation from 2400 to 3800 m (Stewart 2009). With proper management, the reservoir is able to irrigate approximately 15,000 ha farmed by approximately 25,000 families (Ezzat 2001).

Fig. 4 Band-e Soltan dam; *arrow* in "b" is pointing to the original, tenth-century portion and *dash-encircled* section is the repaired wing-wall section represented in a, c and d. **a** March 2005 collapsed wing-wall section; **b** overview of the dam facing westerly; **c** author (second from *left*) inspecting the repaired wing-wall section (reservoir side) and **d** downstream section of repaired wing-wall. (August 2009; Photographs by author)

During the 1990's, the dam was in general disrepair and the Danish Committee for Afghan Aid to Refugees (DACAAR), a nongovernmental organization dedicated to supplying aid to Afghans through water and sanitation projects, worked at repairing the dam from May 2000 to July 2002, based on an associated engineering report (Ezzat 2001). Because the engineering report failed to assess the entire dam, the repair efforts were insufficient and the dam failed in 2005. As a result of this catastrophe, the World Bank in Afghanistan supported the completion of the first of two phases of emergency repairs for approximately US$500,000 . The second phase of the operation was stalled due to the Taliban killing and kidnapping contractors at the site. It is because of this failed second phase that the national and provincial authorities requested assistance from the Texas ADT. The Texas ADT geoscientists completed the assessment of the entire dam, including the recently repaired wing-wall section (Stewart 2009; Fig. 4b, c, and d). Based on 2008 and 2009 observations, it was clear no additional work had been completed on the repaired section (Fig. 4d). Based on the observed 2009 dimensions of the repaired section, Texas ADT geoscientists estimated with engineering calculations the maximum, safe-stage-level of the reservoir at 4.8 m (6.5 m below the crest). This estimate effectively reduced the capabilities of this dam by 42 %. This reduction, driven by improper engineering and its incompletion, affects a significant number of families downstream. The assessment noted that buttressing and/or backfilling of the wing wall would improve the overall safety of the repaired section; thereby, returning the dam to more normal operational conditions.

The assessment and recommendations (Stewart 2009) were sent to Joint Task Force command and provincial and national authorities suggesting that emergency repairs were paramount to the safety of the villages downstream and to continued optimal operation. Recommended repairs, however, were suggested to be completed to western standards with appropriate earthquake mitigation/design. In addition, upon completion, the Texas ADT suggested that an archaeological park (or signage) should be added to conserve/preserve/educate about the remains of the tenth-century portion—an Afghanistan national treasure (Fig. 4b). Based on months of proving their worth, the Texas ADT commander trusted the observational, analytical and postdiction skills of the Texas ADT geoscientists; therefore, the Texas ADT was able to expand its scope and support local needs beyond expectations.

2.2.2 Education

University Agriculture Education Support

The Texas ADT developed a relationship with the University of Ghazni to support the future of Afghanistan's agriculture, and to better prepare its students for post-graduate work in the field of agriculture. Because the University of Ghazni was a new, under-funded extension of the University of Kabul, the Texas ADT, in consultation with its rector, Dr. Ahmed Rafiqi, agreed upon logistical support by modernizing their facilities. Of paramount importance was the Farsi- and

English-language library with redundancy (by language) of each, agriculture and general-education-related textbooks. Additional computers and internet access was also included and, together, the library and connectivity better prepared the university's faculty to educate the student body in modern theory and methods of agriculture.

Based on discussions with Dr. Rafiqi, the Texas ADT realized that University of Ghazni faculty is not able to offer field or laboratory opportunities to their students to help solidify lecture material because of security and transportation concerns. As a result, the Texas ADT developed and implemented both an experimental farm (on FOB Ghazni) and a demonstration farm (outside Ghazni City); giving the faculty and students a secure location to practice their agricultural skills. To help encourage the use of these farms, the Texas ADT geoscientists developed and implemented a series of lecture and laboratory/field courses in "modern" methods of farming (e.g., grape trellising, Fig. 5). The best qualified Texas ADT team members to work with the professors of the University of Ghazni were the geoscientists. Of the 12 soldier-expert members, the geoscientists were the only experts accustomed to extensive

Fig. 5 University of Ghazni Agricultural Education training sequence. *Upper, center* image is the initial meeting between the Texas ADT (author) and the University's Rector, Dr. Ahmed Shah Rafiqi; following *arrows* through in-class lecture, outdoor-laboratory lecture for grape trellising and, finally, a hands-on practical exercise. Projects come *full circle* with a Quality Assessment, Quality Assurance summary and discussion with all involved. (Photographs by author)

laboratory/field training in their education. As a result of many years of laboratory/field training, the geoscientists successfully completed a series of lecture and laboratory practical where the faculty and students were able to apply the tools learned under the close supervision of the Texas ADT instructors. The addition of a hands-on, field component to lecture material was readily accepted by the students and faculty; leading to an improved understanding of the material (cf. Matz et al. 2012). In addition, the Provincial Minister of Higher Education recognized the Texas ADT's support and helped the University better align its academic ideals with a westernized standard thereby, increasing the female enrollment from 13 to 44 % in one academic year. The increase of females into the University is helping to break down traditional barriers to women's rights in Afghanistan. Because education is the key to moving beyond subsistence farming, this relationship with the University was seen as critical in helping develop the nation's capacity to produce and export agricultural goods.

Gabion Training

As part of a routine inspection of a recently implemented demonstration farm, the Texas ADT geoscientists noticed the direct effect of cut-bank erosion on the only access bridge to the farm. Due to the placement of the bridge at a cut-bank section of the river, its wing abutment extension of dry-stacked riprap was being sapped (Fig. 6). In response to much-needed repair, the Texas ADT geoscientists developed a gabion-training program. Gabions are inexpensive, easily used and maintained wire cages that when filled with earth or rocks are suitable for engineering purposes (e.g., mitigation of mass-wasting processes; Burroughs 1979). Because gabions are inexpensive and easy to make and use, they were the perfect tool to repair and protect the bridge (Fig. 6). The objectives of the three-day training program promoted by the Texas ADT geoscientists were three fold: (1) proper training in mass-wasting recognition and emplacement of gabions for University of Ghazni faculty and local farmers (30 persons), (2) repairing and protecting a cut-bank section associated with the bridge wing abutment and (3) promulgation of the training via radio interviews to support the efforts of the Texas ADT, the University of Ghazni, and local farmers. All three objectives were successfully met thanks to the geoscientists' recognition and understanding of the "unseen" natural process of cut-bank erosion.

2.2.3 Geoscience

Mineral Resources

A uniquely geology-oriented project was given to the Texas ADT's geoscientists from the S-2 (Intelligence/Security) section to determine the likelihood of chromite-mine activity in Taliban-friendly territories of the Zana Khan and Deh Yak districts. With the region's proximity to the Kabul-Kandahar route and the Pakistan border, it

Fig. 6 Junghal Bagh Demonstration Farm (Ghazni District) gabion-training/emplacement project photographs. Notice the sapped, dry-stacked rocks in the *upper* image, which did not minimize bank erosion behind the abutment. These rocks in the May 2009 image had been placed approximately 2 months prior to this picture being taken. After the training program, the section was protected with gabions (*lower* image). (Photographs by author)

was of concern that any additional income supporting the Taliban would be an issue that may need to be dealt with.

Based on Internet access to Papp and Lipin's (2006) book chapter entitled "Chromite" and general USGS GIS data, Texas ADT geoscientists predicted possible mining activity in these districts. The prediction was based upon an extrapolation of chromite-bearing rock units, such as peridotites and serpentinites, along structural strike from known mining sites in Logar Province (northeast of Ghazni Province). These predictions were forwarded to Joint Task Force command and perhaps contributed to the news coverage of an estimate that $1 trillion in mineral resources are available in Afghanistan (Risen 2010).

In addition to this geoscience-related mission, it was common for the geoscientists to both train soldiers and/or “assess” their purchase of semi-precious/precious stones from local souk merchants. Unit-level classes were held on occasion presenting some very basic geological techniques to help soldiers overcome the sales experience of the souk merchant with a basic knowledge of minerals and gemology. As a result of these 60-min lectures and demonstrations, soldiers were more confident and informed about gemological terms (e.g., rarity, color and carat); moreover, they were made aware of some of the flashy tools used by the merchant. The “gem tester,” using heat conductivity for identification of a gemstone, was an easy-to-use analog device, but was nearly useless in determining synthetic from natural stones and the differences between non-, semi- and precious stones. The merchant also used a refractometer to “convince” the buyer of gem type/quality. Although the meter can give accurate and precise birefringence values and refractive indices, it is used by inexperienced merchants using inappropriate refraction liquids (e.g., olive oil). Armed with this new knowledge, groups of soldiers were better situated to deal with the merchant and were able to support each other when making relatively significant purchases. Although small in scope, the unit cohesion nurtured by these more confident sojourns to the souk was an important part of unit morale (cf. Campise et al. 2006).

3 Conclusions

The integration of ADTs among the combat forces in Afghanistan is a unique and modern approach to war fighting, which helps foster relationships between the locals and their elected government and to help move communities from subsistence to export-type farming. By developing and implementing locally requested, operated and maintained agriculture-related projects, the ADTs are not only generating over $35 million in economic impacts for the people of Afghanistan (USA 2012), but, more importantly winning their “hearts and minds” at the grassroots level.

The benefits of using civilian-soldier-experts are only beginning to be understood. Importantly for geoscientists, it is confirmation that both civilian and military leaders have recognized the importance of geoscientists and their role on the battlefield. Geoscientists are a critical part of ADTs because of their problem-solving skills, which are paramount to COIN mission success. Winning hearts and minds requires an understanding and compassion for the needs of the local populous. Traditional military units (e.g., infantry companies) don’t have the time or skills necessary to support the local populous. This support comes only from soldier-experts, who are able to take any community need, develop it, manage it and make it a success.

Geoscientists excel on the modern, ever-changing battlefield because they use deductive reasoning based on a synthesis of the other natural sciences (i.e., physics, biology, and chemistry). Geoscience is also unique in that its training is founded in four areas, which are important to counterinsurgency operations: (1) critical thinking on multiple temporal scales, (2) understanding of the Earth as a complex physical-socio-political system, (3) the use of the field environment as an educational tool, and (4) the requirement of spatial thinking (Kastens et al. 2009). This educational mix of approaches allows geoscientists to "stack observations" by assigning different values to various observations, judge their worth, re-evaluate and extrapolate a plausible explanation. These observations and evaluations are placed in a temporal and spatial framework where certain events commonly occur in a particular four-dimensional space. As a result of this flexible approach to problem solving, geoscientists typically approach problems with an intellectual toolbox that contains a variety of tools selected as appropriate to the job at hand. This multifaceted approach to problem solving is paramount in an ever-changing world where data and observations are limited to time, space and support. Real-world problems rarely have a "correct" answer, so assessment of ideas based on probability is reasonable, pragmatic and very familiar to the geoscientist (e.g., Frodeman 1995).

Despite the U.S. conventional forces strength, the U.S. is fighting adaptive insurgent forces that mix modern technology with ancient techniques and terrorism (DoA 2006). Defeating these enemies requires an adaptive and flexible force that is prepared to employ a mix of familiar combat tasks and skills more associated with nonmilitary agencies (e.g., USGS or USDA). In order for COIN operations to be successful, soldiers should be prepared to take on missions infrequently practiced with an ever-increasing reliance on the basic ground troop. The ground, combat troop is where COIN begins and geoscientists are the best prepared to tackle operational changes that are greater than and more rapid than training opportunities within their field of expertise. Their ability to think quantitatively, objectively and descriptively is a winner for the U.S. Army and is being proven with the National Guard's ADTs in Afghanistan (Stewart 2011, 2012).

The use of the civilian-soldier-expert may be the norm for the National Guard Bureau, which has the luxury of a civil-experienced force. This win-win situation has been formally accepted by the former Secretary of Defense, the Honorable Robert Gates, who said "[m]ore programs like this [ADTs] can be developed and we are working with the Services and their Reserve components to find appropriate force structures that can capitalize on the professional skills of Reservists and Guardsmen, while not detracting from the readiness in our conventional formations" (quoted in Nagal and Sharp 2010). For these possible soldier-expert teams one thing will remain, regardless of civilian specialty: the need to convince their traditional, U.S. Army commanders of their abilities and how they will improve their commander's mission and move the nation forward.

Fig. 7 SSG Christopher N. Staats (*left*) and SGT A. Gabriel Green (*right*), both Killed in Action 16OCT09, Ghazni Province, Afghanistan

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Regional Distribution of Salt-Rich Dust Across Southwest Asia Based on Predictive Soil-Geomorphic Mapping Techniques

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Abstract Understanding the source regions of soluble salt-rich dust is critical for military operations, monitoring potential environmental health impacts to military personnel, and for mitigating abrasion and corrosion to military materiél operating in desert regions. Arid regions are characterized by saline soils which are formed by a lack of precipitation and influenced by surrounding and underlying geology, among other factors. The dust content in soils and surface sediments in southwest Asia is commonly associated with specific landforms. This paper uses a soil-geomorphic conceptual model that integrates geographic datasets of Landsat imagery, soil and landforms, precipitation data, and geologic maps to produce derivative map-based predictions of the spatial distribution and content of salt-rich dust-sized particle in soils and surface sediments in the region. The derivative map is based on three regional dust and salt content maps and the assignment of a five-fold rating class and numerical factor value system to individual map polygons [e.g., Very High (5), High (4), Moderate (3), Low (2), Very Low (1)]. The three regional maps include: (1) dust content based on the identification of distinct landform assemblages from 15-m resolution compressed LANDSAT TM+ imagery at a scale of 1:750,000, (2) salt content developed from 1 km^2-resolution mean annual precipitation data, and (3) geologic-based salt content developed from published geologic maps. This study presents an initial step towards the prediction of salt-rich dust sources at regional scales that is aimed to provide information to planning military operations and for mitigating the hazards of dust on military personnel and equipment operating in desert regions. The approach used to predict dust and salt sources could also be used to refine atmospheric dust loading models that require knowledge of the spatial distribution of geomorphic-based input parameters.

Keywords Landforms · Dust · Soluble salt · Predictive mapping · Southwest Asia

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1 Introduction

Mineral dust produced by wind erosion of hyper-arid to semiarid bare soils is transported either locally near the land surface or through the atmosphere at global scales (Pye 1987). Each year, the desert regions of southwest Asia are subjected to some of the greatest dust-producing events on Earth (Middleton 1986a, b; Goudie and Middleton 2006). The real-time prediction and quantitative forecasting of dust storms in terms of dust concentration and visibility is a key meteorological service to military activities in southwest Asia (Liu et al. 2007). Polar-orbiting satellite observing systems designed to provide knowledge of atmospheric and terrestrial environmental conditions have played an important role in military operations conducted in data-sparse regions of the world (Miller et al. 2006). The forecast of environmental conditions are important to military operations, because the effects of dust raising events have significantly disrupted visibility during military operations in the past, such as in 1980 during Operation Eagle Claw (Henderson 2014) and in 2003 during Operation Iraqi Freedom (Anderson 2004), when tactical movements occurred during climatic-induced dust storms or after the ground was disturbed by large-scale, ground-based operations.

Dust emission research has primarily focused on modeling source regions and the global distribution of atmospheric dust (aerosol) by identifying common environmental characteristics using satellite-based sensor technologies, digital elevation models, and atmospheric circulation patterns (e.g., Ginoux et al. 2001; Prospero et al. 2002; Washington et al. 2003; Engelstaeder and Washington 2007; Mahowald et al. 2007). Many dust emission models require knowledge of soil surface properties, including surface roughness height, threshold friction velocity, and the ratio of vertical dust flux to horizontal sand saltation flux, for which global data sets are typically inadequate (Koven and Fung 2008). Few models of dust emission potential, however, are based on soil-geomorphic approaches at local and regional scales (Gerson et al. 1985a,b; Callot et al. 2000; Bacon et al. 2010).

Many dust source areas are commonly associated with topographic lows that contain ephemeral alluvial systems, rivers, lakes, and playas in arid regions where the annual rainfall is less than 200–250 mm (Prospero et al. 2002). In addition to these landscape settings, sand-dominated regions (sand seas or ergs) also are major source areas of dust, because of abrasion from loose sand particles driving saltation that often forms coarse silt-size particles within the margins of sand seas (Crouvi et al. 2008). Dust emission is related to a wide range of surface characteristics, such as soil moisture and texture, presence of physical and biological crusts, the size distribution of soil aggregates, surface roughness, and vegetative and lag covers (e.g., King et al. 2005). The identification of dust source areas and subsequent modeling of dust emission at global scales is usually based on the characterization of undisturbed natural land surface settings, although at small scales, cultivation or pasture usage is acknowledged as an additional dust source (Mahowald et al. 2007; 2009). At microtopographic scales, dust emission has been shown to increase significantly across disturbed surfaces (Belnap et al. 2007; Macpherson et al. 2008).

The chemical and physical properties of mineral aerosols is a concern for global climate change (Dentener et al. 1996) and has gained increasing attention by the U.S. Department of Defense because of its potential human health risks from exposure to ambient particulate matter across southwest Asia (Engelbrecht et al. 2009). In addition to human health risks, the exposure of highly corrosive constituents of desert dust, such as carbonates and soluble salts, impact military materiél ranging from clogging filters to physical abrasion of vehicle parts (e.g., Caldwell et al. 2008), to the functionality of weapon systems (McDonald and Caldwell 2008), to promoting the corrosion of aircraft components (Bloyer et al. 2005).

This paper provides documentation of methods, approaches, and sources of information used to rapidly generate a regional-scale, predictive soluble salt-rich dust content map of a portion of southwest Asia based on soil-geomorphic principles. The initial purpose of this study was to support the U.S. Air Force Research Laboratory (USAFRL) to better understand the regional distribution of salt-rich dust to help mitigate the corrosion of aircraft circuit boards in southwest Asia. In addition to aircraft components, identifying the potential source areas of salt-rich dust may offer critical information for both the planning of military operations and for engineering design and testing of military materiél during research, development and evaluation prior to deployment in the field.

1.1 Methods and Rationale

The geomorphic conceptual model used in this study for predicting soil conditions is related to process-based soil-geomorphologic principles (Birkeland 1999). For example, a soil evolves from a preexisting parent material (i.e., lithology of rock) into a well-defined soil closely related to discrete and identifiable landforms. This relationship allows an ability to reasonably predict soil types if general knowledge of overall climate (especially precipitation), landform age and type, and soil parent material can be identified or surmised (McDonald et al. 2015). This approach follows the soil-forming factor concept of Jenny (1941) that includes: Time, Parent Material, Topography, Climate, and Organisms. The soil-forming factor of Time or landform surface age is not applied in this study because the small map scale of 1:750,000 used to map landforms, which does not allow the resolution to accurately identify the surface characteristics and cross-cutting relations that are required to assign relative age classes to specific landform surfaces. Some of the results presented in this paper are based on previous work for the U.S. Army Yuma Proving Ground to map and quantify the spatial distribution of landforms across southwest Asia to make comparisons with the terrain identified within vehicle test courses (Bacon et al. 2008; McDonald et al. 2009) and for the USAFRL to characterize the salt-rich dust potential of southwest Asia. The compilation of existing soils information and the development of predictive soil techniques in the region also used in this study was initially performed for projects associated with the U.S. Army Research Office (McDonald et al. 2015).

The spatial distribution and magnitude (content) of dust in arid environments is predominately controlled by the association of dust-rich soils or fine-grained surficial deposits that are related to specific landforms (Gerson et al. 1985a,b; Pye 1987). Dust emission potential, however, is the amount of dust that can be released from a unit soil mass under certain environmental conditions, such as wind velocity, soil moisture, vegetation cover or type of surface characteristics (Shao 2008). The methods used to develop regional dust content maps of southwest Asia involved identifying landforms across the region and then assigning a mean particle size distribution to specific landforms based on the compilation of soil profile descriptions from arid regions of the World. Therefore, the estimates of sand, silt, and clay in this study are based on regional projections of a typical landform's soil type independent of geomorphic surface age. Furthermore, the estimate of salt content in the shallow soil is based on mean annual precipitation and bedrock geology.

The regional dust and salt content maps of this study are developed from a variety of methods and sources that include: (1) estimated dust content derived from the assignment of soil characteristics to identified landforms, (2) estimates of salt content in the soil from the distribution of mean annual precipitation, and (3) additional estimates of salt content in the subsurface from geologic maps. The relative magnitudes of dust and salt are depicted on maps using a five-fold rating class system and corresponding numerical factor as follows: Very High (5), High (4), Moderate (3), Low (2), and Very Low (1). The final product is a salt-rich dust content map showing a composite ten-fold class system based on the sum of numerical factors for a given polygon from the three map products.

The following text briefly describes the principal data and approach used to generate the sets of maps and a discussion of the results. For simplicity, this study refers to "dust" as mineral particles with diameters of less than 125 microns, which is equivalent to very fine sand, silt and clay sizes.

2 Dust Content Based on Landforms

2.1 Landform Delineation

The definition of a landform as defined by Peterson (1981) for soil surveys in the Basin and Range Province of the western United States is "a three dimensional part of the land surface formed of soil, sediment, or rock that is distinctive because of its shape, that is significant for landscape genesis, that repeats in various landscapes, and that also has a fairly consistent position relative to surrounding landforms". Mapping of landforms was accomplished by identifying landscape elements that were spatially distinct at a map scale of 1:750,000 and discernable using 15-m resolution compressed LANDSAT TM+ imagery with 7-4-2 wavelength bands from the late 1990s to early 2000s. Often the identification of the margins of landforms were recognizable at the map scale, but in cases where the identification of a landform was not discernable at scales as large as 1:40,000, the use of 15-m LANDSAT ETM+ imagery, 15-m color EarthSat NaturalVue® (MDA Federal Inc.), or DigitalGlobe® pan-sharpened satellite imagery was consulted for landform identification from web-based platforms. Landform mapping was carried out using accepted methods that base delineations on tonal, textural, and topographic qualities (e.g., Ray 1960). Landform unit contacts were digitally created directly on the imagery in a Geographic Information Systems (GIS) platform, and are presented herein using Albers Equal Area Projection, WGS 1984 datum. Digital elevation models (DEMs) from the Shuttle Radar Topographic Mission (SRTM) at a resolution of 3 arc s (~90 m) for areas outside of the United States were also used to assist with delineating landform boundaries.

Thirteen major landform classes were developed to best represent desert terrain attributes with respect to military operating environments in southwest Asia (Table 1; Fig. 1a). The landform classes presented in this study are similar to other studies that characterized desert environments (e.g., Raisz 1952; Clements et al. 1957; King et al. 2004; Ballantine et al. 2005). The more prevalent landform types and the percentage of the total area that they cover across the mapped portion of southwest Asia are: 0.2 % sand dunes, 8.1 % alluvial plains, 61.5 % alluvial fans, 1.4 % badlands, 1.2 % pediments, and 27.3 % mountain highlands. Of note, the landforms characterized at a map scale of 1:750,000 represent the dominant landform type, but should be considered as landform assemblages having finer-scale and different landform types.

2.2 Dust Content

Soil surfaces in arid environments are principally stabilized by gravel covers usually in the form of desert pavements, physical crusts mostly formed in soils with high soluble salt content and fine-grained material, and biological soil crusts composed of cyanobacteria and lichens (e.g., King et al. 2005). The magnitude of surface disturbance critically affects the availability of the underlying soil to be transported, however, dust content strongly controls the potential for surfaces to emit dust. The dust content assigned to individual landforms was calculated using the Desert Research Institute's (DRI) soil database and is based on the mean particle size distribution of the fine earth fraction (< 2 mm). A uniform cutoff depth of 10 cm for each soil profile was used in the statistical analysis because it is assumed that soil below this depth is unlikely to be entrained during dust-raising events. The soil database, created and maintained by DRI, currently contains descriptions of 813 georeferenced soil observation sites, amounting to 4116 pedological horizon descriptions from the Mojave and Sonoran Deserts in southwestern U.S., the Negev Desert in Israel, and selected sites in southwest Asia (e.g., Bacon et al. 2010). The landforms identified in this study were assigned a qualitative dust content class based on: (1) the mean dust content for individual landforms and (2) the general terrain characteristics of relief and surface morphology associated with each landform that commonly limit

Table 1 Definitions, mean particle size, and dust content rating classes of landforms identified in areas of Southwest Asia

Landform	General definition of landform	Mean particle size (%)			General surface characteristics	Dust content class (rating)
		Sand	Silt	Clay		
Broad river valley	A wide and elongated valley of a perennial stream that is fed from highland mountain sources, and typically consists of stratified sand- and silt-rich stream sediments	39	39	22	Loose—hard	Very high (5)
Playa and Sabkha	An ephemerally flooded, barren area on a basin floor that is veneered with interbedded fine-textured sediment and evaporite deposits. *Sabkha*: Arabic term for a supratidal coastal environment of sedimentation and evaporite precipitation formed under hyperarid to semi-arid climatic conditions. Both landforms are grouped together because they are in general, sedimentologically and hydrologically similar, varying only in their boundary conditions (Yechieli and Wood 2002)	39	37	24	Loose—hard	Very high (5)
Badlands	An intricately stream-dissected topography consisting of deep, narrow ephemeral washes interspaced with abundant sharp and narrow ridge tops, developed on surfaces with little or no vegetative cover. Underlying material is generally unconsolidated or weakly indurated fine-grained sediment. This feature is also commonly mantled with sediment composed primarily of silt (loess cap) on stable surfaces	47[a]	33[a]	20[a]	Loose—hard	High (4)
Alluvial plains	A major landform of some basin floors, comprised of the floodplain of a major Pleistocene stream that crossed the floor, or of a low-gradient fan-delta built by such a stream. Deposits typically consist of well-sorted and stratified alluvium (Peterson 1981)	62	25	13	Loose—hard	High (4)
Alluvial fans	A semiconical, or fan-shaped, constructional, major landform that is built of more-or-less stratified alluvium, with or without debris flow deposits, that occurs at the upper margin of a piedmont slope, and that has its apex at a point source of alluvium. This feature is also commonly mantled with sediment composed primarily of silt (loess cap) on old surfaces	66	23	11	Loose—hard	High (4)
Pediments	Erosional feature composed of rock or consolidated sediment at the foot of mountain highlands or within relatively flat and tectonically stable regions. Surfaces are often mantled with sediment composed primarily of wind-blown silt (loess cap)	65	23	12	Loose—very hard	High (4)

Table 1 (continued)

Landform	General definition of landform	Mean particle size (%)			General surface characteristics	Dust content class (rating)
		Sand	Silt	Clay		
Sand sheet	Low-relief sand surface accumulations. Their formation is facilitated by conditions unfavorable to dune formation including high water table, periodic flooding, surface cementation, coarse-grained sands, and presence of vegetative cover.	86	9	5	Loose	High (4)
Sand seas/dunes	An area consisting of mounds, ridges or hills of wind-blown sand, either bare or covered with vegetation. Sand seas or dunes also form aggregates of moving and fixed sand dunes in any given area	90	8	2	Loose	Moderate (3)
Plateau	A relatively elevated area of comparatively flat land which is commonly limited on at least one side by an abrupt descent to lower ground; or extensive land area more than 15–300 m above the adjacent country or above sea level. This feature is also commonly mantled with sediment composed primarily of wind-blown silt (loess cap)	49	32	19	Moderately hard—very rigid	Moderate (3)
Coastal	A low-gradient margin of land on or near or bordering a ocean or gulf that typically consists of coastal marshes, estuaries, deltas, sand dunes or beaches, as well as rocky cliffs.	75	17	8	Loose—slightly hard	Low (2)
Wind erosional features	Wind erosional feature that typically exhibits an elongate ridge or series of ridges carved by wind erosion. The ridges are parallel to the prevailing wind direction and predominately form on poorly- to moderately-consolidated sediment	62[b]	25[b]	13[b]	Moderately hard—rigid	Low (2)
Recent volcanic features	Recent volcanic features are landforms that have been recently formed from volcanic activity. The common type of recent volcanics is basalt flows and fields (plateaus), and volcanic vents (i.e., cinder cones, shield volcanoes, lava flows, etc.)	70	20	10	Rigid—very rigid	Very low (1)
Mountain highlands	A highland mass with high relief and steep topography that rises more than 1,000 feet (300 m) above its surrounding lowlands and has only a crest or restricted summit area (relative to a plateau) (Peterson 1981)	57	28	15	Rigid—very rigid	Very low (1)

Table 1 (continued)

Landform	General definition of landform	Mean particle size (%)			General surface characteristics	Dust content class (rating)
		Sand	Silt	Clay		
Salt domes	A rising bulbous dome of salt that bends up the adjacent layers of sedimentary rock. Wide spread salt dome fields are present in southern Iran and source from Neogene marine sedimentary rock	70[c]	20[c]	10[c]	Rigid—very rigid	Very low (1)

[a] Particle size distribution of badlands is based on the mean particle size distributions of broad river valley, alluvial plain, and playa landforms, as a result of limited soil-geomorphic data in DRI soil database and the rationale that most badland landforms are commonly underlain by deposits associated with a combination of the landform's depositional environments.

[b] Particle size distribution of wind erosional features is based on the mean particle size distributions from alluvial plain landform, as a result of limited soil-geomorphic data in DRI soil database and the rationale that most wind erosional features are commonly underlain by deposits associated with this landform's depositional environment.

[c] Particle size distribution of salt dome landforms is based on the mean particle size distributions from recent volcanic features, as a result of limited soil-geomorphic data in DRI soil database and the rationale that most salt domes are commonly overlain by rocky and gravelly colluvial deposits similar to volcanic deposits

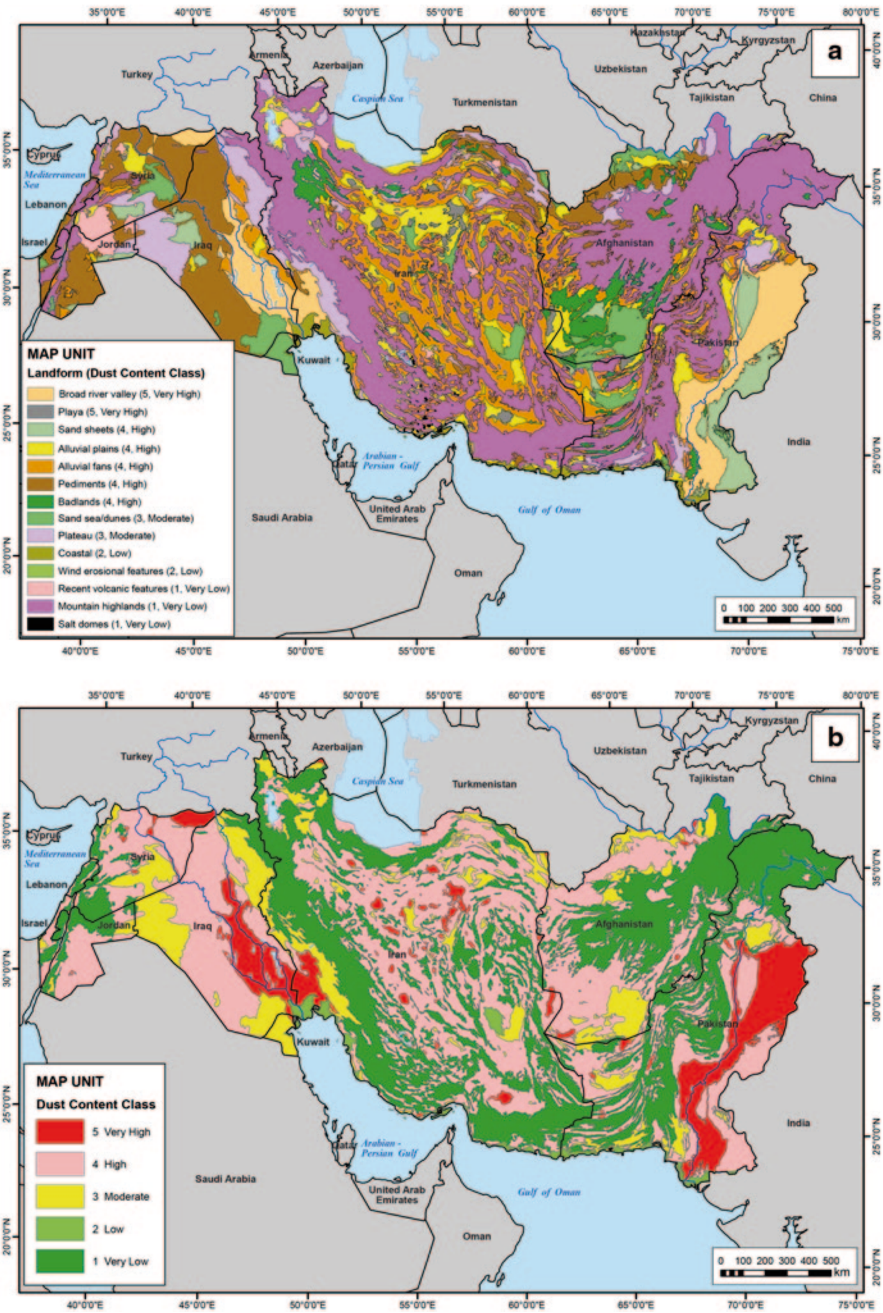

Fig. 1 **a** Landform map of a portion of southwest Asia showing associated dust content classes. **b** Dust content map showing five-fold dust content classes and numerical factor rating based on landforms

dust emission (Table 1). A five-fold rating class system and numerical factor value system ranging from Very High (5) to Very Low (1) was developed to categorize the potential dust content of identified landforms (Table 1; Fig. 1b).

3 Salt Content

3.1 Salt-Affected Soils in Arid Regions

Salt-affected soils occur in all continents and under almost all climatic conditions; such soils have been investigated in detail by the United Nations Food and Agriculture Organization (FAO) (Abrol et al. 1988). The distribution of salt-affected soils is relatively extensive in semi- to hyper-arid regions compared to humid regions. The presence of soluble salts (e.g., halite [NaCl] and gypsum [$CaSO_4 \cdot 2\ H_2O$]) near the soil surface and at depth characterizes all saline soils. In general, soluble salts are concentrated in the upper soil profile through a combination of high surface evaporative rates and limited downward percolation. Salts can be present in the soil through direct accumulation (dust, surface water, capillary uptake, ocean influences) or derivation from primary parent material or bedrock sources (Gerson and Amit 1987; Amit et al. 1993).

The distribution of salts in arid environments is commonly influenced by regional sources consisting of primary inputs from the ocean, breakdown of rock, and secondary, cyclic input from past accumulations preserved in geological deposits (Berger and Cooke 1997). Geologic materials are highly variable in their elemental composition and some materials are higher in soluble salts than others. Sediments composed of evaporite deposits associated with playas and sabkhas or any other sedimentary rocks of shallow to deep marine origin can supply large quantities of soluble salts when traversed by both surface and ground water (Davis 1992; Yechieli and Wood 2002). Soluble salts released through weathering in arid regions with limited rainfall are usually deposited at relatively shallow depth in the soil profile, with the depth depending on such factors as the water retention capacity of the soil, and annual and maximum seasonal precipitation (Yaalon 1965). Additional sources of salt are from the incorporation of salt-rich dust into the subsoil by eolian processes (Gerson and Amit 1987; Reheis et al. 1995) and from the periodic irrigation of agricultural lands that leads to elevated salt content in the soil (Buringh 1960).

The general estimates of soluble salt content shown on the map of southwest Asia is principally based on the concept that the amount of mean annual precipitation in a region will govern the magnitude and depth of soluble salt chemical precipitation in the soil profile (e.g., Dan and Yaalon 1982; Birkeland 1999). This concept does not take into consideration other sources of soluble salts, such as from geologic materials, from ground water or from aeolian derived salt-rich dust and coastal fog/spray, which would collectively increase the potential class ratings in a given area.

3.2 Climate Source Data

The mean annual precipitation used in this study was derived from very high resolution interpolated climate surfaces (WorldClim—Global Climate Data) of Hijmans et al. (2005). The climatic dataset was initially assembled from a large number of sources of weather station data and generated through the interpolation of average monthly climate data on 30 arc-s (1 km^2) resolution grid cells. Weather stations that had records for multiple years were used to calculate averages for the 1960–1990 period. Only the records for which there were at least 10 years of data were used in the interpolation analysis. In areas that had few records available, the time interval was extended to the 1950–2000 period. Altitude was not used as a dependent variable in the interpolation algorithms, but was analyzed to evaluate the uncertainty of calculated climate surfaces by the authors of WorldClim. Their analysis showed climatic gradients commonly associated with mountainous areas had the highest uncertainty. Although altitude was not used in the interpolation, the WorldClim climatic dataset is at a higher spatial resolution (400 times greater or more) compared to previous global climatologies (Hijmans et al. 2005), and for the purpose of this study, is acceptable.

3.3 Salt Content Based on Precipitation

A five-fold rating class system ranging from Very High to Low (factor values 5–1) was developed to categorize the salt content of soils in southwest Asia based on regional mean annual precipitation (Fig. 2). This five-fold rating system was adopted based on the likely occurrence of soluble salts accumulating within the upper ~ 1.0 m of the surface. The content of soluble salt is a function of the projected rainfall or mean annual precipitation (mm/year) in a given area (e.g., Dan and Yaalon 1982; Birkeland 1999). In general, the range of rainfall amount influences the degree and depth of precipitation of soluble salts, which in turn is used to estimate the salt content in the soil. The salt content classes correspond to specific precipitation classes and amounts, which are as follow: Very High (hyperarid: 0–50 mm/year), High (arid: 50–100 mm/year), Moderate (mildly arid: 100–150 mm/year), Low (mildly arid: 150–200 mm/year), and Very Low (greater than mildly arid: >200 mm/year) (Fig. 2).

3.4 Salt Content Based on Geology

In addition to the amount of precipitation an area receives, the surrounding and underlying geology also governs the occurrence of soluble salt in the soil (e.g., Abrol et al. 1988). Furthermore, most Quaternary unconsolidated sediments, as well as Neogene marine sedimentary rock, exhibit a relatively greater proportion of soluble salt compared to other types of older rocks in southwest Asia (e.g., Buringh 1960;

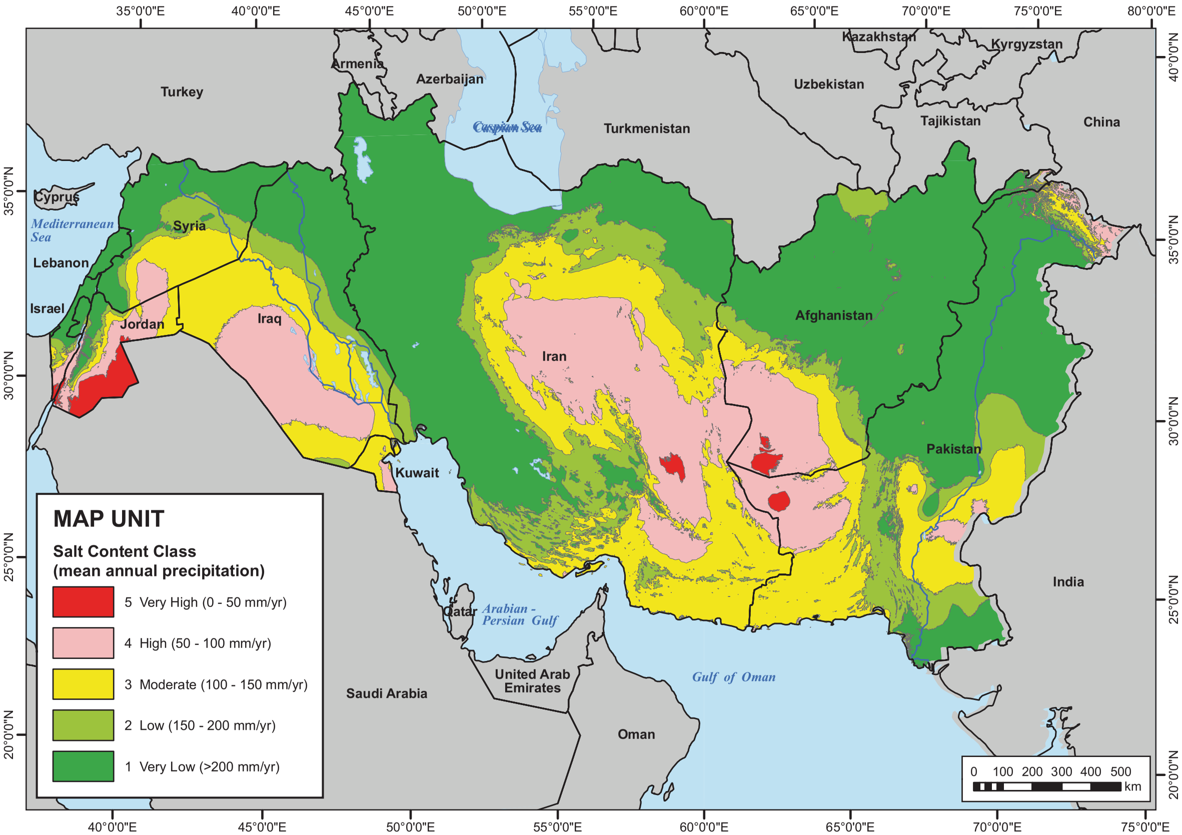

Fig. 2 Salt content map showing five-fold salt content classes and numerical factor rating based on mean annual precipitation from 1 km^2 grid resolution data of Hijmans et al (2005)

Dewan and Famouri 1964). Although geologic factors are likely a small contributor to the overall soluble salt flux in any given region, it is a component of the total soluble salt flux and is considered in this study. In an effort to incorporate this component, a four-fold rating class and factor value system consisting of Very High (3), High (2), Moderate (1), and Low and Very Low (0) was developed to construct a geologic-based salt content map of southwest Asia (Table 2; Fig. 3.). This four-fold factor value (3–0) system differs from the five-fold (5–1) system used previously (e.g., dust content based on landforms) because the geologic factors that control salt content are considered a subordinate effect and not considered to be equally weighted, therefore this value system was intended to increase an area's salt content rating not lower it.

The geologic sources of information used to generate the geologic-based salt content map are from the modification of geologic units compiled by the U.S.

Table 2 Geologic salt content rating classes

Era	Period	System and period (geology)	Series and epoch	Years before present	Salt content class (rating)
CENOZOIC	Neogene	Quaternary (playa)	Holocene	0–11,000	Very high (3)
		Quaternary (alluvium)	Holocene	0–11,000	Low (0)
		Quaternary (dunes)	Holocene	0–11,000	Low (0)
		Quaternary (volcanic)	Holocene	0–11,000	Very low (0)
		Quaternary (marine sediments)	Pleistocene	11,000–1.6 million	High (2)
		Tertiary (marine sediments)	Pliocene	1.6–5.3 million	High (2)
			Miocene	5.3–23.7 million	High (2)
		Tertiary (volcanics)		1.6–23.7 million	Very low (0)
	Paleogene	Tertiary (marine sediments)	Oligocene	23.7–36.6 million	Moderate (1)
			Eocene	36.6–57.8 million	Moderate (1)
			Paleocene	57.8–65.4 million	Moderate (1)
		Tertiary (volcanics)		23.7–65.4 million	Very low (0)
MESOZOIC		Cretaceous		65.4–144 million	Very low (0)
		Jurassic		144–208 million	Very low (0)
		Triassic		208–245 million	Very low (0)
PALEOZOIC		Permian		245–286 million	Very low (0)
		Carboniferous	Pennsylvanian	286–320 million	Very low (0)
			Mississippian	320–360 million	Very low (0)
		Devonian		360–408 million	Very low (0)
		Silurian		408–438 million	Very low (0)
		Ordivician		438–505 million	Very low (0)
		Cambrian		505–570 million	Very low (0)
		Precambrian		>570 million	Very low (0)

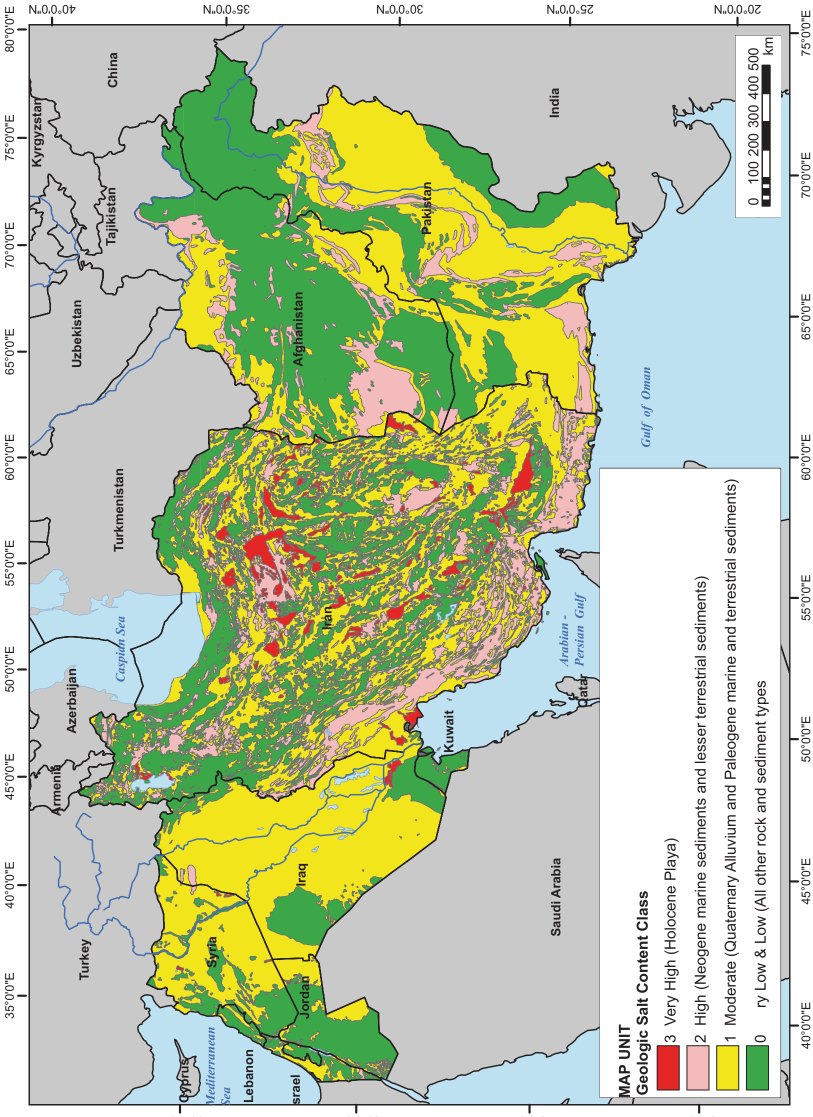

Fig. 3 Geologic salt content map showing four-fold salt content classes and numerical factor rating based on the age and type of underlying geology from U.S. Geological Survey geologic maps of southwest Asia

Geological Survey mapping of southwest Asia (Wandrey and Law 1997), the Arabian Peninsula (Pollastro et al. 1997a), and Iran (Pollastro et al. 1997b). The age and type of geologic units were evaluated and assigned a geologic-based salt content class and factor value. For example, Quaternary playa unit was assigned a rating of Very High (3), whereas units of Neogene marine sediments have a rating of High (2) (Table 2; Fig. 3). Geologic units mapped as Quaternary alluvium and Paleogene marine sediments were assigned a rating of Moderate (1), while all other rock types ranging from active sand dunes to Tertiary volcanics to Mesozoic intrusive igneous rocks to Paleozoic sedimentary and metamorphic rocks all have a ratings of Low and Very Low (0) (Table 2; Fig. 3).

4 Dust and Salt Content of Southwest Asia

4.1 Salt-Rich Dust Content Based on Landforms, Precipitation, and Geology

A 10-fold rating class system ranging from Very High to Very Low was generated from the three dust and salt content base maps (Fig. 4a). This rating class system represents the sum of the three factor values for a polygon of any given area from the landform-based dust content map (Fig. 1b), mean annual precipitation-based salt content map (Fig. 2), and the geologic-based salt content map (Fig. 3). For example, areas near Baghdad, Iraq have Very High dust content rating from the broad river valley with a factor value of 5, a Moderate salt content rating from mean annual precipitation having a factor value of 3, and a Moderate geologic-based salt content rating with a factor value of 1. This yields a summed factor value of 9, which corresponds to a Very High salt-rich dust content rating class (Fig. 4a). The Very High salt-rich dust content class predicted in this study of areas near Baghdad, Iraq, appears to be in good agreement with the soil conditions documented in this same region, which consist mostly of salt-affected soils composed of interbedded sandy silt to silty sand deposits of the Tigris and Euphrates Rivers (Buringh 1960).

5 Discussion and Conclusions

5.1 Spatial Distribution of Salt-Rich Dust

The previous sections of this paper presented a conceptual model used to generate a predictive salt-rich dust potential map of a portion of southwest Asia based on landforms, precipitation, and geology (Fig. 4a). This map includes a ten-fold rating class system that has been subsequently generalized into a five-fold rating class system to provide an example of a more simplified map for operational planning purposes (Fig. 4b).

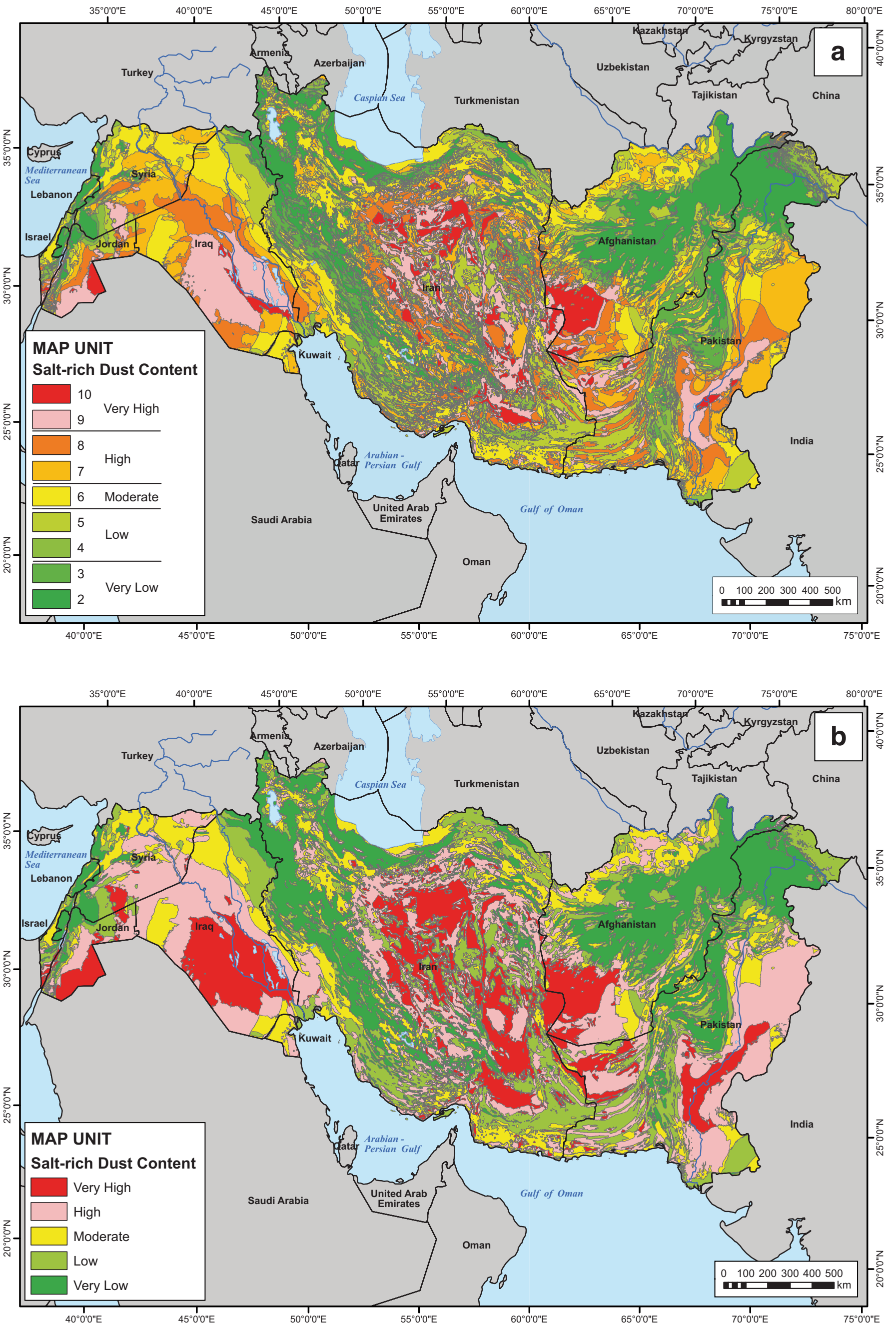

Fig. 4 **a** Composite salt-rich dust content map showing a ten-fold, salt-rich dust classes and numerical factor rating initially derived from the sum of numerical values for a given polygon on the landform-based dust content map, and on the mean annual precipitation- and geologic-based salt content maps. **b** Generalized, salt-rich dust content map showing five-fold, salt-rich dust classes

In general, landforms that have Very High dust content are playas and broad river valleys, which are mostly present within Iraq, Iran, Pakistan, southern Afghanistan, and northern Syria. A wider range of landforms exhibit a High dust content and include sand sheets and sand seas/dunes, alluvial plains and fans, pediments, badlands, and plateaus. These High dust content areas are found throughout central southwest Asia. The landforms that have Moderate dust content are found mostly in coastal areas of the Mediterranean Sea, Arabian—Persian Gulf, and Gulf of Oman, and in areas that are characterized as plateau in western Iraq and western Iran. In addition, landforms classified as having Low dust content generally correspond to mountain highlands and are distributed across the entire area (Fig. 1a). Although we classify mountain highlands as having Very Low dust content, it is likely that low relief examples in hyperarid to arid environments have relatively higher dust content and could be classified as Moderate.

The areas that have the potential to emit salt-rich dust are widely distributed within the ~3,900,000 km^2 portion of southwest Asia of this study. Areas that have Very High salt-rich dust content make-up ~15 % of the map area and are present within small parts of southern Israel and Jordan, western Iraq, and eastern Syria, and large areas within central and southern Iran, southwestern Afghanistan, and southern Pakistan (Fig. 4b). The distribution of areas classified as High is wider and forms ~26 % of the map area. These regions are located in southern Israel, southern and eastern Jordan, a large portion of eastern Syria, and in western and central Iraq. Other regions with High salt-rich dust are widely distributed within the eastern half of Iran, southern Afghanistan, and southwestern and eastern Pakistan (Fig. 4). Areas also classified as Moderate comprise ~33 % of the map area and are mostly found within the upper Tigris-Euphrates river valley of Iraq, portions of northwestern Syria, across Iran, northern Afghanistan, and eastern Pakistan, and small areas of western Israel and southern Jordan. The areas classified as Low and Very Low are distributed across the entire region and typically coincide with mountain ranges (Fig. 4b).

5.2 Further Research and Direction

This study comprises an initial step in the development of methodologies and techniques to rapidly predict the dust and salt content of shallow soil conditions associated with distinct geomorphic features at relatively small, regional scales. We have presented a conceptual model that appears to generally agree with soil conditions documented in most regions of Iraq (Buringh 1960) and in the Negev Desert of southern Israel (Singer 2007), however, the model is in its initial stage of development and remains theoretical until the predictions are validated by testing for accuracy. Validation of the model could include field investigations to "ground-truth" analogues terrain and associated soils in the southwestern U.S. and to perform a geospatial analysis between the salt-rich dust predictions of this study with datasets of published soil surveys and regional soil maps. Further research could also be directed towards integrating other data sets into the model that control the content of dust and salt in soils and surficial sediments. After validation of the model, the same methodologies and approaches taken to generate the predictive maps could also be applied at much larger scales, which would increase the spatial resolution and accuracy of soil predictions. At larger scales, the model could be used to quantify dust emissivity by integrating the geomorphic-based salt-rich dust predictions with geophysical-based climatic and atmospheric models used to forecast adverse dust-raising events in arid environments.

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Part III
Geoscience Technology in Support of Military Activities

Digital Elevation Models to Support Desert Warfare

Peter L. Guth

Abstract Digital elevation models (DEMs) provide a fundamental resource for terrain analysis and military mission planning. Recent developments have changed the quality of the DEMs available worldwide. The Shuttle Radar Topography Mission (SRTM) flew in 2000 and created DEMs with resolutions of 1″ (~30 m) for the US military and 3″ (~90 m) freely available for the general public. The SRTM covered all the earth except for high latitude regions. For the rest of the world its major limitations are the data voids in regions of high relief. Less publicized are the voids in dry desert sand, which account for a larger fraction of the voids than those in high mountains. In contrast to the active radar used for SRTM, which worked day/night and through clouds, the more recent ASTER GDEM used near infrared energy which only worked in daylight and could not penetrate clouds. Development of the ASTER GDEM required years of data collection for relatively complete coverage. Significant anomalies were present in version 1, in large part due to undetected clouds. Version 2 of GDEM offered improvements, but still has anomalies, and the desert regions have the largest concentration of poorly correlated GDEM and SRTM. SRTM or GDEM can provide terrain data for large area, small scale military operations. For very large scale operations, interferometric synthetic aperture radar (IFSAR) DEMs provide point spacings of 3–5 m and LiDAR provides spacings of about 1 m. These data sets are much less widely and freely available, in part because of the huge volume of data: SRTM 3″ requires 35 GB for global coverage, ASTER GDEM about 561 GB, and 1 m LiDAR will require about 1000 TB for full coverage. LiDAR point clouds offer additional visualization and analysis capabilities compared to traditional grids.

Keywords DEMs · SRTM · ASTER GDEM · LiDAR

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1 Introduction

The landscape provides the canvas on which armies operate, and understanding the environment remains fundamental to success in warfare. Shorn of most vegetation, the deserts of the world provide a simpler landscape easier to image and visualize compared with more temperate regions.

Deserts can be classified based on climate, vegetation, or landforms, although the criteria are not mutually exclusive: hot and dry conditions lead to a lack of vegetation, and a suite of geomorphic characteristics. The Köppen-Geiger climate classification system (Rubel and Kottek 2010) has five main climates, with the arid B category comprising about 43.16 million km^2 or 27.52 % of the earth's surface area (computations using the climate grids of Rubel and Kottek (2010)). About 60 % of the arid climates are deserts, with the remainder being steppes or grasslands. The main desert belt between 14–34 N includes 60 % of the world's deserts in Saudi Arabia and the Sahara.

While sparsely inhabited, the desert belt includes a disproportionate fraction of the world's lawless and politically troubled countries. The major recent wars involving the United States and its allies have been in Iraq and Afghanistan, and quasi-wars involving covert operations and drone strikes have been in Pakistan, Yemen, Somalia, and Sudan. Although not involving as great an active role for United States forces, the Western Sahara also faces political instability. The relatively small populations in the desert regions account for a disproportionate share of problems that have plagued, and will continue to plague, western militaries.

2 Digital Elevation Models

Three distinct models can be used to create digital topography: (1) grids, with points on a regular rectangular framework with a uniform density; (2) triangulated irregular networks (TINs), with points arranged in triangles with adjustable and variable density; and (3) point clouds (or mass points), with raw elevation points located where they were collected (Maune et al. 2007). Grids and TINs are both 2.5D representations that can have only a single elevation for any point on the earth's surface, and do not handle cliff overhangs, caves, or the detailed structure of vegetation. In contrast true 3D point clouds can have multiple elevations at the same surface point, although the relationships among the points can be ambiguous; the multiple points will most commonly occur in the vegetation canopy. Grids, usually called digital elevation models (DEMs), have been the preferred method for distributing digital topography. Essentially no elevation data has been widely distributed as TINs, although TINS have been used in intermediate processing. With the proliferation of LiDAR surveys in recent years, and increasing disk storage capacity, computational power, and graphic capabilities, point clouds have started to be used for analysis as well as data collection, although most operational use of LiDAR probably still uses grids created from the point cloud.

The traditional characteristic of gridded DEMs is the resolution or spacing between elevation postings (Table 1 and Fig. 1). The spacing, with the geographic extent of the coverage, determines the size of the DEM. Small scale DEMs, with large point spacing, cover large areas, while large scale DEMs with smaller point spacing, cover small areas. Larger DEMs are typically tiled, to allow selections of smaller regions, although tile sizes have been increasing significantly as memory and storage costs decrease. For example, the Shuttle Radar Topography Mission (SRTM) originally used 1° tiles, but some versions now use 5° tiles which are 25 times larger but decrease the number of tiles correspondingly. DEM size affects the required disk storage, and whether the entire DEM can be loaded into computer memory for fast, random access to greatly speed up many analysis functions. A 32 bit operating system can address a total of up to 4 GB of memory, which realistically means it might load up to 2 GB of elevation data or about 500 million points in a grid. As 64 bit operating systems which can access up to 512 GB for Windows 8 become more prevalent, and rewritten software takes advantage of its increased address space, the amount of data in memory could increase dramatically, allowing analysis of large areas with high resolution data.

As spatial resolution improves, the distinction between a digital terrain model (DTM) and digital surface model (DSM) assumes a greater relevance. The DTM (also called bare earth) removes trees and buildings, while the DSM (also called first return surface) includes both. Early DEMs purported to remove buildings and vegetation, but with 30 m or larger point spacing they could really only provide a generalized depiction of the earth's surface from which it generally proved impossible to see buildings or trees. Current high resolution DEMs can clearly show every building and tree in very natural detail, but the DTMs often look very unnatural because what the land surface should look like with buildings removed can be ambiguous.

As shown in Table 1, at the smaller scales DEMs are freely available for download on the World Wide Web by anyone, including military users and adversaries. However, starting with the resolution of SRTM data, limitations appear. SRTM is freely available at 3″ spacing, but the 1″ spacing is only available to the US military. The ASTER GDEM can be freely downloaded, although it requires a gentleman's agreement that the user works in one of nine societal benefit areas (Japan Space Systems 2012). At the largest scales (smallest point spacing) shown in Table 1,

Table 1 DEMs useful for military terrain analysis

DEM	Spacing	Tiles	Tile Size	Size	Availability
ETOPO5	5′ or ~9 km	1	18.7 MB	18.7 MB	Free, global
ETOPO1	1′ or ~1.8 km	1	445 MB	445 MB	Free, global
GMTED030	30″ or ~900 m	108	16.4 MB	1.8 GB	Free, global
GMTED075	7.5″ or ~225 m	108	263 MB	28 GB	Free, global
SRTM	3″ or ~90 m	14,585	2.8 MB	35 GB	Free, 80 % land area
ASTER GDEM	1″ or about 30 m	22,600	25.4 MB	561 GB	Free, global
IFSAR	~5 m			~40 TB	Commercial
LIDAR	~1 m			~1000 TB	Limited free, commercial

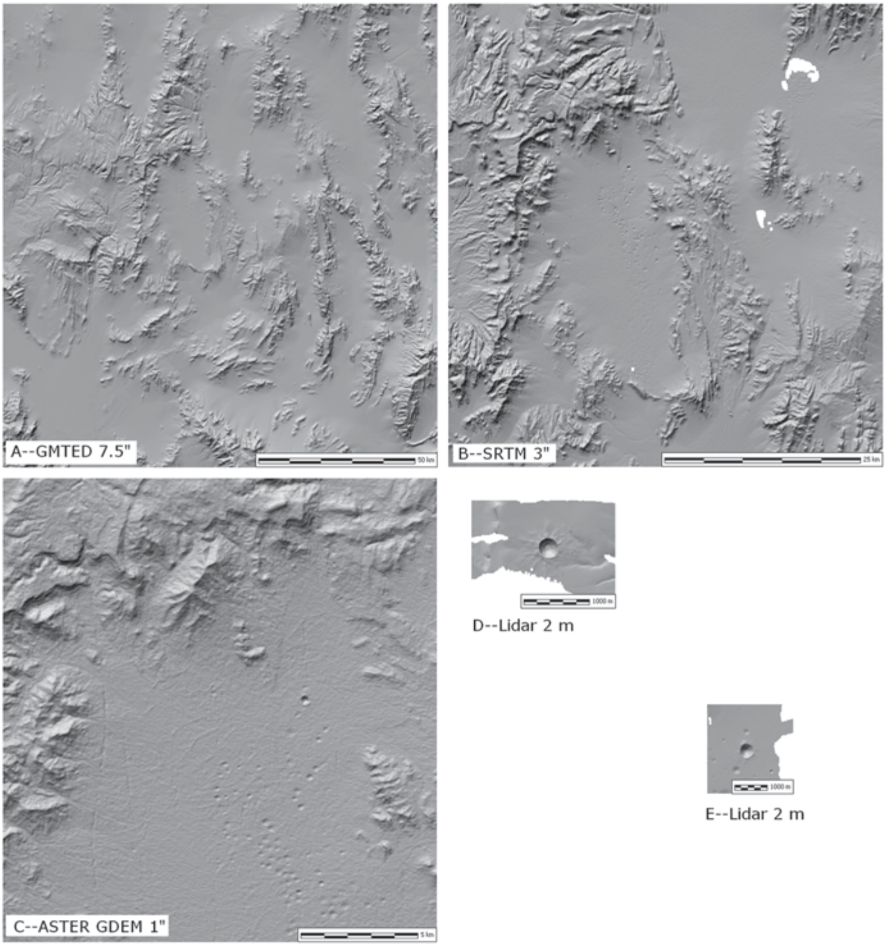

Fig. 1 Four DEMs of the Yucca Flat, Nevada, and the 390 m diameter Sedan Crater. **a** shows GMTED at 7.5″ resolution, whose approximately 225 m resolution does not show the crater. **b** shows 3″ SRTM data with Sedan and a number of smaller craters. The 1″ ASTER GDEM in **c** covers a smaller region than **b**, but does not show significantly greater details. These data sets are freely available on the internet for virtually the entire world. **d** and **e** show 2 m LiDAR datasets for Schooner **d** and Sedan **e** craters. These were collected in 2003 (PDS Geosciences Node 2012) and do not cover much area and have lower resolution than current LiDAR, but they are the only freely available LiDAR that cover Nevada

the coverage is limited, and much of the data is commercial or the military limits distribution. Some militaries can have access to this data, while their adversaries frequently cannot. Very little IFSAR data in the 5 m resolution range is freely available, but a relatively large amount of free LiDAR data is available in parts of the United States from scientific research organizations (OpenTopography 2012) and government agencies (NOAA 2014; USGS 2014).

3 Global and Continental DEMs

The first global dataset was ETOPO5, which had 5 arc minute spacing. This spacing represents about 9 km, which is constant in the y direction but varies in the x direction because of convergence of the meridians. ETOPO5 covered the entire earth, including soundings in the oceans, and required less than 20 MB of computer storage—small by today's standards, but at one time a huge dataset. The grid has 4320 columns and 2160 rows, so even on today's best monitors ETOPO5 cannot be displayed on screen at full resolution. The current version of the data set, ETOPO1, has 1 arc minute spacing or about 2 km (Amante and Eakins 2009) and requires 445 MB, or 25 times the storage required by ETOPO5, but advances in computer technology allow the entire data set to be loaded into memory for rapid processing. For looking at global, or even continental scale, ETOPO1 can show features down to about 4 km scale (the data spacing of about 2 km, combined with the Nyquist sampling limit, gives this critical wavelength). For military planning, global scale data shows at a glance those large regions where armor can effectively operate, and the fundamental differences in terrain that differentiated military operations in Afghanistan from Iraq.

Regional views of terrain can use DEMs like the Global multi-resolution terrain elevation data 2010 (GMTED2010, Danielson and Gesch 2011). This comes in three resolutions between 30 arc seconds and 7.5 arc seconds, created by subsampling the best available, higher resolution data. GMTED also offers a choice of sampling methods (including mean, median, minimum, and maximum elevations with the region covered by the elevation posting), which forces users to decide which they want. For simple visualization, the differences should be minimal, and most detailed analyses will use higher resolution data, so the choice likely will make little difference.

4 Shuttle Radar Topography Mission

Military digital terrain analysis was developed using the Digital Terrain Elevation Data (DTED) produced from cartographic sources by the precursors of the National Geospatial-Intelligence Agency (NGA). DTED had 1–3 arc second spacing, a consistent seamless format and used the global WGS datum. The difficulties in getting this level of detail world-wide led to the US military funding the Shuttle Radar Topography Mission (SRTM) in 2000 to collect elevation data over 80 % of the earth's landmass from 60N to 54S (Farr et al. 2007). This collection used radar energy, so clouds did not block collection during a 2 week period which means that it can be regarded as an instantaneous snapshot of earth's topography. The SRTM suffers from two significant drawbacks: (1) lack of coverage in the high northern latitudes and Antarctica, although treaties restricting military operations in Antarctica mean this does not limit the military; and (2) significant voids, especially in deserts and mountainous terrain. Like other radar-derived topography, SRTM data has a speckle or surface roughness which differentiates it from other production methods. The radar used by the SRTM did not penetrate vegetation, so it supplied a first return DSM, although in desert regions the DSM and DTM will not differ significantly. While only the 3″ resolution data is publicly available, Guth (2006, which includes references to other studies with the same result) showed that the 1″ SRTM data had only an effective resolution of about 3″ for geomorphological work, and that the only "advantage" of the 1″ data was an order of magnitude increase in the required storage and processing times.

Table 2 shows the distribution of the major climate regions in the world and the SRTM dataset. The results combine the Köppen classification grid (½° × ½°) (Rubel and Kotek 2010) and distribution of SRTM voids in 6.73 million sampling regions 2.5′ × 2.5′ (arc minutes) in size (Guth 2007). Because the space shuttle's orbit did not extend to latitudes greater than 60°, the SRTM data under represents the D and especially the polar E climates compared to their global distribution, and slightly over represents the others. Holes or data voids in the SRTM DEM exceed 10 % of the area for less than 2 % of the sampling regions, and predictably a large number of the holes occur in the steepest mountain regions such the Himalayas where topographic shadowing occurs. However, most of the holes occur in the arid regions. The concentration of problems in the deserts increases for regions with 50 % holes and 75 % holes (Table 2 and Fig. 2).

The pattern of void regions in the deserts follows the orbital tracks of the space shuttle, along the edges of which the number of radar looks varies (Fig. 2). Guth (2006) showed that geomorphometric characteristics also inherited this artefact, which must result from subtle differences in data quality since the effects are not apparent in elevation or hillshade displays. JPL (2005) indicated that the SRTM mission missed only 50,000 km^2, all in the United States. However, an entire 1° cell in the Sahara (N24E12) was missing both on the download site in 2012 (USGS 2012) and the USGS DVDs (USGS 2006). The current download has that cell, but it is 85 % voids and the straight edges of many of the voids show that orbital tracks strongly influence the locations of missing data. Dry sand limited the radar return to the space shuttle, and with limited passes the likelihood of data voids increased.

Because of the overall quality of the SRTM data, and the lack of viable alternatives over much of the world, filling the holes in the SRTM would greatly improve

Table 2 SRTM voids by Köppen climate classification

Köppen Category	Description	Earth Surface (%)	SRTM Coverage (%)	SRTM 10 % voids 1.69 % surface (%)	SRTM 50 % voids 0.29 % surface (%)	SRTM 75 % voids 0.11 % surface (%)
A	Tropical	20.39	25.08	7.85	2.34	1.44
BS	Steppe	10.97	13.49	3.78	2.87	2.75
BW	Desert	16.55	20.36	48.67	68.51	73.57
C	Temperate	15.08	18.50	18.71	11.59	10.06
D	Continental	21.54	19.73	11.95	8.85	7.60
E	Polar	15.47	2.84	9.04	5.84	4.58

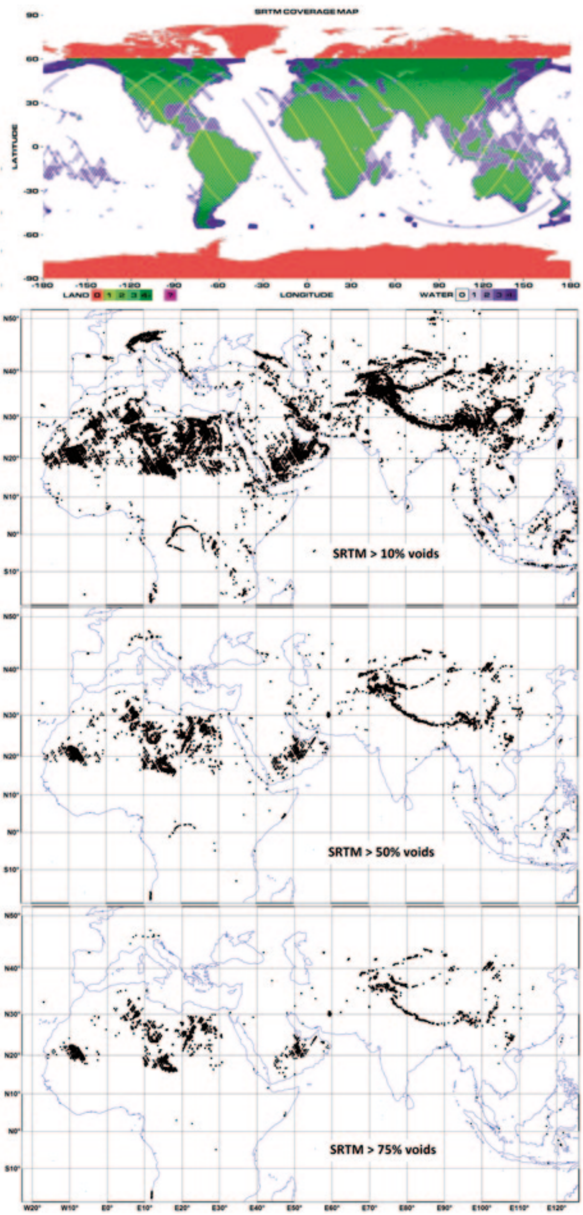

Fig. 2 SRTM coverage and orbital patterns, and voids. The top map shows the number of looks which highlight the curving orbital patterns from NW-SE and NW-SW. The bottom three maps show the void density in Africa and Eurasia. Making the points visible greatly exaggerates the extent of the problem

the usability of the data (Jarvis et al. 2008). This requires an alternate data source, whose accuracy will limit the resulting void filled SRTM data. In areas such the

United States, with freely available high quality DEMs available, the voids could be easily filled, or users could just opt for the higher quality alternative. The SRTM planning placed the lowest priority on covering the United States, and Fig. 2 shows that additional orbits would have been required to complete the coverage, precisely because superior alternatives to SRTM DEMs already existed. In other parts of the world, notably the deserts, there are no good readily available alternatives, and attempts at hole filling resemble alchemy in trying to turn lead (low quality data) into gold. NASA (2013) produced the most recent hole-filling effort. Unless higher quality data exists, in which case the need for SRTM is greatly reduced, the holes will always degrade the quality of the SRTM.

5 ASTER GDEM

The ASTER GDEM covers 99 % of the earth's surface area, between 83 N and 83 S. Because the GDEM uses stereo near infrared imagery, clouds impact coverage and only repeated passes can collect full coverage. Data collection began in 2000, with the first version of the DEM released in 2009 and the second version in late 2011 with additional stereo pairs and improved processing. Numerous published studies found that version 1 of the GDEM had many artefacts and was generally inferior to SRTM 3″ data (e.g. Hengl and Reuter 2011). The analysis that accompanied the release of the version 2 GDEM acknowledged that the GDEM really had a resolution comparable to the 1″ SRTM data, of about 120 m for version 1 and 70–80 m for version 2, and that both the GDEM and SRTM 1″ data might be about 20 % better than the 3″ SRTM data (Meyer 2011). The price for this increase in resolution is additional high frequency noise (Meyer 2011), and the visual quality of GDEM is generally lower than SRTM.

While in general the ASTER data might not provide much improvement over the SRTM, it provides a significant northward extension of coverage, and it offers an independent data set to fill voids in the SRTM data which NASA (2013) used from their version 3.0 of the SRTM dataset. With desert regions having a large portion of the SRTM voids, and often no alternative DEM source for filling the voids, the ASTER GDEM could be a valuable supplement for desert topography.

6 Comparison of SRTM and GDEM

Table 3 shows the results from comparing 1146 1° cells of SRTM and ASTER GDEM version 2, which represent a 7.85 % sample of the total SRTM dataset. Because much of the ASTER data was collected for a study of desert dunes, the sample over represents deserts. The sample was divided into sampling regions ½° × ½° to match the Köppen grid (Rubel and Kotek 2010), leaving 4031 samples after removal of coastal void regions. Because of the problems with excessive noise in low relief topography for both SRTM and ASTER GDEM, the fourth column shows the percentage of the sample regions with an average slope greater than 6% in the SRTM data, which will be termed a moderate slope. The arid climates have the smallest percentages of regions with moderate slope (only about a sixth of the samples with arid climates), and the cold climates have over 90% moderate slopes because the exclusion of the high latitude areas restricts the D and E climates to high mountain regions.

The pattern of correlation coefficients between corresponding elevations in the SRTM and GDEM differs between the complete sample and for those with at least a moderate average slope (Table 3). High values of r show high correlation between the two DEMs (hopefully both are close to the true value), and low values show differences meaning that at least one does not closely measure the true value. Low slope regions have lower correlations because of the increased effects of noise in both data sets. For both the complete sample, and those having moderate slopes, the desert climates have the lowest correlations between the SRTM and ASTER GDEM. Guth (2010) compared SRTM and the first edition of GDEM to high resolution commercial IFSAR data, and that limited sample suggested that correlation coefficients below 0.95 always indicated quality issues in the GDEM. Several papers (e.g. Hugenholtz and Barchyn 2010; Bullard et al. 2011) showed promise for the use of GDEM version 1 for desert geomorphometry, but this result shows that caution must still be exercised even when using version 2 of the data.

7 High Resolution DEMS—IFSAR and LiDAR

The highest resolution gridded DEMs come from IFSAR (Hensley et al. 2007) and LiDAR (Fowler et al. 2007). While these use very different technologies and typically have significantly different resolutions, they share two characteristics: (1) the detailed view of the terrain increases dramatically from that in SRTM or GDEM (Fig. 3), and (2) the technologies allow creation of paired DSM and DTM grids. The second characteristic is most useful in urban and forested regions, and thus is of less importance in desert regions, but increasing detail greatly benefits detailed military planning everywhere. In Fig. 3, the hillshades from the IFSAR and LiDAR show

Table 3 Comparison of ASTER GDEM and SRTM data

Köppen	Sample		Fraction of all sample cells				Fraction cells with slope 6%		
Category	n	Fraction	Slope > 6%	r > 0.99	r < 0.95	r < 0.80	r > 0.99	r < 0.95	r < 0.80
A	736	18.26%	59.65%	61.01%	18.75%	10.05%	85.65%	1.82%	0.23%
BS	175	4.34%	13.71%	55.43%	26.29%	12.57%	100.00%	0.00%	0.00%
BW	2237	55.49%	16.14%	27.13%	41.31%	13.63%	78.12%	4.99%	0.83%
C	622	15.43%	57.07%	70.42%	15.27%	6.59%	99.15%	0.00%	0.00%
D	160	3.97%	90.63%	93.75%	3.13%	0.63%	100.00%	0.00%	0.00%
ET	101	2.51%	99.01%	96.04%	0.00%	0.00%	97.00%	0.00%	0.00%
n	4031		1424	1838	1208	443	1276	26	4

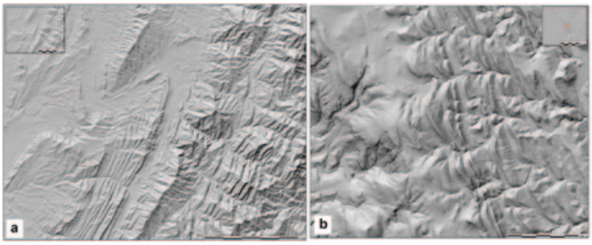

Fig. 3 **a** IFSAR DEM in Afghanistan and **b** LiDAR DEM in Iraq. The corner insets show the same area from the SRTM 3″. The maps have different scales to show the full resolution of the data

the landforms and underlying geology almost as well as high resolution satellite imagery, and many aspects of image analysis can be applied to the elevation data.

High resolution IFSAR data, collected from interferometric radar similar to the SRTM data, has been collected commercially (InterMap 2012) and has been used by the military in the global war on terror (Army Geospatial Center 2014). Its typical resolution of 5 m cannot resolve individual buildings, but as Fig. 4 shows, IFSAR DEMs can show the outline of agricultural compounds in Afghanistan. While the walls may not be crisply delineated, their positions are clear and align with the imagery in Google Earth (Fig. 4b).

LiDAR DEMs increase the level of detail compared to that seen in IFSAR data and can show every building or tree (Fig. 5). While in Iraq LiDAR was used primarily for urban areas and main transportation routes (Army Geospatial Center 2014), in Afghanistan the military sought to create the first country-wide LiDAR dataset for military use. The most common grid spacing in LiDAR DEMs has been 1 m, but current sensors easily support higher resolutions.

Gridded LiDAR data allow a variety of operations, including classification and change detection. Priestnalla et al. (2000) performed building extraction on DSM grids, and specialized filters can find features like domes or minarets that can be key urban terrain features in the Middle East. The relative ease of acquiring LiDAR DEMs allows for multi-temporal views of the ground, which allows change detection. This has been done for coastal erosion (Zhou and Ming 2009) in which the narrow survey swaths from LiDAR prove ideal for pre- and post-storm surveys, for disaster change detection (Trinder and Salah 2011), and potentially for urban battlefields.

A series of point measurements make up a LiDAR collection, and users increasingly use the raw point cloud for both visualization and analysis (Fig. 6). This greatly increases the size of the data files, because the coordinates for every point must be explicitly stored instead of implicitly computed from the position in the grid, and because there are typically several returns for every point in the grid. The increase might be 1–2 orders of magnitude, which presents challenges but no insurmountable obstacles. Because the point cloud can contain a return's location, the intensity (effectively a grayscale image) and a classification code, it allows a significant increase in analysis potential. Point clouds can be classified to extract

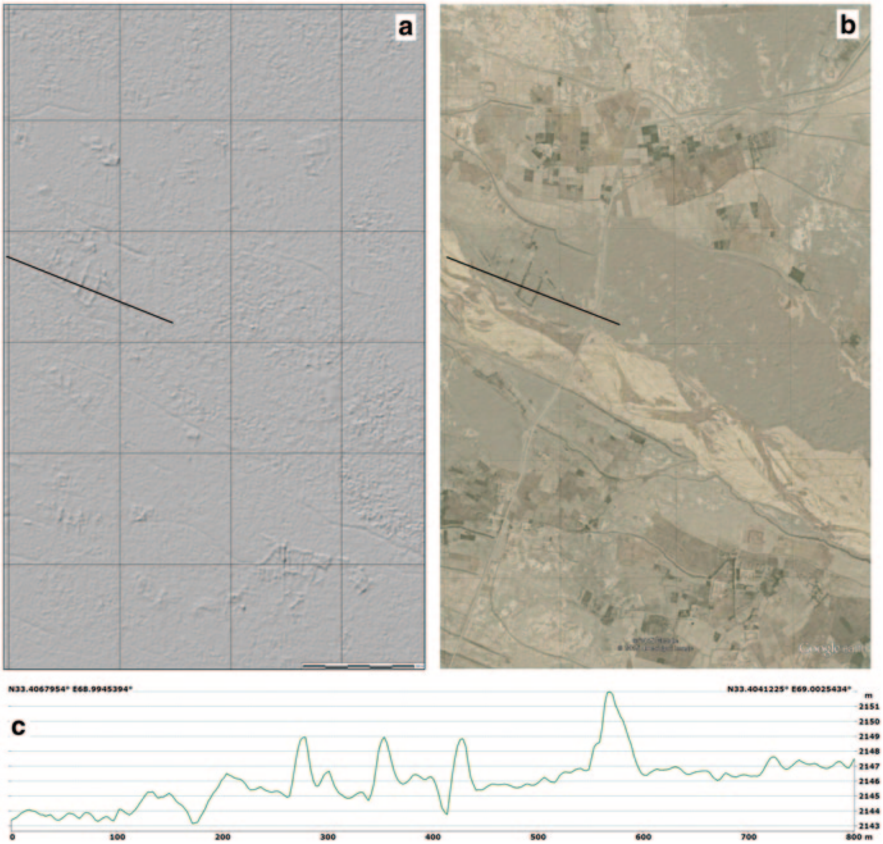

Fig. 4 **a** IFSAR DEM in Afghanistan and **b** Google Earth imagery for an agricultural area. The profile in **c** show the several meter high wall surrounding agricultural compounds. With 5 m spacing, the walls have artificial, gradual slopes

buildings (e.g. Butkiewicz et al. 2008), vegetation (e.g. Evans and Hudak 2007), power lines (e.g. McLaughlin 2006), and transportation features such as bridges (e.g. Sithole and Vosselman 2006). Algorithms for change detection can now use the raw LiDAR point clouds (Butkiewicz et al. 2008). While desert regions do not have significant vegetation, cultural feature extraction offers significant benefit for military operations.

Full LiDAR waveforms, rather than just discrete individual returns (Mallet and Bretar 2009) promise another steep increase in data set size and processing requirements, but also additional information. Most work on full waveforms has been in forestry applications, but the techniques may have unexplored potential in urban areas (Mallet and Bretar 2009). So far the repositories for large LiDAR data sets (e.g. OpenTopography 2012; NOAA 2014), have not provided the full waveforms. Like the change from grids to point clouds, that transition will likely arrive.

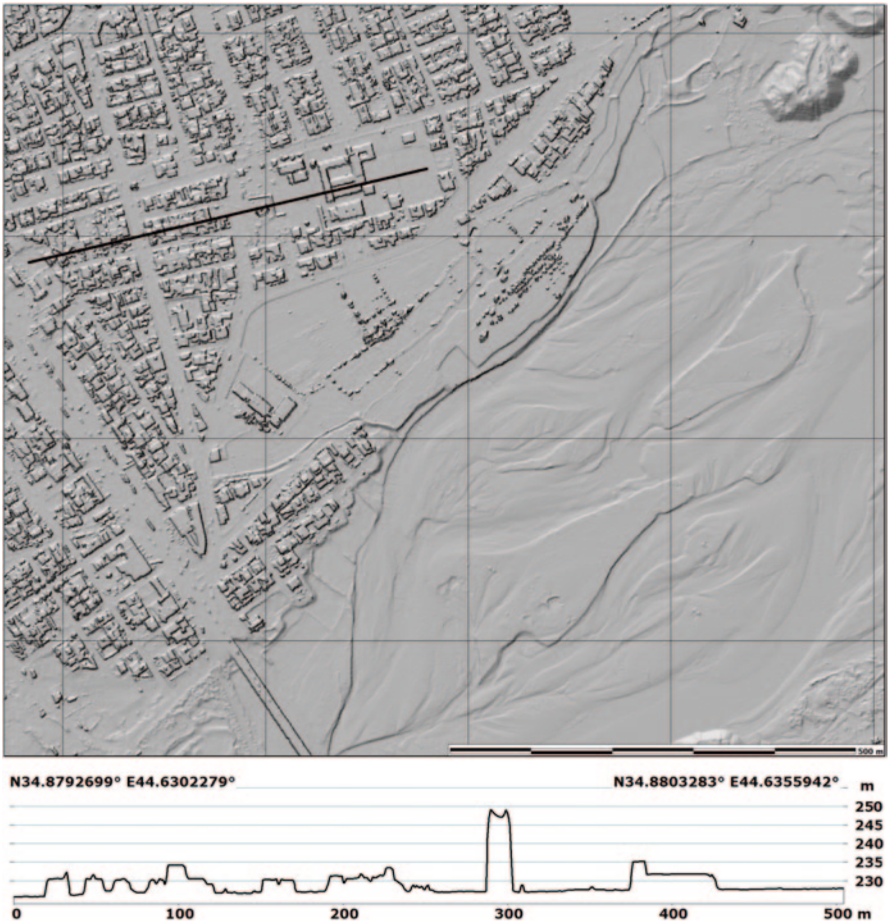

Fig. 5 **a** LiDAR DEM in Iraq and **b** topographic profile. With the 1 m spacing the buildings have a much more realistic depiction compared to the IFSAR DEM in Fig. 4

While the Iraq and Afghanistan wars have been winding down, the desert regions of the world will continue to demand attention. The US Army's Buckeye program has started to deploy in Africa, with the first surveys for LiDAR topography and high resolution imagery in Burkina Faso (Army Geospatial Center 2014). This landlocked west African nation lies at the south edge of the desert belt, and current events suggest increasing emphasis there (Whitlock 2012). In the failed states of the desert belt, feature extraction and classifications from LiDAR and IFSAR data might provide population and development estimates that central governments cannot provide as a significant supplement to conventional imagery analysis.

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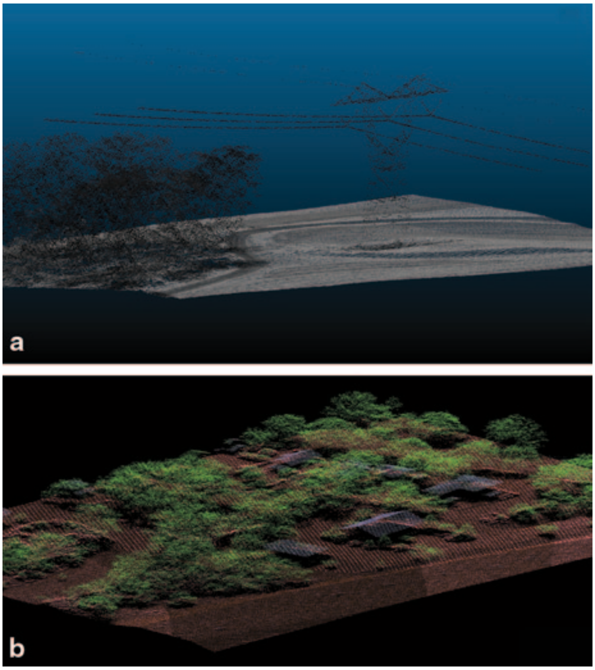

Fig. 6 High density LiDAR point clouds (>10 points/m^2) in Pennsylvania **a** and New Hampshire **b** showing trees, power lines, and buildings

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Military Test Site Characterization and Training Future Officers—An Integrated Terrain Analysis Approach

Steven Fleming, Eric V. McDonald and Steven N. Bacon

Abstract U.S. military equipment has become more sensitive to environmental conditions than ever before, especially with increasing application of sophisticated microprocessors, wireless connectively, and sensors commonly employed on highly maneuverable armored vehicles. Increasing development of military technology requires considerably more comprehensive information about the extreme testing environment (i.e., natural environmental test sites) than was required nearly a half century ago. An all-encompassing research, development, and testing program for current and new designs of tracked and wheeled military vehicles, the primary means of transport for U.S. ground forces, depends on the use of an extensive network of vehicle mobility and durability (i.e., endurance) test courses located in a variety of temperate, tropical, desert, and cold region environments. Most of these test courses consist of unimproved, dirt or gravel roads, primarily developed on the native soil and landscape. Although several of these test courses have been in use for nearly 50 years, many of their geotechnical attributes have not been characterized. In support primarily of the Army's Test and Evaluation Command (ATEC) mission, the Department of Geography and Environmental Engineering (GEnE) from the United States Military Academy (USMA) at West Point and the Desert Research Institute (DRI) characterized numerous test courses at various geographic locations. Since 2007, multiple teams from West Point, primarily consisting of Cadets with supervising officers, have worked in collaboration with DRI to characterize geotechnical attributes of soils along test courses in desert, arctic, temperate and tropical landscapes. These data collection activities also support the Army in providing future officers with field training associated with sample collection and data

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management. The characterization activities focused on making geotechnical measurements, sampling soils, collecting imagery, generating map data, and developing geospatial databases. This effort also included the preparation of databases of in situ geotechnical properties along test courses at representative locations to a depth of ~0.3 m (1 ft) that included the measurements of: soil stiffness and modulus, penetration and shear resistance, bulk density, and particle size distribution. These new data sets will assist the Department of Defense (DoD) and the Department of the Army (DA) in maintaining a varied and detailed inventory of characterized soil-landform assemblages in different fundamental environments from various test sites throughout the U.S. and abroad. In addition, the data collected and the information compiled through these site studies will also benefit the DoD community that tests emerging technologies for the detection and defeat of Improvised Explosive Devices (IEDs), which require significant understanding of the natural variability of both physical and chemical soil attributes.

Keywords Terrain · Mobility · Operational testing · Soil · Tropic · Desert · Temperate

1 Introduction

A growing challenge facing development and testing of current and future military equipment (vehicles to electronics) is the requirement that equipment must work across all global military operating environments: deserts, tropics, temperate, and cold regions. Increased awareness of sensitivities to extreme environmental conditions is needed especially given the expanding dependencies of military weapon systems on microprocessors and sensors that are inherently more affected by climate and other factors (such as atmospheric aerosols, diurnal temperature fluctuations and frequent shock and vibration during transport and deployment) than are mechanical parts. Going forward, military test and evaluation strategies will require greater detail and understanding of the structure, function, and complex interrelationships of the combined landscape and ecosystem. The Department of Defense (DoD), specifically, the U.S. Army Test and Evaluation Command (ATEC), through the Yuma Proving Ground (YPG) is increasingly adapting current scientific knowledge of soils and landforms to improve Technical Operating Procedures (TOP) in developing and testing of military equipment and soldier systems (YPG 2012, YTC 2012). The incorporation of important soil and other detailed terrain information from selected sites across YPG (and other ATEC and foreign) test sites into current and future testing programs has been a major focus of on-going data collection since the early 1990s (ATEC 2014).

For over a decade, GEnE has supported YPG with test site evaluations, terrain characterizations, and soil and image data collection. Many of these evaluations

Table 1 Locations of test sites evaluated by USMA, ARO, and DRI

Test site or military installation[a]	Military operating environment	Integrated activity
Cold Regions Test Center (CRTC): Ft Greely, AK[ab]	Cold regions	Map, soil and terrestrial image data collection
Tropics Regions Test Center (TRTC): Panama[ac]	Tropic	Map, soil and terrestrial image data collection
Mocoron, Honduras[c]	Tropic	Site characterization
Yuma Test Center (DTC): Yuma Proving Ground[ad]	Desert	Map, soil and terrestrial image data collection
Aberdeen Proving Ground (APG), MD[a]	Temperate	Map, soil data collection
Southern Cayo in Western Belize	Tropic	Map, soil and terrestrial image data collection
Fort A.P. Hill (VA)[a]	Temperate	Map, soil and terrestrial image data collection
Afobaka Test Track, Suriname	Tropic	Map, soil and terrestrial image data collection
Camp Pendleton Marine Corps Base, CA[a]	Temperate	Map, soil and terrestrial image data collection

[a] Test site locations where data collected by USMA cadets
[b] Additional test site characterization: Harmon et al. 2008
[c] Additional test site characterization: King et al. 2009
[d] Additional test site characterization: King et al. 2004

also included the participation of DRI subject matter experts from DRI and Army Research Office (ARO) researchers, all working in collaboration with the USMA Cadets and their GEnE supervisors. Test site evaluations conducted since 1998 (summarized in Table 1) involved a range of activities across all major military operating environments. The objective of many of these activities, and part of the focus of this paper, was to integrate training of USMA Cadets in performing geotechnical site characterizations at a variety of test sites that include georeferenced and efficiently organized data, and for YPG (and ATEC) in support of their testing programs. Collected geotechnical data and site evaluations have become and remain critically important to supporting testing of military vehicles and technologies for the detection and defeat of enemy activity (including Improvised Explosive Devices—IEDs), as well as for vehicle endurance testing.

The focus of this paper is threefold: (1) to discuss the need for natural environmental testing using "lessons learned" from U.S. military activities in the tropics of Southeast Asia; (2) to describe the integrated training activities involving the field collection of geotechnical soil data by USMA Cadets; and (3) to evaluate some of the geotechnical soil data collected by Cadets from three diverse environmental settings representing temperate, desert, and tropic biomes.

2 The Need for Environmental Testing Research—A Tropical Climate Example

The history of conflict has documented the challenges for armies to conduct military operations in unfamiliar environments. This is recorded in detail and evidenced through the work of the United States and its coalition partners to successfully adapt operations to the desert climate and landscapes over the period of recent military operations in the Middle East and Southwest Asia from 2001 to 2014. A more striking (and some would argue, worrisome) example of a complex, "unaccustomed" environment, the heat, humidity, and dense biologic setting that characterize the tropical environment have proven a significant "thorn in the side" to U.S. fighting forces for much more than the past decade. History reinforces that the tropics have challenged the U.S. military for over half a century. The U.S. experience during World War II in the Southwest Pacific, in Southeast Asia during the Vietnam War, and, albeit limited, in Panama during Operation Just Cause (1989–1990) clearly demonstrated the hazards to personnel and equipment posed by the extreme tropical environment. From this, two clear lessons emerge: (1) equipment must be tested to assure it can stand up to and perform under a variety of variable and demanding environmental conditions; and (2) units must train in the harshest settings (in this example, tropical climates) to be prepared to accomplish full spectrum operations within these unique domains.

Roughly 15 % of the earth's land mass is classified as tropical, primarily using parameters of climate and land cover; however, 75 % of all international and internal conflicts since 1960 have been in countries whose borders are totally or partially within the wet, tropical environment (King et al. 2009). Researchers examining past conflicts to better understand the security threats of the future have reached the conclusion that the countries lying within the tropics are the most likely locations for future conflicts (King et al. 2009). Further, studies examining the sources of insecurity posed by global environmental degradation regard the tropical regions of Africa, Asia, and the Americas as the most likely locations of instability in the future. Recent operations in Somalia, Rwanda, Haiti, Panama, East Timor, and elsewhere have only reinforced the need to be prepared for tropical conditions. Clearly, by any metric, the DoD must be prepared to deploy and operate successfully in the tropical environment.

2.1 A History of Testing in Tropical Environments

The U.S. and several of its military allies have a long history of operating testing and/or training facilities in the hot, humid tropics (e.g., the United Kingdom in Belize, France in French Guiana, and Australia in its state of Queensland). Guided by requirements in numerous performance military standards (MIL STDs), environmental conditions and their effects are to be given realistic consideration in the research, development, test, and evaluation (RDT&E) process for equipment used in combat by the U.S. military. As a result, testing and evaluation in a variety of environments of equipment and systems, as well as human performance, is well established. The mission of testing in extreme natural environments for the Army resides with the ATEC and is vested with YPG. Presently, this mission is accomplished at desert, cold region (arctic), sub-tropical and tropical test facilities in the United States and abroad. Principal U.S. Army test centers, all operating under the command of the YPG, include: Cold Regions Test Center (CRTC) at Fort Greeley, Alaska (CRTC 2014); desert conditions at the Yuma Test Center (YTC), Yuma Proving Ground, Arizona; and sub-tropical conditions at Schofield Barracks, Hawai'i and routinely in Panama through the Tropics Regions Test Center (TRTC). Most recently, testing through TRTC has been expanded to include testing of heavy tactical vehicles in Suriname and Belize. Testing in temperate and sub-tropical environments is primarily the responsibility of the Aberdeen Test Center (ATC) located at the Aberdeen Proving Ground (APG), Maryland.

Testing of equipment and systems, together with human performance evaluation under tropical conditions, took place in the Canal Zone area of the Republic of Panama as far back as WWI. This mission evolved into the Tropic Test Center (TTC) in 1962, which supported specific Army test functions in response to evolving military needs through the 1990s. In parallel, the Army's Jungle Operations Training Center (JOTC) was operated at Fort Sherman in Panama, conducting individual soldier and collective unit training for the Army and land forces from all services within the DoD. The tremendous value of the JOTC experience- preparing units for missions in the tropics and to develop troop leading skills- was well respected throughout the Army; however, under the terms of the Carter-Torrijos Treaty of 1977, the U.S. military mission in Panama was required to relocate from the country by December 31, 1999.

In 1998, at the request of YPG, the Army Research Laboratory's Army Research Office convened an expert panel to undertake a study to identify areas across the globe that could replace the tropical test environment that was being lost as a result of the Army's departure from Panama. The initial product (first phase) of the study panel examined the DoD (Army) tropical test mission to define the conditions that best provide the environmental challenges needed for tropical testing in the 21st century (King et al. 2009). This study defined the climatic, physical, and biological characteristics of the "ideal tropical test environment" and identified regions of the world that best provided the combined parameters for such an ideal location. Worldwide, 16 areas were identified as suitable localities for DoD tropical testing (Fig. 1). The first group of six geographic areas, ordered in terms of their relative proximity to the continental U.S., included: northern Honduras, the Isthmus of Panama, French Guiana/coastal northeastern Brazil (including Suriname), the southwestern New Guinea lowlands, low-moderate altitude areas of the East Indies in east-central Java and southeastern Borneo, and the Isthmus of Kra in Malaysia. The premier localities in this group for tropical testing were the Isthmus of Panama and the Isthmus of Kra because both areas offer a spectrum of tropical conditions and environments within a compact geographic area. A second group of 10 loca-

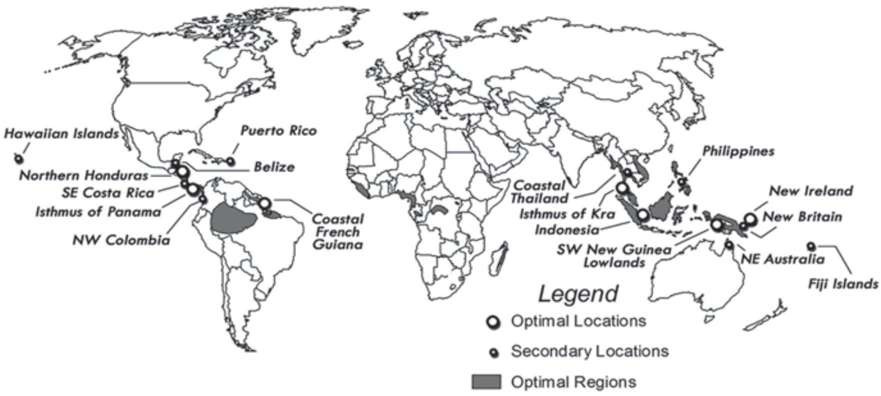

Fig. 1 Optimal locations for developmental and operational tropical testing of military equipment, vehicles, and weapon systems. (from King et al. 2009)

tions was identified that exhibited the general physiographic and biotic character, but failed to provide one or more of the critical elements considered requisite of the ideal tropical environment for DoD testing. This group consisted of coastal Belize, Puerto Rico, southeastern Costa Rica, northwestern Colombia, portions of the Hawai'ian Islands and the Fiji Islands, the Philippines, New Britain-New Ireland, the coastal region of northern Queensland in Australia, and the Bangkok area of coastal Thailand.

2.2 Developing a New Suite of Tropical Test Sites

The second phase of the ARO-led study followed on from the conclusion of King et al. (2009) that no ideal tropical test location existed in the U.S. or in U.S. controlled properties, therefore, a suite of sites should be developed to better support a broad range of environmental requirements for tropical testing and training. The primary product of the second set of tropical testing studies (King et al. 2009) was a geographic characterization model which subsequently was used to evaluate the suitability of candidate sites to the ideal conditions for tropical testing. This model allowed candidate sites to be examined and rated against the critical and important environmental criteria applicable for each type of test to be conducted.

As of 2012, DoD is actively engaged in tropical testing; now employing a suite of sites that has evolved from the results and recommendations of the ARO-led studies conducted from 1999 to 2007. Sites include locations in Hawai'i and capability for selected test studies in Panama, Honduras, Suriname, and, most recently, Belize. The requisite characteristics of the ideal environment for a tropical test facility are derived from complex interrelationships among the key factors of climate, terrain, and vegetation. Climate is the defining characteristic of a tropical region, whereas physiographic and geologic factors are closely associated, and the biologic manifestations (land cover/vegetation type) are a direct function of the combination of climate, physiography, and geology within a given region. Climatic criteria for the humid tropics are defined in Army Regulation, AR 70-38 (Department of the Army 1979), which broadly classifies world climates into four “basic climatic design types.” Each of these design types is characterized by one or more daily weather cycles. Two daily cycles in the ‘basic climatic type’ represent the humid tropics.

According to AR 70-38, the ideal setting for a tropical test facility would lie in a hot and humid tropical climate regime to provide extremes of high relative humidity (RH) in a very high rainfall and near-constant high temperature environment. As such, the area encompassing the site should have annual precipitation in excess of 2000 mm, monthly-averaged minimum temperature and RH in excess of 18–20 °C and 60 %, respectively, and mean monthly temperatures and RH of at least 25 °C and 75 %, respectively. Average rainfall would not fall below 100 mm in any single month, nor exceed 6000 mm per year. These precipitation requirements address a desire for minimal seasonal variability and no impact on vegetation growth patterns (i.e., a preference for no absolute dry season). Regions experiencing tropical cyclone (hurricane or typhoon) activity should be avoided, unless all other physical factors indicate the site to be an optimal location. Ideally, a relatively compact area would exhibit variable conditions of climate (e.g., frequency/distribution of precipitation and temperature) across the spatial domain encompassing a landscape varying from coastal lowlands to steep mountainous relief.

The requirements defined in the ideal test environment are best met by an area of sufficient size to contain the test mission, possessing significant variations in slope and relief across the site, with surface streams sufficiently large to support a variety of tests, surrounding land use that is compatible with the testing mission, and the absence of cultural/historical resources or conservation pressures that could infringe on testing. The area should not be a high-risk zone in terms of frequency of natural hazards (e.g. tropical storms, volcanic activity, earthquakes, landslides, flooding, etc.). Also, it should not be affected by significant adverse anthropogenic activities (e.g. high adjacent population density, upstream pollution from urban, industrial, and/or farming activities). Soils need not be a specific type, but must be of sufficient thickness and health to support a diverse suite of lush tropical vegetation and offer significant challenges to the mobility of troops and vehicles.

Given the specific climatic, topographic and geographic constraints listed above, the major biological considerations for a tropical testing site are specific tropical vegetation characteristics, soils unique to tropical landscapes, and the presence of a diverse community of tropical above- and below-ground organisms. Today, as in the past, military interest in tropical vegetation is based on the forest structure and distribution in both horizontal and vertical dimensions as challenges to vision, mobility, communication, and performance of personnel and equipment. For other organisms, especially microbes, concerns focus primarily on sufficient density to produce high rates of the metabolic processes and by-products that foul physical material and interfere with equipment and systems. According to the model developed by King et al. (2009), the ideal tropical environment has been defined by 14 variables related to climate, physical setting, and biologic conditions. The regional and site specific tropical environment studies conducted by King et al. (2009) and the desert and cold regions studies undertaken by King et al. (2004) and Harmon et al. (2008), respectively, have greatly advanced the ability of the DoD to understand the complexities of different extreme environments and, therefore, how best to test in them (King et al. 2009).

3 USMA Cadet Data Collection, Management Methodology, and Procedures

Lessons learned from the history of incorporating environmental considerations into test strategies indicate the current and future importance for a global-based approach in testing and evaluation. One of the issues confronted in conducting test site evaluations (Table 1) was lack of geotechnical terrain and soil data that would provide both local data for test operations, as well as a means to compare geotechnical data among major test sites. The need for comparative geotechnical data inspired DRI and YPG to develop a research project where USMA Cadets would use field collection of geotechnical data as a field training exercise that would support students in the GEnE program of study and provide YPG and ATEC with important test site information (Fleming et al. 2009a, Fleming et al 2009b).

A principal component of USMA and DRI efforts to provide geotechnical soil data to the U.S. Army is the training of Cadets in procedures in the collection and analysis of field data. Training activities included: (1) field identification and properties of soil and terrain features; (2) learning the operation of field equipment; (3) learning data preparation and sampling methodologies, including proper documentation to record field data; and (4) developing leadership skills among field team members in formulating a daily work plan for collection of data. Collection of geotechnical data primarily occurred over a three week operational period. Cadets were also required to efficiently organize and geo-reference geotechnical engineering (soil characterization) data and imagery data into a final report organized for efficient retrieval and future examination, analysis and test community use. Military installations selected for Cadet field activities included test and training areas (e.g., Fort Greely, Yuma Proving Ground, Camp Pendleton, Aberdeen Proving Ground, and in Panama) that are critically important to supporting testing of military vehicles and technologies for the detection and defeat of enemy activity (e.g., IEDs).

Specific information collected by the USMA Cadets at each test site included: (1) exact coordinate locations; (2) soil stiffness and modulus; (3) soil moisture and density; (4) soil penetration and shear resistance; (5) two physical soil samples (one at 0–6 in. (0–15 cm), and another at 6–12 in. (15–30 cm) deep); and (6) terrestrial imagery (see Tables 2 and 3 and the discussion that follows).

Table 2 Sample data collection sheet used during field data collection

Site no.	Proposed location		Actual location		Elevation (m)	Date of test	Start time	End time	Humboldt (0–6″)		Humboldt (6–12″)		Troxler						Samples collected	Comment
	Northing	Easting	Northing	Easting					Y (Mpa)	S (MN/m)	Y (Mpa)	S (MN/m)	Depth (″)	DD (PCF)	WD (PCF)	WD (PCF)	M	%M (%)		
1																				
2																				
3																				
4																				
5																				
6																				
7																				
8																				

Table 3 Types of geotechnical data collected and methods or equipment used

Measurement or data collected	Equipment	Notes	Reference
Coordinate data	Trimble Nomad and Trimble GeoXT, Garmin GPSMap60Csx, Garmin Rino520HCx	GPS used to locate selected sites	Trimble 2009a; Trimble 2009b; Garmin 2007a; Garmin 2007b
		Data collected at each sample site	
		Time of collection, PDOP, weather conditions, trail/road classification	
Soil stiffness and modulus	H-4140 Humboldt GeoGauge	3–5 measurements at ~2 m separation parallel to direction of trail or road	Humboldt 2009a
		Measurements at surface, 6 in.	
		Loose surface material (gravel, litter, vegetation) removed from surface	
		Stiffness in MN/m	
		Young's modulus Mpa	
Moisture content and bulk density	Troxler Roadmaster nuclear density gauge	Readings at 0, 2, 4, 6, 8, 10, 12"	Troxler 2009; Humboldt 2009b
		Not used at all sites	
Soil penetration and shear resistance	Rimik digital static cone penetrometer (CP40)	Surfaced only	Rimik 2009
		Depth > 10	
		Refusals noted	
		10 measurements per site	
Physical soil samples	Shovel	Bulk soil samples: 0–6", 6–12"	
		Sampled from 1 Geogauge excavation	
ArcGIS geospatial database	ESRI's ArcMap	Maps produced showing sample locations	ESRI 2012; Li 1997
Terrestrial image collection	iPIX® system	Provides interactive 360° field of view	Minds-Eye-View 2009

3.1 Collection of Geotechnical Data

3.1.1 Site Selection

Collection sites were selected by DRI scientists to focus on soil and landform assemblages that provide the best analogs to terrain attributes present in current places of strategic interest to the U.S. military (e.g., Iraq, Afghanistan, Iran, North Korea, etc.). Locations were selected using existing map data (e.g. Bacon et al. 2008) when available and supplemented with field reconnaissance of each sample area. A complete list of sample sites with location and general landform-type attribute data were provided to the Cadets prior to the start of each project.

3.1.2 Coordinate Data

Coordinate data were collected at each sample site using Global Positioning System (GPS) technology with a Trimble Nomad (Trimble 2009a), Garmin GPSMap60Csx, or Garmin Rino520HCx receivers (Garmin 2007). Attribute data were also annotated on field collection sheets, including time of collection, PDOP (position dilution of precision), weather conditions, and trail classification and/or test course. When available, receiver accuracy was evaluated twice per day by comparing a point collection (as detailed above) to local survey control points. The commercial mapping software package from ESRI (e.g., ArcMap) was then used to create point shapefiles for each of the individual sites to be plotted on maps.

3.1.3 Soil Stiffness and Modulus

The H-4140 Humboldt GeoGauge (Humboldt Manufacturing Company 2009a) was used to record the stiffness and modulus at each site (Fig. 2). The GeoGauge measures the lift stiffness and soil modulus (i.e., elasticity) which is the ability of a soil to maintain its structural integrity under a given amount of applied force. At each sample location, two GeoGauge measurements were made at three different places, spaced about 2 m apart with one reading taken at the surface and a second reading at 15 cm below the surface (after hand-excavation). Loose organic litter (leaves, twigs, branches, etc) were removed from the top of the soil before measurements were taken. Soil strength (in terms of stiffness) was recorded in MN/m and Young's Modulus was recorded in MPa.

Fig. 2 West Point cadets and a DRI researcher prepares to record data with the Humboldt GeoGauge in Yuma, AZ

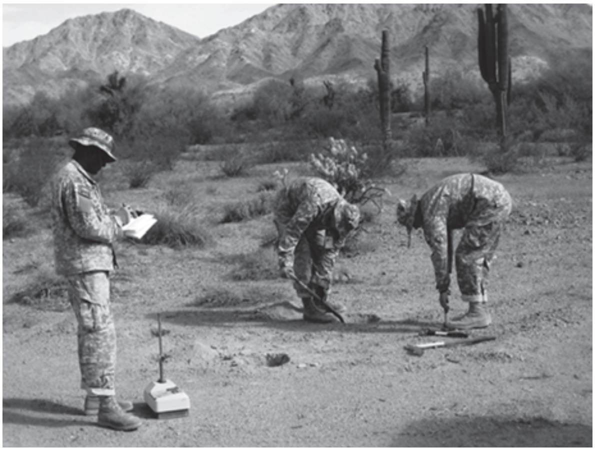

Fig. 3 Cadets collect data with a Nuclear Density Gauge in Yuma, AZ

3.1.4 Density and Moisture Content

In addition to soil stiffness and modulus, measurements of soil density and moisture content were also collected using a HS-50001EZ nuclear density gauge (Fig. 3; Humboldt Manufacturing Company 2009b). Specifically, the gauge produces readings for wet density, dry density, moisture content, percent of moisture, percent of compaction of a known Proctor or Marshall curve, void ratio and air voids. The instrument emits radiation from Cesium 137 within an external probe and the response by the soil target area is then directed back towards onboard sensors. Essentially, the strength of radiation returning back to the instrument sensors through the soil is proportional to the soil moisture content of the target area. Field measurements were taken at 12, 10, 8, 6, 4 and 2 in. deep by inserting the gauge's probe into a 12 in. deep hole in the ground created by Cadets. Surface measurements were also recorded. Five different sets of measurements were taken at each depth interval at each site that include: dry density (in pounds per cubic foot, PCF), wet density (PCF), water content by weight (lb water/lb soil), and percent moisture content (%).

3.1.5 Soil Penetration and Shear Resistance

Soil penetration and shear resistance were collected using a Rimik CP4011 cone penetrometer (Fig. 4; Rimik 2009) at TRTC and YPG. Essentially, the collection tool is used to analyze soil penetration resistance or bearing capacity. The cone is inserted into the ground by the operator applying a continuous downward force until the cone cannot penetrate any deeper. Penetration (in cm) was measured by applying steady pressure to the penetrometer and analyzing the depth of soil penetration by the cone. In addition, shear resistance (in kPA) was computed by the cone penetrometer system for each measurement. A total of ten measurements were taken at each site and stored in the penetrometer. The data was later extracted from

Fig. 4 Cadets collect soil data in Panama using the Cone Penetrometer

the penetrometer as part of the data post-processing procedures. The data from the penetrometer was identified and distinguished by site using the data/time stamps stored onboard the device. All data values were recorded if the instrument achieved a penetration depth of 10 cm or greater; otherwise, a re-test was conducted. After a re-test, the data was recorded if the minimum penetration was reached (10 cm) or "refusal" if the minimum depth was not obtained. For recorded data, the instrument displays a graph showing soil resistance by depth. In desert terrain, some of the sites had rocky or heavily compacted soil and resulted in a large number of readings not achieving the minimum penetration. Penetration resistance was also measured at APG, but with a different type of instrument, which consisted of a Humboldt HS-4210 digital static cone penetrometer (Humboldt Manufacturing Company 2009c).

3.1.6 Physical Soil Samples

Two separate bulk soil samples were taken from each site for laboratory analysis, primarily for particle-size distribution determination (i.e. texture) and soluble salts in desert terrain or iron oxides in tropical terrain and cold regions. One sample represented the soil from the surface to a depth of 0–15 cm (0–6 in.) (Fig. 5). The second sample represented the soil from a depth of 15–30 cm (6–12 in.).

3.1.7 Terrestrial Image Collection

The collection of terrestrial imagery was conducted with the iPIX® system (Minds-Eye-View Inc 2009) in order to provide interactive visual references of the sample locations. A Nikon CoolPIX 8700 or CoolPIX 6100 hand-held camera was used to collect the imagery (Fig. 6). The camera was equipped with a specialized fisheye lens which captured a 185° field of view (FOV) at the focal point. In addition, a cus-

Fig. 5 Cadets conduct a soil sample collection in a low area along a trail network in Alaska

Fig. 6 Cadets collect iPIX ® imagery in Alaska

tom-designed, tripod-mounted bracket held the camera in place which enabled two pictures to be taken from opposite. The result from this image collection method was two 185° FOV photos from the same focal point, pointed in the exact opposite directions. Before collection of imagery, the camera was adjusted to account for the fisheye lens attachment as well as the variability in lighting due to rotation of the camera during collection of image pairs. A north-facing orientation marker was placed on the ground in each scene in order to provide a directional reference within the imagery when post-processing. The two photos collected were then integrated ("stitched" together) using specialized software, producing a 360° interactive iPIX product. From this, a user is able to explore the entire 360° area captured in the photograph from the viewpoint of the camera, giving a complete all around view from where the iPIX system was located.

The geospatially-reference field data collected by the Cadets were then cataloged and entered into an ArcGIS geospatial database (ESRI 2012; Li 1997) for future analysis by the academic community and test/evaluation command. High spatial resolution satellite imagery was also used in generating the mapping products (DigitalGlobe 2004; Emap International 2002; Geoeye IKONOS 2009). Current GIS data standards (e.g., DIGEST) were used in the generation of these products to insure that the data was sharable with other DoD geodatabases (Chan 1999). This database is now accessible both on external hard drives, as well as from a secure, on-line portal for those conducting future research and testing on current and future landscapes of interest to DoD.

4 Examples of Geotechnical Data Collected from Tropical, Temperate, and Desert Test Sites

Geotechnical data collected by the USMA Cadets provides a means to compare soil properties illustrating differences between among the three very diverse test site settings represented at APG, YPG, and TRTC. The data collected from these sites reflect a range of soil conditions from engineered to disturbed and undisturbed native soils within temperate (APG), desert (YPG) and tropical (TRTC) environments (TRTC 2012). These three sites are selected for discussion because they have the most complete data that was collected by the Cadets, and when taken together, these sites illustrate important differences in geotechnical and soil properties between tropical test sites and the temperate and desert test sites in the U.S. where the majority of testing of military equipment occurs.

The geotechnical data for APG was collected from three principal vehicle test courses each composed of an improved, hard packed, road surface consisting of a layer of an engineered mix of imported soil consisting mostly of moderately-graded (moderately-sorted) silty sand with gravel from distant river burrow sources and lesser proportion of road surfaces composed of a mix of the important granular soil with fine-grained native soil. The APG test road conditions are basically an improved dirt road surface designed and maintained to minimize variation in surface characteristics and geotechnical properties over time related to frequent use. Geotechnical data from YPG was collected from a wide range of dirt and gravel roads used for testing vehicle durability, counter-IED technology, and transportation. Most of the measured sites are roads graded ("bladed") into the native alluvial gravelly soil and with minimal efforts to improve or maintain. The geotechnical data collected from the TRTC locations in Panama included a variety of dirt roads, footpaths, and firing ranges used for testing a wide range of military equipment. Most of the measured sites are either roadways or cleared surfaces graded into the native soil with minimal efforts to improve or maintain. Footpaths were largely developed based on frequent use (McDonald et al. 2006).

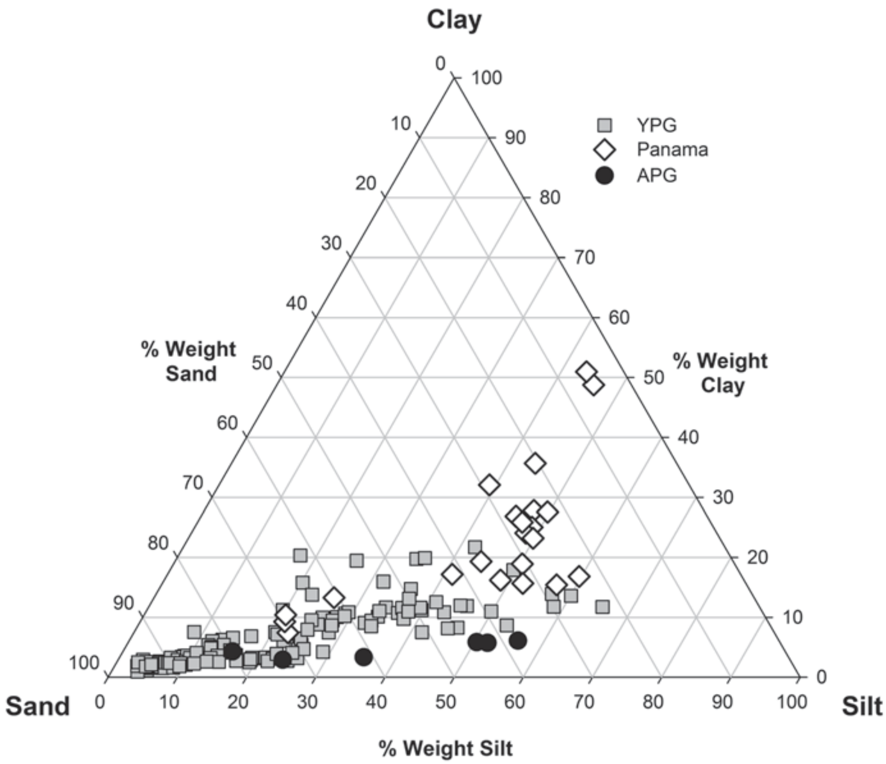

Fig. 7 Ternary diagram showing ratio of sand, silt, and clay content for soil samples collected from *APG, YPG*, and *TRTC*. Particle size measured using standard laser light scattering techniques. (ASTM 2000)

4.1 Soil Texture Results

Comparison of soil texture data illustrates how each test setting is different (Figs. 7, 8). Soils from the TRTC generally contain more silt and clay and less gravel relative to the soils at both YPG and APG. Soils at the TRTC are formed in strongly weathered volcanic rocks under high precipitation and high temperate, conditions that typically yield fine-textured soils. By comparison, soils at YPG are generally formed in poorly weathered gravel- to cobble-rich alluvium derived from igneous and metamorphic rocks under low precipitation and high temperature climatic conditions. Much of the silt and clay in the soils at YPG is from the long-term accumulation of desert dust that infiltrates into the shallow subsoil (McDonald and Caldwell 2005; Caldwell et al. 2008). Only a few of the samples from APG could be analyzed because of the hard consistency (soil strength) of the road surface. Clay content is low at APG, with variation largely in the sand, silt, and gravel content because of the gravelly sand barrow source. Native soils around the APG test roads are

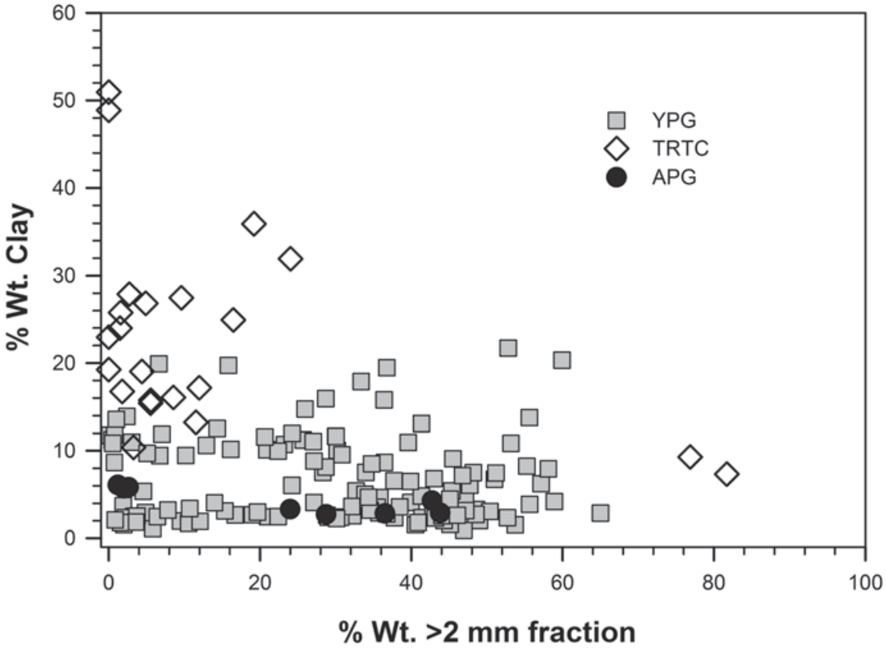

Fig. 8 Comparison between % weight gravel (>2 mm size fraction) and % weight clay for *APG, TRTC*, and *YPG*

primarily fine-textured, alluvial and estuarine deposits associated with the coastal plain that fringes Chesapeake Bay.

4.2 GeoGuage Results

GeoGuage measurements of Young's modulus and stiffness vary considerably among the three sites (Fig. 9). Generally, Young's modulus is a measure of a soils resistance to deform due to shear stress (i.e. soil strength) and stiffness is a measure of the resistance to bending (i.e. load capacity). The hard-packed, engineered soil surfaces of the test courses at APG have the highest mean value for Young's modulus relative to either TRTC or YPG due to compacted soils. In contrast, the mean value for stiffness at APG relative to either TRTC or YPG is similar (within uncertainty) and much lower, respectively. This is likely due to the roadbed at APG composed of relatively uniform and fine-grained soil that was not dry at the time of testing similar to TRTC, albeit with greater sand and lower moisture contents. By comparison, the soils (roads, firing ranges, and footpaths) at TRTC have low values of Young's modulus and stiffness reflecting the low resistance to deformation typical of the largely moist and gravel-poor character of clay-rich tropical soils. The

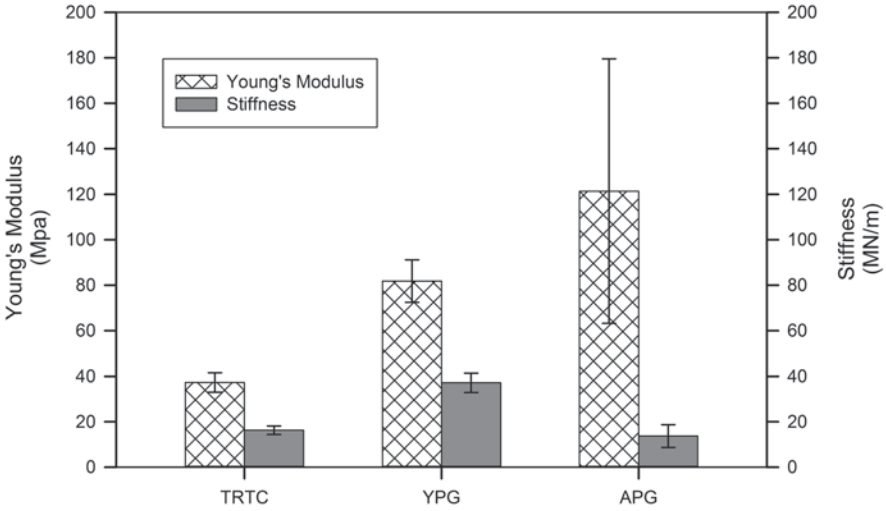

Fig. 9 Bar chart showing mean values (*top* of bar) for Young's modulus and soil stiffness as measured using a Geogauge. Vertical error bars for 1 σ standard deviation

values for Young's modulus and stiffness soils at YPG lie between the values for TRTC and APG largely due to the typical character of desert soils formed in weakly consolidated alluvium that consist mostly of gravel and sand mixtures with high pore (void) space. In addition, the dry and coarse-grained nature of the desert soils with subrounded particle shapes at YPG also inhibits soil compaction, even when subjected to similar vehicle traffic impacts to what occurs at APG.

4.3 Cone Penetrometer

Results from cone penetrometer measurements reflect large variations in soil strength similar to the trends in the GeoGauge data (Fig. 10). Penetration resistance was highest at APG with all road surface measurements exceeding the penetrometer resistance maximum of 5600 kPa (100 % refusal). Mean penetration resistance was considerably lower for TRTC (0 % refusal) and YPG (51 % refusal). Differences in resistance reflect the compaction of the road surface (highest at APG), variation in relative amounts of gravel (greatest at YPG), and soil moisture and fine-textured soil (highest at TRTC).

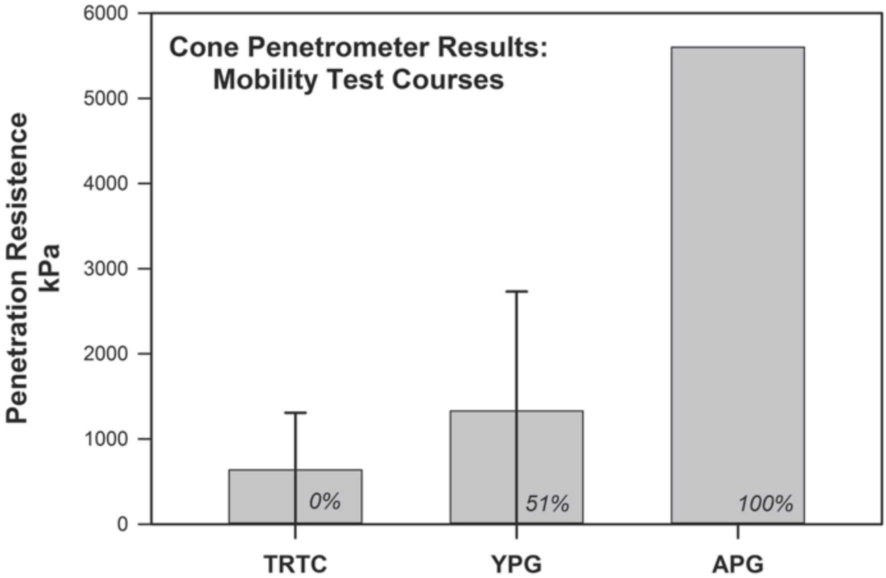

Fig. 10 Bar chart showing mean values (*top* of bar) for penetration resistance measured using a cone penetrometer. Vertical error bars for 1 σ standard deviation (no value for *APG*). Percent values show proportion of measurements where refusal (i.e. no penetration) occurred

4.4 Moisture Content and Bulk Density

Soil moisture and bulk density was measured with a nuclear density gauge at the TRTC and YPG (Figs. 11, 12). Not surprisingly, moisture contents of soils at TRTC are considerably higher than the moisture contents at YPG reflecting the large difference in precipitation between the tropic and desert test sites. Mean bulk density is higher at YPG than at TRTC and is primarily due to the abundance of gravel within the soil at YPG relative to the fine-grained and weathered soils at TRTC.

5 Summary and Conclusions

U.S. military equipment will become more sensitive to environmental conditions because of technological advancements and will require more comprehensive information about the testing environment (test sites) compared to test site information that was required half century ago. A long history of testing military equipment under extreme tropical conditions has demonstrated that extreme tropical conditions will have a considerably different impact on the operation and durability of military equipment relative to other military operating environments. Moreover, continued research, development, and testing of current and new designs of tracked and wheeled military vehicles will continue depend on an extensive network of ve-

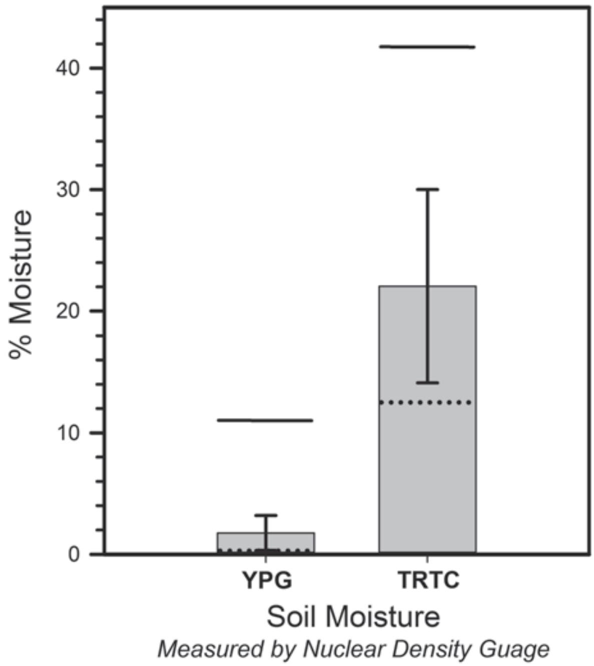

Fig. 11 Bar chart showing mean values (*top* of bar) for % volumetric soil moisture measured using a nuclear density gauge for soils at *YPG* and *TRTC* (no data for *APG*). Vertical error bars for 1 σ standard deviation. *Upper horizontal line* is maximum measured soil moisture and *lower dotted line* is minimum measured soil moisture

hicle mobility and durability test courses located in a variety of temperate, tropical, desert, and cold region environments. Most of test courses currently used consist of unimproved, dirt or gravel roads primarily developed on the native soil and landscape. Although several of these test courses have been in use for nearly 50 years, many of their terrain and geotechnical attributes have not been characterized.

Since 2007, multiple Cadet teams from the USMA's GEnE department have worked with DRI SMEs to characterize soils in desert, arctic, temperate and tropical environments. This work provides direct support to ATEC in the development of data collection methodologies for test site evaluation and follow-on products about many of DoDs primary test sites. The importance of proper test site characterization is not a new idea; future use of equipment by personnel is often only as accurate as the knowledge of and proper correlation to the test site where it was fielded. The different test site biomes are distinctly different, requiring extensive characterization work before testing is initiated and/or completed. For this work, specific collection protocols included soil sample collection, soil characterization at depth, terrestrial (iPIX ®) image collection, and positional location. In all cases, preliminary learning, on-site preparation, followed by weeks of collection efforts have proven successful in characterizing numerous sites, representative of varied climates. Final field collections have resulted in over 500 soil samples with corresponding in situ

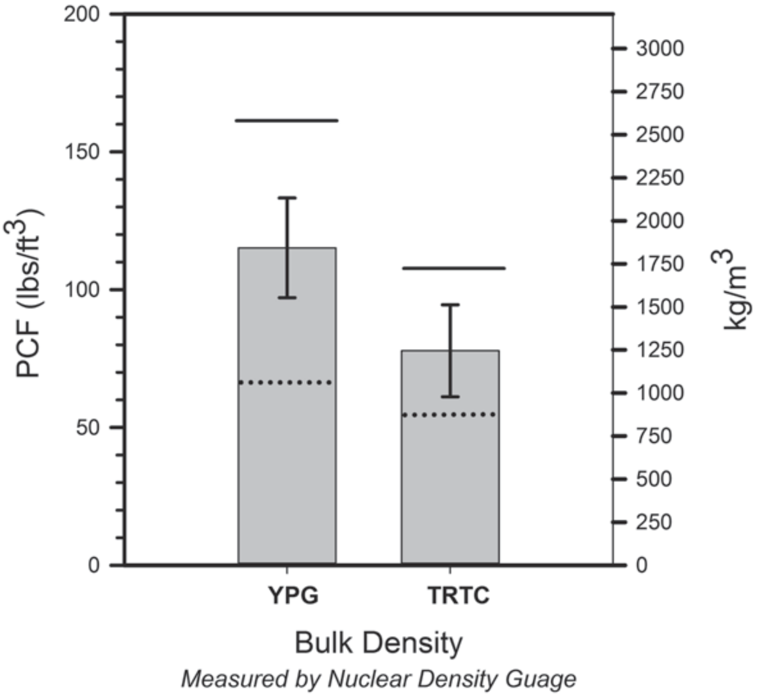

Fig. 12 Bar chart showing mean values (*top* of bar) for bulk density measured using a nuclear density gauge for soils at *YPG* and *TRTC* (no data for *APG*). Vertical error bars for 1 σ standard deviation. *Upper horizontal line* is maximum measured bulk density and *lower dotted line* is minimum measured bulk density

geotechnical properties and iPIX ® terrestrial imagery of each site. The sample data and images of each test site have since been linked in a geospatial database (ArcGIS data files) for each test course. USMA Cadets and faculty have been provided a hands-on, application-based learning experience to heighten their understanding of data collection. Further work by USMA with DRI and YPG is planned for future years, whereby needed characterization of ATEC test sites (and other DoD sites) are necessary. In addition to providing the DoD with new and updated data sets, this applied research serves as an ideal opportunity for USMA Cadets and faculty to apply their knowledge and skills of environmental science and geospatial information science in support of the Army's test community.

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Use of Ground-Based LiDAR for Detection of IED Command Wires on Typical Desert Surfaces

Eric V. McDonald and Rina Schumer

Abstract The potential for using ground-based LiDAR to detect representative improvised explosive devices (IED) triggering command wires was investigated using a simple field test and complex image analysis. Six typical desert soil surfaces, ranging from smooth compacted silt to rough loose gravel, where scanned using a LiDAR (terrestrial laser scanning) mounted on a tripod at about 1.8 m above the ground surface. Identification of wires in scanned images was evaluated using surface elevation (microtopography) and surface image intensity (reflectance) with best results using image intensity. Wire detection required segmentation of intensity images using only the lowest 1 % reflectance values and detection of linear elements using algorithms that combines the LoG edge detection method and the Hough Transform function. Wire detection was possible only for wires greater than 3 mm and only for surfaces with the lowest surface roughness. Results indicate that LiDAR may be able to detect command wires at the ground surface using image intensity but critical issues such as rapid image and data processing would be required to utilize LiDAR imaging of surface, especially for application of LiDAR from a moving vehicle.

Keywords Surface cover · Geomorphology · Soil · Microtopography · Image analysis

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1 Introduction

Improvised Explosive Devices or IEDs are responsible for many casualties in asymmetric warfare. The use of IEDs has risen steadily since 2003 accounting for almost 70 % of the casualties in both Iraq and Afghanistan (JIEDDO 2010). Various methods have been used to trigger IEDs with command wire, radio, cell phone, and direct or pressure plate contact being the most common. Success in the development of methods that jam or disrupt the radio or cell phone signals used to trigger IEDs during operations by US and Coalition forces in Iraq and Afghanistan resulted in higher use of command wires. Detection of the command wire before detonation is currently the best method for defeating the IED device and any method that enhances wire detection may be of benefit to the warfighter.

Detection of command wires is extremely difficult because of background interference from clutter, topography, and because the wire may be buried in places. Common methods used to detect command wires include hand-held devices (e.g. ground penetrating radar (GPR), metal detectors) which require use by dismounted troops (McCullough 2012). Vehicle mounted methods include optical, infra-red, and GPR. Airborne methods include change detection based on evaluation of high resolution terrain images (i.e. identification of changes to the soil surface related to emplacement of IEDs from footprints to excavations) and synthetic aperture radar (SAR). All of these methods have had various levels of success, with dismounted use of metal detectors and GPR being increasingly successful (McCullough 2012).

Methods of command wire detection using light detection and ranging radar (LiDAR) have not been investigated relative to other technologies (e.g. GPR, SAR, metal detectors) even though the expanding applications of LiDAR provide new capabilities for the detailed characterization of the soil cover and surface microtopography. Aircraft mounted LiDAR has successfully been used for real-time identification and avoidance of linear features such as power lines or support lines (McLaughlin 2006). Aircraft type applications are able to distinguish hanging wires from linear features such as roof lines and the horizon. The use of LiDAR for detailed morphologic and volumetric surface change analysis has created a revolution in geomorphic characterization of land surfaces. Sub-centimeter precision of the measurements available with terrestrial laser scanning (TLS) systems provides quantification of microtopographic features, allowing for laterally-continuous surface characterization and rapid data collection. The high resolution characterization of the surface using ground-based LiDAR should provide sufficient capabilities to separate linear wires against an uneven surface background. Detection of wires flush with a rough ground surface, however, creates additional algorithmic challenges especially given the low angle associated with vehicle-based applications and close proximity of the wire to the ground.

The purpose of this study is to evaluate the potential for using ground-based LiDAR (e.g. vehicle-mounted rather than airborne) for the detection of command wires against common desert ground surfaces associated with dirt roads or trails (i.e. not paved) that typically would be encountered during military operations in deserts. Project objectives require identification of (1) the appropriate metric for visualizing wires and terrain, (2) algorithms for automatic detection of linear features that may have curvature in any plane, and (3) algorithms to reduce false positive identification of linear features like road edges or vehicle tracks. First, a thin wire across or near a rough surface may not stand out as an elevated feature in a 3-D point cloud and may also be partially hidden from the scan by microtopography. In this work, terrestrial LiDAR scanning was conducted on a variety of geomorphic surfaces to determine the general capability of terrestrial LiDAR systems and processors to automatically detect surface wires of various material and thickness.

2 Methods

2.1 Desert Study Sites

The area selected for this study lies north of Yuma, Arizona within the Sonoran Desert (Fig. 1). The study area includes a wide range of landforms that occupy the valley between the Muggins and Laguna Mountains that typify many arid desert regions where un-improved roads and trails are common. Six types of geomorphic surfaces were selected for their similarity with landforms common to Iraq and Afghanistan (Table 1; McDonald et al. 2009; Bacon et al. 2008). Surfaces selected included (1) an active sandy-gravel ephemeral wash, (2) a Holocene age fluvial terrace with cobble-rich bar and swale surface topography, (3) a Pleistocene age alluvial fan surface with a well-develop desert pavement locally disturbed and compacted by vehicles, (4) a recently graded, sandy-silt road surface developed across a Pleistocene age alluvial fan surface, (5) a gently-sloping sand dune surface; and (6) a gravel-armored hillslope within badlands formed from deeply incised and eroding alluvial fans (Fig. 2). Most of the sites are areas where vehicle activity is common and the surfaces have noticeable vehicle tracks.

Fig. 1 Map of the southwest U.S. showing approximate location of study area (star) near Yuma, Arizona.

Table 1 General site characteristics of the six surfaces used in this study

Site name	Landform	NRCS[a]: Soil cover texture	USCS[b]: Soil classification	Primary surface features	General surface relief (cm)	Geologic age of landform
Wash	Active, ephemeral wash	Very gravelly sand	Well-graded gravel	Bar and channel, vehicle tracks	±10	Modern
Young fan	Alluvial fan surface	Very gravelly/cobbly sand	Poorly graded gravel	Bar and swale, few vehicle tracks	±25	Holocene
Old fan	Alluvial fan surface	Very gravelly loam	Silty gravel	Smooth desert pavement, multiple vehicle tracks	±20	Pleistocene
Road	Alluvial fan surface	Loam to silt-loam	Silty sand	Bladed smooth compacted surface, multiple vehicle tracks	<5	Pleistocene
Sand	Active, sand surface	Sand	Well-graded sand	Small ripples, few vehicle tracks	±5	Modern
Badlands	Toe-slope, highly eroded alluvial fans	Gravelly silt-loam	Silt to clay: high plasticity	Small rills and channels, common vehicle tracks	±50	Pleistocene

[a] Natural Resources Conservation Service
[b] Unified Soil Classification System

2.2 Field Methods

Eight wires of varying diameters (0.4–3.7 mm), all considered analogs for the most commonly used command wires for triggering IEDs (Table 2), were used in the wire identification study. Wires were stretched for a distance of ~7 m between two wooden boards ~4 cm in width. Each wire was spaced 45 cm apart along the lateral length of the board in order from coarsest to finest gauge. The eight wires and frame were stretched across each surface prior to the laser scanning with the boards held in place using metal rods driven into the soil. The size of the area scanned included both the wire frame and several meters of the surface surrounding the frame and wires.

LiDAR data were collected with a Leica Geosystems ScanStationII terrestrial laser scanning (TLS) system at a resolution of ~3 mm in the center of the wire frame setup. The LiDAR unit was positioned on a tripod with the lens height of ~1.8 m above the ground. Point clouds become increasingly diffuse as the laser footprint fans out beyond the specified distance or area of interest. Point locations are recorded as the return signal from a continuous laser output that is interrupted momentarily using a series of automated internal mirror mechanisms. The resulting rapid laser flashes are reflected by objects in the environment and received

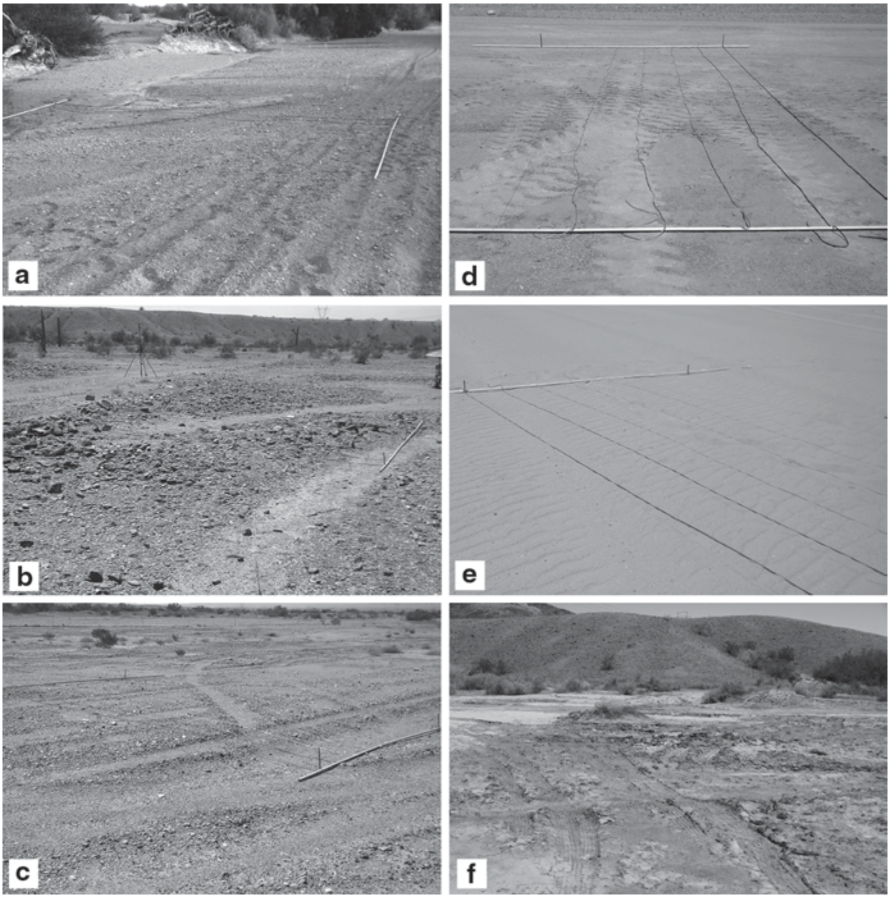

Fig. 2 Images of the six sites showing general features of the surface cover. Sites as listed in Table 1: **a** wash, **b** young fan, **c** old fan, **d** road, **e** sand, and **f** badlands. The position and layout of the wires and wood frame is visible in most of the images except (**f**) badlands, where wires were not present when the image was collected. Image **d** shows layout of wires with wire size increasing from *left* to *right*.

Table 2 Characteristics of wires used for LiDAR identification

Diameter (mm)	Color, jacketing	Wire type
7.0 × 3.7	Black, plastic	Stranded, double
5.4 × 3.0	Black, plastic	Stranded, double
5.4 × 2.7	Clear, plastic	Stranded, double
4.6 × 2.6	Clear, plastic	Stranded, double
3.8 × 2.0	Clear, plastic	Stranded, double
0.7	Green, none	Single-strand
0.5	Yellow, none	Single-strand
0.4	Orange, none	Single-strand

again by the scanner. The scanner records detailed topography as a series of (x, y, z) coordinates received as solitary point laser reflections in a 3-dimensional space whose origin is defined relative to the position of the scanner head. Each point is attributed with an intensity and color (RGB) value, which represents the strength of the reflected laser signal received by the instrument, and the color at that point recorded by a photographic scan of the same feature, respectively. Variability in intensity is determined by the physical properties of the reflective surface (i.e. texture, color, material type), as well as the ambient weather conditions. Surface scans were conducted at each site from three opposing station locations each pointed towards the wires frames to minimize laser shadows that will produce gaps in the datasets. Stationary targets distributed throughout the scan area provided anchors to register multiple scans together during post-processing.

Conventional data processing of TLS collected data involves combining data from multiple scans (usually 3 or more) into merged, aligned, georeferenced point cloud dataset that can be used to generate surface models (e.g., DEMs). The data below are based on using TSL data derived from a single direction which is analogous to using TSL imaging from a moving vehicle where only one single direction is most probable.

2.3 Initial Data Processing

A single high resolution scan employed for this project may produce millions of individual data points. At present, there is not a standard processing method for handling datasets of this magnitude in the geostatistical scientific community; data analysis methods are generally defined by the user and tailored for specific analytic methods or products as directed by the research objectives. Our objective during data processing was to maximize retention of surface detail in point cloud datasets, which would then be digested using MATLAB to a resolution suitable for microtopographic characterization and semi-automated wire detection.

Point clouds were processed initially using Leica's Cyclone 7.0 software, which provides a suite of tools for combining, visualizing, and sampling point cloud datasets collected by Leica Laser Scanners. The Cyclone software, however, has limited capabilities for surface analysis or geomorphic applications because its application is intended primarily for engineering applications (e.g. rendering three-dimensional images of structures). The full resolution, registered point clouds were subsequently exported in ASCII format for detailed analysis in MATLAB.

A digitized image is a two-dimensional function f(x, y), where x and y are spatial coordinates and the amplitude of *f* at any pair of coordinates is the intensity of the image at that point (Gonzalez et al. 2009). This results in two types of information obtained for each x, y point in the LiDAR scan: elevation (z) and intensity (I). Intensity measures the return signal strength based on the way an object reflects the

LiDAR energy. To perform image processing, the digital image must be in matrix form, with an amplitude value in each uniformly sized pixel. The LiDAR readings must first be mapped onto an evenly spaced grid because the raw point cloud data are not in matrix form (i.e. not evenly spaced and with variable resolution). Moreover, there can be more than one LiDAR reading per grid point because of the fine resolution (mm scale) of the LiDAR scan. For this study, we tested use of the median, maximum, and minimum LiDAR intensity and elevation values within a grid cell. For LiDAR scans performed in this study, we used 5 cm × 5 cm grid cells to represent the image. Finer resolution grids resulted in patchy data that were difficult to interpret.

2.4 Roughness Characterization

One of the objectives of this study is to compare wire detection across surfaces with different degrees of surface roughness (microtopography). Collected LiDAR data was also used to quantify surface roughness. There are a number of ways that roughness has been quantified in the geomorphic and materials literature. For example, common methods include the absolute difference between highest and lowest points, the standard deviation of elevation, or standard deviation of slope. For this study, we found that roughness was best characterized using the standard deviation of elevation of any given pixel in the 3-by-3 neighborhood of pixels around it (Fig. 3). Box plots were used to display the median and quantiles of roughness across an entire scanned area (discussed below). The scale at which we measured roughness was chosen based on its relationship with the scale of wire thickness. Roughness quantified over larger scales showed similar results.

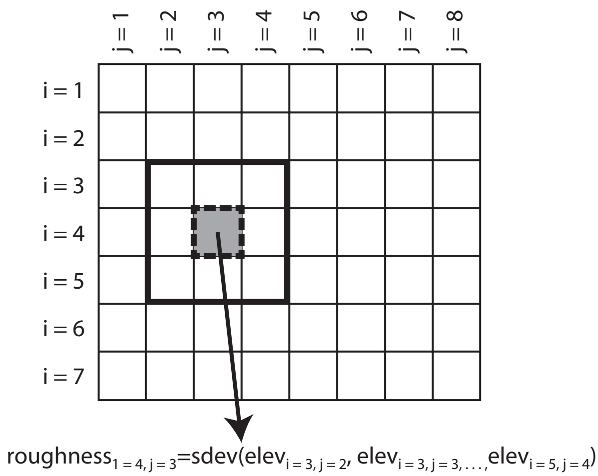

Fig. 3 Surface roughness at each pixel is quantified using the standard deviation of elevation in a specified window around the pixel.

3 Image Manipulation: Wire Detection and Surface Roughness

One of the basic questions of this project was determining how LiDAR might detect thin wires against various types of background soil cover and surface microtopography. Initially it was thought that any linear extent of the wire that was elevated above the soil surface (i.e. stretched across microtopographic lows) would register as a separate microtopographic feature relative to the background surface roughness. As a result, elevated portions of the wire might be easier to detect given the high surface resolution of ground-based LiDAR. Evaluation of the results of the LiDAR data after initial processing, however, indicated that image intensity, specifically low wire reflectance, provides a much higher contrast between wires and bare soil relative to the elevation data (Fig. 4). Accordingly, image intensity was further evaluated for wire detection and elevation data was used instead to quantify surface roughness.

Manipulation of the image intensity required separation of wire reflectance from background soil intensity using image segmentation. Segmentation of non-trivial images is one of the most difficult tasks in image processing and frequently data manipulation is more complicated than determining the actual line detection algorithm because there are a variety of line detection algorithms that fall under the broad category of image segmentation. Results of image analysis in this study indicate that the segmentation process for the wire detection required three steps: image filtering, edge detection, and line detection.

Image filtering is used to enhance and separate the difference between wires and bare earth. Wire intensity tended to fall in the lowest range of intensity, most at ~1 % intensity, regardless of absolute intensity values of bare earth and wire images. A binary filter was applied to the image to highlight the wire at the lowest intensity of 1 %, masking values > 1 % and producing a simple white and black image enhancing separation of the wires from the background surface (Fig. 4).

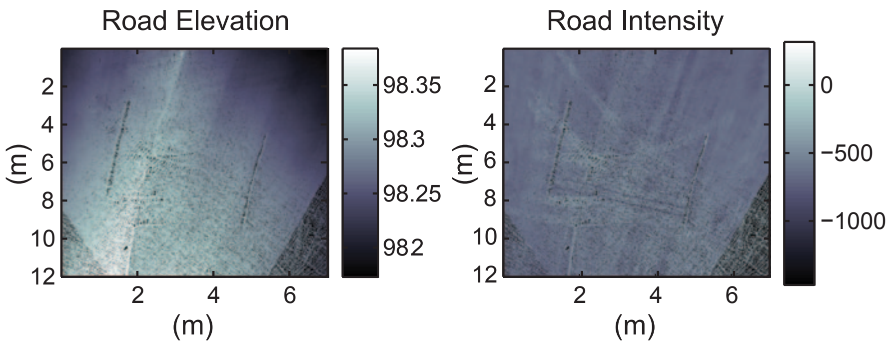

Fig. 4 Wires stretched between two wooden boards (*dashed lines*) are centered within both images. No wires can be seen in the elevation data (*left*), while some are visible to the eye in the intensity data (*right*).

Edge detection was used to highlight breaks between the black and white sections of the binary images. We tested the following edge detection methods for power in extracting the wires from the filtered intensity images: Sobel, Prewitt, Roberts, Laplacian of a Gaussian (LoG), Zero crossings, and Canny (c.f. Al-Amri et al. 2010; Juneja and Sandhu 2009; Shrivakshan and Chandrasekar 2012). The LoG algorithm, which finds edges by searching for zero crossings after filtering the image with the Laplacian of a Gaussian filter resulted in the largest number of wires captured when combined with a line detection method. The Hough Transform (Gonzalez et al. 2009) algorithm was also used to assemble discontinuous edge segments identified using LoG and to identify linear segments. In the example shown in Fig. 5, this method highlighted the three thickest wires (7.0 × 3.7, 5.4 × 3.0, 5.4 × 2.7 mm) and captured portions of the next two thinnest wires (4.6 × 2.6, 3.8 × 2.0 mm).

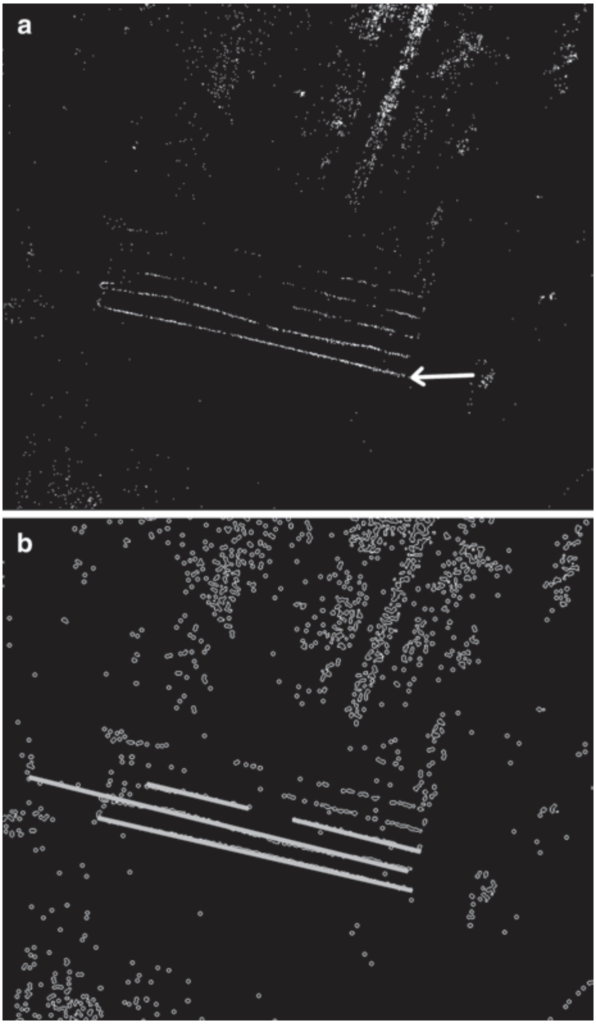

Fig. 5 **a** Binary image mask for the lowest 1 % of intensity measurements at the road site highlights both wires and tire tracks. Five wires are visible with the thickest wire at the bottom of the image (*arrow*). **b** Same image as **a** but showing the detection of the three thickest wires (*highlighted*) using an automated line detection algorithm that combines the LoG edge detection method and the Hough Transformation.

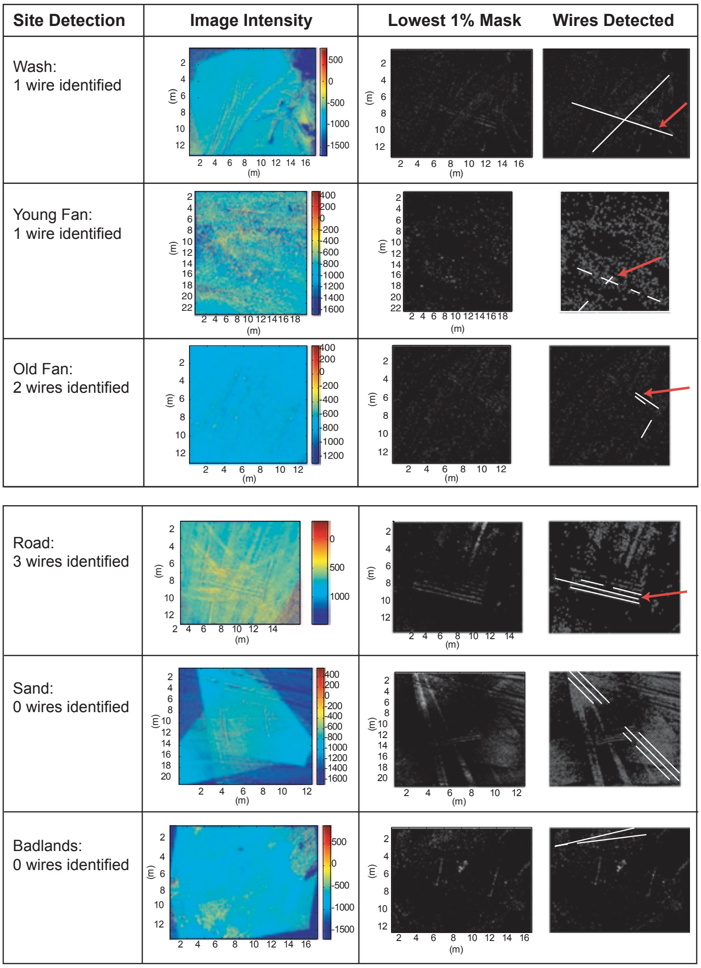

Fig. 6 Wire detection results for each of the six sites. Images shown for each site include intensity (*color image*), image with masking using only 1 % reflectance (*center image*), and detection of linear elements using algorithms (Fig. 5b). Detection of linear features included vehicle tracks and 1, 2, or 3 wires (location of wires shown by *red arrow*). Only the thickest wires were identified by this method.

Results for all six sites using image intensity, masking, and detection using the algorithm discussed above are shown in Fig. 6. The thickest wire (7.0 × 3.7 mm) was identified at the Wash and Young Fan sites and the two thickest wires (7.0 × 3.7, 5.4 × 3.0 mm) at the Old fan site. Tire tracks and other linear features were also be captured by the filter in the images at these three sites. The highest level of wire detection was identification of three wires (and with no other linear features captured) at the Road site, as discussed above (Fig. 5). No wires and only linear features (rills, line of ripples) were captured by the image processing for the Sand and Badlands sites (Fig. 6). Wires less than 3.8 mm were not detected or visible in the images. One reason for this is that the LiDAR working scan resolution is ~3 mm which limits detection of objects or features that are less ~3 mm in size.

3.1 Wire Detection and Surface Roughness

Bare earth surface roughness is quantified at a pixel based on the standard deviation value of elevation for the 3-by-3 neighborhood around the corresponding pixel (Fig. 3). Accordingly, increasing values of standard deviation correspond with greater relative surface roughness. Surface roughness for each of the six sites is visually depicted in Fig. 7 using box and whisker plots (including data outliers). The distribution of surface roughness has the lowest mean standard deviation value of ~0.1 for the Road site which is a very smooth surface of compacted silt (Fig. 2d). The Badlands site has the highest roughness with a mean value of ~0.4 that corresponds with the highly variable surface roughness due to abundant shallow rills and soft soils that easily form tire tracks (Fig. 2f).

Results indicate that wire detection decreases with increasing surface roughness using the algorithm described in earlier sections (Fig. 7). Specifically, the thickest 2 or 3 wires were correctly identified at the Road and Old Fan sites which have the lowest quantified roughness. Only one wire was identified at the Wash and Young Fan sites which have a higher standard deviation of roughness; visually these two sites also have greater surface roughness relative to the Road and Old fan sites (Fig. 2). No wires were identified at the Sand or Badlands sites which have the highest standard deviation values for roughness. No identification of wires at the sand site is surprising given that the site is visually smooth except for the abundance of small (1–2 cm high) ripples that were perpendicular to wire direction (Fig. 2e).

4 Conclusions

Results indicate that LiDAR can detect command wires at the ground surface using image intensity that is lower than 99 % of bare earth surface intensity readings. Wire detection was not possible using elevation data for the field sites used in the study. Automatic detection of the three thickest wires (7.0 × 3.7, 5.4 × 3.0, 5.4 × 2.7 mm) at 4 of the 6 sites was possible using data filtering based on intensity with subsequent edge detection using a LoG zero crossing algorithm and line detection by a Hough transform function. Detection of wires decreased with increasing surface roughness. False positive wire detection, largely associated with straight vehicle track edges, also occurred at some sites. Elimination of false positives will require a post-processing method for distinguishing between tire track edges and wires. Other methods of using LiDAR to detect command wires, such as changes in surface microtopography due to burial of wires, may also provide promise as technology

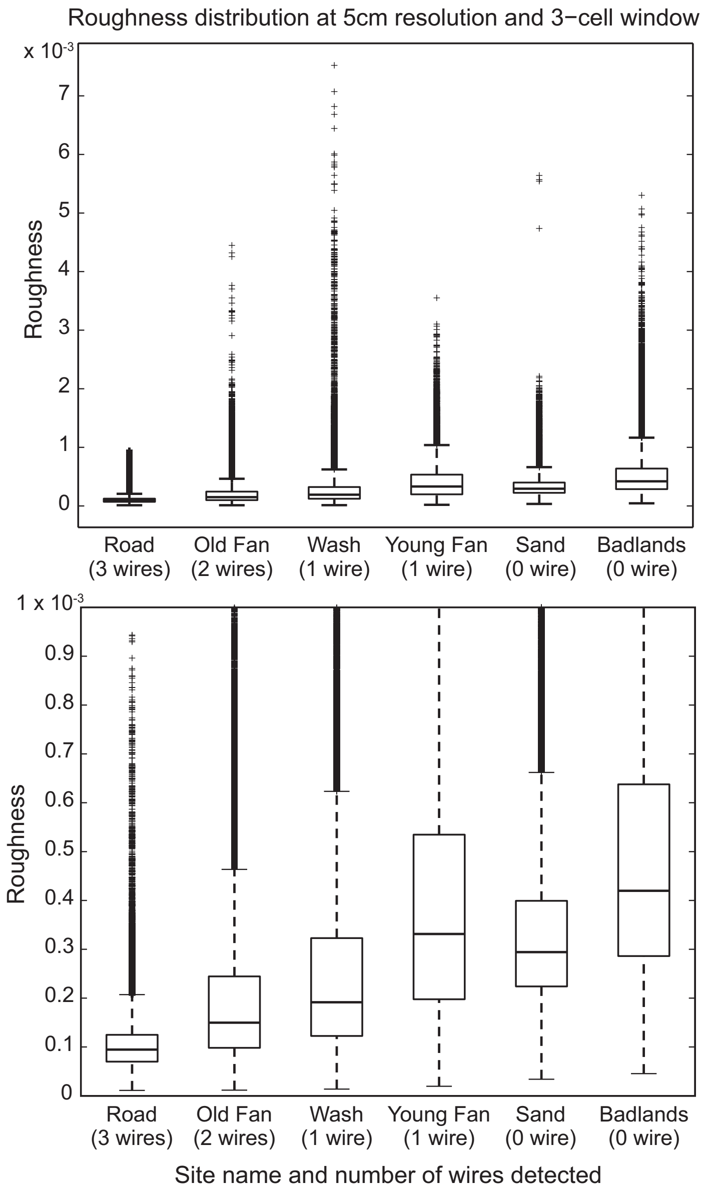

Fig. 7 Box plots depicting the distribution of surface roughness for each site at 5 cm intervals around each pixel (*normal view*: upper box, *zoom view*: lower box). For each plot the central mark is the median, the horizontal edges of the box are the 25th and 75th percentiles, the whiskers (*dashed line*) extend to the most extreme data points not considered outliers, and outliers are plotted individually (*crosses*). Generally, roughness increases from *left* to *right*, as the central 50 % of roughness values at each site increases. The number of wires detected using LiDAR intensity data decreases as surface roughness increases.

and image processing improves. Although results indicate that wire detection is possible, critical issues such as rapid image and data processing would be required to utilize LiDAR imaging of surface, especially for application of LiDAR from a moving vehicle.

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Parent Material Mapping of Geologic Surfaces Using ASTER in Support of Integrated Terrain Forecasting for Military Operations

Donald E. Sabol, Timothy B. Minor, Eric V. McDonald and Steven N. Bacon

Abstract Predicting soil physical and chemical properties for military operations requires knowledge of the geologic and lithologic component of the soil parent material. Geologic maps, a traditional source of geologic information, are often limited in coverage or inadequate for determining the basic characteristics of a soil parent material. We describe an approach for the rapid development of geologic surface maps that identify the lithologic composition of soil parent material generated from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data. Generated maps of parent material, in turn, provide key input parameters for a comprehensive terrain predictive model that forecasts key soil and surface cover characteristics in support of military operations. Parent material maps are generated using a multilayer approach where calibrated image data are mapped into lithologic units that best identify soil parent material and corresponding landform units (i.e. bedrock, fan, playa, dune, etc.). A unique and critical aspect of our approach is that expert-based analysis of spectral and geospatial information can produce a geologic map, covering 1000–5000 km^2 of terrain, of soil parent material and surface cover in as little time as nine staff-hours. The approach was developed with a guiding principle that terrain predictions in military operations must be rapidly developed for areas where available ground information is limited. Results indicate that it is possible to quickly produce a realistic map of soil parent material using ASTER data without any additional geologic information or data. Results also indicate that analysts developing parent material maps require expert knowledge in both spectral analysis of remotely sensed data and the geologic and geomorphic processes that form desert landforms.

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1 Introduction

Tactical military operations require up-to-date and readily available terrain information for the area where operations are to take place. Adequate terrain data, especially regarding soil and terrain condition, is commonly non-existent, limited, or inaccurate. Recent conflicts in Southwest Asia have increased interest in mapping terrain for military planning and operations given the common occurrence of terrain hazards impacting a wide range of military operations including trafficability, dust brownouts, and the of detection of improvised explosive devices. Rapidly evolving and expanding airborne and satellite remote sensing resources can yield information on the surface composition and condition of the terrain through a variety of data types. For example, technological advancements have been made that allow for the rapid use of remote sensing image data to readily identify surface lithology at scales that are usable for terrain mapping (1:10,000 to 1:24,000). Integration of new and high quality terrain data into applications that can benefit military planning and operation is a growing field of military geosciences.

In this paper, we describe an approach for the rapid development of surface maps, generated from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) image data, that describe the lithologic composition of bedrock and sediments exposed at the surface in deserts. The remote sensing efforts described in this paper are part of a much larger project, "Integrated Desert Terrain Forecasting", a soil and terrain cover predictive model being developed for the US Army (McDonald et al. 2015). The purpose of this terrain forecasting model is to accurately predict or map soil characteristics and surface conditions in areas of potential military operations that lack either mission adequate or any pre-existing information. Remote sensing inputs are an integral part of the process (Fig. 1) especially in the identification of the primary geologic and lithologic terrain information.

1.1 Predictive Model: The Need for Geologic and Lithologic Data

Adequate knowledge of the geologic and lithologic component of the terrain surface is essential for generating soil and geomorphic maps that provide reasonable estimates of a wide range of soil properties including the types of major horizons, texture, dust emission potential, and the presence of carbonate and soluble salts. This is because the primary mineral and chemical properties of a soil parent material have a strong control on the basic soil morphology as well as the nature of the surface cover. Four other basic factors—topography or landform, climate, vegetation,

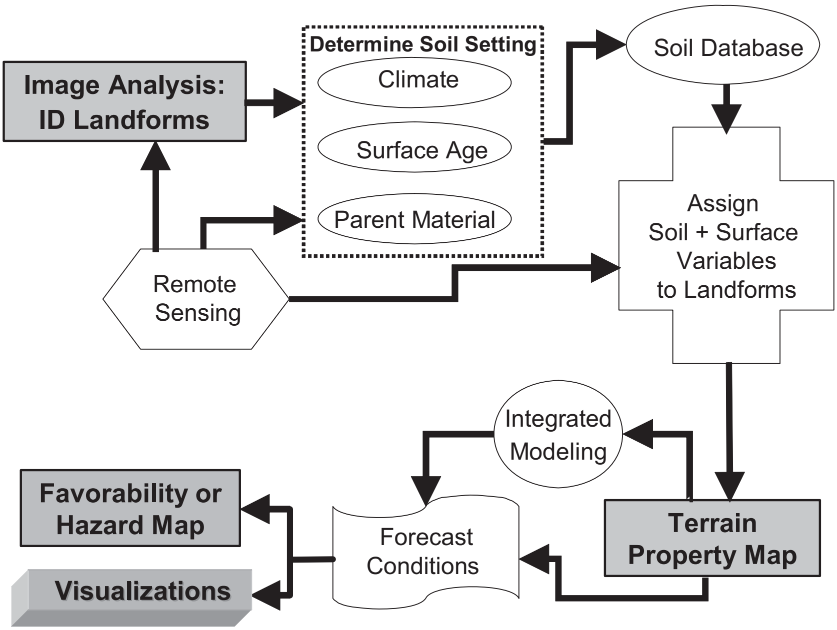

Fig. 1 Desert terrain model schematic. Remote sensing plays an integral role in the model

and time—also control the nature of soil properties (c.f. Jenny 1941; Birkeland 1999). Adequate mapping and predictions of the character desert soils, therefore, can be made by knowing or estimating these five soil forming factors (McDonald et al. 2015). The general type of landform, topographic setting, and the age of landform or surface can be determined through expert-based analysis of airborne or satellite imagery of the desert landscape. Basic climate data (largely temperature and precipitation), and by extension vegetation, can be derived from a variety of established databases.

By comparison, knowledge about the geologic and lithologic properties of the terrain surface is more difficult to obtain for several reasons. First, geologic data can only be partially extracted through expert-based image analysis (e.g. identification of a young basalt flow or sand dunes). Existing geologic maps, where available, can provide additional data but are typically inadequate. This is because traditional geologic maps describe bedrock units by both age and rock type. Mapped rock units may be of a single lithology or a wide range of undifferentiated lithologies that formed together under specific environmental or depositional conditions and often grouped into formations. Often times, the formations are massive, cover an extensive region, and incorporate a wide range of lithologies that are not individually separated. Although the traditional approach is intuitive as it generally describes both the geologic units and the geologic history of an area, it is often of little use for military applications since specific surface composition (mineralogic-based rock type) are needed as opposed to age-specific formations and generalized rock type.

Also, traditional geologic mapping in the field takes weeks to months to produce and field check, whereas mapping for military operations must be done quickly, on the order of hours to days. Perhaps the biggest challenge with using traditional geologic maps to predict soil conditions is that the maps, especially in desert regions, are often not available in a digitized, georeferenced format or are lacking in coverage or availability. Procedures that can readily extract or interpret information about the geologic and lithologic setting, from remotely sensed data, provide the most viable means of generating required data for developing predictions and maps of terrain soil and surface cover.

1.2 Objectives

The principal goal of this project was to develop an approach to rapidly (i.e. hours to a few days) create the best map of surface lithologic compositional and landforms using only ASTER satellite image with no additional outside ancillary information. The rationale for developing this approach was to test if reasonable geologic information can be generated quickly, especially for areas with limited pre-existing geologic or lithologic information. In cases where geological maps do exist, they can be used to verify results of the ASTER-based methodology. The methodology used, therefore, would be most applicable when: (1) time and logistics will not allow field verification of map datasets, and (2) good geological or geomorphological maps have not been produced or are not readily available in areas of concern.

The mapping detail produced here is governed by the minimum requirements for input to the predictive model, which is used to forecast surface and subsurface soil and surface conditions. The ideal geologic units for this project are listed in Table 1, where ‘Primary Type’ is the minimum required level of information and the ‘Secondary Type’ would provide a higher or more beneficial level of information. Geomorphic units (i.e. bedrock, fan, playa, dune, etc.) also help in the subsequent application of the model and are included as much as possible. The inputs developed from the ASTER-based methodology identify surface composition and condition as map datasets including: (1) rock or soil types and/or geomorphic units, (2) vegetation cover and, (3) surface roughness.

1.3 Description of Aster Data

ASTER was launched on 19 December 1999 on NASA’s Terra satellite platform along with four other remote-sensing instruments; including MODIS (a regional, “moderate-resolution” scanner), MISR (Multi-angle Imaging Spectro-Radiometer), CERES (Clouds and Earth’s Radiant Energy System), and MOPITT (Measurement of Pollution in the Troposphere). ASTER is the higher-resolution “zoom lens” for Terra, with four 15-m VNIR (visible/near infrared bands), including stereo, five

Table 1 Parent material types used for the integrated desert terrain forecasting predictive model

Primary type	Secondary type	Possible rock types
Igneous, extrusive	Fine grained, acidic-intermediate fine-grained, basic	Rhyolite, trachyte, latite, porphyry, welded tuff andesite, dacite, basalt, diabase, tholite, porphyry
Igneous, intrusive	Coarse-grained, acidic-intermediate coarse-grained, basic	Granite, syenite, quartz- monzonite, monzonite, pegmatite granodiorite, diorite, gabbro, tonalite
Metamorphic, foliated	Mafic/basic felsic/ quartzose-feldspathic	Amphibolites, eclogite, serpentine, talc gneiss, granulite, migmatite
Metamorphic, non-foliated	Quartzitic, calcareous	Quartzite, marble
Sedimentary, calcareous	Calcareous, biochemical-soft calcareous, biochemical-hard calcareous, chemical	Chalk, coquina, marl limestone, dolomite travertine, tuffa
Sedimentary, evaporative	Non-calcareous, evaporative	Anhydrite, gypsum, halite
Sedimentary, organic	Biogenic, calcareous non-biogenic, calcareous	Black shale, coal, peat diatomite, chert, flint, jasper
Sedimentary, clastic	Fine-textured, laminated-fissile medium-textured, bedded to massive	Argillite, shale, mudstone, claystone, siltstone
	Coarse-textured, bedded to massive	Sandstone, arenite, arkose, greywacke breccias, conglomerate
Sedimentary, volcaniclastic	Acidic-intermediate basic	Ignimbrite, tuff, pumice, scoria (e.g. basaltic)
		Ignimbrite, tuff, pumice, scoria (e.g. andesitic, rhyolitic)

30 m SWIR (shortwave infrared) bands, and five 90 m TIR (thermal infrared) bands (Kahle et al. 1991; Yamaguchi et al. 1993). The spectral characteristics, high resolution, and data availability for most of the earth's surface makes ASTER data well suited for rapid surface analysis.

In general, the VNIR bands on the ASTER platform are useful for detecting iron and iron oxides, green vegetation, and some rare earth minerals, whereas SWIR bands are very useful for mineral mapping, particularly in the 2.0–2.5 µm range where characteristic absorption features of certain hydroxyl and carbonate-bearing minerals can be detected (i.e. hydroxyls, carbonates, sulfates, micas, and amphiboles). Furthermore, the TIR bands are useful for detecting carbonates and silicates (Kruse 1994).

For this project, the only ASTER data used was collected prior to April 2008, because after this date the ASTER SWIR detector temperatures were anomalously high, making the SWIR data unusable. Three ASTER Level II products were used in: AST07XT (cross-talk corrected VNIR/SWIR reflectance (Iwasaki and Tonooka 2005)), AST05 (TIR emissivity), and AST14 (digital elevation model) (Jet Propulsion Laboratory, 2001). In addition, Level 1B data (radiometric and

Table 2 ASTER bands, spatial resolution, and data products used in this study; only L1B data for the two looks of band 3 (nadir and 30° off nadir) were used

Band	Wavelength (μ)	Spatial resolution (m)	ASTER data product used
1	0.520–0.600	15	AST07XT
2	0.630–0.690	15	AST07XT
3 nadir	0.760–0.860	15	L1B, AST07XT
3 30° back	0.760–0.860	15	L1B, AST07XT
4	1.600–1.700	30	AST07XT
5	2.145–2.185	30	AST07XT
6	2.185–2.225	30	AST07XT
7	2.235–2.285	30	AST07XT
8	2.295–2.365	30	AST07XT
9	2.360–2.430	30	AST07XT
10	8.125–8.475	90	AST05
11	8.475–8.825	90	AST05
12	8.925–9.275	90	AST05
13	10.25–10.95	90	AST05
14	10.95–11.65	90	AST05

geometric corrections applied) that contain the band 3 nadir and 30° back-look data were used to derive sub-pixel, relative roughness (Table 2).

2 Study Sites

The ASTER-based approach for parent material mapping has been applied to several different areas in the southwestern United States (Arizona, California) with each site proving a different set of analytical challenges. Principal sites include Owens Valley and the Carrizo Impact Area, both in California (Fig. 2). These sites were selected because they collectively exhibit landscape elements similar to those found in southwest Asia. Only the results from sites in Owens Valley and the Carrizo Impact Area are presented in this paper. Owens Valley provided a topographically challenging test in a well-known area with good geologic information and maps; whereas, while the Carrizo Impact Area provided a blind-test of the methodology in an area with limited geological map information.

2.1 Owens Valley

The Owens Valley study area is a deep north-south trending tectonic basin formed between the Sierra Nevada Range on the west and the White-Inyo Mountains on the east on the boundary between the northern Mojave Desert and the Great Basin. The Sierra Nevada Range is principally composed of Mesozoic granitic rocks, whereas

Fig. 2 Location of study sites mentioned in this paper

the White-Inyo Mountains predominantly consist of Paleozoic metasedimentary, metamorphic rocks and a lesser extent of Mesozoic granitic and volcanic rocks that are partly mantled by younger Cenozoic volcanic rocks (Danskin 1998). The valley fill is composed primarily of alluvial detritus eroded from the surrounding mountains. The mountain peaks bounding the valley reach above 4300 m elevation while the valley floor has an elevation of ~ 1400 m. The Sierra Nevada Mountains produce a rain shadow resulting in an arid climate characterized by 10–15 cm of rainfall/year (Hollett et al. 1991). The Owens River flows to the south and terminates at Owens Lake at the southern end of the valley as a closed basin playa prone to dust storms.

Owens Valley was selected in particular because of its complicated geological and high relief setting, which offered an opportunity to test the approach under difficult terrain conditions. Also, published detailed maps of Owens Valley allowed for a statistical comparison between the published maps and the map produced in this study.

2.2 Carrizo Impact Area

The Carrizo Impact Area lies within the Anza-Borrego Desert State Park and within the Colorado Desert in southern California. The area consists of steep mountains of the east side of the Peninsular Range, alluvial fans, and extensive badlands. This area was originally used as an air-to-ground bombing range by the U.S. Navy during World War II and the Korean War, and as a result has remained closed to the public due to the presence of unexploded ordnance. The area also lacks site-specific geologic investigations with only general and small-scale geological maps covering the area. The majority of the area is hyper-arid with an annual rainfall of < 5 cm per year (Chester et al. 2012). This area also has similar environmental and terrain attributes to areas of southwestern Afghanistan (e.g., Borrego Badlands), and with the restricted public access and lack of detailed geologic maps, provided an ideal area to test our mapping approach.

3 Explanation of the Multilayered ASTER Mapping Approach

The approach to the ASTER-based mapping uses a multi-layer approach that requires five steps: (1) preprocessing the data, (2) spectral analysis, (3) preliminary unit identification, (4) final unit identification, and (5) final processing. Both analytical tools and expert analysis is required to produce the geologic maps. The use of "expert" in this paper refers to the application of the image analyst's expertise in mapping bedrock and depositional landform surfaces. This section describes the procedures and rationale for each of the five steps.

3.1 Preprocessing Image Data

Preprocessing and calibration of raw image data to reflectance (VIS-SWIR) or emissivity (TIR) is necessary for spectral identification of surface components in the image data. The ASTER data products used in this study were previously corrected for effects of atmospheric transmission due to gaseous absorption and path radiance due to molecular scattering using atmospheric profile information from NOAA (NCEP) models. The ASTER products include: AST07XT, reflectance data for the VIS/SWIR cross-talk corrected (Iwasaki and Tonooka 2005) and the AST05 emissivity data for the TIR, which have either 30-m (VIS), 60-m (SWIR), or 90-m (TIR) resolutions. An additional step to preprocessing is to convert the SWIR (30 m) and TIR (90 m) band data to the same resolution as the VIS (15 m). The spectral data can then be combined into a single file for analysis.

3.1.1 Spectral and Spatial Analysis

The spectral and spatial analysis component of the study includes dividing the imaged surface into divisible categorical units using several different mapping techniques (discussed below) in a stepwise approach. The mapping techniques combine both spectral and spatial information in the image data. As individual units are identified, they are mapped into data layers until the entire study area is covered. In addition to identification of probable rock types from spectral signatures, map units are distinguished by the surface morphology typically exhibited by certain rock types. For example, a large outcrop of steep and fractured granodiorite would be mapped separately from an alluvial fan at its base, which, although composed of the same parent material, has much smoother topographic characteristics and different geomorphic attributes (e.g., drainage patterns). The relationship of the two units is important in that the outcrop helps identify the lithologic composition of the fan deposit which is important input for the predicting soil properties.

The spectral signature of rock, soil, and vegetation compositions can be mapped using passive multispectral visible/near-infrared (VIS/NIR) scanners. Additionally, the thermal infrared (TIR) can be used to classify differences in silica and carbonate content in rocks and soils, which then can be shown on maps. A variety of methodologies were used in this study to map out different units, based on spectral mixture analysis, absorption band mapping, spectral angle mapping, decorrelation stretch, vegetation mapping, and classifiers.

Spectral mixture analysis (SMA) has different levels of complexity ranging from a simple linear model that uses a single set of end members in a scene (i.e., an ASTER image) (Adams et al. 1995), to non-linear models (Mustard and Pieters 1989), to complicated models that use different end members throughout an image (Roberts et al. 1998; Dennison and Roberts 2003). Since this study was designed to be a rapid analysis, the use of a simple linear model consisting of a few (3–6) spectral end members was used to describe the surface composition of each pixel in an ASTER image. Each end member is the spectral representation of a basic constituent in a scene (i.e., rock, soil, shade), which is calculated as:

$$R_b = \sum_{em=1}^{Ne} F_{em} R_{em,b}; \quad \sum_{em=1}^{Ne} F_{em} = 1$$

where Rb is the reflectance for each channel (b), Ne is the number of spectral end members (components in the scene) and Fem is the fraction of end member. The sum of the fractions equals one. The spectral contrast between components should be high for best results. This approach should only be used when there is sub-pixel mixing of high-spectral contrast components. In the scenes used in this study, the sub-pixel mixing primarily occurred where adjacent alluvial fans composed of different parent material intermingled. Typical spectral end members included shade areas and where two or three rock/soil types were present. Vegetation, which is commonly sparse due to the arid environment, was not a major factor in the scenes analyzed. The results of SMA are fraction images (one for each end member) of relative fractions of each end member (scaled between 0 and 1), as well as a root-mean-squared (rms) image that indicates how well the mixture model fits the image data. For example, a particular pixel may have fractions of 0.1, 0.3, and 0.6 respectively in each of three fraction images representing shade, a particular rock type, and a particular soil. A fraction of 0.1 means that 10 % of the surface in that pixel is modeled as that particular end member (shade in this example) and the sum all the fraction images for each pixel sums to 1 (100 %).

Absorption band mapping is used with hyperspectral image data to identify materials with narrow bands that have distinct absorption features, such as carbonates, sulfates, and specific clays (Clark et al. 1993). Key geologic materials, however, may not be spectrally unique, which in turn limits the spectral identification to one of a series of possibilities. For example, the ASTER spectral signatures of igneous rocks (e.g., gneiss, granite, granodiorite) can be similar to some types sedimentary rocks (e.g. shale) because the spectral shape of the laboratory spectra (Fig. 3) of these rock types are comparable (Baldridge et al. 2009). There can also be a wide range of spectral variability (± 20 % reflectance) for the same type of rock that is laterally exposed across a given surface. Spectral variation can occur due to (1) inherent variations in rock mineralogy, (2) rock surfaces modified by surface weathering (e.g. development of rock varnish), and (3) by the presence of dust, soil cover, and vegetation. This spectral variability can make spectral separation of many rock types difficult, especially for those having similar basic mineralogy, such as granitic, andesitic, and gneissic rocks (Fig. 3). The spectral sampling interval of the imaging system is very important when attempting to separate rock types. For example, any subtle spectral differences evident in very high-resolution spectra (~ 1000 bands) are greatly muted when viewed by the ASTER system (9 VIS-SWIR bands; Fig. 4). Despite these challenges, band mapping can be particularly useful for mapping carbonate lithologies because of their unique, narrow absorption features, even in some multispectral systems like ASTER (Fig. 5).

Spectral angle mapping is use to determine the spectral similarity between two spectra by calculating the angle between a test spectrum from an image and a reference spectrum from the spectral library (Kruse et al. 1993). This approach treats the spectra as vectors in space where the dimensionality equals the number of bands and dissimilar spectra have larger angles. The spectral angle mapping method is

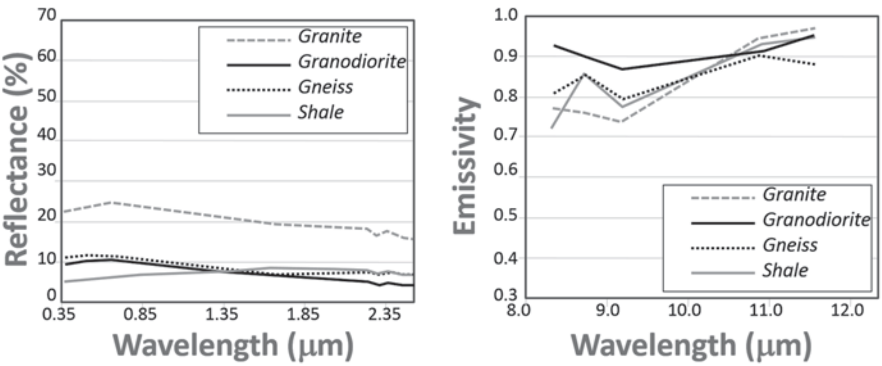

Fig. 3 ASTER spectra of a granite, granodiorite, gneiss, and shale. In the VIS/SWIR, the spectra can have similar shapes; especially the granodiorite, gneiss and shale. Note the Gneiss and shale are spectrally similar in the TIR. The spectra for these materials can be variable and further complicate spectral separation

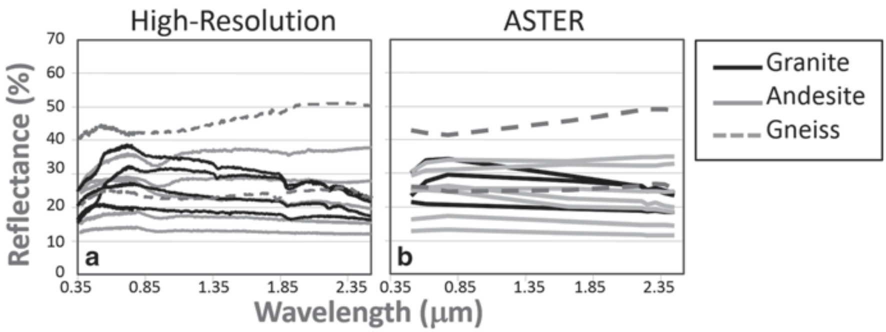

Fig. 4 High-resolution (**a**) and ASTER (**b**) spectra of a granite, andesite, and gneiss. The spectral variability of these rock types make them difficult to separate; especially when viewed with reduced spectral resolution of ASTER

relatively insensitive to illumination and albedo effects, thereby producing higher resolution or more accurate image products.

Decorrelation stretching is used to enhance color differences by removing the high correlation between some bands found in image data (Gillespie et al. 1986). This methodology maximizes the difference between three bands of data at a time. A linear transformation can be found that results in removing the correlation among the vectors by diagonalizing the covariance matrix of the three bands. Each band is rescaled to equalize the band variances. The data at this point are uncorrelated and fill the coordinate system. Finally, the inverse transform is used to map the data back into the original coordinate system. This method allows the analyst to visually see subtle differences between the bands in an image. An example of how this is useful is shown in Figure 6, where an area of Owens Valley and the Inyo Mountains is shown both as an aerial image and with three decorrelation stretched images

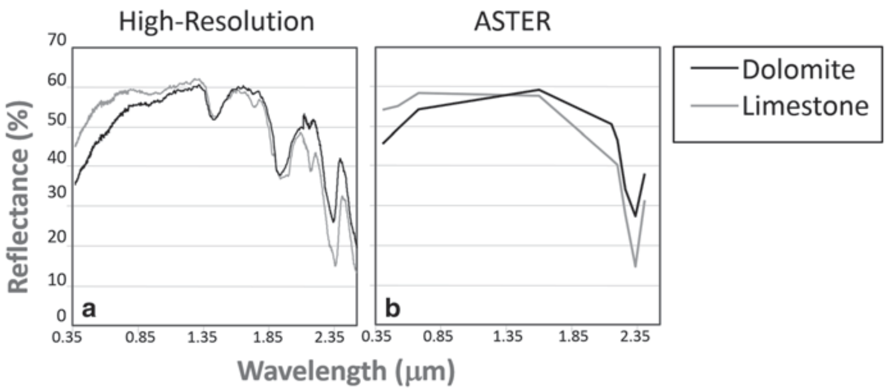

Fig. 5 High-resolution (**a**) and ASTER (**b**) spectra of a dolomite, and limestone. The ~2.34 mm absorption feature is indicative of carbonate. The slight offset of this feature, detectable in the high-resolution spectra (**a**) is not separable in the ASTER spectra (**b**)

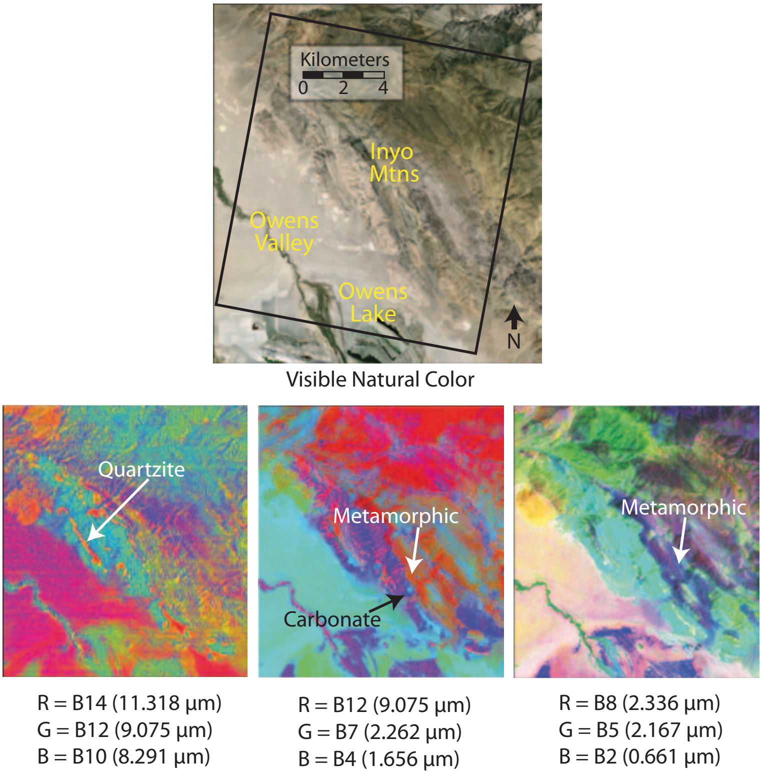

Fig. 6 Examples of using different band combinations with a decorrelation stretch to separate units in a small area in Owens Valley, California

using different combinations of SWIR and TIR ASTER bands. Different cohesive units within this area are clearly discernible and can be effectively mapped.

Vegetation mapping can also be accomplished using the approaches described in this section (i.e. mixture analysis, spectral angle mapping, and classification). We used the NDVI (Normalized Difference Vegetation Index) transformation to map areas containing green vegetation. This was not a significant factor in the study sites investigated, because most of the sites are located in semiarid and arid areas with a limited cover of vegetation. The NDVI takes advantage of the high reflectance of green vegetation in the near-infrared (0.7–1.1 μm) relative to the high spectral absorption of vegetation in the visible (0.4–0.7 μm) (Tucker 1979). NDVI is one of the most commonly used approaches to simply and quickly identify vegetated areas in multispectral remote sensing data and is calculated as:

$$\mathrm{NDVI} = (\mathrm{NIR}_{(0.7-1.1\mu m)} - \mathrm{VIS}_{(0.4-0.7\mu m)}) / (\mathrm{NIR}_{(0.7-1.1\mu m)}) + \mathrm{VIS}_{(0.4-0.7\mu m)})$$

where NIR is the near-infrared reflectance and VIS is the Visible reflectance.

Supervised classification can be used to quickly subdivide map units without making any estimates of composition. This approach is a common application to create discrete classes on surface maps. The analyst defines training classes, each of which covers the full range of variability of each assigned class. The software uses the trained class information to determine spectral signatures (and variability) and then assigns each pixel to a specific class (land cover) (Alrababah and Alhamad 2006). Although not extensively used in the study, the method was applied to help separate individual units in the images.

3.1.2 Spatial Analysis

The shape and roughness of a surface (i.e. surface texture) was considered at both the sub-pixel scale and macroscale (greater than pixel size). In both cases, it was done at the highest spatial resolution in the data (Bands 1, 2, and 3 at 15 m for ASTER). The application of sub-pixel spatial and macroscale analysis is dependent on the surface type. Sub-pixel analysis is only appropriate on surfaces that are relatively flat (i.e. playas, alluvial plains), while macroscale analysis applies to large topographic features with surface variability.

Sub-pixel Spatial Analysis can be performed using data from an imaging system (such as ASTER) that has at least one band that views the scene from two different angles. This is because the apparent shadows in a scene will increase on "rougher" surfaces, as opposed to "smoother" surfaces. ASTER is well suited for this as Band 3 (~0.81 μm) is collected in two views; a nadir view (3 N) and a 30° back-looking view (3B). These two looks give ASTER a stereoscopic imaging capability that allows production of a surface digital elevation model. Mushkin and Gillespie (2011) produced a relative surface roughness images using a simple ratio between the co-registered ASTER 3B and 3N images. The approach is limited to sub-pixel roughness and is not applicable to roughness scales greater than the pixel size of 15 m for ASTER data.

The fans in Owens Valley site provide an excellent example of the kind of "roughness" information that can be derived from the ASTER data. Figure 7 shows an ASTER-derived surface roughness image where a younger fan (rougher/brighter) overlays the older, smoother (darker) fan. This type of surface roughness analysis can be useful in the relative dating of alluvial fan surfaces, because younger Holocene fan surfaces are generally rougher (i.e. greater surface microtopography) relative to older Pleistocene fan surfaces that appear smoother at scales of greater than 15 m-grid resolution (Mushkin and Gillespie 2011).

Macro Spatial Analysis performed in this study was accomplished by expert visual analysis of the image data. The 15 m scale of the visible image data was at high enough resolution to use geomorphic surface patterns during the spectral analysis to identify "most probable" map units. For example, dunes, playas, alluvial fans, etc., all have a diagnostic set of surface characteristics that can aid in identifying each landform type. In addition, some erosional surface patterns are suggestive of certain rock types. Granitic rocks in desert environments tend to have a "blocky"

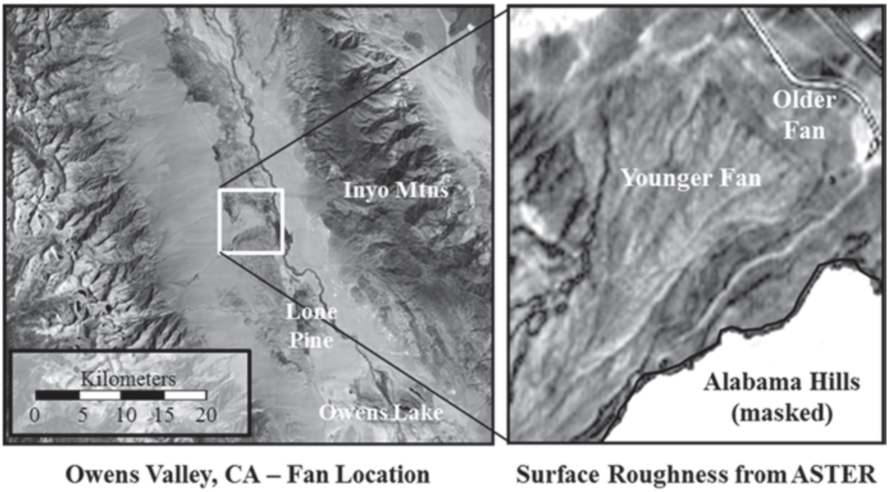

Fig. 7 Surface roughness from ASTER for selected fans in Owens Valley, California

appearance that is often controlled by conjugate rock fracture patterns, while fine-grained rocks such as slate and mudstones tend to be less "blocky" and have a "smoother" surface appearance. To aid in the identification of landforms and rock types, a 3-dimensional view can be used to determine approximate unit thickness and slope in conjunction with digital elevation models (DEMs). The integration of spectral information with the identified surface features allowed the assignment of geologic units. In addition, the spatial distribution of identified units can also be useful in identifying "most likely" compositions of adjacent landform or rock types (Fig. 8), such as alluvial fan surfaces that are mostly composed of material derived from upslope source areas. Figure 8 shows a variety of surfaces in the Carrizo Impact Area study site from two perspectives, from space and on the ground. The ability to relate macro spatial information to determine probable rock compositions using geomorphic surface patterns observed with ASTER relies heavily on the experience of the mapper, and therefore, is considered an expert based approach.

3.2 Preliminary Unit Identification

Once all units in the study area are identified and mapped, preliminary unit identification is assigned. In many cases, the assignment of geological or geomorphological unit names would be performed in the previous step (spectral/spatial analysis), but there are often Quaternary units (alluvial fans, fluvial deposits, etc.) that are better identified in the context of adjacent rock units/outcrops so they are assigned preliminarily unit identifications during the this step. An example of a preliminary map is shown for the Carrizo Impact Area site in Figure. 9, where map units are identified from the interpretation of spectral, textural, and spatial information based solely on ASTER image data.

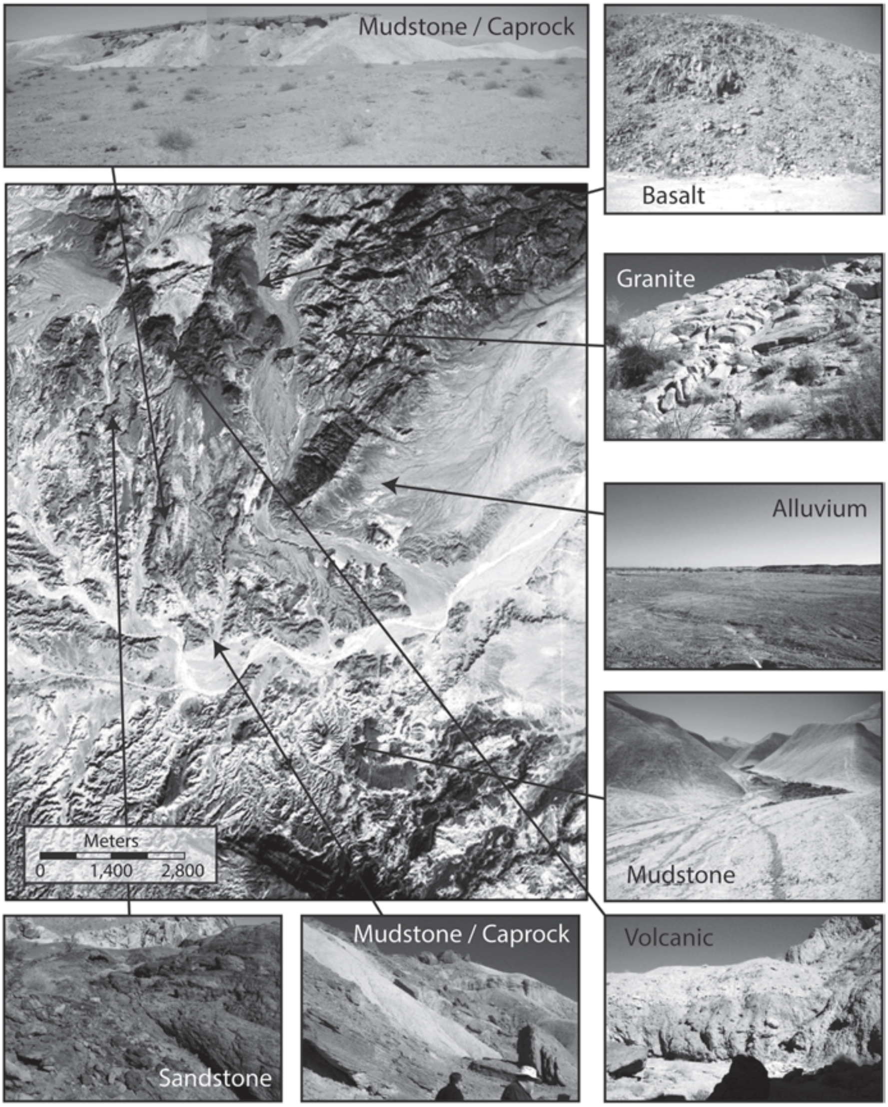

Fig. 8 Surface texture on ASTER (*Visible Bands*) with corresponding field photos of rock type. (Carrizo Impact Area, California)

3.3 Final Unit Identification

After preliminary unit identification is completed, the map result is often more complicated than what would be required for input into the terrain predictive model. For example, most all of the spectral mapping methods used in the previous steps can result in areas that have isolated units composed of small unit clusters (1–6 pixels). This commonly occurs when two adjacent units are spectrally similar within the

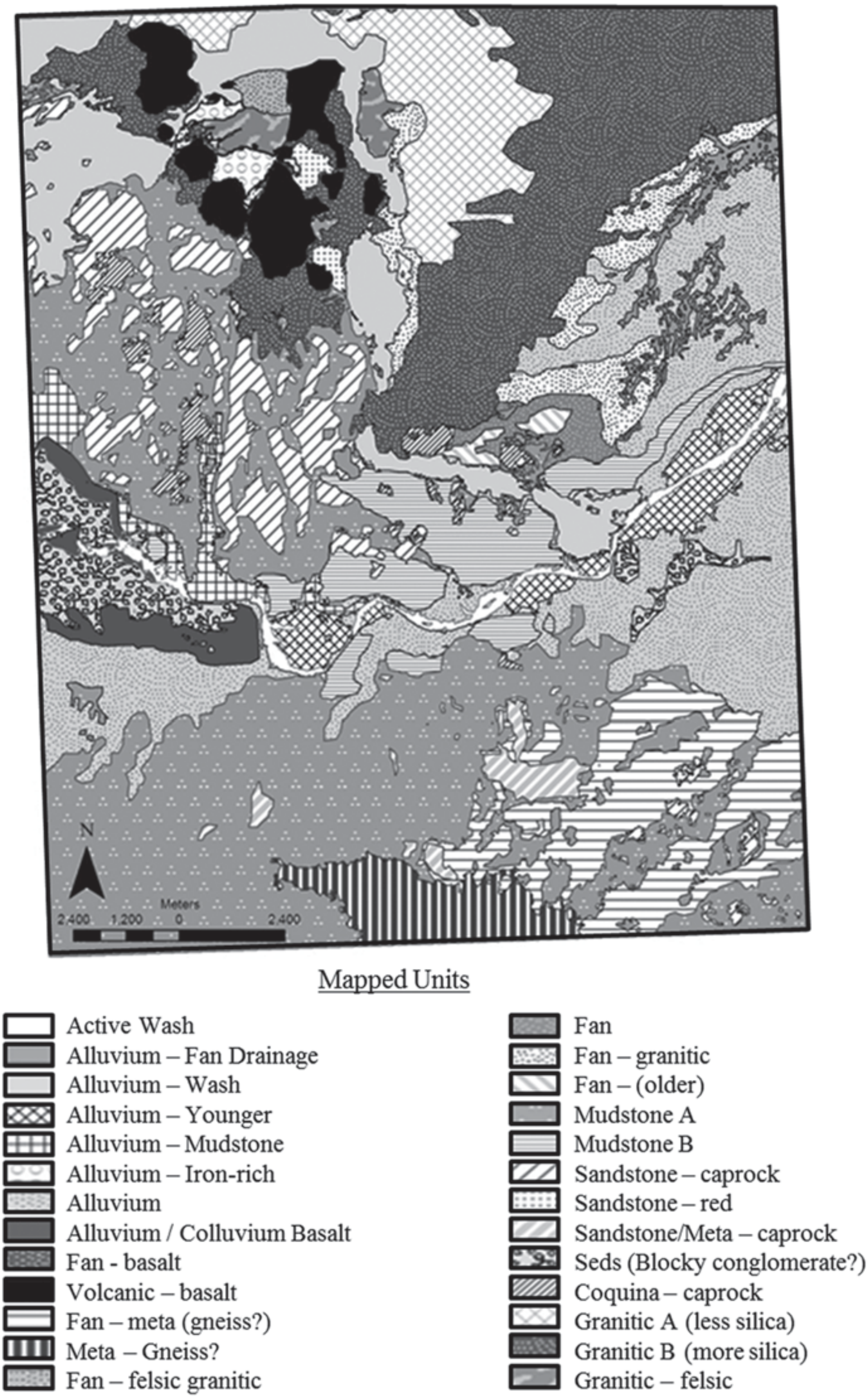

Fig. 9 Surface compositional map derived from ASTER for Carrizo Impact Area, California

uncertainty range of the data. Generally, these small isolated clusters are removed and reassigned to the predominant unit of the surrounding or adjoining area. Occasionally, when checked against a DEM, some larger clusters are found to be related to bedrock outcrops and are allowed to remain. A check is done to ensure all pixels are assigned a unit. Once this is done, the map is reviewed again and final units are assigned. Depending on the application of the map, the preliminary and final units can be very similar or the preliminary units can be combined to yield units more appropriate to the needs required from the map (i.e. map units as shown in Table 1).

3.4 Final Processing

Final processing of the ASTER data requires two steps to prepare the map for input into the forecasting model. First, the final map is georectified and projected into World Geodetic System (WGS84) datum, Universal Transverse Mercator (UTM) projection. This step occurs at the end of the process because this step requires rotation of the ASTER data to align with the UTM which increases the size of the data file. We use the imbedded translation/rotation data in the ASTER file for this step. Finally, the raster image is converted into a vector data set (polygon features) so it is applicable for other model inputs.

4 Geologic Mapping Results

4.1 Owens Valley

The ASTER scene used for Owens Valley was collected on 26 August 2005 and all mapping was done without the aid of field observations or external geologic maps. The initial mapping resulted in a list of 30 units used to identify lithologic composition, landform type, or other types of surface cover (Table 3, column 1). Many units were of the same general lithologic composition, but were spectrally different from each other (i.e. three basalts, four granitic units, etc). This is primarily due to variations in mineralogic content and/or weathering of exposed rock or surficial sediments. Similar units from the initial list of 30 were progressively combined through 2 additional classification steps (Table 3, columns 2–3) to reduce the number of identified lithologic units. The final list of lithologic units (7 total, 6 lithologic) generated in step 3, although substantially reduced and simplified, accurately reflects the general geology of the area and is at a level adequate for using in a terrain predictive model (Fig. 10). Geologic mapping of the ASTER Owens Valley to produce the level of date presented in the images in Figure 10 took ~8 h of staff time.

Table 3 Owens Valley units from initial mapping to final model output

Initial mapping units step 1	2nd mapping units step 2	Prob. composition step 3	Final model input step 4
Windblown_Med	Snow	Alluvium	Alluvium
OV_Dust	Alpine lakes	Basalt	Igneous, extrusive
OV_Dust II	Vegetation	Dolostone	Igneous, intrusive
OV_Playa Wet	Quat_Valley	Dune sand	Sedimentary, clastic
OV_Lake	Playa Seds	Felsic volcanic	Sedimentary, calc
OV_Base	Quat_Windblown_<silica	Granitic	Sedimentary, organic
Saline Valley_Base	Quat_Windblown_>silica	Limestone	
Basalt I	Quat_Playa Dust_fine	Mudstone	
Basalt II	Carb_Limestone I	Rhyolite	
Basalt III	Carb_Limestone II	Sandstone	
Volcanic—bright red	Carb_Dolomite	Shale	
DV_Volcanic A	Granite		
DV_Base	Volcanic_Basalt		
Inyo_Dolomite	Volcanic_Cones		
Inyo Silica rich	Metamorphic/Seds I		
Inyo_Limestone	Metamorphic/Seds II		
Inyo_SS.Cong limey	Metamorphic/Seds III		
Inyo_Limestone II	Metamorphic/Seds IV		
Inyo_Base	Metamorphic/Seds V		
Inyo_Meta Seds II	Metamorphic/Seds VI		
Inyo Meta Basalt?	Epidote Rich		
Inyo Sed (Meta) I	Inyo Mtn		
Inyo Sed (Meta) II	Death Valley Mtn		
Inyo_shale?	Unknown—interesting		
Inyo Red Med Seds I			
Inyo Red Med Seds II			

Table 3 (continued)

Initial mapping units step 1	2nd mapping units step 2	Prob. composition step 3	Final model input step 4
Alabama Hills Granitic			
Sierra Granitic Base			
Sierra Granitic I			
Sierra Granitic II			
Sierra—Epidote			
Carbonate Rich			
Alabama Hills Med Sed			
Limey but not?			
Bright Veg			
Dark Veg			
Snow			
Lakes			

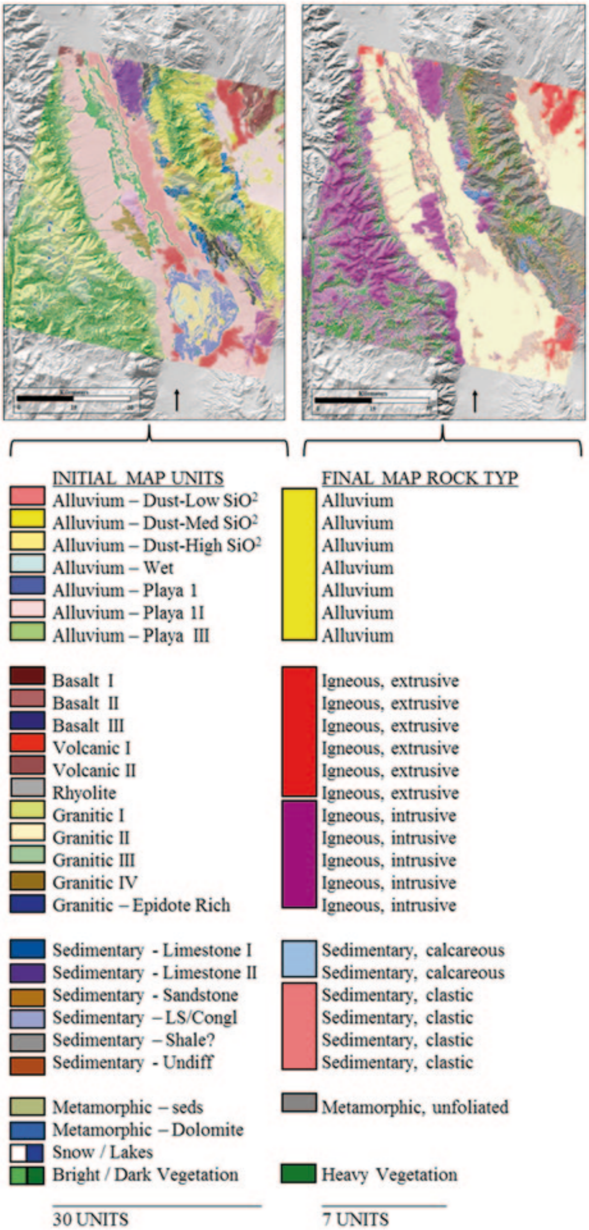

Fig. 10 Surface compositional maps derived from ASTER showing the initial, rock type, and final rock unit maps for Owens Valley, California

4.2 Carrizo Impact Area

The surface geologic/compositional map of a portion of the Carrizo Impact Area in the Anza Borrego desert was produced using the ASTER reflectance product (AST07) and emissivity product (AST05) (Fig. 9). Development of this map was a "blind" test map such that the geologic map produced was without the aid of field observations or measurements and without use of any preexisting geologic maps. The resulting map units represent our "best estimate" of the primary rock types. The area was mapped using two ASTER scenes (collected on 19 October 2003) and took a total of ~9 staff hours to produce the map and convert into a GIS compatible format for model input.

The map was produced for input into a soil predictive model, therefore the units had to be converted into units usable for the model. In this case, the ASTER-based map units were converted into the primary parent material units used in the predictive model input (Table 1). This involved combining mapped units into the required classes as shown in Figure 11. Figure 11a is the geologic/surface map of the "best guess" of the surface composition (26 units). An intermediate step (Fig. 11b) shows the units mapped as possible rock types (8 units) while the final map for model input is shown in Figure 11c (6 units).

4.3 Accuracy Assessment Results

To test the validity of the above described mapping approach, and the accuracy of the resultant maps, accuracy assessments were performed for the Owens Valley and Carrizo Impact Area study sites. The Owens Valley assessment was performed by directly comparing the ASTER-based mapping results to published geologic data of the area. The Carrizo Impact Area assessment was conducted by comparing the ASTER mapping results to field observations (i.e. ground truth) made in the study area.

Owens Valley provided a rugged accuracy test due to its complex geologic environment and variable topography. An objective test of the mapping was done by comparing the map of probable composition rock types (Fig. 10) to the 1:750,000 geologic map of California (Jennings et al. 1977). To do this, the ASTER-based and published geologic maps were co-registered using GIS software, and 175 random points were selected using a random point generator. A comparison between the basic rock or sediment type for each map was made for each point and used to generate a contingency table (Table 4). The results show a 60 % agreement between the map produced using ASTER data and the geologic map. This level of agreement is good given that the ASTER data analysis was preformed quickly and for a geologically complicated area consisting of steep and rugged mountains and low valleys with ~15 % vegetation cover. Assignment of the ASTER data units using the shorter list of units developed for model input resulted in an agreement of 64 % between maps (Table 5).

An accuracy assessment of the Carrizo Impact Area proved difficult, because there is no high-resolution geologic map published for the area. Map unit verification was performed by making 20 field-based "spot checks" of identified map units in locations accessible within the Carrizo Impact Area, much of which is readily

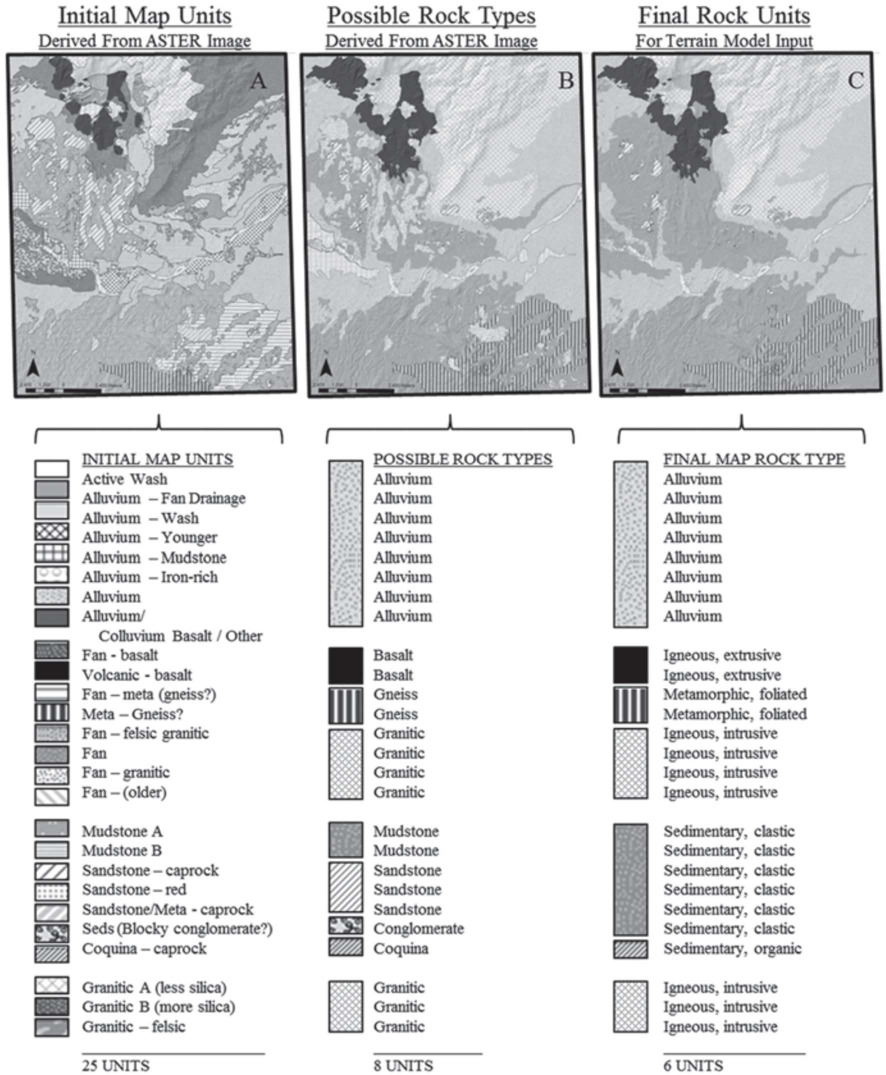

Fig. 11 Surface compositional maps derived from ASTER showing the initial map units (*left*), possible rock types (*center*), and final rock unit assignments (*right*) for Carrizo Impact Area, California

accessible. A few small map areas were incorrectly identified. For example, a volcanic tuff deposit in the north-central part of the map that covered ~25 pixels was not identified, because the ASTER spectral signature for this small area was not different from the surrounding alluvial fan material composed primarily of granitic (quartz-rich) material. Of the 20 sites we spot checked, 17 were correctly mapped (85 %).

Table 4 Owens Valley accuracy table using estimated rock type (See Table 1). Rock types estimated from ASTER data and compared to 1:770,000 geologic map of Owens Valley, CA (Jennings et al. 1977). Our "blind" analysis (performed in <8 h) using ASTER data was ~60 %

	Alluvium	Basalt	Dolostone	Dune Sand	Felsic Volc.	Granitic	Carbonate	Mudstone	Rhyolite	Sandstone	Shale	Total row
Alluvium	80	3	0	2	0	1	2	2	0	1	1	92
Basalt	2	7	0	0	0	0	0	0	3	0	0	12
Dolostone	1	0	1	0	0	2	4	0	0	0	1	9
Dune sand	4	0	0	0	0	0	0	0	0	0	0	4
Felsic volc.	2	0	0	0	4	3	1	0	0	0	3	13
Granitic	1	0	4	0	0	2	0	0	0	1	1	9
Carbonate	0	0	0	0	5	2	3	1	0	0	1	12
Mudstone	0	0	0	0	0	0	0	0	0	0	0	0
Rhyolite	0	0	0	0	0	0	0	0	0	0	0	0
Sandstone	0	0	0	0	0	0	0	0	0	0	0	0
Shale	7	0	0	0	1	4	3	1	0	0	8	24
Total column	97	10	5	2	10	14	13	4	3	2	15	105/175

Owens Valley Image Overall Accuracy = 105/175 = 60 %

Table 5 Owens Valley accuracy table for primary rock type (see Table 1) by combining units from Table 3. Simplification of the mapping units improved the accuracy slightly from ~60 to 64%

	Alluvium	Ig—Intrusive	Ig—Extrusive	Sed—Clastic	Sed—Calcare-ous	Sed—Organic	Total Row
Alluvium	80	1	3	5	2	1	92
Ig—Intrusive	1	2	0	1	4	1	9
Ig—Extrusive	4	3	14	0	1	3	25
Sed—Clastic	4	0	0	0	0	0	4
Sed—Calcareous	1	4	5	1	8	2	21
Sed—Organic	7	4	1	1	3	8	24
Total column	97	14	23	8	18	15	112/175

Owens Valley Image Overall Accuracy = 112/175 = 64%

5 Discussion

Overall, the approach proved successful in terms of providing reasonable and adequate data as a key input geologic and lithologic variables for developing predictions of soil and surface cover. First, the approach used clearly identifies and maps the distribution the most basic lithologic data required to support predicting or estimating primary soil and surface cover characteristics. For example, identification if the primary rock or sediment composition is either igneous-extrusive (e.g. basalt, rhyolite) or igneous-intrusive (e.g. granite, diorite) is important for making predictions about soil properties because the weathering (both soil and exposed rock) of these rocks type is generally quite different. Second, the approach is developed to produce required data in a matter of hours or only a few days. This is because the application was developed with the idea that to be useful in mission planning, required geologic data had to be quickly developed and available in a format useful for terrain predictive models. In addition, this approach would prove beneficial if very large areas (e.g. >10,000 km^2) requiring basic geologic mapping because if could greatly decrease the time required relative to more traditional types of mapping.

Results also indicate that recognition of specific and recognizable patterns of surface topography (macro topography), especially topography related to depositional features and weathering, were as important as spectral information in identifying different surfaces. Shading and shadows cast by hills and mountainous topography, however, can hinder surface mapping; as was the case in the Owens Valley mapping. Although ASTER was also able to provide relative roughness over low-relief surfaces, such as alluvial fans, it is not useful for many other surfaces such as foothills, mountains, incised drainages, canyons, etc. If available, the higher spatial resolution and more accurate topographic information from LiDAR data could greatly improve the roughness component of the mapping and give greater insights into the surface composition and condition.

The approach does have significant limitations. One limitation with this methodology is the limited spectral and spatial information inherent in ASTER data.

While the spectral resolution is not sufficient to separate and/or uniquely identify some materials, it is adequate for many others. Even when rock type identification is unclear, the spatial distribution of spectrally similar pixels often allows separation of units. Even so, higher spectral and/or spatial resolution data can enhance surface composition identification and detection. The downside of higher resolution data is the increase in the data volume, which usually results in more time required to process and interpret the data. We found that the ASTER data was a good compromise between spatial resolution and spectral information for producing the maps needed for the larger Desert Terrain project (McDonald et al. 2015). The other potential limitation is the high level of experience required of the data analyst. The analyst must be competent in both applying quantitative spectral analysis and using these results in combination with image spatial and textural information to create an appropriate map. Good working knowledge of geology and basic desert terrain and landform features is essential to develop the required geologic map.

6 Summary and Conclusions

We use a digital elevation model and two ASTER Level II products to map surface composition: (1) AST_07XT; Reflectance data (cross-talk corrected) for visible through short wave infrared (0.56–2.40 µm), and (2) AST_05 Emissivity (8.29–11.32 µm). The pixel size of these data, which range from 15 m (VIS) to 90 m (TIR) are resampled to 15 m. Mapping layers or different units are produced using a combination of algorithms (spectral angle mapper, band absorption mapping, spectral unmixing, decorrelation stretch, and various classifiers). Expert visual analysis of the highest-resolution data (15 m for ASTER) yields spatial-textural information on possible composition, relative age, and landform. The spectral and spatial units are combined to produce a map of surface composition.

The unit maps, made prior to grouping units for model inputs, would be very useful for conducting preliminary geologic mapping where subsequent field work could clarify and/or validate unit identification. However, in cases where geological maps are non-existent and field work is not possible, a basic understanding of surface composition and distribution of materials can be derived from ASTER data using the general approach described.

This integrated approach works well to rapidly produce (commonly within 9 staff-hours) an adequate reconnaissance level surface composition map in areas where no appropriate geologic map exists and where time and/or access precludes field investigations. The rapid mapping approach presented here is not intended to replace traditional geologic field mapping or remote sensing mapping involving specific site field work. The approach can, however, quickly produce an initial map for immediate use that can be further refined when additional field data is collected and added to the analysis.

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Analysis of Recurring Sinking Events of Armored Tracked Vehicles in the Israeli Agricultural Periphery of the Gaza Strip

Joel Roskin

Abstract The second (Al-Aqsa) intifada that erupted across Israel in 2000 eventually led the Israeli Defense Forces to deploy armored tracked vehicles (ATVs) (tanks, armored personal carriers, and D-9 bulldozers) within Israel's agricultural periphery of the Gaza Strip to counter daily attempts of guerilla and terrorist squads to infiltrate Israel. During operations in the winter rainy season, it was reported that ATVs often sank in muddy terrain. This study investigated what caused ATVs to sink and stall in order to develop and suggest preventive measures. The principal environmental data collected included land-use characteristics, soil association and type and daily rainfall. Reconnaissance surveys and field soil cone penetrometer tests were conducted at sites having different characteristics. Interviews with commanders were conducted to obtain details on the ATV sink events. The soils, especially in agricultural fields, were generally found to be favorable for ATV traffic, even shortly after rainstorms of 10–30 mm. However, following several rainfall events in excess of 10 mm, ATVs and tanks regularly sank in local topographic depressions in short segments of dirt roads where runoff and suspended sediment collected. ATV traffic cut ruts in the mud and compacted soils. These changes to topography and soil characteristics altered drainage patterns by directing significant surface flow and suspended sediment into the depressions and effectively creating "tank-sinks" where trafficability ranged from "untrafficable" to "trafficable with constraints." This study shows that intense, routine, defensive military activity operated without adequate terrain and/or environmental analysis and monitoring can produce repetitive, self-inflicted, environmental and combat problems.

Keywords Tank-sinks · Trafficability · Loess · Desert fringe · Military geology · Palestinian terror

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1 Introduction

Terrain often has a powerful impact on offensive, operational, and ground military activity (Roskin and Aharoni 2012). Trafficability, namely, the ability of vehicles to traverse various terrains types, plays an important role in mobility, and is essential for achieving operational goals. Occasionally, however, personnel involved in routine, defensive military activity overlook terrain as an important factor in mobility and overall trafficability. The repetition of certain activities and movements in a given environment can produce a false sense of terrain knowledge among active personnel. However, the combination of seasonal climate and intense military activity on a given terrain can lead to severe alteration of natural terrain characteristics. Changes in terrain characteristics can profoundly affect military mobility, and can have additional implications for the surrounding environment.

History has repeatedly shown the potential negative effect of near-surface hydrology on military mobility (Priddy et al. 2012). When the percentage of combat vehicle sinking incidents reaches roughly several tens of percentages per military unit, the operational impact can be significant (e.g., Liddel-Hart 1970). Although sinking events are commonly not expected in semi-arid and arid regions, they were reported during warfare and routine defense activity during the war in Iraq (Swain 1995). Military commanders of all ranks often accept the potential for vehicles sinking into mud as an inevitable part of winter warfare and have in place effective evacuation teams; however, proactive prevention research and corrective measures are not commonly practiced. This is one of many examples of the absence of terrain evaluation in military thinking and planning described by Dekel-Dolitzky (2010).

The Al-Aqsa intifada that erupted across Israel in 2000 eventually led the Israeli Defense Forces (IDF) to deploy armored tracked vehicles (ATVs) within the Israeli agricultural periphery of the Gaza Strip (Catignani 2005). These vehicles included tanks, armored D-9 bulldozers, and various heavy armored personal carriers, some of which utilized converted tank hulls. This was the first time since 1967, that intensive military activity was deployed in this region in civil and agricultural areas. Following rainfall events during the winter season, ATVs were reported stuck (bogged down) by sinking in muddy ground.

This study investigates the ATV sinking-events in an attempt to improve military operational effectiveness. The paper is based on a preliminary report (in Hebrew) submitted to the IDF concerning data collected during the winter of 2002–2003 and complementary data collected during the winter of 2004–2005. It was hypothesized that due to the geotechnical characteristics of the loessial and valley soils typical in the periphery of the Gaza Strip, the soils become soft and lose strength under changing hydrologic conditions, and that certain types of soil (after Committee on Soil Classification in Israel 1979) differ in trafficability properties due to their texture.

2 Regional Setting

2.1 General

The IDF's routine military activities in the Gaza area were confined to a narrow 1–3 km strip outside and to the southeast of the Gaza Strip (hereafter: "Gaza Strip periphery") (Fig. 1b). At the time of the study, a security separation fence divided the Gaza Strip from Israel along the 1949 armistice line. The southwest-northeast trending fence runs for 40 km along a semi-arid fringe of the northwestern Negev desert. Rainfall in this part of the Negev, which occurs intermittently during Mediterranean-derived cyclonic storms in October to April, decreases from about 400 mm in the north to about 200 mm in the south. Seasonal deviations in annual precipitation values are frequent and large. Potential evaporation rates during summer are 7–8 and 2–3 mm/day during winter. The summer diurnal temperatures are 19–31 and 6–20 °C during winter (Gat and Borsok 1986).

The study area is situated in a part of a belt of aeolian loess deposits (Dan and Yaalon 1980) (Fig. 2a) that encompass the northwestern Negev dunefield (Roskin et al. 2011) and sandy-soil periphery (Zilberman et al. 2007; Roskin et al. 2013), which collectively contain a sequence of palaeosols (Bruins and Yaalon 1992). The geomorphology of the central and northern part of the Gaza Strip periphery is composed of aeolianite (coastal sandstone locally termed 'kurkar') ridges and inter-ridge valleys that run parallel to the Mediterranean coast. Agricultural plots, mostly planted with wheat, barley, and potatoes link the local villages. The agricultural plots are bordered by a dense matrix of mainly dirt roads.

2.2 Soil Characteristics

The regional soil associations are defined on the basis of rainfall gradient and the predominantly aeolian-derived substrate, which generally becomes finer from southwest to northeast. The soil associations are divided into several classes (types), chiefly on the basis of catena location, physiography and particle sizes (Table 1). The main and northern part of the study area in the region of Nahal Oz (Fig. 2a, b) (Dan et al. 1976) consists of moderate slopes covered with loessial Arid Brown soils (Xerosols according to the FAO (1968) consisting of a sandy loam texture (Bergman et al. 2014).

Loess soil types are known to undergo dramatic changes in physical properties in response to rainfall and radiation fluctuations. Water infiltration in the medium-textured cumulic light Brown loam and loessial light Brown soils has been reported to reach a depth of about 1 m in a normal rainfall year and more than 2 m in a rainy year (Eisenberg et al. 1982), with gravimetric moisture content in the 10–20 % range (Eisenberg et al. 1982; Michaeli and Wolf 1986). Following intense rainfall, the upper parts of the soils attain moisture contents of 25 % and become liquefied

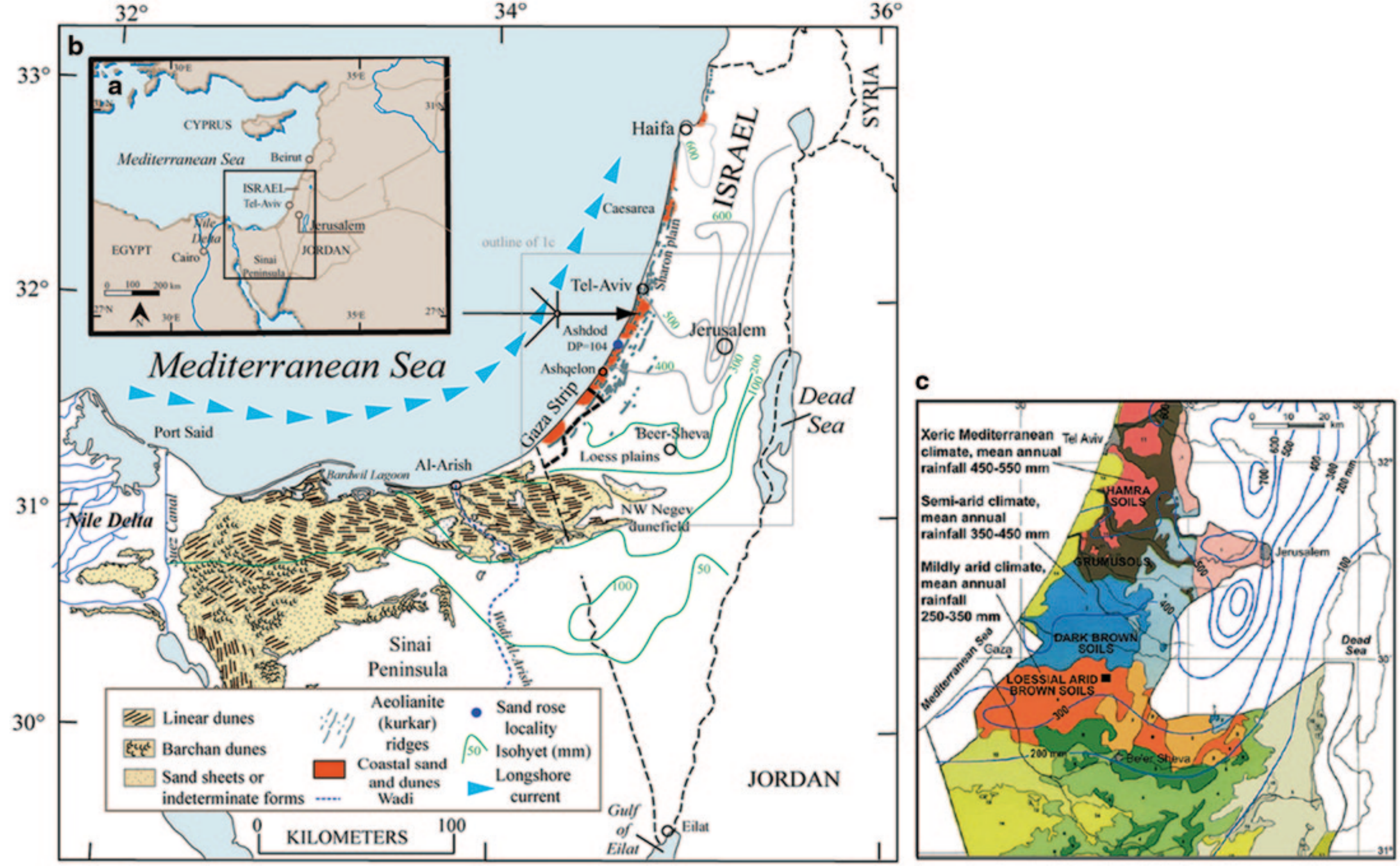

Fig. 1 Geographical setting. **a+b** Regional location of the study area (modified after Roskin et al., 2015). *Grey box* shows locations of the Gaza Strip and Fig. 1c. **c** The Soil Association Map of Israel units of the semi-arid Negev desert fringe (after Wieder et al. 2008). The study area (Gaza Strip Periphery) is located between the 1949 armistice (*black*) line of the Gaza Strip and the *thick blue line*. The *thin blue lines* are isohyets (in mm) exemplifying the semi-arid climate of the study area

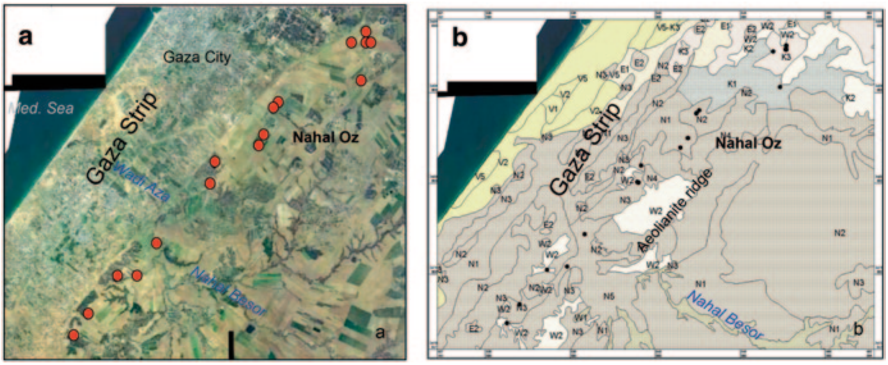

Fig. 2 Cone penetrometer (CI) measurement site locations (*red dots* on (**a**) orthophoto and *black dots* on (**b**) soil map). Soil association markings are N (Loessial arid Brown), K (Dark Brown), E (Hamra), W (Regosol), V (Sand dunes) and T for Sandy soils. (After Dan et al. 1976)

Table 1 Soil associations and types analyzed in this study. (After Dan et al. 1976)

Soil association and symbol	Soil type symbol	Soil type	Physiography
Dark Brown (K)	K1	Alluvial dark brown grumusolic soils and dark brown silty alluvial soils	Drained floodplains
	K3	Dark brown grumusolic soils and residual dark brown soils	Undulating to low hilly plains
Loessial arid Brown (N)	N1	Northern Negev loess (brown soil region)	Plains, broad valleys, young alluvial terraces
	N2	Loessial light brown soils and loess	Undulating plains and plateaus
	N3	Loessial light brown soils, residual quartzic-psammic light brown soils and loess	Undulating to low hilly plains and plateaus
	N5	Loessial regosol and loess	Low hilly plains
Hamra (E)	E1	Hamric alluvial soils and gley	Alluvial valleys with low terraces
	E2	Pararendzina	Steep hills
Regosol (W)	W2	Sandy regosol, hamric regosol and brown fine-textured regosol	Badlands
Sand dunes (V)	V1	Shifting sand, sand fields and pararendzina	Sand dunes and sand fields covering mostly kurkar ridges and parallel valleys among them
	V2	Shifting sand and sand fields	Seif dunes with transverse valleys among them; sand fields
	V5	Shifting sand, sand fields and pararendzina	
Sandy soils (T)	T1	Loess and sandy soils	Broad valleys
	T2	Gevulot (region) sand and residual quartzic-psammic light brown soils	Undulating plains
	T6	Sandy regosol and sand fields	

with low geomechanical properties such as stiffness and strength. Soil plasticity ranges from low to medium depending on the amount of clay minerals (Michaeli and Wolf 1986).

In the north end of the study area, clay-rich dark Brown soils [Luvisols, Cambisols and Vertisols, according to the FAO (1968)] are present in wadi (Arabic term for ephemeral stream) valleys. In some locations there are patches of Hamra [Luvisols according to the FAO (1968)] soils on aeolianite ridges. Regosols are associated with eroded slopes along wadis, which resemble the form of badlands (Dan et al. 1976). Sand plains overlying quartzic Brown soils are found in the south part of the study area.

2.3 Nature of Military Activity

Most of the IDF activity was intended to monitor and patrol the security separation fence as a deterrent to hostile Palestinian activities along the fence and incursions into Israel. Because of an escalation in hostile activity, IDF military activity, traditionally defined as routine defense activity, took on a more intense nature with the introduction of ATVs into the region, and was therefore internally redefined by the military as routine warfare. Military traffic for purposes of routine surveillance, access to lookout points, and rapid movement towards engagement, observation and intelligence collection, was limited to dirt roads wherever possible in order to limit damage to infrastructure and agriculture.

Military activities were controlled from headquarters and consisted of non-field operative soldiers and officers positioned in forward areas for extensive time-spans. Routine warfare activities in the study area were mainly conducted by reserve combat units that served in three-week tours of duty. Each new unit's initial acquaintance with their assigned region was based upon information conveyed from the previous unit.

3 Assumptions and Methods

The aim of the study was to investigate the cause of sinking events involving ATVs, which were the common IDF deployed combat vehicles. The critical depth for trafficability of ATVs was defined at 30–40 cm, which is the common distance between the ground surface and the tank hull.

Data about sinking-events were drawn from documentation forms that were provided to field intelligence, munitions, and engineering officers. The officers were asked to provide data that included coordinates and description of sink-event sites, date, type of vehicle and registration, sink-event description, vehicle damage description, and estimated value of vehicle damage. Additional and complementary data included interviews with commanders, and daily precipitation data taken from five Israeli Meteorological Service (IMS) stations in and near the study region.

The practical nature of the research project resulted in several constraints. Because of the army's demand for quick results and recommendations within one winter, data acquisition was complicated and data completeness was less than ideal. For example, field officers' reports on sinking-events were often inconsistent and at times biased. In one instance a young engineering officer supplied abundant data for an extended period. During his posting, the frequency of documented sinking events of D-9 bulldozers appeared high relative to tanks and ATVs attached to armored units and engineering and infantry units. Upon examination of the data, because the bulldozers were engineering vehicles, the data collection was more skewed toward his unit. Prior to and following his posting, the documenting of ATV sink-event information showed fewer events.

Ten sites having different pedological, surface, and land-use characteristics were chosen for studying the variation in trafficability properties during the winter (Fig. 2a, b). The study area was mapped according to land-use geomorphic units using aerial photos, reconnaissance surveys, and soil maps (1:50,000 scale). Information collected at each site included the different land-use and soil characteristics encountered in the study area: wadis, thalwegs, wadi banks, dirt roads, tank ruts, paludal depressions, and ridges and furrows in potato and wheat fields.

Between the fall and spring of 2002–2003, reconnaissance surveys and weekly/bi-weekly cone penetrometer tests (CPT) taken at a majority of the sites using a U.S. Army manual trafficability cone penetrometer. When feasible, measurements were made following rainfall events.

The cone penetrometer is a simple probe-type instrument designed for quick and easy field use to rapidly assess soil-trafficability. The penetrometer determines the shearing strength of low-strength soils as bearing and traction capacities of soils are functions of their shearing resistance. Shearing resistance is measured by the cone penetrometer and is expressed in terms of cone index (CPT or CI). The penetrometer used is a handheld device with a dial-type load indicator equipped with a choice of two sizes of 30° cones. The dial gauge for the cone penetrometer typically ranges from 0–300 and the numbers are often reported as unitless CI values or as pressure (pressure in psi can be read directly from the 0–300 dial gauge depending on the cone size and proving ring calibration.) The use of the trafficability penetrometer is described in ASAE Standard S313.2 (American Society of Agricultural Engineers 1999) and various online US Army publications such as U.S. Army Engineering School (1992) (Shoop et al. 2008).

During field surveys, sink-event locations, such as those near Nahal Oz (Fig. 2a, b) were visited and measured to determine the CI values associated with vehicle sinking and trafficability constraints for heavy ATVs. These measurements were due to a shortage of CI data for the heavy ATVs. Sink-event locations were identified and mapped based on interpretations of aerial photographs showing heavy ATV tracking and ruts.

4 Results and Discussion

4.1 Patterns of ATV Sink-Events

The reconnaissance field surveys helped identify potential causes of ATV sink-events. Following the first substantial winter rainfall of approximately 10 mm on the Brown and Dark Brown valley soils, ATV traffic through pristine mud resulted in deep ruts and a ridge and furrow pattern. During transit through the mud, ATV hulls often make contact with the ground surface and the ridge between track ruts is shaved, with ruts attaining depths of 30–40 cm (Fig. 3a). Though the ridge and furrow pattern does tend to slow ATV movement, in general ATVs do not stall. Typically the first substantial rainfall of the rainy season is followed by a prolonged dry spell (Fig. 4a) and the compacted ruts quickly dry into highly indurated ridge and

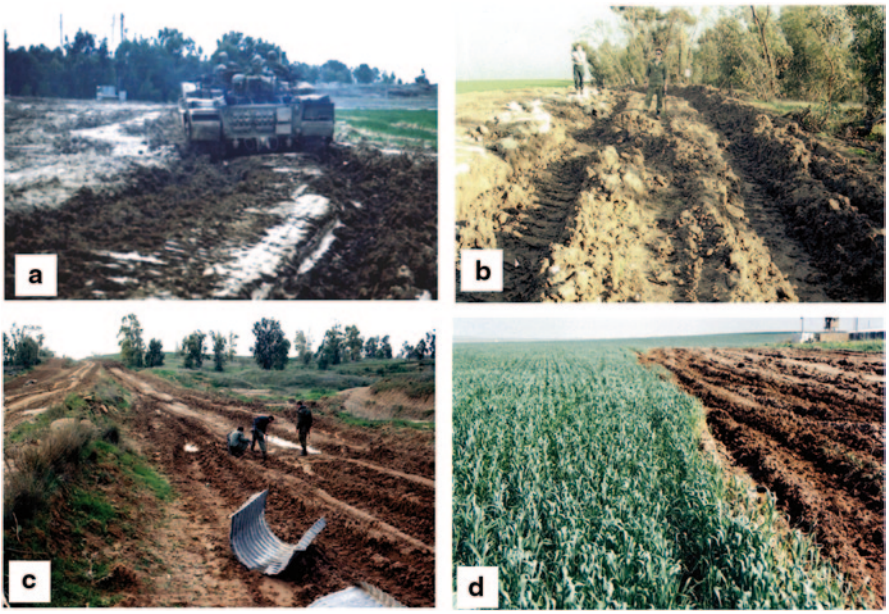

Fig. 3 The influence of ATV movement in muddy terrain and dirt roads. **a** Heavy ATV traffic in an area characterized by low-relief topography in loessial Arid *Brown* soils. The ATV tracks sink until the soil is compacted and at the same time the base of the hull flattens the soil. The friction between the hull and the ground considerably slows movement and can lead to a stall. **b** As rainy events are intermittent, dry spells harden the ATV ruts formed when the terrain was muddy. During the dry interval, the ridge and furrow pattern hardens. The dirt road becomes untrafficable for vehicles with wheels. The compacted loess, which is impermeable to rainwater leads to erosion, new drainage patterns and mud-filled depressions (Fig. 3c). **c** Tank-trap sink/depression between the edge of regosol badlands on the right and a historic British Mandate cement road on the *left*; the cement road was eventually degraded because of ATVs bypassing the sink. **d** A wheat field, which has high cone index (CI) values (Fig. 5) due to its artificially compacted soil, is slowly overridden by ATVS that avoid a large sink of mud that remains undrained because of ruts and flat topography

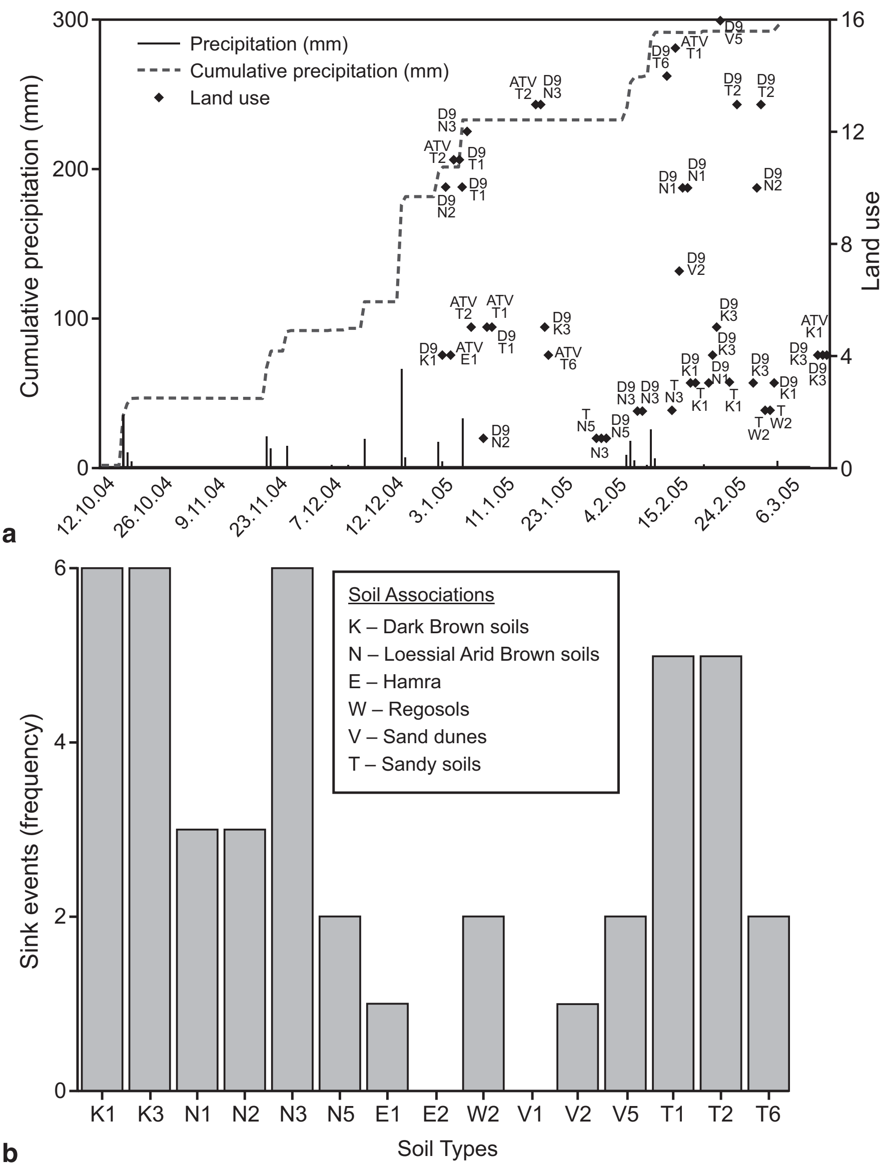

Fig. 4 Sink-event data. **a** sink-event (*black diamond*) with vehicle type and soil type according to regional land-use/geomorphic units vs. cumulative and daily precipitation (Besor station, IMS). *ATV* armored tracked vehicle, *T* tank, *D9* bulldozer. The land uses are: (1) Wadi Besor drainage: valleys and badlands, (2) Small agricultural plots, (3) Nahal Oz agricultural fields, (4) Orchards, (5) Sandy agricultural fields, (6) Field crops, (7) Dune sands, (8) Aeolianite ridges, (9) Nahal Shikma floodplains, (10) Mixed crops agriculture, (11) Village area a, (12) Village area b, (13) Sandy loam, (14) Sandy loam agricultural fields, (15) Sandy agricultural fields, (16) Terraced sandy agricultural fields. **b** Sinking-event frequency according to soil type. (See Fig. 2 and Table 1 for explanation of soil types)

furrow patterns. The hard ridges and furrows caused serious trafficability problems for small ATVs and wheeled (4X4) vehicles (Fig. 3b).

The frequency of ATV sink-events increased following rainfall in excess of 30 mm that was often followed by successive rainfall events exceeding 10 mm, over intervals of several days. Topographic depressions (hundreds of square meters) created by ATV traffic at road and gulley crossings and near military bases where ATV traffic concentrates (Fig. 3c) serve as excellent sediment and water traps. During the summer months, repetitive ATV activity, especially along dirt roads, churn the ground and form deposits of fine grained unconsolidated powder. With the arrival of seasonal rain events, large quantities of fine particles derived from the dirt roads and adjacent fields flow into the depressions and convert them into mud ponds that act as traps ('tank-sinks') that cause ATVs to sink and stall. Because of their size, some of these tank-sinks persisted throughout the rainy months where ATVs repeatedly sank. The tank-sink formation process was apparently exacerbated by the compaction of the dirt roads by track and hull pressure and ridge and furrow formation. The persistence of water in the depressions for weeks following rainfall events indicates the likelihood of a local change in hydraulic conductivity, hence infiltration rate, in response to compaction of the road. In an effort to avoid depressions, ATVs crossed cultivated fields and damaged farming infrastructure, such as water pipes that burst and intensified the problem (Fig. 3d). Traveling off the road also results in altering the existing drainage patterns, the gradual enlarging of depressions, and depriving agricultural fields of natural sheet flow.

Between December and March, all types of ATVs were found to sink, mainly on dirt roads characterized by different soil associations (Fig. 4a, b) as shown in the map of Fig. 2b. Sink-events were more common in all types of loess arid Brown soils and clay-rich Dark Brown valley soils. In sandy soils in the southern part of the study area, less marked and shorter stretches of ridge and furrow structures developed. In this flatter environment small depressions formed into local traps where sink-events also occurred. When operating on sandy quartzic Brown soils in the southern sector of the region, ATV traffic across areas where calcic loess (Brown) palaeosols are found 0.3–1 m beneath the sand deposits (Zilberman et al. 2007), caused mechanical mixing of the subsoil with the surface sand and a change in soil porosity and permeability. The soil mixing enhances water retention and the formation of mud during rainy periods. In some cases, the churned thin sand cover was blown away revealing the underlying loess soil, which develops into mud following rains. Sink-events in pure sand were attributed to well-drained and dry sand.

The intensity and/or proximity of military activity, soil association, and land use affected trafficability. Based on field observations, the trafficability of infilled depressions was correlated with their size and the intensity of military movement. For example, a muddy pond adjacent to a military base, several hundred square meters in size, remained wet through mid-spring. Distal routes that were travelled less frequently were found to develop short-lived depressions in small, local topographic lows. The frequency of sink-events is associated with land use type (Fig. 4a). However, these land uses are usually associated with the arid Brown soils and clay-rich dark Brown valley soils where sinking was abundant (Fig. 4b). For example, the land use category orchard, is associated with numerous sink-events, likely because the orchard trees limited the opportunities for ATVs to bypass depressions. These finds suggest that the soil association is the major factor controlling ATV sinking.

4.2 *Cone Penetrometer Results*

Throughout the winter, other than days following two or three of the largest precipitation events–usually on the order of 20–50 mm (Fig. 4a), most of the pristine terrain not impacted by ATV traffic, dirt roads, and the cultivated fields (and 'furrows and ridges' along slopes), were found to have high and trafficable CI values of 100–300 at the critical depths (Fig. 5a–c). ATV ruts were virtually non-penetrable by the CPT and revealed very high CI values (<200) due to the compaction of the ATV tracks.

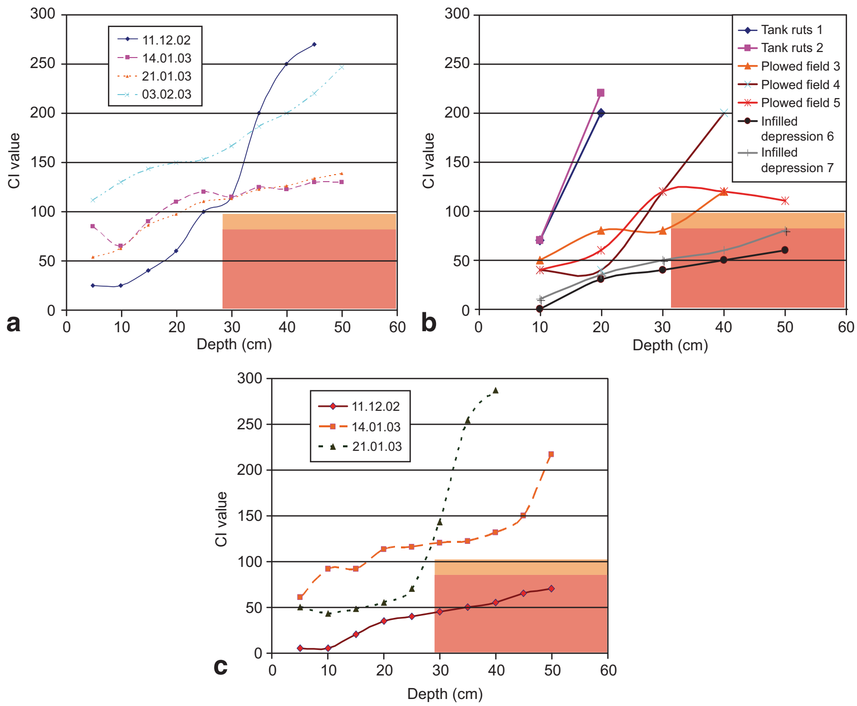

Fig. 5 Generalized cone penetrometer profiles of main land-use types in the study region. The *red polygon* marks untrafficable values and the *orange polygon* marks the range of trafficable with constraints for ATVs. **a** CI results for a potato field. The field was trafficable throughout the winter. **b** CI results for a dirt road, plowed (wheat) fields, and sink depressions in the Nahal Oz region measured at 11.12.2002. **c** A wheat field near Nahal Oz. For several days after 30 mm of rain, on 11.12.02, the field was untrafficable for ATVs

CPT measurements were taken along the dirt road ridges, which often extended for hundreds of meter, to identify the conditions that considerably slowed down ATV movement during combat operations despite the imminent possibility of stalling or sinking (Fig. 3a). CI values were in the range of 80–100 and these values, in cases taken beyond the critical depth of 30 cm, were defined as “trafficable with constraints” (Fig. 5, light orange polygons). However, due to compaction of the ruts, the track depths usually did not increase following later ATV movement and additional rainfall, thereby preserving the low but possible trafficability condition.

CI values for tank-trap depressions (sinks) ranged from very low 40 CI to 100 CI. Here, CI values did not increase with depth because the water and fine-grained sediment collection and corresponding infiltration enabled deep infiltration of water. Based on measuring sites shortly after ATV sinking and on CI values found for ridges in the order of 80–100 as mentioned above, untrafficable CI values were defined as <80 CI (Fig. 5, red polygons). Thus the depressions were assessed to consist of trafficability ranging from untrafficable, to trafficable with constraints.

The untrafficable periods based upon field CPT measurements (Fig. 5b, c) correlated with the onset of ATV sinks, usually in the mid- and late winter (Fig. 3a). At this time the soil has accumulated half of the annual precipitation and evaporation rates are at their lowest (Gat and Borsok 1986).

5 Military Coping with ATV Sinking

In the winter of 2002–2003, being the first year of ATV deployment in the Gaza Strip periphery, the IDF’s operational orders for this area were to respond immediately to hostilities near the security fence. The operational concept at the time was to mobilize forces for every expected and ongoing attack. This deployment resulted in several months of repeated sink events and extraction missions, both of which undermined operational efficiency.

Eventually, the regional IDF headquarters came to appreciate the cost of vehicle sinking events. Relevant wintertime orders changed and generally instructed that in the absence of specific orders to the contrary, no movement of forces should be undertaken in response to hostile activity targeting the security fence, citing ATV sinking, extraction missions, and loss of effectiveness as the reasons. During the dry summer months, field engineering units traditionally level the dry tank ruts and depressions, but without installing preventive engineering measures, such as adequate drainage diversion. This was probably due in part to the limited dissemination of the preliminary report to field units, operational headquarters, and officers. Thus, ATV sink-events continued to recur during following winters.

6 Summary

This study examines the military and environmental implications of repetitive routine military activity using ATVs on fine-grained soils in a semi-arid environment that experiences alternating rainfall events exceeding 10 mm and dry intervals. Whereas agricultural fields remained trafficable throughout most of the rainy season, dirt roads behaved differently. After the early rains in late fall, tank ruts solidify and become conduits of concentrated runoff and fine particles released by ATV activity during the summer months. Topographic depressions evolve into mud-filled sinks causing trafficability constraints. The study found that vehicle sinking in winter was widespread in both soils of silt (loess) and clay (valley) dominated textures. ATVs even sank in sandy soils overlying loess palaeosols in areas impacted by ATV caused surface disturbance and mixing of sandy soils with underlying finer-grained units.

This study demonstrates the effectiveness of field observation and measurement, complemented by basic applied and empirical geomorphic methods and methodologies to analyze the causes of rapid anthropogenic geomorphic changes of military and environmental importance. However at a practical level, adjustments in tactical and strategic military policy due to changes in government policy, combined with a lack of awareness of the impact of terrain on routine and operational military activity, makes it difficult for the military to cope with self-inflicted geomorphic changes and their negative military and environmental consequences in a prudent and timely fashion.

The scope of this work further demonstrates that it is vital to persistently promote and market the application of military geoscience products in order to save lives, limit expenses and preserve the environment to a relative degree, often for the short and long-term benefit of both sides of a conflict. Implementation of such products within the complex military industry requires further substantial discussion.

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Integrated Terrain Forecasting for Military Operations in Deserts: Geologic Basis for Rapid Predictive Mapping of Soils and Terrain Features

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Abstract During the past three decades, the U.S. armed forces have been called on repeatedly to operate in the deserts of the Middle East and southwest Asia. Avoiding locations susceptible to extreme dust emissions and other terrain-related hazards requires the ability to predict soil and terrain conditions, often from limited information and under dynamic environmental conditions. This paper reports the approach used to develop an integrated, predictive tool for forecasting terrain conditions to

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support military operations in desert environments at strategic, operational, and tactical scales. The technical approach relies on the systematic integration of desert landform parameters in geomorphic models for predicting terrain conditions. This integrated effort is performed in a geographic information system (GIS) framework using expert-based analysis of airborne and spaceborne imagery to identify terrain elements. Advances in earth science research have established that unique, predictable relations exist among landscape position, soils, vegetation, and geology. Furthermore, new instrumentation allows the collection of a wide range of environmental information to characterize surface and subsurface conditions. By integrating models and methods from geomorphology, soil science, climatology, and atmospheric science with remote sensing and other technologies, a predictive model can be developed to support military operations.

Keywords Predictive mapping · Terrain hazards · Landforms · Soils

1 Introduction

Deserts are now, and will continue to be strategic sites for military operations. Military success in deserts requires familiarly with these environments for training and materiel testing that is appropriate for them. Specifically, the need for mobility, flexibility, and rapid deployment of forces requires the ability to predict diverse conditions, a challenge in deserts which are extreme and complex environments characterized by frequent and rapid change. Terrain conditions, coupled with a lack of sufficient training and knowledge of desert environments, previously challenged U.S. military operations in North Africa during Operation Torch in World War II (Atkinson 2002; Gilewitch and Pellerin *this volume*) and during Operation Eagle Claw, the failed rescue effort of American embassy hostages in Iran in 1980 (Kamps 2006). More recently, military operations in Iraq and Afghanistan have shown that sudden losses of visibility from dust emission caused by military operations (e.g., brownouts) have created an ever-present hazard. A majority of the losses of rotorcraft aircraft during military operations in these countries was due to brownout conditions, also referred to as degraded visual environments (Gaydos et al. 2012; Acquisition and Technology Programs Task Force, 2009). In addition to brownouts, the exposure of equipment to desert dust probably caused the frequently reported malfunctions of combat weapons during the initial phase of Operation Iraqi Freedom (McDonald and Caldwell 2008). Another risk of military operations in desert environments is related to dust-rich desert soils, which can become non-cohesive and impassible when wet, drastically reducing trafficability.

Avoiding terrain-related hazards for military operations requires the ability to quickly identify and predict soil and terrain conditions, often from limited information (e.g. existing soil or geologic maps), and often under variable and dynamic environmental conditions. At present, the U.S. military does not have the scientific tools to rapidly and efficiently perform terrain hazard forecasting that is necessary in the desert environments before personnel, vehicles, and weapons are deployed. New technologies are required to significantly enhance intelligence gathering in the desert, guide tactical operational planning, and benefit battlefield readiness requirements for the twenty-first-century U.S. military.

Recent advances in earth science research demonstrate that unique and predictable relations exist among landscape position, soils, vegetation, and geology (see e.g., Birkeland 1999; Schaetzel and Anderson 2005). These relations account for the complex distribution of common soil types and surface conditions in desert terrains. Thirty years ago, desert military geology (e.g., field geology, geomorphology, and soil science) included aerial photograph interpretation, field geomorphic mapping, and ground "truthing" with soil excavations and sampling. This application was characterized by Gerson et al. (1985a, b) in a study in Israel and Sinai which addressed the availability of dust in desert terrains. Additional studies have been conducted that demonstrate systematic relations exist between desert surficial processes and the location of soils across diverse desert landscapes, ranging from dry lake beds to alluvial plains and valleys (see e.g. Gile et al. 1981; Parsons and Abrahams 2009), which are common types of terrain used during military operations, training, and testing. It is the knowledge of these systematic relations that can be used to predict terrain conditions based on analysis of airborne- or satellite-based spectral imagery and high resolution digital elevation model (DEM) data. Moreover, application of new instrumentation will allow the collection of a wide range of environmental information to directly characterize surface and subsurface conditions in the desert, including the use of tension infiltrometers, ground penetration radar, and portable wind tunnels (e.g., Caldwell et al. 2008a; Meadows et al. 2006; Sweeney et al. 2008, 2011).

The purpose of this paper is to summarize the general concept and research design of an ongoing project to develop an expert-based, integrated GIS-base predictive model for forecasting terrain conditions and surface responses at different scales in desert regions to support military tactical operations, training, and materiel testing. The conceptual model driving the GIS-based framework is designed to rapidly integrate geomorphology, soil science, climatology, and atmospheric sciences, as well as remote sensing and other technologies into this dynamic predictive tool. The development and testing of this model follows three objectives: (1) advance knowledge of soil and surface processes, assess the applicability of remote sensing technologies, and compile existing data for predictive assessment of desert terrain conditions; (2) integrate knowledge of desert surficial processes, remote sensing, and numerical modeling to develop a dynamic GIS platform for predicting desert terrain conditions and potential hazards; and (3) validate a predictive model across diverse desert terrains in key deserts of the world. Future efforts will likely incorporate information from unmanned airborne vehicles operating remote sensing instruments to quickly link surface observables over a wide area in near real-time.

2 Scientific Basis for Terrain Predictive Models

Desert landscapes are typically a complex mosaic of contrasting soil types and surface characteristics (Gile et al. 1981; McDonald et al. 2003). This complexity is due to the juxtaposition of surficial deposits of variable age and lithologic composition, as well as climatic variations and extremes, the abundance of mineral aerosols (dust), and the ephemeral nature of surface water and related sedimentologic processes. The complexity of deserts, however, can be addressed by subdividing the terrain into distinct physiographic units or landforms using a range of geologic, topographic, hydrologic, and biologic variables. The ability to subdivide the terrain provides the means for predicting surface conditions, because each subdivision or mapping unit represents a predictable set of soil and surface properties based on landform type and age.

Prediction of desert terrain conditions has advanced to another level through development of geophysical and geochronological methods and application of models of desert surface evolution in arid regions. Several geomorphic models have been developed that establish links between regional climate, tectonic events, and landscape evolution that can be used to predict the age and spatial distribution of key landforms, as well as the soils and surface conditions likely to be associated with each landform (e.g., Bull 1991; Amit et al. 1993; McDonald et al. 2003). Recent investigations have also enhanced our ability to predict soil and surface properties through demonstration of how key soil hydrologic and physiochemical properties are linked with landscape evolution and surface age (Gerson and Amit 1987; Amit et al. 1993; McDonald et al. 1996; McFadden et al. 1998; Young et al. 2004). Results of these studies have provided insight into how the accumulation of desert dust is a principal driver in the formation of soils and how desert pavements (reg soils) control soil hydraulics, and impact short- and long-term landscape stability.

2.1 Rationale and Significance of Landform-based Terrain Predictions

Existing geographic data sources (e.g., digital elevation models, geologic maps, soil surveys, satellite and aerial imagery) can provide some information regarding general terrain conditions, but they are insufficient for predicting trafficability or identifying localized terrain hazards, especially under changing environmental conditions. Perhaps most importantly, these sources do not provide detailed spatial information on subsurface (<100 cm depth) conditions, information that can now be provided by geomorphic modeling (here modeling refers to application of conceptual as well as numerical models). By systematically integrating the observational knowledge about the distribution, age, and geology of desert landforms and associated soil and surface features, geomorphic models provide an essential platform for predicting terrain conditions. Using these models, knowledge of how desert landscapes evolve, and of the principal surficial processes that drive surface evolution, can be inverted to provide a powerful means to predict soil conditions and to assess terrain hazards, such as trafficability or dust emissivity (Fig. 1).

The concept of geomorphic-model inversion simply refers to the integration of surface observations with models of landscape evolution to predict what lies below the immediate surface. In other words, years of research have demonstrated that systematic relationships exist between landscape position and soil formation processes that account for the observed distribution of soils across desert terrains. This

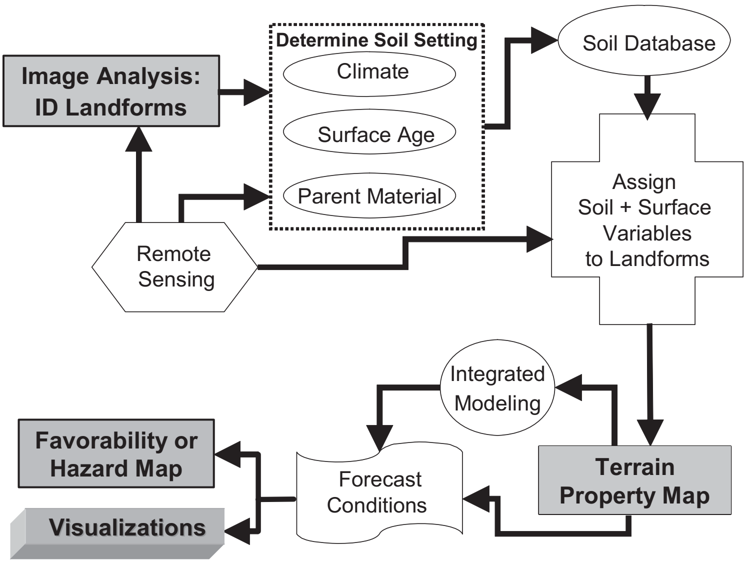

Fig. 1 Flowchart summarizing GIS platform designed for dynamic predictions of desert terrain conditions. Diagram shows relative position of three fundamental components or products (image analysis, terrain property map, and output in maps or visualizations) and associated degrees of data integration and application

knowledge can be essentially applied in reverse: knowledge of soil forming processes can now be applied to identified or mapped landforms to develop predictive soil maps. Prediction of critical surface and subsurface conditions can be further augmented (in terms of time and quality) by linking the inversion of geomorphic models with surface observables, most of which can be supplied by remote sensing from satellites or unmanned airborne vehicles (UAVs) operating in advance of ground troops, followed by expert-based analysis. Once surface and subsurface conditions are estimated, the ability of vehicles to operate in specific locations can be assessed.

3 Model for Predicting Terrain Conditions

The procedure for predicting soil and terrain conditions is based on two concepts. First, a soil evolves from a preexisting parent material, usually surficial deposits composed of a single or mixed lithologic (i.e. bedrock-type) composition, into a well-defined soil closely related to discrete and identifiable landforms (e.g. alluvial fans). This systematic relation allows experts the ability to reasonably predict soil types if general knowledge of overall climate (especially precipitation), landform age and type, and soil parent material can be identified or surmised. This approach is primarily based upon the five soil-forming factor concept of Jenny (1941) that includes: time, parent material, topography, climate, and organisms. Second, most landforms can be easily identified using available aerial imagery (e.g., Jayko et al. 2005). Application of this approach represents the idea of geomorphic model inversion. Predictions of subsurface conditions are based on the integration of conceptual models of how desert surface and soils evolve, with observation of existing surface characteristics (e.g., landform morphology, surface cover, microtopography). The procedure, which can be adjusted to strategic, operational, and tactical scales, consists of three general steps: image analysis, development of a soil predictive map, and generation of a terrain property map based on the spatial distribution of the predictive soil properties.

3.1 Image Analysis

Analysis of aerial imagery to identify key landforms, soil parent material, and other related terrain features are performed in the first step of the procedure. The assignment of relative age classes to each landform or geomorphic surface map unit is based on cross-cutting relations, surface morphology and roughness, and topographic relief observable on imagery. Principal soil and surface attributes are assigned to each map unit using soil data supplied through a linked database of desert soil parameters. Other tools such as image classification techniques within remote sensing applications and a variety of imagery sources and digital elevation model (DEM) can also be used to provide information about exposed lithologies and surface roughness to aid in the image analysis. The resulting product consists of GIS layers representing a georeferenced soil and surface dataset.

3.2 Soil Database and Predictive Soil Map

Principal soil and surface attributes are assigned to geomorphic map units using soil data supplied through a linked database using four soil-forming data layers: time (surface age), parent material (lithology or rock type), topography (landform), and climate (precipitation). Parent material information is supplied through either analysis of existing geologic maps or through identification of primary lithology of surface materials using imagery from the satellite-borne ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) sensor (Sabol et al. Chapter "Parent Material Mapping of Geologic Surfaces Using Aster in Support of Integrated Terrain Forecasting for Military Operations"). Climate information is primarily derived from high resolution interpolated climate surfaces (WorldClim—Global Climate Data) of Hijmans et al. (2005). Identification of both surface age and landform are based on expert-based analysis of available air-borne or space-borne imagery (e.g. IKONOS satellite imagery). Landform unit contacts were digitally derived from the imagery in a geographic information systems (GIS) platform, and are presented herein using Albers Equal Area Projection, WGS 1984 datum. Vegetation (one of the five major soil forming factors of Jenny (1941)) is not included, because of the generally sparse vegetation cover in most deserts.

Table 1 List of age classes assigned to mapped units

Age class	Minimum age (kyr)	Maximum age (kyr)
Tertiary (or older)	1640	5000000
Early Pleistocene	800	1640
Middle Pleistocene	125	800
Mid-late Pleistocene	80	125
Late Pleistocene	12	80
Early-middle Holocene	4	12
Late Holocene	0	4

The four soil-forming data layers (Tables 1, 2, 3, 4) are integrated together to query a soil database through the use of an interactive GIS tool with pull-down

Table 2 List of parent material classes assigned to mapped units

Primary type	Secondary type	Possible rock types
Igneous, extrusive	Fine grained, acidic-intermediate	Rhyolite, trachyte, latite, porphyry, welded tuff
	Fine grained, basic	Andesite, dacite, basalt, diabase, tholite, porphyry
Igneous, intrusive	Coarse-grained, acidic-intermediate	Granite, granodiorite, syenite, quartz-monzonite, monzonite, pegmatite
	Coarse-grained, basic	Granodiotite, diotite, gabbro, tonalite,
Metamorphic, foliated	Metamorphic, mafic/basic	Amphibolite, eclogite, serpentine, eclogite, talc
	Metamorphic, argillaceous	Slate, phyllite, schist
	Metamorphic, felsic/ quartzose-feldspathic	Gneiss, granulite, migmatite
Metamorphic, non-foliated	Metamorphic, quartzitic	Quartzite
	Metamorphic, calcareous	Marble
Sedimentary, calcareous	Calcareous, biochemical-soft	Chalk, coquina, marl
	Calcareous, biochemical-hard	Limestone, dolomite
	Calcareous, chemical	Travertine, tufa
Sedimentary, evaporative	Non-calcareous, evaporative	Anhydrite, gypsum, halite
Sedimentary, organic	Biogenic sediments, calcareous	Black shale, coal, peat
	Biogenic sediments, non-calcareous	Diatomite, chert, flint, jasper
Sedimentary, clastic	Fine-grained, laminated-fissile	Argillite, shale, mudstone, claystone, siltstone
	Medium-grained, bedded to massive	Sandstone, arenite, arkose, graywacke
	Coarse-grained, bedded to massive	Breccia, conglomerate
Sedimentary,volcaniclastic	Volcaniclastics, acidic-intermediate	Ignimbrite, tuff, pumice, scoria (e.g. Basaltic)
	Volcaniclastics, basic	Ignimbrite, tuff, pumice, scoria (e.g. Andesitic, rhyolitic)

Table 3 List of primary and secondary landform classes assigned to mapped units (modified from Mabbutt (1977) and Peterson (1981)

Primary landforms			
Alluvial fan	Broad river plain	Low relief erosional feature	Volcanic features
Alluvial plain	Coastal feature	Plateau	Eolian depositional feature
Badlands	High relief highlands	Saline plain (playa, sabkha)	Eolian erosional feature
Secondary landform type			
Lacustrine/coastal	*Erosional*	*Fluvial/alluvial*	*Volcanic*
Shoreline feature	Rocky hillslope	Active channel	Cone
Playa	Pediment	Alluvial fan	Flow
Sabkha	Ballena	Alluvial plain	Dome
Beach	Plateau/mesa	Flood plain	
Mudflat	Inselberg	Levee	Misc deposits
Delta	Soil caprock	Terrace (fluvial/alluvial)	Moraine
Lake plain	Grooved terrain (yardangs)		Salt dome
Marsh	Deflations hollow		Landslide
Marine terrace	Badlands		Talus

Table 4 List of precipitation classes assigned to mapped units

Precipitation class	Annual precipitation (mm)
Hyperarid	0–50
Arid	50–100
Mildly arid	100–250
Semiarid	250–500
Subhumid	500–1000

menus that searches the database for the most representative soil attributes. The database, created and maintained by the Desert Research Institute (DRI), currently contains descriptions of about 815 georeferenced soil observation sites, amounting to 4120 pedological horizon descriptions from the Mojave and Sonoran Deserts of the southwest U.S., Negev Desert of Israel, and selected sites in southwest Asia. The sources of information are primarily from published peer-reviewed journal articles, the U.S. Department of Agriculture (USDA) Natural Resource Conservation Service soil database, and published soil surveys from the southwest U.S., Israel, and globally (e.g., FAO-UNESCO-ISRIC 1998; Soil Survey Staff 1999; Nachtergaele et al. 2000; Singer 2007).

3.3 Terrain Hazard or Favorability Map

The spatial distribution of hazardous or favorable terrain across the landscape is based on soil attributes from the resultant predictive soil map. The soil attributes of each soil map unit can be used as input into numerical process models (e.g. surface hydrology, dust emission), terrain computer visualizations, or qualitatively represented as specific terrain properties that can be combined into specific-purpose maps depicting either potentially hazardous or favorable terrain conditions. For example, attribute data consisting of soil texture, surface roughness, topography, and soil erodibility quotients can be combined to develop hazard maps, such as for the forecasting of areas that are susceptible to rotorcraft-induced dust emission (brownout) during landing (e.g., McAlpine et al. 2010). The identification and location of terrain conditions can be portrayed as GIS layers or hard-copy maps, with the location of hazards displayed via a five-fold hazard class system (e.g. very low, low, moderate, high, and very high). Another example of the utility of this approach is for determination of target area suitability for specific types of operations, instruments, or vehicles (based on soil conditions, surface roughness, dust availability, and other surface characteristics). The generated output can range from red-yellow-green (go/no go) terrain hazard maps to grid-cell location data required as input parameters for numerical environmental and surface process models.

4 Study Areas

Principal study areas have been established in both the western U.S. and in southwest Asia to develop required soil landscape knowledge and to test results of soil and terrain predictions. The areas selected provide either a combination of desert terrain and active defense facilities or critical desert soil and terrain that has been extensively studied. Principal test areas in the U.S. include: (1) U.S. Army Yuma Proving Ground (YPG; Yuma, Arizona), (2) U.S. Army National Training Center (NTC; Ft. Irwin, California), and (4) select areas within the East Mojave National Preserve and Death Valley National Monument. Outside the U.S., the principal area in southwest Asia is the Negev Desert of Israel (Gerson et al. 1985a, b) because the soil and terrain of the Negev Desert are common to many other arid areas across southwest Asia. Additional areas in Egypt, Chile, and Mexico have recently been reconnoitered for potential future investigations.

5 Examples of Soil and Terrain Predictive Mapping

Examples of project results include success in establishing systematic linkages between common desert landforms and soil properties, and in developing a GIS-based platform linking expert-based analysis of desert terrain imagery with soil data queried from a database to produce soil property maps that can be used to predict potential terrain hazards. Intensive field examination of desert soils has been conducted in both the southwestern U.S. and across Israel to determine systematic relations between landscape position, physiography, and soil surface and sub-surface properties

(McDonald et al. 2003; Sweeney et al. 2011; Amit et al. 2011). Together, the sites reflect a broad range of desert soil types that dominate areas of tactical operations in southwestern Asia (e.g., Bacon et al. 2008). Results indicate that the expert-based image analysis of landforms in these desert regions can delineate principal soil and terrain types and provide important information about regional soils and associated soil properties to identify potential terrain hazards at strategic, operational, and tactical scales.

5.1 Strategic Scale

Strategic scale terrain characterization is typically performed at map scales ranging from 1:5,000,000 (global) to 1:750,000 (continental). Mapping of physiographic or landform features at this scale is interpretive in nature and performed at a fixed map scale within a geographic information system (GIS) platform. The identification of terrain elements is typically done using 250- and 500-m resolution MODerate-resolution Imaging Spectroradiometer (MODIS) or 30-m resolution Landsat Thematic Mapper ™ or Enhanced Thematic Mapper (ETM+) satellite imagery. In addition to the spectral imagery, 90-m resolution Shuttle Radar Topography Mission (SRTM) digital topographic data can be used. The assignment of dust potential rating classes to physiographic or landform features is based on the typical surface characteristics and soil properties found associated with these features based on data from small-scale geologic maps and soil surveys (Fig. 2a). Figure 2b provides an example of a strategic-scale dust potential hazard map from Bacon and McDonald (*this volume*) with a five-fold hazard class system (very low, low, moderate, high, and very high). This class system is developed to categorize the dust potential of the upper 0.5 m of the surface on landforms in a portion of southwest Asia during dry environmental conditions (Fig. 2b).

5.2 Operational Scale

Operational scale terrain characterization is performed at map scales ranging from 1:750,000 (continental) to 1:100,000 (regional). Mapping of landform features at the operational scale is similar to the strategic scale, but terrain elements are identified and digitized in a GIS platform at larger scales using relatively higher resolution imagery; such as 30-m resolution Landsat satellite imagery or 15–90-m ASTER products. Also, the 90-m SRTM DEM and 10- and 30-m resolution U.S. Geological Survey (USGS) national DEMs can be used. If accurate soil surveys are available at the desired scale, then the soil mapping units presented in these soil surveys can also be used, such as for the country of Iraq (Fig. 3a). The assignment of a five-fold

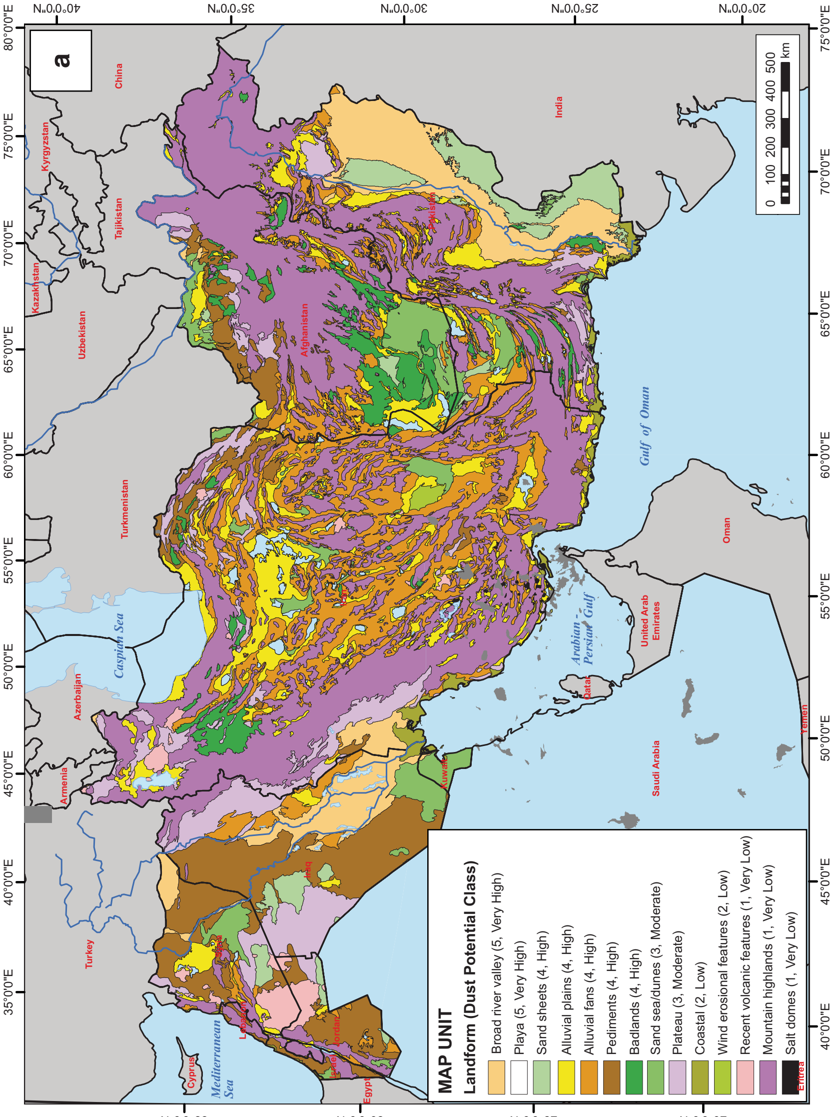

Fig. 2 **a** Landform map of a portion of southwest Asia at a strategic scale of 1:750,000 showing associated dust potential classes

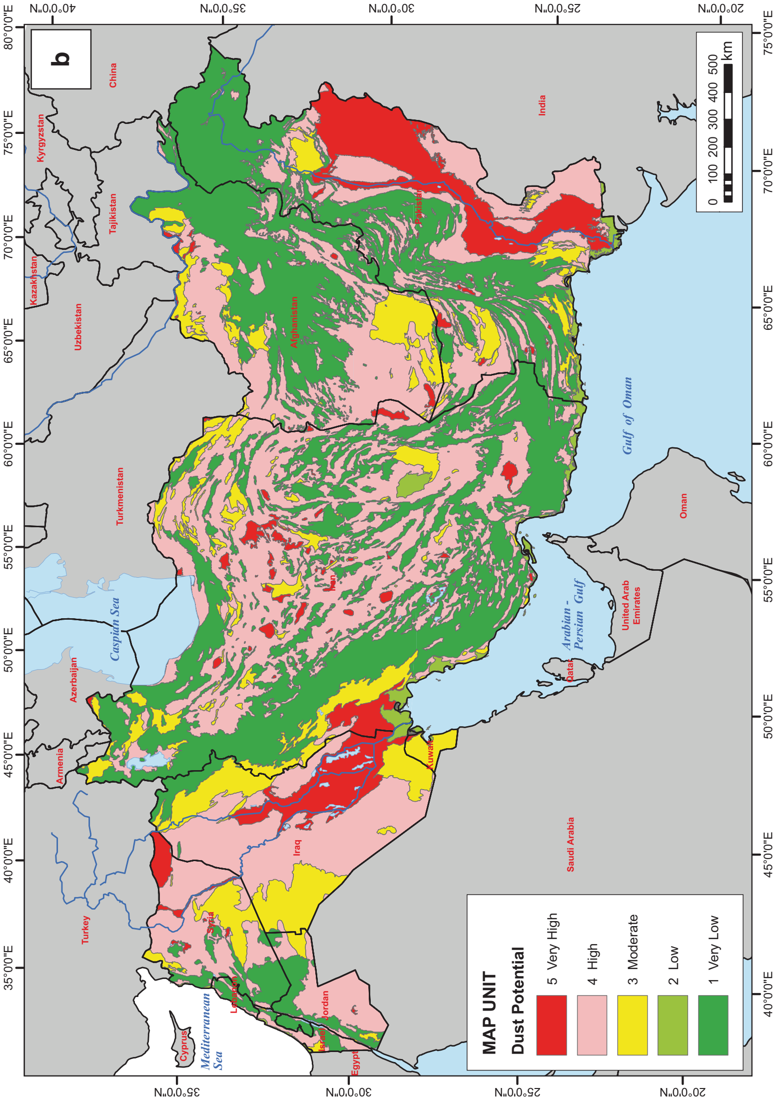

Fig. 2 **b** Dust potential map showing five-fold rating classes based on the typical soil associated with identified landforms

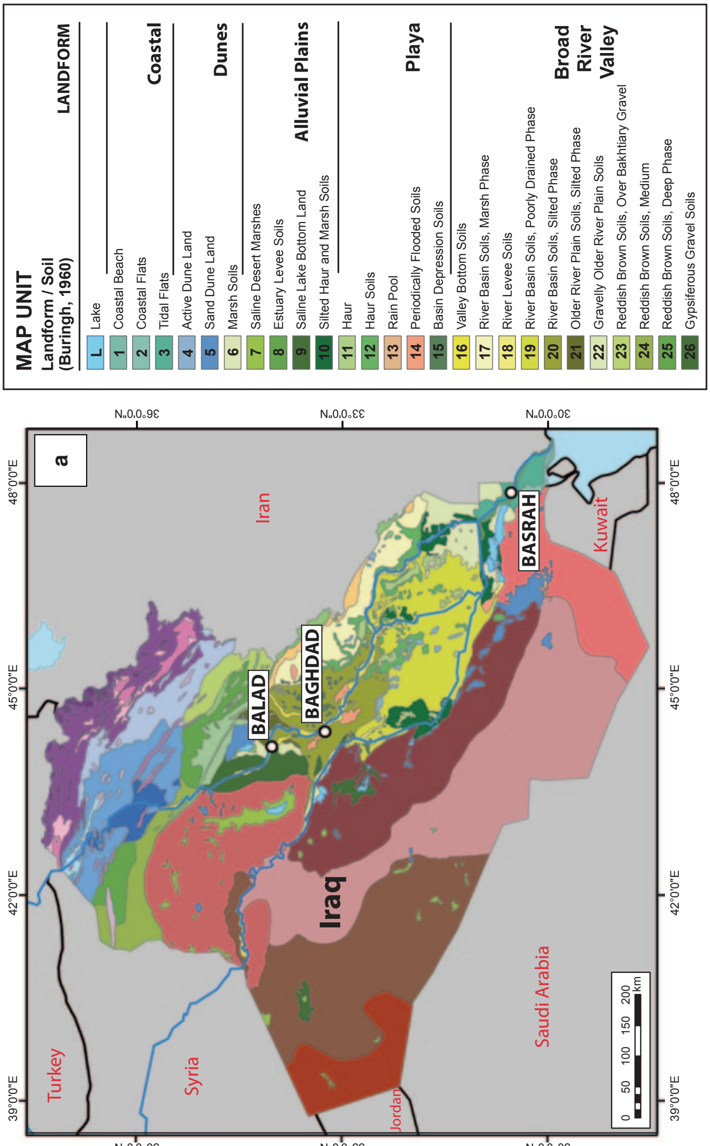

Fig. 3 **a** Geomorphic map showing the distribution of soil-geomorphic units in Iraq

dust potential rating class system to landform features or soil units is also similar to strategic scales, but principally based on the more country- or regional-specific soil surveys that include detailed land surface and soil descriptions, as well as soil geochemical information (Fig. 3b).

5.3 Tactical Scale

Tactical scale terrain characterization is performed at map scales ranging from 1:100,000 (regional) to 1:5000 (site-specific). Base map imagery typically used to identify landscape elements at tactical scales include ~1-m (panchromatic) and 2–4-m (multispectral) resolution imagery from the IKONOS and QuickBird satellite platforms or 1-m resolution, natural color National Agricultural Imagery Program (NAIP) airborne imagery. To enhance the identification and delineation of landform boundaries, 10-m resolution USGS DEMs or ~1-m resolution Light Detection And Ranging (LIDAR) digital elevation data may be used. The higher resolution of image data at tactical mapping scales allow more accurate digitizing of landform boundaries in a GIS platform, as well as aiding in the identification of surface characteristics and cross-cutting relations that are required to assign relative age classes to specific landforms. As a result, the soil database can be applied to assign soil attributes directly to map units to generate a predictive soil map. Furthermore, if accurate and detailed soil survey information is available at large scales, then these can also be used, such as the soil map for the vicinity of Balad along the Tigris River in Iraq (Fig. 4a). Based on the soils information from Buringh (1960), a five-fold hazard class system was developed to categorize the dust potential of the upper 30 cm of the surface with respect to military operations in the vicinity of Balad. The criteria used to assign hazard classes included surface characteristics and cover, the silt, clay, and sand particle-size fractions, as well as the salt content in the upper soil profile (Fig. 4b).

5.4 Application of Predictive Maps at Different Scales

It should be noted that maps produced at strategic and even operation scales are limited to general overview of the principal types and spatial distribution of dominant terrain features and may not provide sufficient detail to identify terrain hazards likely to be encountered during military operations. As a result, the maps are not intended for use in detailed or site-specific hazards analyses, as would be possibly required for conducting mobility assessments or avoiding potential rotary-wing aircraft landing sites prone to producing degraded visual environments (dust brownouts). Use of these, small-scale maps should be restricted to situations where a generalized understanding of physiographic features and surface characteristics is useful. These scale maps are not recommended as a data source for situations in

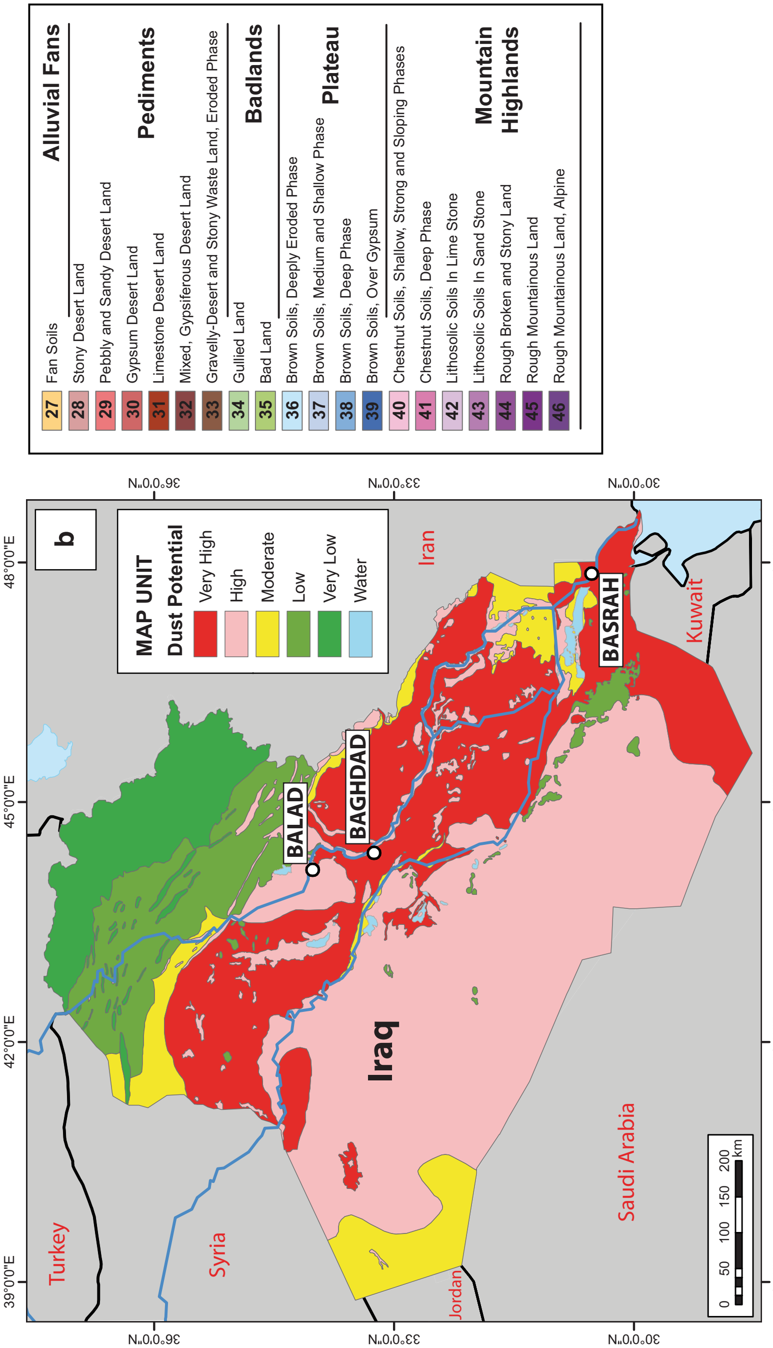

Fig. 3 **b** Dust potential map of undisturbed (natural) surfaces based on the soil-geomorphic descriptions in Buringh (1960)

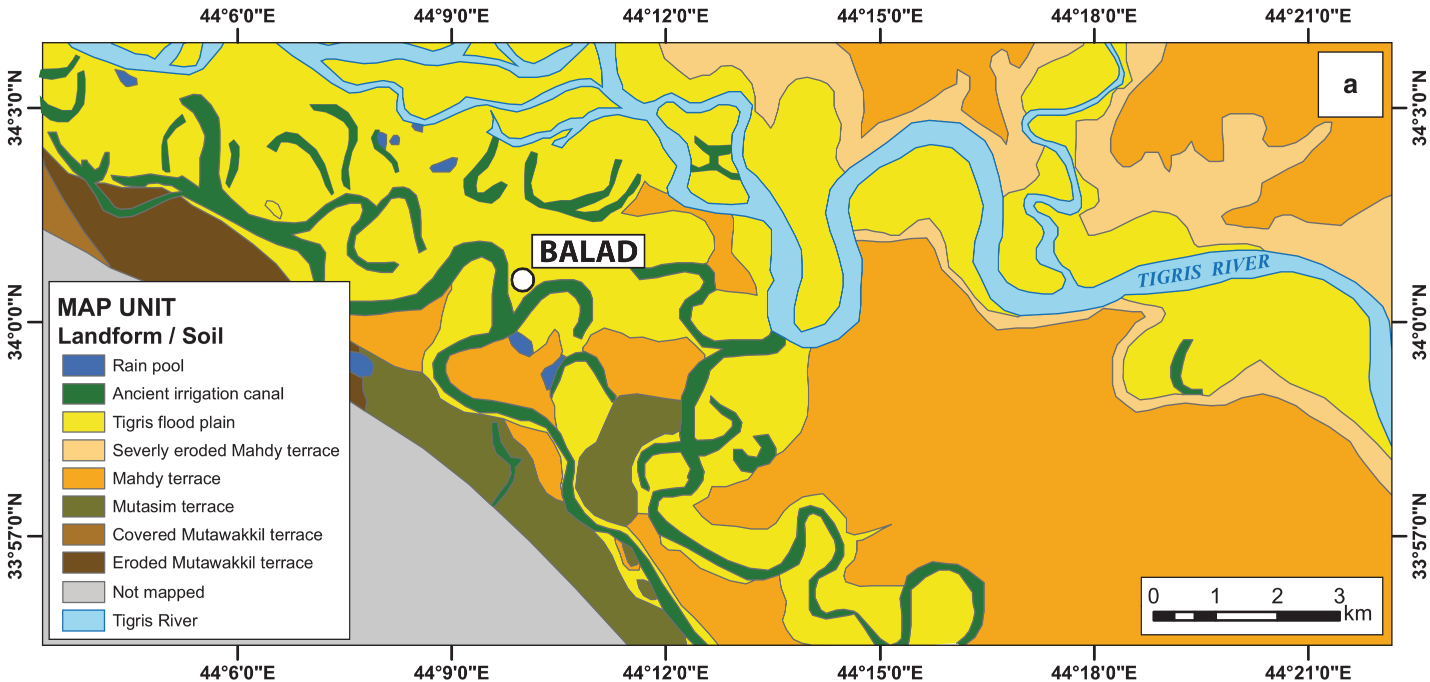

Fig. 4 **a** Geomorphic map showing the distribution of Quaternary Tigris River terraces and ancient (historic) river courses and irrigation canals near Balad, ~70 km north of Baghdad

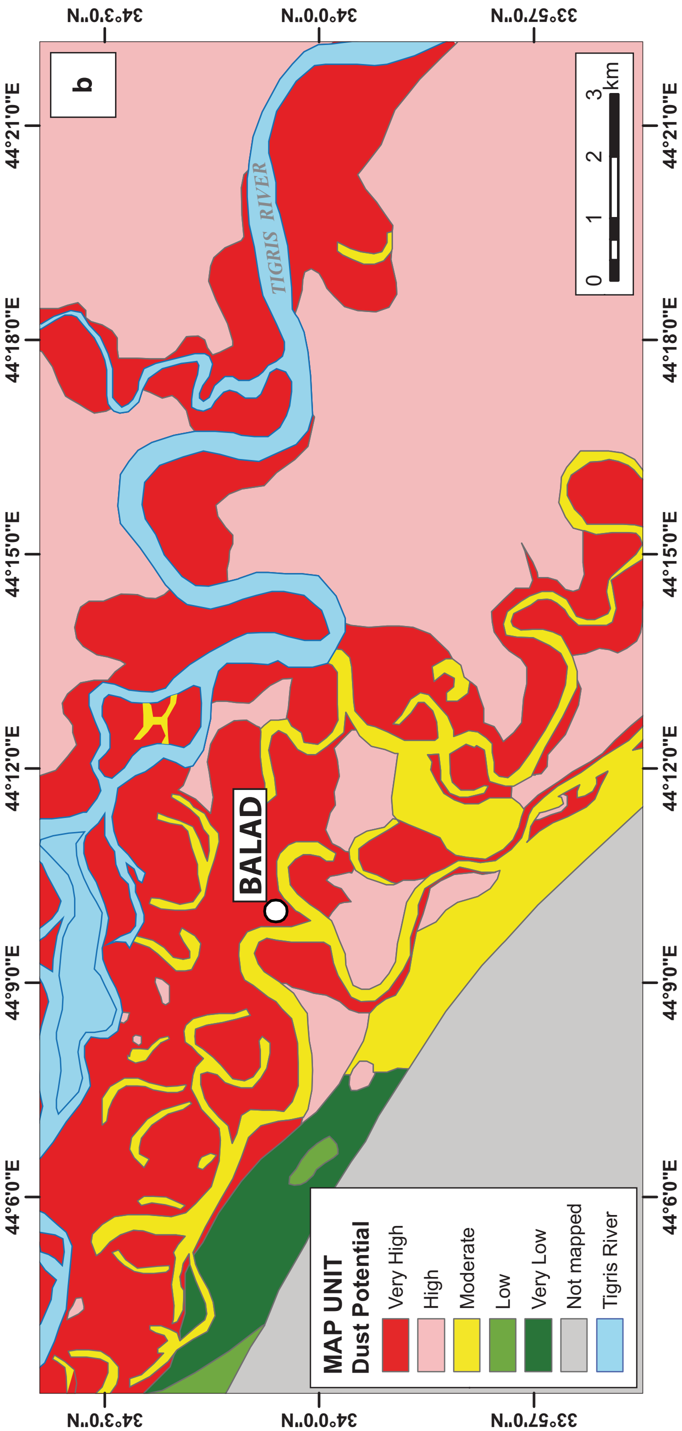

Fig. 4 **b** Dust potential map of undisturbed (natural) surfaces based on the geomorphic mapping and soil descriptions as modified from Buringh (1960)

which a highly detailed, large-scale interpretation of surface characteristics is necessary, such as at tactical scales, because the small scales do not have the resolution needed to identify the surface characteristics and cross-cutting relations that are required to assign relative age classes to specific landforms. The level of terrain information available in maps produced at strategic and even operational scale maps do provide important terrain information that can be used to design soil and geologic sampling strategies to develop continental-scale datasets to evaluate propagation of dust storms (Engelbrecht et al. 2008; Bacon and McDonald, *this volume*).

6 Remote Sensing Technologies to Support Predictive Mapping

The application of remote sensing imagery to readily identify surface lithology at a scale that is usable for terrain mapping (1:10,000–1:24.000) is required to identify the dominant lithology in bedrock outcrops and in surficial sediments to determine soil parent material. Current procedures rely predominantly on ASTER data as it is appropriate to these scales (60 km^2 footprint), spectral coverage in the visible (VIS), shortwave infrared (SWIR), and thermal infrared (TIR) (14 bands), and worldwide data coverage. We have, however, used high-spatial resolution airborne data (5 m pixel size) from the MODIS/ASTER airborne simulator (MASTER) (50 spectral bands) and Probe 1 (128 spectral bands) on specific test sites. Details regarding this approach are in Sabol et al. *this volume*, but generally consist of determining lithology through a combination of spectral angle mapper, band absorption mapping, spectral unmixing, decorrelation stretch, and various classifiers (see e.g. Adams et al. 1995; Mustard and Pieters 1989; Roberts et al. 1998; Dennison and Roberts 2003). Results of image analysis are used to generate maps of primary lithologies for a given area. These lithologic maps are used by expert analysis to assign parent material attributes to each mapped landform (Fig. 1, Table 5).

6.1 Data Integration for Terrain Forecasting

Data integration through use of the GIS framework during this project has resulted in significant advances in desert terrain characterization. New tools developed to link the DRI-generated soils database with existing GIS platforms created a means whereby geomorphologists could efficiently and rapidly identify landforms and assign soil characteristics to digital data layers. Implementation of this new tool represents the first attempt to describe surface soil characteristics simultaneously with landform identification. The new tool creates a delivery format readily usable by modelers of dust emission or trafficability, as well as to predict other terrain-related hazards.

Major progress has also been made in field characterization of dust, including measuring dust from surfaces using the Portable in situ Wind Erosion Lab

Table 5 Summary of terrain components and associated properties that can be predicted by the desert terrain forecasting model

Terrain condition	Terrain component	Examples of measured properties
Soil properties	Soil type and distribution	General soil attributes
	Subsurface properties	Texture, depth/type of restrictive layers
Surface properties	Desert pavement development (reg soils)	Size, percent cover, sorting
	Surface clasts and boulders	Abundance, size
	Macrotopography (>1 m height)	Flatness, distribution and size of washes or scarps, surface continuity
Dust availability	Texture	Clay, silt, and fine sand particle-size distribution
	Dust emission potential (disturbed/undisturbed soil conditions)	Resistance to soil erosion and dust transport, moisture content
Soil mechanical properties	Soil strength	Penetration resistance and shear strength
	Soil density	Nuclear density gauge data, proctor tests
	Hydraulic conductivity	Modeling
Soluble salt content	Composition, amount	Vertical distribution, electrical resistance
Vegetation cover	Dominant plant species	Percent cover, height

(PI-SWERL), determining dust sources using geochemical correlation methods, and collecting field-based data for use in dust emission modeling (e.g., Sweeney et al. 2008; Bacon et al. 2011; Bacon and McDonald, *this volume*). These activities will offer crucial ground-based data to support or refine the ability to predict locations of high dust emissivity (e.g. brownouts), as well as regional patterns of dust emission and aerial transport.

6.2 Significance to Military Operations

Predictions of soil and terrain attributes at variable scales can provide multiple benefits to military operations. Weapons testing and training activities in desert environments require a substantial investment in range instrumentation, ground-truthing, restoration, and ongoing research to validate material performance. Information about soils and dust have been provided to support evaluation of: (1) soils used in construction materials in Iraq as well as in similar training and testing analog sites in the U.S.; (2) impacts of dust mineralogy on electronic sensor operation; (3) generation of brownout conditions from soil and dust; and (4) mitigation of desert soils on U.S. military training sites. Results and technology produced during this project also directly support military activities. Examples include: (1) determining regional distribution of salt-rich dust potential across southwest Asia for mitigating impacts of desert dust on aircraft electronics or to providing information to support dust emission models (e.g., Bacon and McDonald, *this volume*; Bacon et al. 2011); (2) assessment of natural background levels of metals and minerals in dust for elucidating potential impacts to the health of U.S. military and civilian personnel (e.g., Engelbrecht et al. 2009); and (3) identification of analogous terrain within the world's deserts to improve the fidelity of desert testing during material research, development, and evaluation prior to deployment in the field (e.g., Bacon et al. 2008; Caldwell et al. 2008b).

7 Conclusions

During the past two decades, the U.S. armed forces have been called on repeatedly to operate in the deserts of southwest Asia. We developed an expert-based system using a GIS platform that provides a flexible, scalable, and adaptable approach to predict soil and terrain conditions in desert regions. The approach combines expert analysis of remotely collected imagery of desert terrain to classify landscape features into geomorphic map units with available data on soils, geology, and climate. Based on landform mapping and image analysis, these data are integrated in a GIS platform and used as a predictive tool for unknown areas that could also be used to assess the environmental response to the impact of military activity.

Models of terrain conditions and response—e.g., potential for dust generation under differing use intensities and duration—can be generated in user-friendly digital image format to indicate areas most or least suitable for specific military activity. These models may be used in both training and operational situations, to prolong the useful life of our military installations, weapons and equipment, and to protect service personnel. Data integration through use of the GIS framework over the past several years has resulted in significant advances in desert terrain characterization and predictive soil mapping. New tools developed to link the DRI-generated soil database with existing GIS technologies created a means whereby geomorphologists can efficiently and rapidly identify landforms and assign soil characteristics. Implementation of this new tool represents a first attempt to describe surface soil characteristics simultaneously with landform identification. The new tool creates a delivery format readily usable for the prediction of terrain hazards. The soil-forming model presented here is geomorphic-based, and considers soil age as a significant factor in accurately predicting soil conditions in hyper arid to mildly arid regions, which differs from most pedometric derived predictive soil mapping techniques (e.g., McBratney et al. 2000; Scull et al. 2003).

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