ORIGINAL ARTICLE

A review of natural geological hazards in Oman

M. H. Al-Kindi[1] · R. Hird[1]

Abstract

Oman has a diverse geology and physiography as a result of its location close to active tectonic plates. Oceanic and continental rocks spanning in age from the Proterozoic to the Tertiary are overlain by mobile sediments of the Quaternary. Infrastructure is expanding due to demands for industrial and residential land and associated transport networks, though the geology can abate this progress. Shifting dunes threaten road networks, residential areas and agricultural land. Ophiolite and mantle rocks can contain natural asbestos minerals which when fragmented can be hazardous to health. Large expanses of carbonate and evaporitic rocks are prone to karst morphology and where existing examples include caves and sinkholes. The recent tectonic events have given rise to earth tremors, fissures, ground displacements and tsunamis. A review of the main natural hazards in Oman is presented to assist with high-level land development planning in accordance with the geology and minimise its potentially hazardous effects.

Introduction

Geological natural hazards in one form or another are widespread across most of the world, and in Oman a variety of different natural geohazards are associated with its complex geology, physiography and climate. These hazards become noticeable during land development planning where measures need to be taken to minimise or prevent their effect. To accommodate future needs in mining and petroleum exploration, processing, storage and export, as well as population growth, infrastructure in Oman is encroaching into regions which once contained small settlements reliant on small subsidence farming or fishing. Oman is the third largest country in terms of land mass in the Arabian Peninsula with land borders between Yemen in the south, Saudi Arabia in the west and the United Arab Emirates (UAE) in the north. It is also split into three territories. The main part of Oman situated at the side of the Indian Ocean and Gulf of Oman where the capital Muscat is located. The Musandam peninsular which separates the Sea of Oman with the Persian (or Arabian) Gulf and is bounded to the west and south by the

UAE, and Madha which is a small enclave surrounded by Fujairah (UAE) and containing an even smaller enclave of Sharjah (UAE). The region is arid subtropical with a hot dry climate and a very low rainfall except in the Dhofar region in the south near the Yemen border, which catches the summer monsoon. Its geology ranges from the Proterozoic, comprising igneous and metamorphic rocks exposed in patches along certain areas close to the eastern and southern coastal ranges of Oman, to Quaternary which includes dunes, salt flats and alluvium deposits. Humans have existed in Oman since the Palaeolithic, far back in time to the dawn of our species (Rose and Bailey 2008).

The risk management and land use planning are all important topics and the purpose of this study is to present some of the natural hazards which occur in Oman directly related to the geology. If hazards are known or can be foreseen through similar geological strata then risks can be mitigated. Seismicity, inland dunes and tsunamis have been individually researched and documented in Oman. However, naturally occurring asbestos, active faults and karst features have not been adequately studied especially with regards to their potential hazard to land development. Flooding and subsequent wadi erosion is another major hazard but is not necessarily related to geology but rather to a combination of elevation and precipitation where sun-baked soils can impede initial infiltration. Other forms of ground risk are

✉ R. Hird
rh500@cantab.net

1   Earth Sciences Consultancy Centre, Ghala, Muscat, Sultanate of Oman

accentuated by anthropological activities, which include ground contamination from mining activities, saltification through over-pumping of groundwater and rock falls along highways due to slope regrading where the geology (and its structural components) are not fully understood. Oman contains large expanses of desert where soils and rocks contain natural minerals which exhibit swelling or collapse (due to dissolution) upon contact with water. These areas of mainly Tertiary and Quaternary sedimentary formations are not a hazard if left untouched by man, but can cause construction problems during land development. The location and effects of these anthropological induced hazards to manmade structures in Oman are part of a separate study and will be reported later.

In the Arabian Peninsula, countrywide natural geological hazards have been studied by a few authors in Saudi Arabia and United Arab Emirates, though only one comprehensive study on multiple natural and geohazards has been conducted in Oman and only for the Muscat area by MMTEC (2012).

This manuscript begins with a simplified geological background followed by a description of each chosen natural hazard including where the hazards are typically located and what information exists in the public domain. Basic maps accompany some hazards showing their known location along with shaded areas where hazards are also to be expected, based on the similar geological formation.

The aim of this manuscript is to make readers more aware of what natural geological hazards exist within the region and to mitigate against any 'unforeseen' events by means of site relocation or specific site investigations to minimise potentially adverse effects. Awareness of actual and potential hazards could eventually be incorporated into regional geohazard maps using GIS techniques (see Hird et al. 2019).

Geological background

Major geological domains exposed in Oman

The Sultanate of Oman covers an area of about 310,000 km^2 with coastal lines stretching for more than 3000 km. The surface of Oman could be divided generally into four main geological and geomorphological domains (see Fig. 1): (1) the Al Hajar Mountains in northern Oman with its associated alluvial fans that discharge water to the sea in the north and to inland saline soils of the Umm As Samim in the west, (2) the Al Huqf Mountains and Masirah Ophiolite in central Oman, (3) the chain of the Dhofar Mountains in southern Oman with its alluvial plains and finally the desert, (4) sabkha plains and sand dunes, mostly covering the central and southern parts of Oman (Al-Kindi 2018). Each morphological terrain has its specific geological record and associated
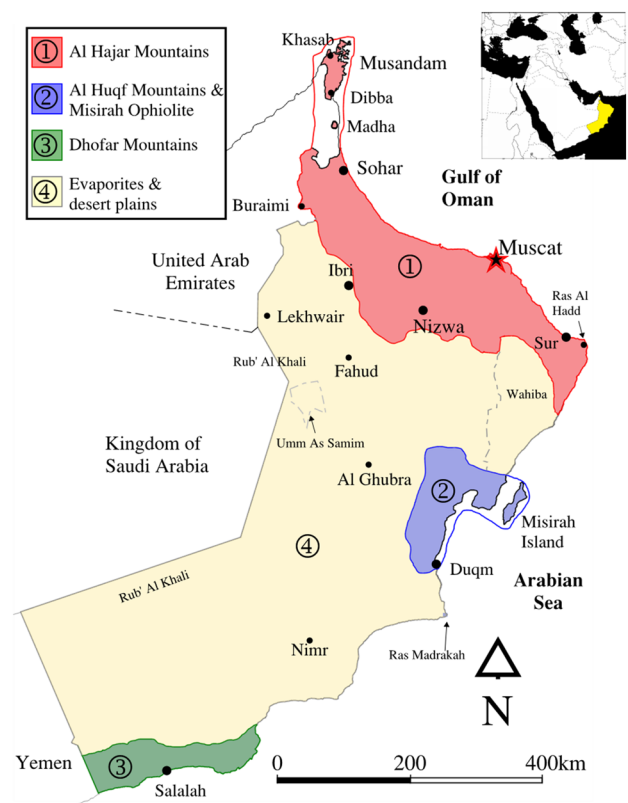

Fig. 1 Main geomorphological domains in Oman

natural hazards. They also differ quite significantly in their climatic setting throughout the year, which can accelerate the natural hazard potential. An example here is the seasonal monsoon in Dhofar which contributes to dissolution of carbonate rocks and leads to the potential of sinkhole development and ground subsidence. Past and present, the communities living in these different terrains have interacted differently with the geological setting around their lands, according to many records, experienced various risks due unaccounted natural geological hazards.

The coastal lines of Oman significantly vary between mountainous terrains with steep cliffs overlooking the sea, such as in Musandam in the northern Al Hajar Mountains and in the Dhofar Mountains, to sand beaches, such as in the sand dunes area in north-eastern Oman, alluvial fans, as in the northern side of the central Al Hajar Mountains, flat escarpments and small hills as in most of the south-eastern coast of Oman. These coastal domains also have different geological history and present setting. The communities in these areas face different natural hazards related mainly to slope stabilities, tsunami, active tectonism and karstification.

The Al Hajar Mountains extend for more than 700 km from the Musandam Peninsula to Ras Al Hadd, forming an arc-shaped sequence of mountain chains and long wadis that represent the backbone of the northern Oman area and make

up one of the largest mountain terrains in Arabia. The geology of the Al Hajar Mountains is primarily characterised by thick deposits of Mesozoic carbonates, exposed in the massifs of Al Jebel Al Akhdar, Saih Hatat and Musandam and oceanic rocks of ophiolite and oceanic deposits forming the areas in between these two massifs, as well as clastic and carbonate rocks from the Proterozoic and Palaeozoic exposed in the deeply incised geological windows of Al Hajar Mountains. The eastern side of the Al Hajar Mountains is dominated by wide exposures of white Cenozoic carbonates. These contain many large caves and sinkholes, some of which are amongst the largest in the World including Majlis Al Jinn (see Hoffmann et al. 2016). The piedmont Batinah plain extends from Muscat to north of Sohar and contains many braided recent and sub-recent (buried) alluvial channels and localised pockets of mobile sand dunes.

Al Huqf forms the eastern part of central Oman and extends for about 200 km north–south and 75 km east–west. Generally, the area is covered with small escarpments and hills above flat coastal sabkha plains and sand dunes of both clastic and carbonate rocks spanning the time from Late Proterozoic to the Cenozoic. The ophiolite rocks of Masirah Island and Ras Madrakah form a different terrain on the eastern side of Al Huqf. Most of the south-eastern side of the Omani coastal line is covered by Early Cenozoic carbonates and evaporites. In south Oman the Dhofar Mountains continue for about 250 km in a NE–SW direction.

A southern and central desert plain occupies an area of about 170,000 km^2 which is mostly covered by Cenozoic limestone pavements and with braded shallow wadis. Evaporite soils occur within and around the Umm As Samim in the Rub' Al Khali desert. The largest bodies of sand are found at Wahiba sands in the north-east and the Rub' Al Khali desert in the south-west of Oman.

Recent tectonic events in Oman

Figure 2 shows the major fault zones in Oman. The current maximum horizontal in situ tectonic stress (σHmax) is mostly oriented NNE–SSW and is manifested from various datasets including petroleum borehole breakouts (see Filbrandt et al. 2006) and micro-seismicity data from petroleum fields (see Al-Harrasi et al. 2014). This is broadly related to the collision of the Arabian Plate with the Eurasian Plate, caused primarily because of the opening of the Red Sea and the subsequent NNE–SSE movement of Arabia. The rate of opening of the Red Sea is estimated at 20 ± 3 mm/year, whereas the collision with Eurasia happens at a faster rate (Reilinger et al. 1997). Recent geomorphological changes have occurred as a result of this stress and its relevant tectonics, such as the change of shoreline level in various parts of Oman (see Hoffmann et al. 2013a) and the subsidence and uplift in different parts of Oman.
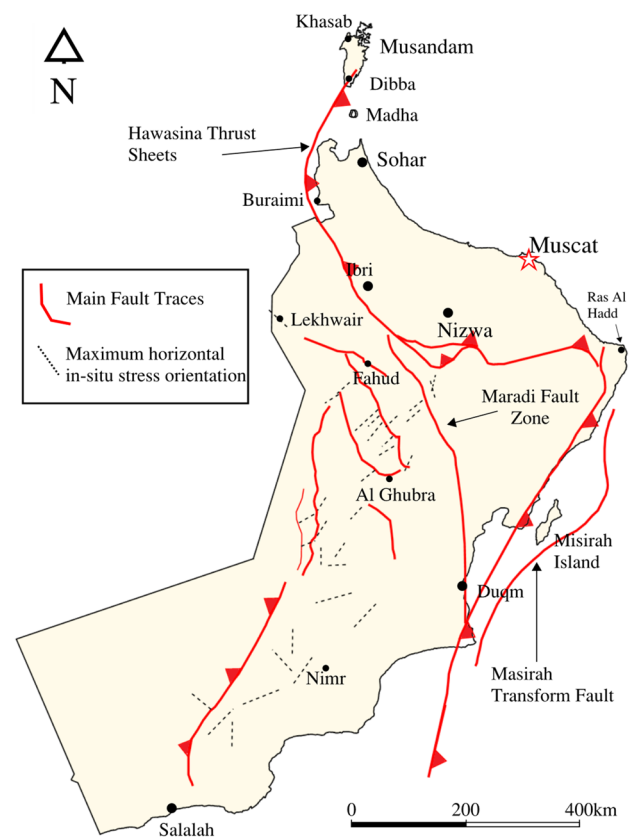

Fig. 2 The major fault zones in Oman, with the orientation of the in situ stress [modified from Filbrandt et al. (2006)]. Note that the orientation of the maximum horizontal in situ stress can be diverted from the regional trend (NE–SW) close to major fault zones

For example, the coastline of Musandam is currently submerging below sea level at a rate of several millimetres a year due to the collision between Arabia and Eurasia, whereas most of the coastal line from Muscat to Ras Al Hadd is uplifted a few millimetres every year.

The NNE–SSW to NE–SW orientation of the in situ σHmax is generally consistent across Oman. However, in places where major fault zones exist, stress perturbations occur and the orientation and magnitude of in situ stress could be quite substantially different than the other parts of Oman. An example of these major fault zones is the Maradi Fault Zone, which continues for probably about 500 kms from Ibri to the central eastern shoreline of Oman, assuming here that it connects in the subsurface with Haushi-Nafun Fault system in central Oman. The Maradi Fault Zone has most likely been recently active in its northern segments (Al-Gahaffi and McClay 2010). Furthermore, the north-western side of Oman, known as the Lekhwair area, where many petroleum fields occur, the σHmax orientation is NW–SE, perpendicular to that prevailing in other parts of the country.

Main identified natural hazards

Dunes

The distribution of sand dune bodies in Oman are presented in Fig. 3 [extracted from Le Métour et al. (1993)]. Barchan and linear dunes are considered hazardous because of their ability to migrate and threaten cultivated land, irrigation channels and wells, residential houses and road networks. In Oman there are two main sand bodies: the Rub' al Khali on the western side of the country (total area of 522,340 km^2 extending from parts of UAE, Oman, Saudi Arabia and Yemen) and the Wahiba sand (approximately 16,000 km^2) (see Goudie et al. 1987; Radies et al. 2004; Pease and Tchakerian 2014) in the central eastern region of Oman to the south east of the Al Hajar mountains. These sand bodies were apparently deposited by water prior to aeolian reworking dating back to the Quaternary (Besler and Ritter 2009). The desert plain in central Oman and along the SE coast has a limestone plain covered with rubbly sediments and some patchy dunes (Hoffmann et al. 2016). Other smaller bodies of sand with ridges orientated NE–SW exist at Wadi Al Abyad (about

Fig. 3 Location of sand dunes in Oman [extracted from Le Métour et al. (1993)]

100 square km), Bousher (1.4 km^2) which is an administration district in Muscat and dotted along the Batinah plain close to the coastline.

The main Wahiba sand morphologies have been identified by Radies et al. (2004) to be (1) an area of high complex linear mega-ridges (or draa) in the northern central part called Al Hibal or the High Sands; (2) an area of low and stratigraphically younger linear and barchan dunes called the Low Sands (see Fig. 4a); (3) the Coastal Area characterised by high transverse dunes and aeolianite outcrops in coastal cliffs and interdune depressions.

The northernmost part of the Wahiba Sands (High Sands) in eastern Oman consist of mega ridges aligned approximately north to south and spaced at 1.4 km where in the north they are truncated by the Wadi al Batha running SE. The compound dunes or draa are 45–55 m high and include several rows of secondary dunes with steep flanks (27°) on both sides (Besler and Ritter 2009). The distinct inter-draa corridors are partly vegetated (used as pasture) and house small seif dunes.

Although the morphology of the aeolian dunes in the Rub' Al-Khali are many and varied, three principal forms can be defined as transverse (orientation of the dune crest-line is close to perpendicular to dominant wind direction), linear orientation of the dune crest-line is close to parallel to dominant wind direction) and star forms which exhibit a multi-facetted pyramid-like structure due to reversing wind (Al-Masrahy and Mountney 2013).

To understand migration rates of the large dune bodies in Oman, Tatum and Francke (2012) used remote sensing to internally profile determine the extent of radar penetration in Wahiba sands and dunes in the Rub' Al-Khali near Lekhwair. It was found that Wahiba sands are composed of extensive, complex, linear mega draa which had limited penetration (30 m) due to increased moisture content in the dune core (presumed vegetation), elevated capillary fringe, and mineral complexity due to the ophiolite content from the mountains. These large dunes are probably static whereas small dunes at the surface were observed dry and therefore mobile. Small active mobile linear dunes migrating across the surface of the larger dunes remain yellow in colour. In the Low sand areas of Wahiba Sand Sea, comparison between satelite images between 2004 and 2013 indicated that the barchan dunes north of the village of Al Ashkharah are moving with a speed of 10 m to 15 m per year (Hoffmann et al. 2016).

The main sand bodies currently lie in areas where human settlements and infrastructure are remote owing to the exploration and production of oil and gas in the Rub' al Khali and largely tourism in Wahiba sands. However, a study on the migratory rates in the Rub' Al-Khali is required to determine whether infrastructure being built in relation to the oil and gas industry is at risk.
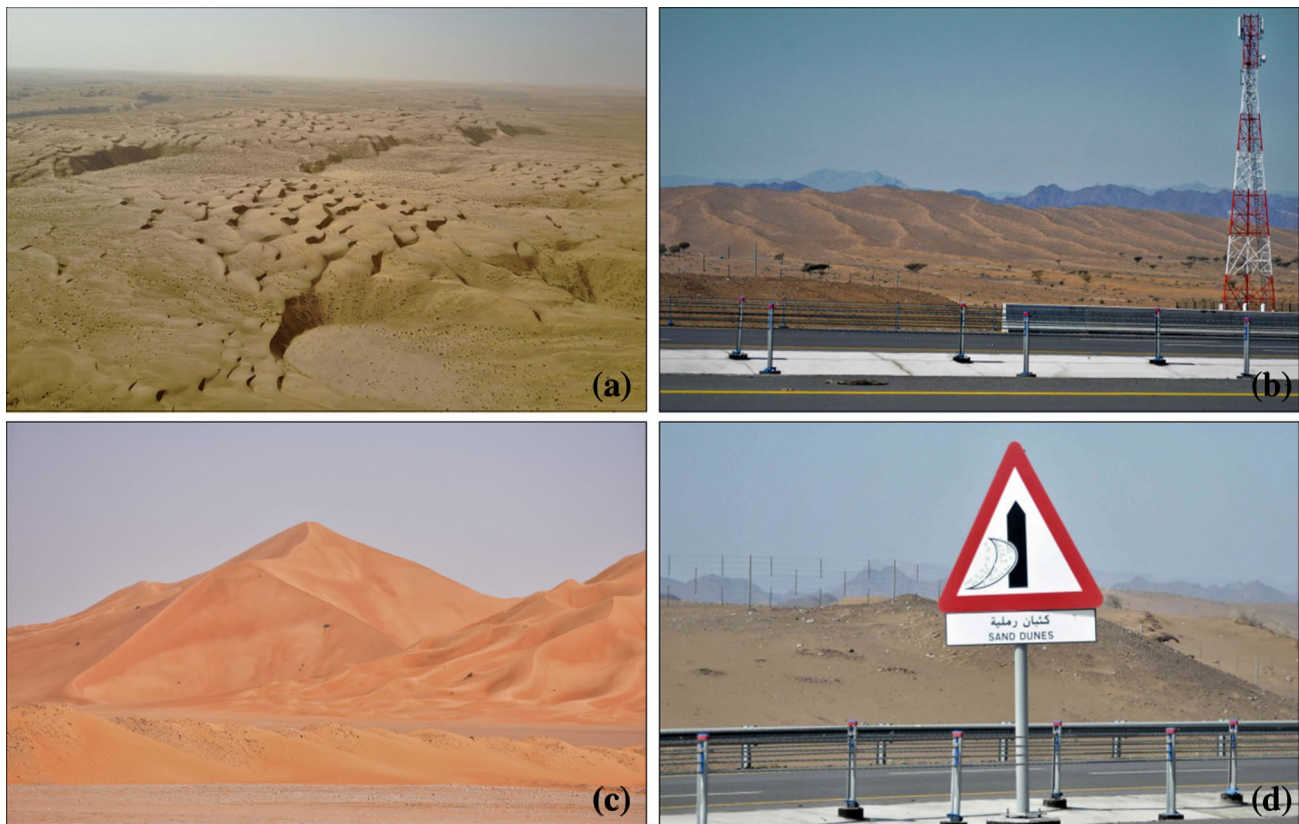
Fig. 4 Inland dunes, **a** low sand area of Wahiba Sands, **b** linear dunes in Wadi Al Abyad, Batinah South; **c** dunes of the Rub'Al-Khali (close to Yemen and Saudi Arabia border); **d** warning sign for drifting sands along the Batinah Expressway

The small dune areas in the Batinah region cause sand to drift across road networks which is a constant hazard especially during high traffic volume, low daytime visibility and at night (see Fig. 4c, d). The dune environment may be modified by the change in wind direction caused by placement of highways, bridges and buildings within or in close proximity to these sand bodies. This can be seen in Bousher (Muscat) where the dunes are being slowly surrounded by residential developments and the drifting of sand into artificial drainage channels enhances the risk of flooding. Whilst land users need to consider the impact of dunes on their development, they also need to consider what anthropogenic changes may alter the way the sand bodies naturally evolve and equally ensure that this natural heritage is largely or wholly preserved.

Naturally occurring asbestos (NOA)

Asbestos refers to naturally occurring fibrous minerals that have the ability to resist heat, fire and electricity and is extremely hazardous when it becomes disrupted and airborne. Inhalation or ingestion of asbestos can lead to health concerns, including mesothelioma. The principal varieties of asbestos are chrysolite (a serpentine mineral) and crocidolite, amosite, anthophyllite, tremolite and actinolite, which are amphibolites (WHO 2014). Tremolite, actinolite and anthophyllite occur in both asbestiform and non-asbestiform habits, whereas both crocidolite and amosite occur only in the asbestiform habit. Chrysotile is also fibrous and is one of the three principal serpentine polymorphs (chrysotile, lizardite and antigorite).

Other minerals containing asbestiform fibers with the potential to cause serious health problems include amphibolites winchite and richterite (Sporn 2011), the zeolite mineral erionite (Wagner and Lemen 2008), fluoro-edenite (Travaglione et al. 2003) and taconite iron ore (see Lambert et al. 2016). Naturally occurring asbestos (NOA) is a hazard to those involved with tunneling, quarrying the stone for aggregates, users of aggregates for use in construction and rock slope cutting which may disturb asbestos within natural rock and provoke the formation of potentially inhalable airborne dust.

Vignaroli et al. (2011) suggests that chrysolite deposits can be concentrated in ultamafic rocks (peridotes, serpentinised periodotes, serpentinites) whereas amphibole asbestos minerals may be present in pentinoschists and various metasedimentary rocks. To extend this study to Oman, a small selection of rock samples from a range of
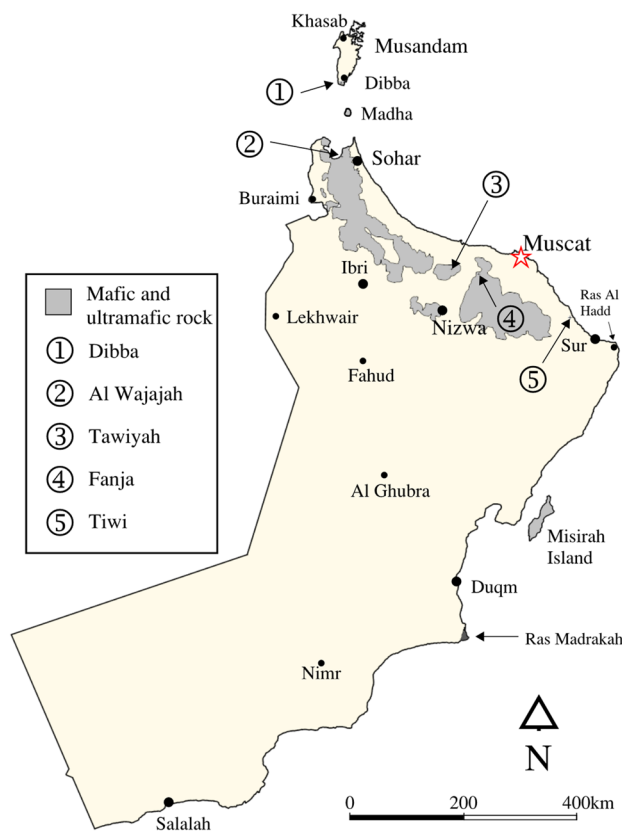
Fig. 5 Confirmed locations containing XRPD tested asbestos mineral groups and shaded areas showing rocks with the potential for containing asbestos minerals

Table 1 Detection of asbestos minerals in selected Oman ophiolite rocks using XRPD

Location (rock type)	Asbestos mineral present
Dibba (Basalt)	Chrysolite
Al Khoud (Gabbro)	–
Al Wajaja (Dunite)	Tremolite
Tawiyah (Serpentine)	Chrysotile
Tiwi (Serpentised Harzburgite)	Chrysotile
Fanja (Amphibolite)	Crocidolite, Fluoro-edenite

ultramafic and mafic rocks were collected (see locations shown in Fig. 5) and tested by X-ray powder diffraction (XRPD) (see Table 1).

Asbestos minerals were found in most of the samples collected although further analysis would be required to confirm whether the asbestos mineral present exhibited an asbestiform habit and to differentiate between serpentine varieties where XRPD peaks overlap each other. This could be achieved using techniques such as scanning electron microscope combined with energy dispersive spectrometry (SEM–EDS), thermogravimetric analysis (TGA–DTG) and petrological thin section.

In northern Oman the rock distribution across the extent of a commercial rock quarry or tunnel location is seldom homogeneous. The ophiolite suite comprises a complex assemblige of ultramafic and mafic rocks, and there are also inclusions of mantle rocks and other areas of ultra mafic veins and dykes within metasedimentary formations. Serpentinisation of ultramafic rocks is also widespread in Oman and a geologist needs to be employed by the quarry and aggregate user to determine whether there could be an asbestos health risk using a multidisaplinary approach based upon field evidence combined with textural, mineralogical, petrological and geochemical investigations (Vignaroli et al. 2011). However, risks could also be mitigated by detecting potentially asbestos-bearing rocks prior to rock extraction using remote sensing techniques such as Airborne Visible/ Infrared Imaging Spectrometer (Swayze et al. 2009) and Landsat TM (Abrams et al. 1988) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Rajendran et al. 2012). The health risks posed by naturally occuring asbestos are taken to a different level in some countries outside Oman. Production of local maps indicating areas where asbestos is present in outcropping rocks are already established (Bloise et al. 2019) and the Australia New South Wales Geological Survey has released its maps showing naturally occurring asbestos. More studies into the potential health risks from NOA in Oman are required.

Karst

Large scale ground subsidence is generally attributed to areas of karst morphology whereas small scale subsidence can be attributed to changes in the soil structure normally instigated by anthropogenic activity (loess and evaporitic soils are not covered in this paper). Karst is a geomorphological feature formed through the dissolution of bedrock, typically carbonate or salt (gypsum and halite) in composition, by ground water to produce a network of enlarged joints and cavities through which the water then preferentially flows. When these cavities are large enough to allow some form of access, they are known as caves. Karstic landscapes in Oman are often relatively dry, with surface streams being seasonal or non-existent and most drainage takes place underground. Karst environments can have a range of characteristic surface features, including bare rock exposures such as crags and pavements, sinkholes and poljes. The presence of natural voids and cavities in subsurface karstic rocks can pose major problems for land development. Dissolution cavities vary in size from millimetres to tens of centimetres occurring at the surface of sedimentary rock formations are widespread throughout Oman, and particularly in the limestone and dolomite in the mountainous Musandam region.

Little research has been done on the distribution of karst in Oman, perhaps because of the remoteness outside of settlements and the complex geology especially in the Al Hajar mountain region. Locally, Rajendran and Nasir (2014) have attempted to redress this by using remote sensing to map limestone formation associated with caves, springs and depressions in the Tanuf valley and regions close to Sur.

Major sinkholes and caves in Oman occur at the edge of the Al Hajar Mountains such as the Selma plateau and north of Bimah, Jarnan in Izki, Al Hoota cave in Al Hamra, areas to the north east of Salalah (Tawi Atair and Teeq). Other sinkholes have been discovered near Shihayt, Al Burj, Muqshin and Hafeet near Buraimi, which illustrate that where carbonate rock is prevalent, a risk of ground collapse remains. The location of these sinkholes and caves are associated with sedimentary formations, including the Tertiary Lower Fars Group situated in central Oman, Lower to Middle Hadhramaut Group occupying the southern part of Oman, with smaller outcrops east of the Al Hajar Mountains in the north west and around Buraimi. Formations within the Cretaceous are associated with the caves in the Al Hajar Mountains close to Nizwa. Figure 6 shows the location of major sinkholes and caves and Fig. 7 shows some examples of karst morphology in Oman.

Aside from carbonate rocks, salt (halite) occurs in the Ghaba, Fahud and south Oman salt basins of interior Oman (Vandeginste et al. 2017) and can lead to complications of well drilling due to dissolution by water used in exploratory well drilling operations. A knowledge of the carbonate and evaporite formation locations in Oman is essential so that appropriate investigative techniques can be employed to locate actual or potential sub-surface karst features detrimental to land development.

Active faults

Evidence of active faults is prominent in many locations in north and south Oman. There are many examples that indicate active tectonics until recent times. For example, the graded road from Dibba to Khasab in the governorate of Musandam exposes several fault zones that display evidence of shearing along the recent wadi gravels that fill the fault apertures (Fig. 8a). Moreover, these fault zones show different stages of opening and filling by the Quaternary wadi deposits, hence indicating various stages of fault activity in recent times.

The Maradi Fault Zone is one of the major fault systems that probably continues for more than 350 km, as evident from surface and subsurface data, from the city of Ibri to the Huqf Area and beyond, as shown in Fig. 2. The fault was active since the Proterozoic and has been reactivated in different senses of movement throughout the Palaeozoic, Mesozoic and Cenozoic. The NW side of the fault clearly
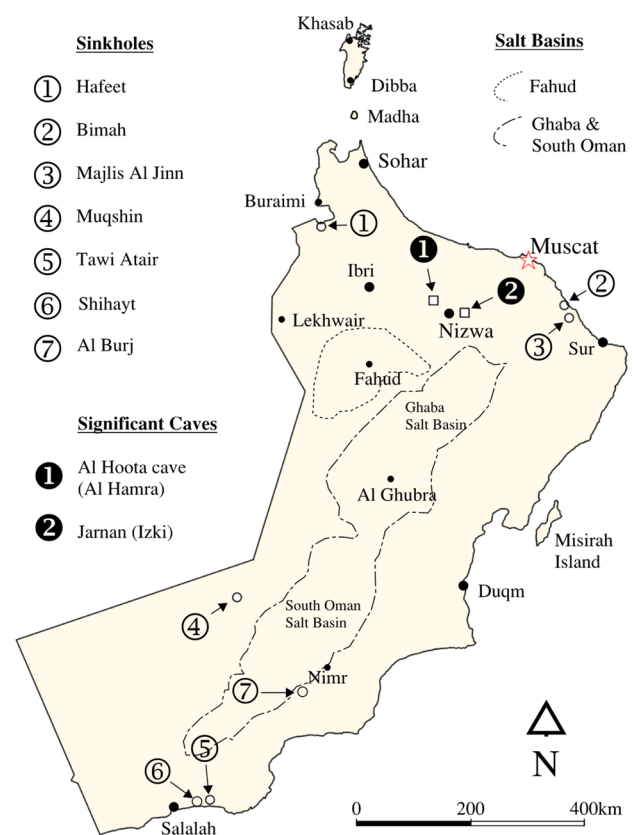

Fig. 6 Locations of known sinkholes and caves associated with carbonate and evaporate formations

indicates that the fault was active during the Neogene and Quaternary. The segmented stepping nature of the fault zone and its opening indicates that the fault has moved with a dextral transtentional sense of movement under a NW–SE in situ stress regime, consistent with the orientation of the in situ stress along the Maradi Fault Zone as shown in Fig. 2. The recent alluvial fan deposits have been partly diverted along the fault trajectory and some show clear displacement. Recent movement of the fault is also seen near the city of Ibri, where fissures appeared on the surface sediments (Fig. 8b). Major cracks appeared in several houses near the area.

In one of the petroleum fields in North Oman, the Haban fault was reactivated with a left-stepping (dextral) sense of movement in 2008, (similar to the movement seen near the city of Ibri along the Maradi Fault Zone) hence causing a significant risk to the surface operations in the area. The seismic data (Fig. 8c) indicates that the fault zone is a deep-seated structure that possibly continues to surface as shown by surface depressions in Fig. 8d.

Across Oman the recent faults have poor surface expression and are difficult to trace and forensic mapping to identify potential fault-induced signatures on surface land forms
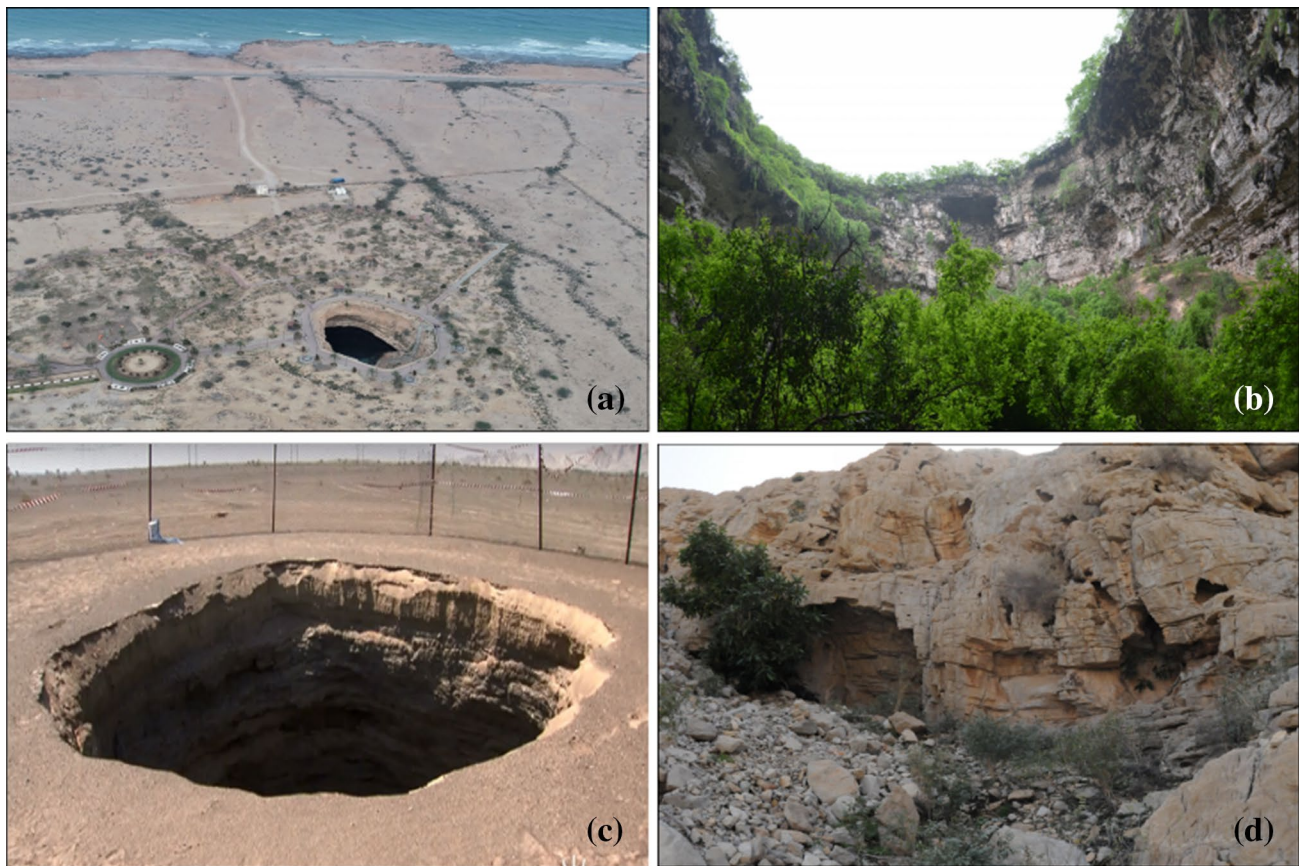
Fig. 7 Sinkholes at **a** Bimah; **b** inside Tawi Atair; **c** Hafeet; **d** large dissolution cavities near Lima (Musandam)

or manmade structures may present the only method to recognise these natural hazards.

Earthquakes

Overall, the current level of seismicity in Oman is considered low to moderate, though geological, geophysical and historical data do suggest the occurrence of earthquakes of Modified Mercalli (MM) intensity of VII (very strong) or greater (Qamaruddin and Al-Harthy 2000). A good example of such earthquakes can be sighted from the geological, archaeological and historical information in the medieval city of Qalhat (Fig. 9a), which used to be an important trade along the sea routes in the Indian Ocean and was visited and described by the famous Moroccan traveller, Ibn Battuta, in the fourteenth century when the city was an important administrative and political centre. The city occupation went into decline at the beginning of the sixteenth Century and has been massively destructed since then. Today, only one intact building can be seen in the ancient city. The reasons for this decline are speculated to be related to a major earthquake or to a tropical cyclone that occurred in the last quarter of the fifteenth century AD (Bhacker and Bhacker

2004). Qalhat was later occupied and looted by Portuguese troops in AD 1508 and later lost its importance as the main hub along the eastern coast of Arabia. Ermertz et al. (2019) indicated that the coastal terraces adjacent to Qalhat terminate on the Qalhat Fault (Fig. 9b), hence suggesting that a tectonic activity along the fault around 500 years ago is likely and the hypothesis that an earthquake along this fault resulted in the destruction of the ancient town of Qalhat is plausible.

According to El-Hussain et al. (2012), most of Oman appears as aseismic. However, the earthquake hazard level in Oman increases toward northeast, within the Al Hajar Mountains, owing to the increasing proximity of the Zagros and Makran seismogenic zones where significantly higher seismic activity takes place. The hazard is relatively high in the northern tip of Oman (i.e. the Musandam Mountains). The historically documented devastating earthquakes that occurred in north Oman date back to 879 AD including events that occurred near Sohar region in 879 (Ambraseys et al. 1994) and more recently the earthquake occurred in 1883 (Ambraseys et al. 1994), which was strongly felt at the southern part of the mountains in Muscat and Nizwa, in the vicinity of which nine villages were destroyed and ground
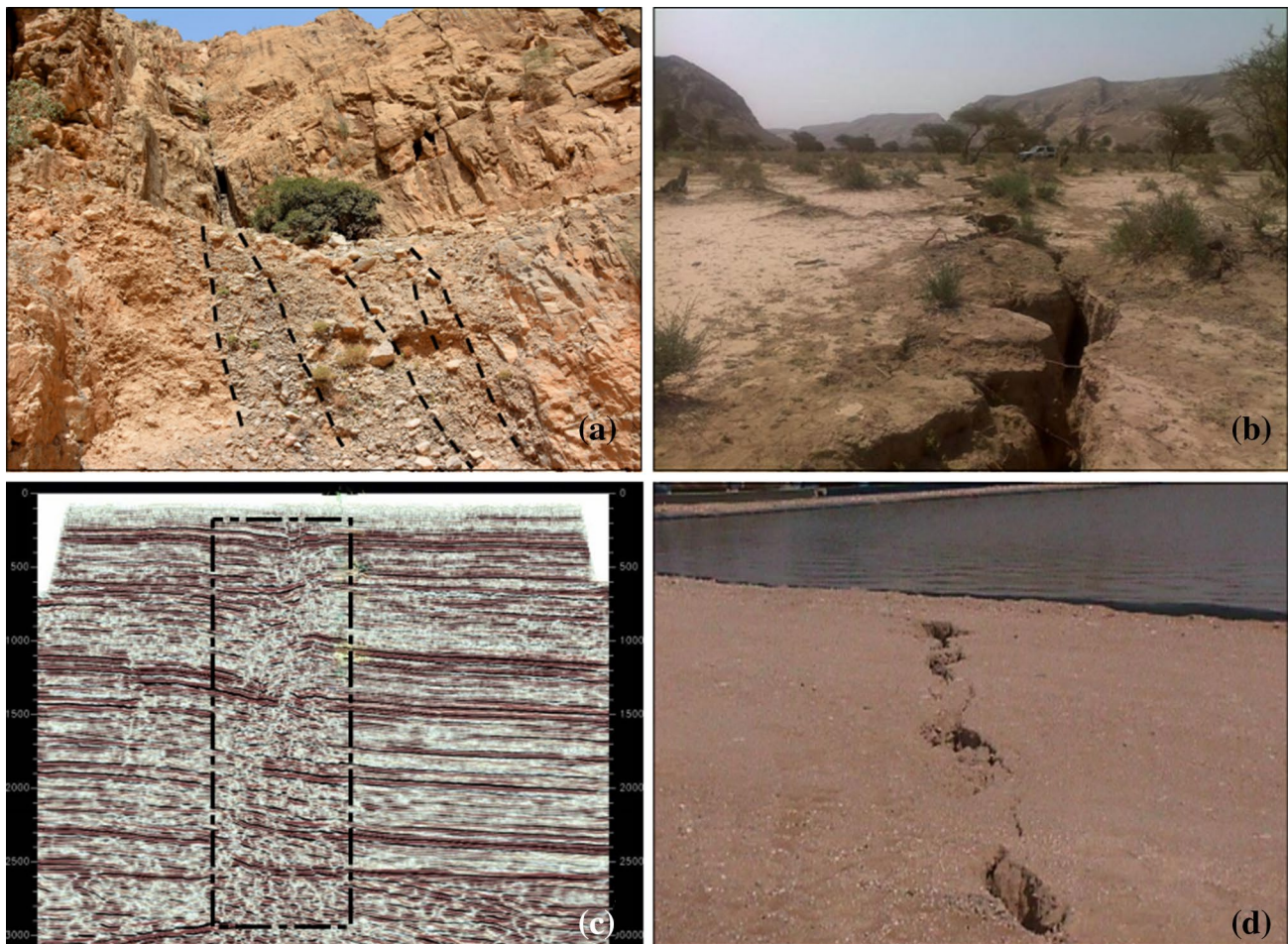
Fig. 8 Evidence of recent faulting, **a** shear zones (dotted black lines) in recent wadi filling of a fault zone seen on the side of the graded road from Dibba to Khasab in Musandam; **b** NW part of the Maradi Fault System near the city of Ibri, looking SE; **c** seismic section running NE–SW through the Haban Fault showing the extent of the fault trajectory to the shallowest seismic reflections (near earth-surface reflections) [adapted from Al-Kindi and Richard (2014)]; **d** surface depressions caused by fault reactivation at Haban near the Fahud Field

deformation was observed. The earthquake hazard in Oman can be generally related to major faults rather than averaged over broad areas. On the other hand, the seismicity in south Oman is related to the opening of the Gulf of Aden, under a tensile stress regime. Overall, the seismicity level decreases drastically away from the extensional ridge and only minor seismic events have been reported in the Dhofar Mountains in south Oman.

The Earthquake Monitoring Center (EMC) at the Sultan Qaboos University in Muscat records data from a large array of seismographs across Oman and is often published. Regional seismic hazard maps presenting horizontal peak ground acceleration and 5% damped spectral accelerations through bedrock for 475- and 2475-year return periods have been published by Deif et al. (2020). However, associated seismic amplification due to topographic and geomorphological features (slope angle, paleo-landslides,

subsurface cavities etc.) and earthquake induced liquefaction of low-lying saturated loose granular soils, which dominate the coastal regions in Oman, must still be carried out using localised geophysical and intrusive geotechnical investigations.

Tsunamis

Owing to the presence of the Makran subduction zone (which is less than 500 km from Muscat), the Owen fracture zone (which lies some 300 to 400 km east of Oman in the Arabian Sea) and exposure to seismic and volcanic activity at tectonic plates in the Indian Ocean, Oman is at risk from tsunamis. A tsunami is a series of travelling waves of extremely long length and period generated by a sudden displacement of the seabed which can be due to earthquakes, submarine landslides and volcanic eruptions. In deep ocean
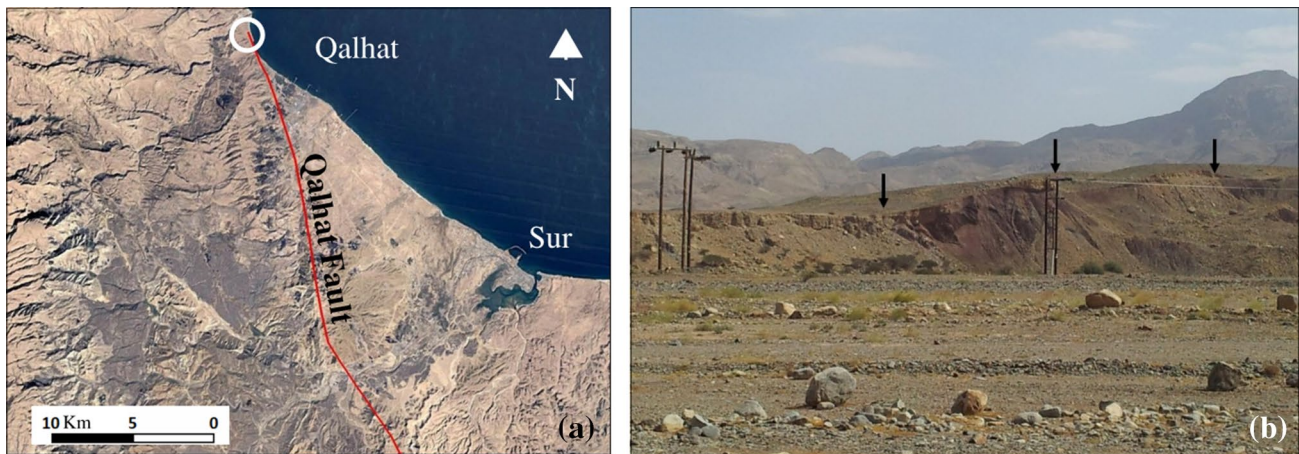
Fig. 9 Qalhat Fault, **a** Landsat image from Google Earth showing the trajectory of the fault and the location of the medieval city of Qalhat; **b** photo showing a road section with elevated recent wadi deposits that have been displaced by the Qalhat Fault (shown by arrows).

Throughout the Neogene and Quaternary, the fault vertically displaced the rock formations for thousands of metres, juxtaposing the Proterozoic basement rocks against Cenozoic sequences

tsunamis travel in excess of 900 km/h, but with a small wave height but upon reaching shallow water they slow down and the wave height increases. On landfall, the waves may be several meters high.

An earthquake at the Makran subduction zone in 1945 resulted in a tsunami of several meters along the coast of Pakistan (directly opposite the seismic event) and up to several meters elsewhere along the adjacent coastlines (including northern Oman) as reported in Heidarzadeh et al. (2008) and Hoffmann et al. (2013b) largely through eye witness accounts. Physical evidence of this tsunami has been examined from core samples taken in the lagoon at Sur through taphonomy and particle size analysis of shell fragments (Donato et al. 2009) and taxonomy of foraminifera (Pilarczyk and Reinhardt 2012). Other studies of physical evidence of tsunamis of even greater magnitude have been studied on and behind a cliff terrace at Fins (between Qurayat and Sur). Here, inferred tsunami debris includes huge angular boulders, imbricated flagstones of a single orientation and marine deposits all relating to a high energy run-up wave (Koster et al. 2014; Hoffmann et al. 2013a). Examples of these features are presented in Fig. 10. Further evidence of an extreme flooding event which could be due to a tsunami was found by Hoffmann et al. (2015) in a Bronze-age settlement at Ras al Hadd. The Great Sumatra earthquake of 2004 also created a tsunami wave that affected the Indian Ocean coastal areas including Oman. Data gathered by Okal et al. (2006) showed the extent of tsunami wave inundation on land in terms of physical identification and eye-witness reports from the coastal communities.

Potential hazards may also arise from submarine landslides. The Makran subduction zone is marked by a thick sedimentary cover which could slump triggering a tsunami.

Fig. 10 Evidence of a previous tsunami as researched by Hoffmann et al. (2013a) along the 'cleaned' coastal cliffs south of Fins showing **a** imbricated flagstones; **b** large boulders (camera bag for scale shown by arrow)

The active strike-slip Owen fracture zone contains a prominent submarine relief called the Owen ridge. Using multibeam bathymetry, Rodriguez et al. (2013) showed voluminous submarine landslides along the Owen ridge which could have been the source of previous tsunami events and show the potential for future landslide failures which could lead to a tsunami risk for coastline communities between Salalah and Ras al Hadd.

Tsunami hazard predictability has been attempted by a few studies largely using numerical simulations. The recorded events of 1945 were used by Heidarzadeh et al. (2008) to predict the seafloor deformation from a maximum regional earthquake of (Mw 8.3) to create a 3 to 7 m tsunami along the northern coast of Oman and 1 to 5 m along the southern coast of Oman. Using numerical simulations of tsunami generation from the Owen ridge largest submarine landslide, Rodriguez et al. (2013) calculated maximum tsunami wave heights between 0.7 and 3.3 m which would affect the cities of Salalah and Duqm, as well as low populated areas in between.

Browning and Thomas (2016) examined two submarine earthquake scenarios triggering ±0.2 m up thrust movements in the Makran subduction zone (Mw > 8) and the Sunda-Sumatra (Mw > 9) megathrust to estimate the effect of tsunami inundation in Muscat (Sultan Qaboos port) and Salalah, respectively. A further scenario created by a submarine landslide on the Makran seaward forearc was assessed to determine the tsunami potential affecting Muscat. All scenarios assessed using open source data with simple deterministic and probability approaches showed significant tsunami inundation, especially in Muscat.

In 2015, a National Multi-Hazard Early Warning Centre (NMHEWC) was opened in Muscat to monitor for tsunamis in the Indian Ocean that could be a threat to Oman. Although signage along low lying areas at risk from tsunamis and areas for refuge could also be considered.

Conclusions

This paper provides a comprehensive review of the main natural hazards which directly relate to geology in Oman. The sand dunes are considered hazardous because of their ability to migrate and threaten cultivated land and infrastructure. Owing to the presence of the active oceanic plates, Oman is at risk from tsunamis and physical evidences of past large tsunamis have been reported on the eastern and northern coast. Sinkholes are present in various parts of the country and some of these have formed in the last few decades. A variety of naturally occurring asbestos (NOA) minerals are common in the ophiolite sequence. Most of Oman appears as aseismic; however the earthquake hazard level increases towards the northeast and a few devastating earthquakes have been historically reported, mostly in relationship to movement along active faults. Potential hazards may also arise from submarine landslides, triggered either by movements on the adjacent plate boundaries or related to piling of alluvial sediments offshore. This paper, which appears to be first in Oman to review some of the country's natural geological hazards, has revealed significant gaps in the knowledge. Suggestions have been made where more studies are required to explore the phenomena further and mitigate against their potential hazardous effects.

References

Abrams MJ, Rothery DA, Pontual A (1988) Mapping in the Oman ophiolite using enhanced Landsat Thematic Mapper images. Tectonophysics 151:387–401. https://doi.org/10.1016/0040-1951(88)90254-5

Al-Gahaffi A, McClay K (2010) 4D Evolution of the Maradi fault system, Oman. In: AAPG GEO 2010 middle east geoscience conference and exhibition, Manama, Bahrain

Al-Harrasi O, Busaidi S, Lewandowski H, Fraser J, Jahdhami A (2014) Impact of passive microseismic monitoring on business and reservoir management: examples from Oman. In: Fifth EAGE passive seismic workshop, Lisbon, Portugal

Al-Kindi MH (2018) Evolution of land and life in Oman: An 800-million-year story. Springer, Cham

Al-Kindi MH, Richard PD (2014) The main structural styles of the hydrocarbon reservoirs in Oman. Geol Soc Lond Special Publ 392(1):409–445. https://doi.org/10.1144/SP392.20

Al-Masrahy MA, Mountney NP (2013) Remote sensing of special variability in aeolian dune and interdune morphology in the Rub'Al-Khali, Saudi Arabia. Aeol Res 11:155–170. https://doi.org/10.1016/j.aeolia.2013.06.004

Ambraseys NN, Melville CP, Adams RD (1994) The seismicity of Egypt, Arabia and Red Sea. Cambridge Univ Press, Cambridge

Besler H, Ritter M (2009) Environmental histories and some Arabian Sands (Oman, UAE) deduced from extended sedimentary analysis. Z Geomorph NF 53(4):487–504

Bhacker MR, Bhacker B (2004) Qalhãt in Arabian history: context and chronicles. J Oman Stud 13:1

Bloise A, Ricchiuti C et al (2019) Assessment of naturally occurring asbestos in the area of Episcopia (Lucania, Southern Italy). Fibers 7(5):45. https://doi.org/10.3390/fib7050045

Browning J, Thomas N (2016) An assessment of the tsunami risk in Muscat and Salalah, Oman, based on estimations of probable maximum loss. Int J Disaster Risk Reduct 16:75–87. https://doi.org/10.1016/j.ijdrr.2016.02.002

Deif A, El-Hussain I, Alshijbi Y et al (2020) Updating a probabilistic seismic hazard model for Sultanate of Oman. Arab J Geosci 13:502. https://doi.org/10.1007/s12517-020-05394-8

Donato SV, Reinhardt EG, Boyce JI, Pilarczyk JE, Jupp BP (2009) Particle-size distribution of inferred tsunami deposits in Sur Lagoon, Sultanate of Oman. Mar Geol 257(1–4):54–64. https://doi.org/10.1016/j.margeo.2008.10.012

El-Hussain I, Deif A, Al-Jabri K et al (2012) Probabilistic-seismic-hazard-maps-for-the-Sultanate-of-Oman. Nat Hazards 64:173–210. https://doi.org/10.1007/s11069-012-0232-3

Ermertz AM, Kázmér M, Adolphs SK, Falkenroth M, Hoffmann G (2019) Geoarchaeological evidence for the decline of the Medieval City of Qalhat, Oman. Open Quat 5(1):8. https://doi.org/10.5334/oq.56

Filbrandt JB, Al-Dhahab S et al (2006) Kinematic interpretation and structural evolution of North Oman, Block 6, since the Late Cretaceous and implications for timing of hydrocarbon migration into Cretaceous reservoirs. GeoArabia 11(1):97–140

Goudie AS, Warren A, Jones DKC, Cooke RU (1987) The character and possible origins of the aeolian sediments of the Wahiba Sand Sea, Oman. R Geol Soc 153(2):231–256. https://doi.org/10.2307/634875

Heidarzadeh M, Pirooz MD, Zaker NH, Synolakis CE (2008) Evaluating tsunami hazard in the Northwestern Indian Ocean. Pure Appl Geophys 165:2045–2058. https://doi.org/10.1007/978-3-0346-0057-6_5

Hird R, Di Matteo N, Gulerce U, Babu VLS, Rafiq A (2019) Geohazards of Saudi Arabia. J Maps 15(2):626–634. https://doi.org/10.1080/17445647.2019.1642245

Hoffmann G, Reicherter K, Wiatr T, Grützner C, Rausch T (2013a) Block and boulder accumulations along the coastline between Fins and Sur (Sultanate of Oman): tsunamigenic remains? Nat Hazards 65(1):851–873. https://doi.org/10.1007/s11069-012-0399-7

Hoffmann G, Rupprechter M, Al Balushi N, Grutzner C, Reicherter K (2013b) The impact of the 1945 Makran tsunami along the coastlines of the Arabian Sea (Northern Indian Ocean)—a review. Zeitschrift für Geomorphologie Suppl Issues 57(4):257–277. https://doi.org/10.1127/0372-8854/2013/S-00134

Hoffmann G, Grutzner C, Reicherter K, Preusser F (2015) Geo-archaeological evidence for a Holocene extreme flooding event within the Arabian Sea (Ras al Hadd, Oman). Quat Sci Rev 113:123–133. https://doi.org/10.1016/j.quascirev.2014.09.033

Hoffmann G, Meschede M, Zacke A, Al-Kindi M (2016) Field guide to the geology of Northeastern Oman. Geological field guides 110. Borntraeger Science Publishers, Germany

Koster B, Hoffmann G, Grützner C, Reicherter K (2014) Ground penetrating radar facies of inferred tsunami deposits on the shores of the Arabian Sea (Northern Indian Ocean). Mar Geol 351:13–24. https://doi.org/10.1016/j.margeo.2014.03.002

Lambert CS, Alexander BH et al (2016) A case-control study of mesothelioma in Minnesota iron ore (taconite) miners. Occup Environ Med 73(2):103–109. https://doi.org/10.1136/oemed-2015-103105

Le Métour J, Platel J-P et al (1993) Geological map of Oman 1:1,000,000 scale. Ministry of Petroleum and Minerals, Directorate General of Minerals, Sultanate of Oman, Muscat

MMTEC (2012) The geologic, tectonic and geohazard map of the Muscat Area. Ministry of Commerce and Industry, Directorate general of minerals, Muscat

Okal EA, Fritz HM, Raad PE, Synolakis C, Al-Shijibi Al-Saifi M (2006) Oman field survey after the December 2004 Indian Ocean Tsunami. Eathquake Spectra 22(S3):S203–S218. https://doi.org/10.1193/1.2202647

Pease P, Tchakerian V (2014) Source provenance of carbonate grains in the Wahiba Sand Sea, Oman, using a new LIBS method. Aeol Res 15:203–216. https://doi.org/10.1016/j.aeolia.2014.06.001

Pilarczyk JE, Reinhardt EG (2012) Testing foraminiferal taphonomy as a tsunami indicator in a shallow arid system lagoon: Sur, Sultanate of Oman. Mar Geol 295:128–136. https://doi.org/10.1016/j.margeo.2011.12.002

Qamaruddin M, Al-Harthy A (2000) Earthquake hazard potential in Oman. In: Proc. 12th world conference on earthquake engineering 12WCEE, paper: 1943. https://www.iitk.ac.in/nicee/wcee/article/1943.pdf

Radies D, Preusser F, Matter A, Mange M (2004) Eustatic and climatic controls on the development of the Wahiba Sand Sea, Sultanate of Oman. Sedimentology 51(6):1359–1385. https://doi.org/10.1111/j.1365-3091.2004.00678.x

Rajendran S, Nasir S (2014) ASTER mapping of limestone formations and study of caves, springs and depressions in parts of Sultanate of Oman. Environ Earth Sci 71(1):133–146. https://doi.org/10.1007/s12665-013-2419-7

Rajendran S, Al-Khirbash S et al (2012) ASTER detection of chromite bearing mineralized zones in Semail Ophiolite Massifs of the northern Oman Mountains: Exploration strategy. Ore Geol Rev 44:121–135. https://doi.org/10.1016/j.oregeorev.2011.09.010

Reilinger RE, McClusky SC et al (1997) Global Positioning System measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone. J Geophys Res Solid Earth 102(B5):9983–9999. https://doi.org/10.1029/96JB03736

Rodriguez M, Chamot-Rooke N, Hébert H, Fournier M, Huchon P (2013) Owen Ridge deep-water submarine landslides: implications for tsunami hazard along the Oman coast. Nat Hazards Earth Syst Sci 13:417–424. https://doi.org/10.5194/nhess-13-417-2013

Rose JI, Bailey GN (2008) Defining the palaeolithic of Arabia? Notes on the Roundtable Discussion. In: Proceedings of the Seminar for Arabian Studies, vol 38. pp. 65–69. https://www.jstor.org/stable/41223938

Sporn TA (2011) Mineralogy of asbestos. In: Tannapfel A (ed) Malignant mesothelioma. Recent results in cancer research 189. Springer, Berlin

Swayze GA, Kokaly RF et al (2009) Mapping potentially asbestos-bearing rocks using imaging spectroscopy. Geology 37(8):763–766. https://doi.org/10.1130/G30114A.1

Tatum D, Francke J (2012) Radar suitability in aeolian sand dunes—a global review. In: 14th International conference on ground penetrating radar (GPR), Shanghai. https://doi.org/10.1109/icgpr.2012.6254951

Travaglione S, Bruni B, Falzano L, Paoletti L, Fiorentini C (2003) Effects of the new-identified amphibole fluoro-edenite in lung epithelial cells. Toxicol In Vitro 17:547–552. https://doi.org/10.1016/s0887-2333(03)00118-8

Vandeginste V, Stehle MC et al (2017) Diagenesis in salt dome roof strata: barite—calcite assemblage in Jebel Midar, Oman. Mar Pet Geol 86:408–425. https://doi.org/10.1016/j.marpetgeo.2017.06.008

Vignaroli G, Rossetti F, Belardi G, Billi A (2011) Linking rock fabric to fibrous mineralisation: a basic tool for the asbestos hazard. Nat Hazards Earth Syst Sci 11:1267–1280. https://doi.org/10.5194/nhess-11-1267-2011

Wagner GR, Lemen RA (2008) Asbestos. In: Heggenhougen HK (ed) International encyclopedia of public health. Academic Press, New York, pp 238–245. https://doi.org/10.1016/B978-012373960-5.00294-X

WHO (2014) Chrysolite asbestos. World Health Organisation, Geneva. https://www.who.int/ipcs/assessment/public_health/chrysotile_asbestos_summary.pdf. Accessed 8 Nov 2019