

Effects of recent anthropogenic activities on the surface deposits of Kuwait

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Abstract Kuwait experienced severe land degradation over the last 30 years due to different factors. This is reflected in soil loss, crusting, salinization, oil contamination, and vegetation cover deterioration. The recent surface deposits are considered as the local source of sand and dust storms, which have acute environmental hazards on the public health, the State's economy, and the life quality. They are classified into two main categories: desert and coastal deposits. The distribution of the areas affected by deflation processes and those affected by depositional processes revealed that the northern desert of Kuwait is receiving intense sand supply, but on the other hand, the southern desert of Kuwait has a lower frequency of sand deposits. This study is based on visual comparison between the records of the 1980s and recent field surveys during 2001–2011, as they are the available sources of the relevant information to the scope of the study, to investigate the impact of the anthropogenic activities, the significant role of the aeolian processes, soil type, and climatic conditions on the land degradation, and subsequently the severe loss of vegetation and surfacial cover. A detailed sedimentomorphologic map, scale 1:100,000, was prepared for the State of Kuwait based on the topographic map of Kuwait (scales 1:50,000, 1:100,000, and 1:250,000) and photomaps (scale 1:29,000), which were created as per the delineated information from the aerial photos (scale 1:29,000, years 1990, 2001) along with spectral and spatial resolution data of the Radarsat, Landsat-7, IRS-1D (Indian Remote Sensing), ERS, TM, SPOT-4, Advanced Space-borne Thermal Emission and Reflection, and IKANOS data in raw format for Kuwait images for the available years (1989, 1994, and

2000–2004), keeping in view of the terrain in Kuwait and the objective of the study.

Keywords Sedimentology · Geomorphology · Aeolian · Desert · Coastal · Degradation

Introduction

The severe land degradation that Kuwait has suffered and is still suffering from in the recent decades could be attributed primarily to anthropogenic activities including overgrazing, camping and recreation, off-road driving, industrial activities, and specifically quarrying, in addition to the severe damage that the area was subjected to during the Iraqi invasion and liberation with the associated hostilities (1990–1991). Misak et al. (1999) reported that Kuwait has 44 % of its land surface moderately degraded and 32 % severely degraded. Gharib et al. (1987) proposed that, in addition to the existing quarries in Kuwait, most probable source of the dust fallout in Kuwait is derived from the southern areas of Iraq, which were drying due to drainage “Al-Ahwar” activities carried by the Iraqi regime. Accumulated sediment in Al-Ahwar wetlands area are fluvial clay and sand during the Pleistocene, while the Holocene sediments are of fluvial sand, marsh organic sediment, marine sand and silt, peat and fluvial clay and silt (Al-Ameri and Jassim 2011). In 2003 when the USA invaded Iraq, only 7 % of the original marshland remained (Vinez and Leonard 2010). Such an action converted previously green, lush fields of the marshlands into brown dry deserts feeding the aeolian deflation processes with their load of sand, mud, and silt airborne deposits. Due to the depletion of marshland, the shoreline along the Kuwaiti coast has been significantly “degraded” (Vinez and Leonard 2010). The Shatt al-Arab's coastal delta, no longer fed by the sediments of the Al-

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Fig. 1 A photograph showing the development of desert pavement due to aeolian processes

Ahwar, has begun to retreat, and there are fears that the entire geomorphological character of the Northeast Persian Gulf will be affected. Sandstorms in general and suspended dust in particular constitute acute environmental problems as they adversely affect the economy and life quality in Kuwait (Khalaf and Al-Ajmi 1993).

In Kuwait, plants usually grow in soils of fine sediments, as well as characterized by short fibrous roots. By deflation as a wind action, and sheetwash from occasional rainstorms removes all smaller fine particles leaving behind one-grain-thick layer of wind-polished, closely packed pebbles, boulders, and other rock fragments, known as desert pavement,

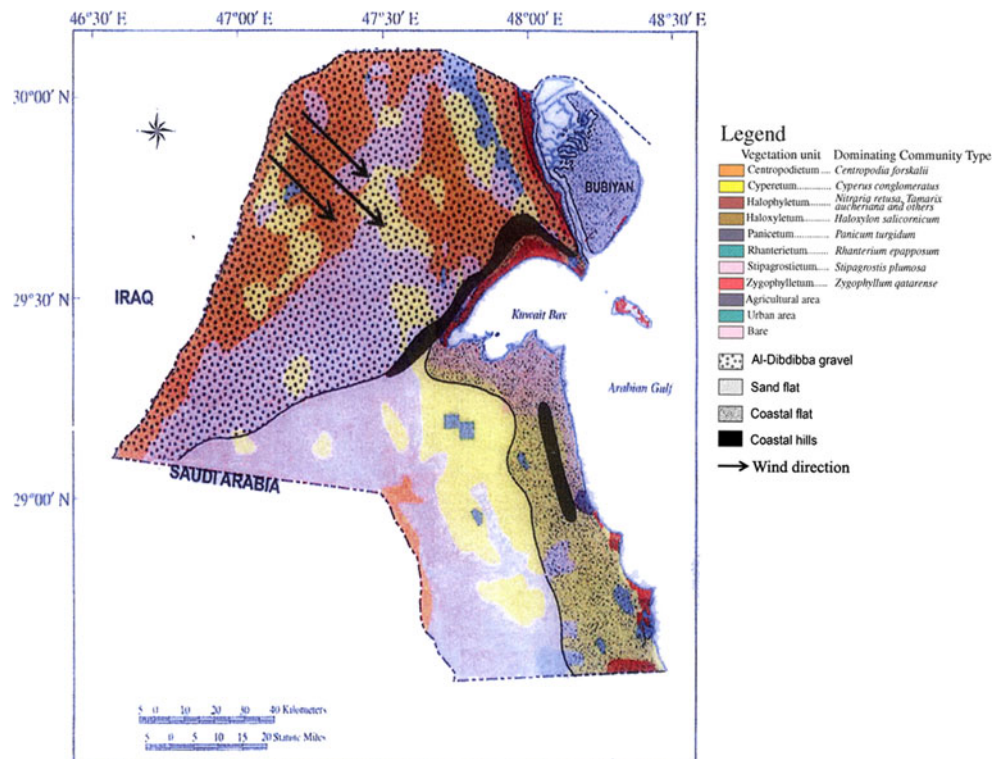
protecting the underlying fine-grained materials from being eroded by the wind (Fig. 1). Sometimes, such fragments are cemented by minerals and form a crust. Consequently, such a feature works as an obstacle for water to reach the near subsurface soil of fine sediments disturbing the environment for plants in Kuwait to grow. Their short roots cannot get needed water resulting in vegetation cover deterioration which constitutes a major indicator for desertification. Dust storms deflate fine particles of soil and desert sediments that cover the agricultural soil at Al-Qashaniyah and Al-Wafra. The cultivated area is constantly being threatened by wind-driven migrating sands. Furthermore, sand and dust storms constitute a serious challenge to Kuwait’s future development plans for constructing railways, solar collectors, and panels.

This new study is an attempt to investigate the recent surface deposits that cover the entire area of the State of Kuwait by comparison with the older maps of surface deposits of Kuwait that were constructed by Khalaf et. al. (1984) and Omar et. al. (2002).

Climate of Kuwait

Generally, Kuwait and surrounding areas are located in a hot desert zone, and hence have dry climate (Koppen classification of the world climate regions; Haurwitz and Austin 1944). There are three main factors controlling the climate of Kuwait: the pressure distribution, sea and land distribution, and regional topography. Figure 2 shows the direction of the wind vectors

Fig. 2 A map of Kuwait showing the prevailing wind direction, physiographic provinces of Kuwait, and vegetation cover distribution of Kuwait (modified after Khalaf et. al. 1984 and Omar et. al. 2002)



affecting Kuwait most of the year. The annual mean wind speed in Kuwait is 4.8 m/s, and the windiest months are June and July, and the quietest months are October and November (Dashti 1993). The weather is calm for 16 % of the year. The average wind speeds are 6.2 and 4.1 m/s during June and January, respectively (Khalaf and Al-ajmi 1993). Evaporation is high, where the daily mean is 6.6 mm (Safar 1984, 1985). Dashti (1993) reported that the northwesterly wind is the prevailing wind direction for 43 % of the year; southeastern winds constitute 19 %, northeastern 11 %, and southwestern 12 %. The northern desert of Kuwait receives the maximum sand supply, while the southern desert of Kuwait receives a minimum (Fig. 2; Khalaf et al. 1984).

Summer is very hot, particularly in July and August, where the mean and the maximum temperatures can reach 37.4 and 45 °C, respectively (Al-Ajmi and Safar 1987), with a considerably large diurnal temperature range. In June–July 2010, the absolute maximum temperature recorded was 51 °C at Kuwait airport. Winter is cool, where the mean temperature in January can drop close to 12.0 °C and the absolute minimum was recorded as −4 °C at Kuwait International Airport on 20 January 1964 (Safar 1984).

Precipitation is scarce with a mean of 115 mm year^{−1}, and the rainfall fluctuates widely. The mean annual of rainy days and the highest monthly rainy days (in January) are 25 days year^{−1} and 5.8 days, respectively. Evaporation is extremely high and fluctuates in terms of location and season.

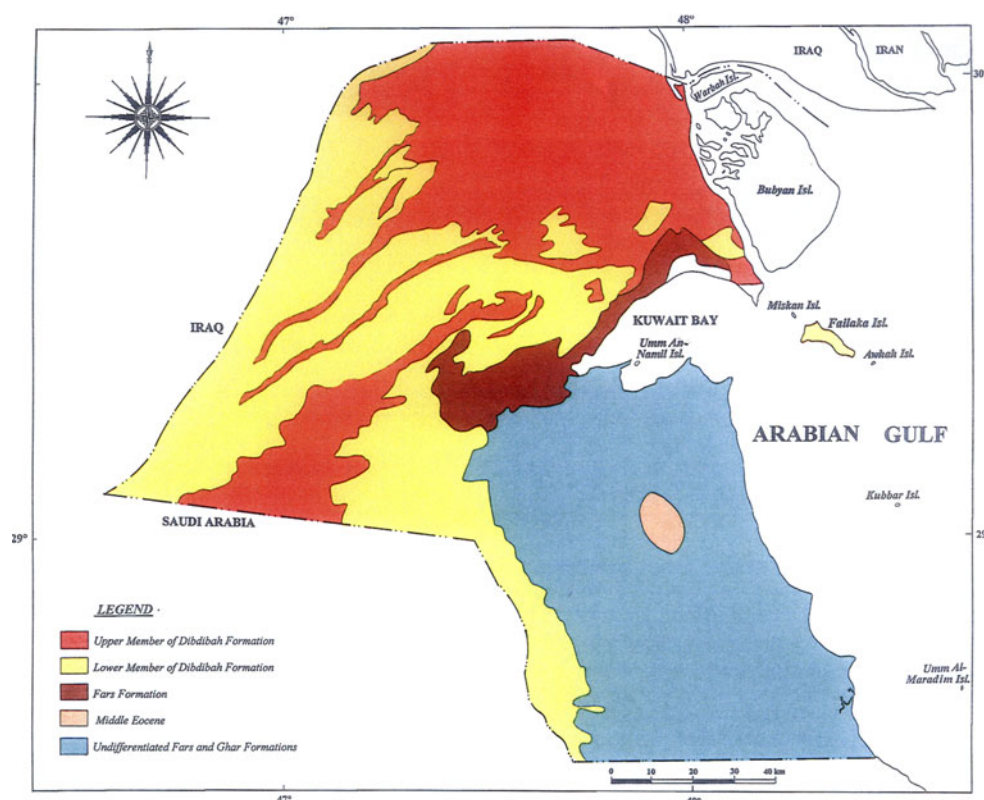
The winter dust storms and rising sand result from strong south-easterly winds. April is known as the season of “*Sarayaf*” that is characterized by the development of thunder clouds in the afternoon and during the night, associated sometimes with severe dust storm. In summer, dust storms occur more frequently during June and July, associating with prevailing dry and hot north-westerly winds, locally named as “*Simoom*” as the monsoonal low pressure system affects the Arabian Gulf countries.

Physiography

Kuwait is located at the northeastern corner of the Arabian Peninsula, covering an area of approximately 17,600 km², between 28°30′–30°5′N latitudes and 46°33′–48°30′ E longitudes. In general, Kuwait has a flat gently undulating desert plain including a few low hills, escarpments, and depressions. The area gradually slopes down north-eastward. The average gradient is close to 2 m/km.

Physiographically, Kuwait is located between the northern part of the Arabian Gulf coastal region and the southern border of Al-Dibdibba plain and the lower Mesopotamian plain of Iraq. It is bordered by Al-Dahana sand sea of Saudi Arabia to the west and by the Arabian Gulf to the east (Fig. 2). According to Khalaf et al. (1984), Kuwait can be divided into four physiographic provinces: (a) Al-Dibdibba gravel, (b) sand flat, (c) coastal flat, and (d) coastal hills (Fig. 2).

Fig. 3 Geological map of the State of Kuwait (after El-Baz and Al-Sarawi 2000)



Geology of Kuwait

The area of Kuwait forms part of the interior homocline of the Arabian peninsula, as the rocks ranging from Eocene to Recent in age are exposed. Dammam Formation of Eocene age (the oldest) outcrops at Al-Ahmadi ridge. Dammam Formation is constituted of dolomitic micrite containing large irregular dark chert nodules. The formation is uniformly overlain by a terrigenous clastic depositional sequence, locally called the Kuwait Group, ranging from Miocene to Recent in age. This group is divided into three formations in the northern part of Kuwait and it is barely differentiated in southern areas (Figs. 3 and 4); they are Ghar, Fars, and Al-Dibdibba Formations. Al-Dibdibba Formation is a fluvialite sequence of sands and sandy gravels and covering most of the northern area of Kuwait (Owen and Nasr 1958; Milton 1965; Fuchs et. al. 1968; and Salman 1979).

Vegetation

Halwagy and Halwagy (1974) stated that the vegetation of Kuwait is composed of open scrubs, under-shrubs, perennial herbs, and ephemerals, which indicate seasonal variations controlled by the winter rainfall. Five main plant communities were identified and included: *Haloxylon salicornicum*, *Rhanterium epapposum*, *Zygophyllum coccineum*, *Cyperus conglomeratus*, and *Panicum turgidum*. Omar et. al. (1989, 2002) stated that previously recorded five plant communities dominate in Kuwait, but as a result of both the natural and human activities, the vegetation cover has been severely deteriorated and the plant distribution pattern has changed and altered. A vegetation map was produced, constituting eight vegetation map units (Fig. 2), by the integration of soil and vegetation information in a Geographic Information System (GIS). A significant fact was revealed by this study

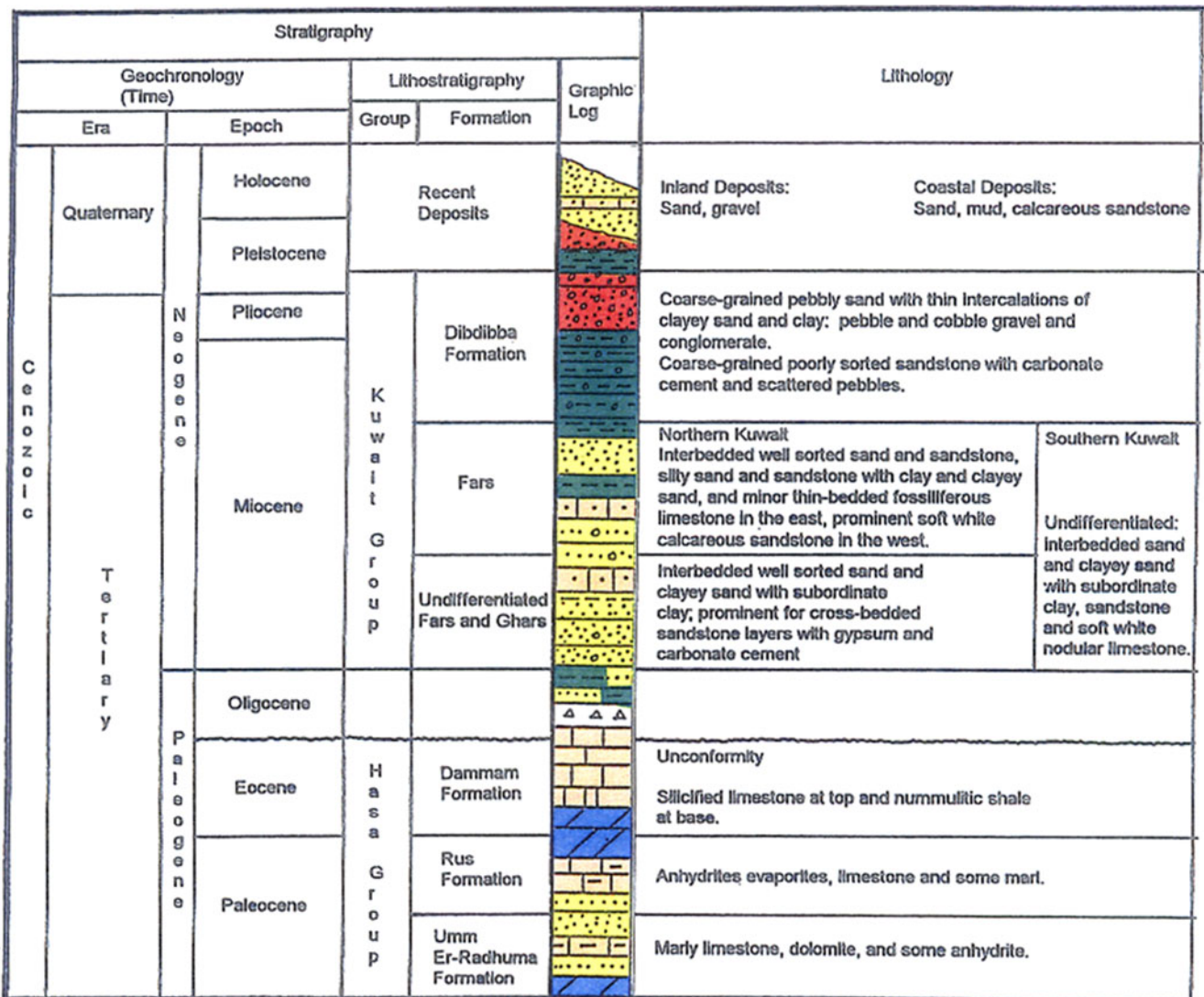


Fig. 4 Stratigraphy of the lithological structures of the State of Kuwait (modified after Misak et. al. 2000)

for the first time in the northwestern area of Kuwait, the growth of new plant species like *Eremoblym aegyptiacum* is recorded, which is known to be native to Iraq. This can be attributed to the possible seeds transported from Iraq during the northwesterly dust storms. Comparing with previous studies, it is evident that there was an alternation in the plant communities' distribution. Moreover, the study highlighted intensive land degradation, except in the prohibited or protected areas, where the vegetation cover is still maintained. Omar (1990) stated that the average productivity of the protected range lands was 140 kg/ha, which is much higher than those of unprotected ones, where it is near 19 kg/ha, due to irrational overgrazing, and irregular and improper land use (Figs. 5 and 6). Zaman and Sudairawi (1993) indicated that, in those areas with oil lakes (Fig. 7) as a result of explosion of about 720 oil wells during the Gulf war, the vegetation cover has completely vanished; in areas subjected to the soot, the vegetation cover was severely damaged.

It is worth mentioning that in Kuwait, there are no regulations directing the use of rangelands. Perennial grazing is a traditional practice for hundreds of years, where such heavy grazing would probably affect the plant species without the interference of man.

Kuwait's vegetation cover is a highly significant factor in reverse desertification. It acts as sand binder and wind breaker. There are several grasses and perennial shrubs that can sustain even when covered with sand during hot seasons. Examples are: *Cyperus*, *Penicum*, *Zygophyllum*, *Calligonum*, and *Haloxylon* (Omar et. al. 2002). Vegetation cover can have a significant role to play in the deposition of wind-transported sand. Vegetation cover changes surface roughness over large areas in arid environments (Bagnold 1941). Despite the accumulating sand, vegetation can penetrate through and the coalescence of vegetated micro-environment results ultimately in the vegetated sand sheet development.



Fig. 5 An aerial photograph of protected area adjacent to a non-protected overgrazed area, December 3, 1996 (after Kwarteng and Al-Ajmi 1997)

Methodology

This paper concentrates on two main aspects—geomorphological and sedimentological studies. The two studies were performed simultaneously to ensure optimal use of time and effort, to identify the interrelationships between the physical parameters.

Before starting the field and laboratory investigations, a preliminary survey of different locations throughout Kuwait was carried out during several reconnaissance visits. The purposes of this reconnaissance survey are to identify the general characteristics of the desert landforms and to provide information for planning the field survey and the sampling program. Fieldwork was conducted to validate the geomorphic features delineated from satellite images, aerial photographs, geological maps, and topographic maps. Fieldwork included recognition, as well as, investigational survey on the study areas, documenting the current on land facts and information, compared with the earlier delineated information. Sampling field trips were conducted for the required investigations and analyses.

The different landforms and topographic features of Kuwait were identified and delineated on the basis of topographic maps of Kuwait (1989 and 1994 at a scale of 1:50,000; Fig. 8), aerial photos (Fig. 9; 1991 at scale of 1:29,000), LANDSAT images of 1990s (Fig. 10) and 2000–2004 (Fig. 11), in addition to the field observations. Surface sediment sampling was done from different areas of Kuwait involving in-field description, photographic documentation, and preparation for laboratory analyses.

Remote sensing and GIS analysis

Thematic mapping using remote sensing data and applying image enhancement and classification techniques

Remote sensing data are extremely useful, particularly in a desert terrain, to extract surficial features on the land because of lack of thick vegetation cover. Extremely powerful image enhancement techniques are available to selectively identify surficial material characteristics and geomorphic patterns (Lillisand and Keifer, 1994). These techniques include a multitude of filtering methods, principal component and classification analyses, band rationing, etc. In this study, sedimentomorphic features were mapped using visual and digital methods.

The process of selection of appropriate remote sensing data is inherent with the issue of trade-off between spectral and spatial resolutions. A wide variety of spectral and spatial resolution data are commercially available. Among the many, Landsat-7, IRS-1D (Indian Remote Sensing), SPOT-4, and Advanced Space-borne Thermal Emission and Reflection are selected for consideration, keeping in view of the terrain in Kuwait and the objective of the study. IRS and IKANOS data in

Fig. 6 Field photographs showing the camels and livestock (goats and sheep) overgrazing on rangeland and rugged vegetated sand sheets in different areas of Kuwait



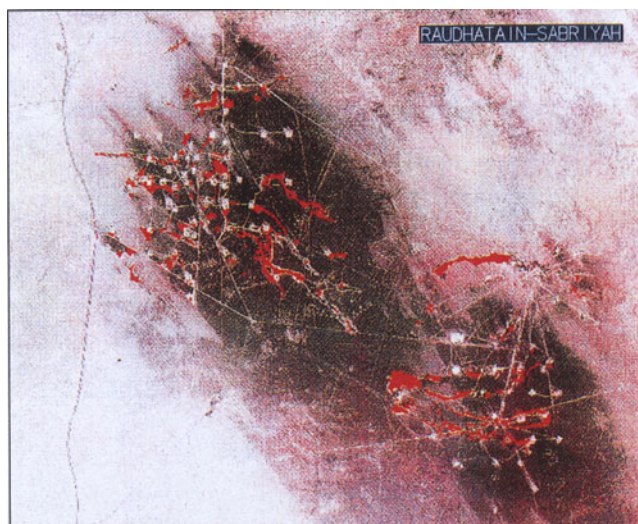


Fig. 7 A landsat image (1992) showing oil lakes (red) in Al-Raudhatain and Al-Sabriyah oil fields due the burned oil wells by the Iraqi troops during the Gulf war (source, Al-Ajmi et. al. 1994)

raw format for Kuwait images were obtained for the study with the available years of 2000–2004, which were compared with first images of 1990s for the purpose of change detection.

Digital image processing Different image processing actions were conducted on the LANDSAT images to extract the needed information as follows:

Image restoration For the digital image processing, ERDAS Imagine software version 8.6 was used where the available first LANDSAT images of 1990s (Fig. 10) were geometrically corrected based on the images derived from the topographic maps (scale, 1:50,000). Then, their geo-referenced images were mosaicked and used as a master image to register the second LANDSAT image of 2000–2004 (Fig. 11). ERDAS Imagine software was used to pick up the different studied locations from the first and the second LANDSAT images.

Image enhancement Using ERDAS Imagine software, the geo-referenced images were enhanced by which the visual capabilities of interpreting the images increased, and used in investigating and updating the sedimentomorphological map of the area.

Change detection Change detection is one of the remote sensing techniques applied to identify changes in the state of a surface, phenomenon, or object by observing it at different periods of time (El-Baz and Al-Sarawi 2000). In change detection, satellite images are used in comparing and analyzing the time-sequential images of the same region aiming to identify the changed features,

as well as showing their location and extent. Comparing the geo-referenced images of 1990s and 2000–2004, changes were detected using the layer stack function of ERDAS Imagine to produce new stacked images showing the changed areas in colored tone. Figure 12a, b shows an example of change detection from 1990 to 2001 in Ras Al-Subiyah area in north-eastern Kuwait. As for Kuwait in general and for the purpose of detecting the changes in the desert surface due to the activities of the Gulf war, change detection technique was applied by comparing the images of Kuwait pre and post the Gulf war to identify and map the changes that occurred. El-Baz and Al-Sarawi (2000) used change detection and came with a detection map for Kuwait (Fig. 13) produced by comparing those geo-referred images of Kuwait city, the different oil fields, and variant desert surfaces before the war with those after the war. After the war, new and additional land cover features were found as a direct result of the military activities and/or burning of the oil wells (Fig. 14).

Data integration and analysis using GIS methods

The necessity and utility of recently developed GIS technology in any spatial data capture, manipulation, analysis, and visualization have become obvious from the explosion in GIS market around the world. In this study, the sedimentomorphologic thematic data collected were digitized and analyzed to derive associative characteristics of the sedimentomorphologic variables. Apart from the routine usage of procedures to capture, manage, manipulate, and integrate data from maps (topographic, geological, etc.) of different scales, GIS was used to co-register (after rectification through rubber sheeting or other, if needed) remote sensing data (also of different scales/resolutions) with the map data. With overlaying techniques, correspondence between image-based (classified) thematic boundaries and ancillary map boundaries was assessed and corrected (e.g., ADJUST command in ArcInfo GIS). The effect of pixel resolution on thematic definition and discrimination was studied using GRID modules in GIS, by varying cell sizes in the analyses. In particular, the thematic raster data layers were analyzed using Overlay Technique in GIS, to derive spatial correlations between the variables (Bonham-Carter 1997).

For software selection, the selected image processing software is ERDAS IMAGINE Professional (8.6) with graphical spatial data modeling and Arc View extensions, and the selected GIS software is ESRI's ArcGIS (8.2) which includes ArcInfo, ArcView, and ArcEditor; its extension ArcGIS Spatial Analyst provides a broad range of powerful spatial modeling and analysis features.

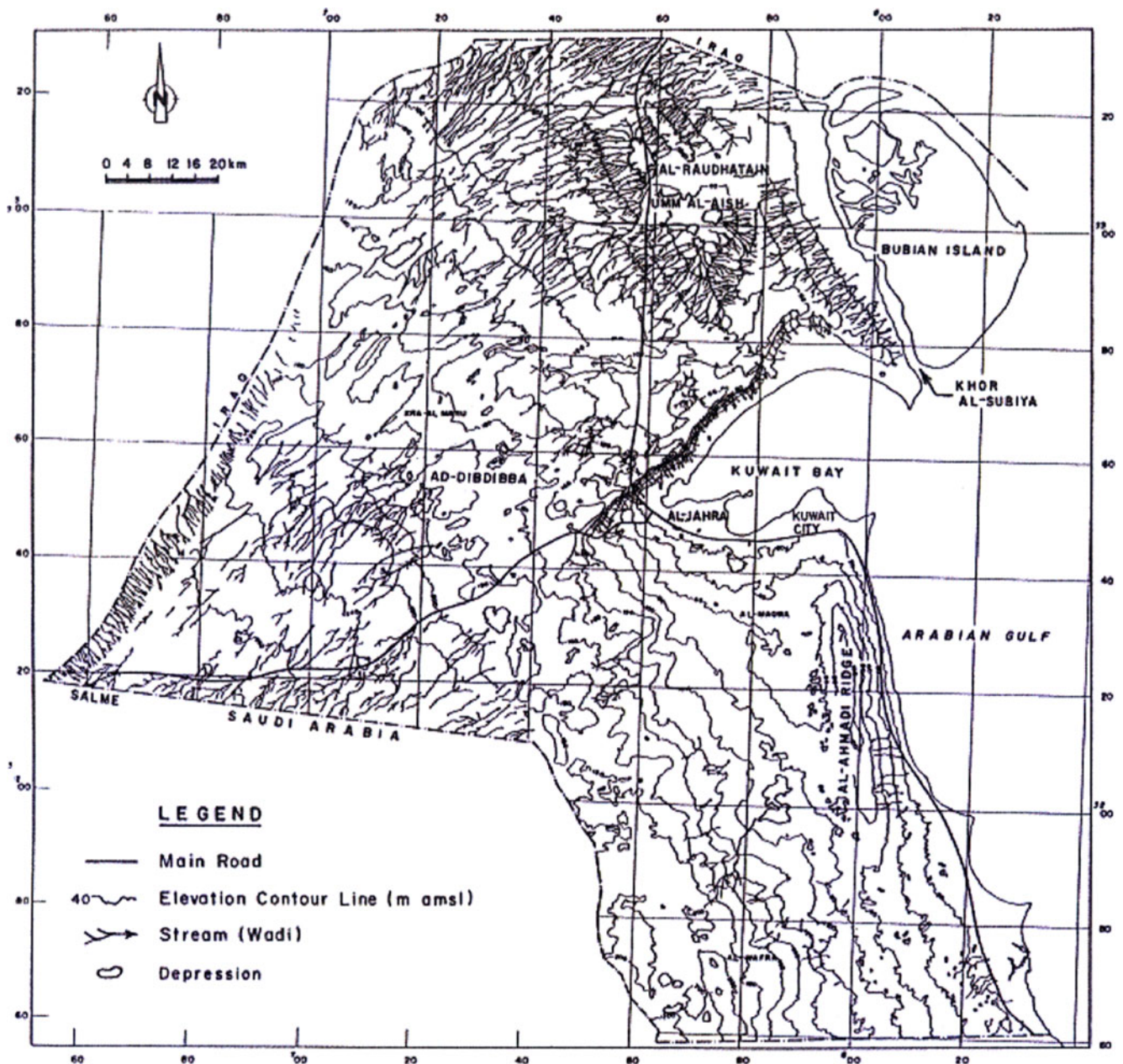


Fig. 8 A topographic map of Kuwait

Geographic information system ESRI'S ArcGIS8.3 & 9 (ArcView) and some of their extensions (Spatial Analyst, 3D Analyst, and ArcScan) and the Autodesk's products AutoCAD Map 2000, Autodesk Map 3D, and Autodesk Raster Design ArcGIS software version were used to conduct the GIS functions and analyses. The topographic maps have been scanned and manipulated, and converted into digital format, using the AutoCad 2000 software, which were then edited, cleaned, edge-matched, and geo-referenced using ArcGIS software. Then, the layers of contour lines, spot heights, shorelines, drainage systems, and roads network were extracted as GIS ready layers.

Integration of remote sensing and GIS Remote sensing techniques were applied to analyze and interpret images of the study areas to delineate geomorphic zones. IRS and IKANOS data in Raw Format for Kuwait were obtained for different years and areas.

The software Geomatica 9 for remote sensing analysis was installed; Geomatica 9 is a powerful software that makes every geo-processing step manageable and every geospatial processing achievable.

A geomorphic map of Kuwait was produced using the integrated remotely sensed data, the extracted GIS ready layers, and the extracted information from previous surface deposits

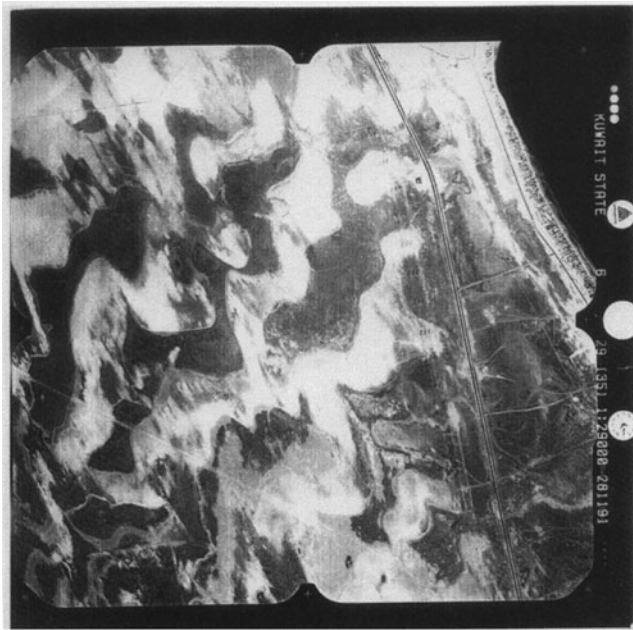


Fig. 9 An example of the aerial photographs (scale, 1:29,000, 1991) used in the study (southern area of Kuwait)

maps (Khalaf et. al. 1984). The LANDSAT images and the different GIS ready extracted layers were overlaid and used for extracting the geomorphological units in the area. Then, the resulting geomorphological map was analyzed and compared with the previously prepared sediment-geomorphic maps to produce the final recent sedimentomorph map of Kuwait.

Geographical distribution of surface deposits

Based on the genesis and mode of occurrence of the sediments, the recent surface deposits can be classified into two main classes: desert and coastal deposits. They are presented in a map in Fig. 15, where sand sheet deposits, sand dunes, wadi fill, sabkhas, and others constitute 40, 10, 20, 20, and 10 %, respectively, of the total recent surface deposits. Table 1 shows how these types of surface deposits are changed from the 1980s, along with the factors that played in the occurrence of these changes.

Desert deposits

Desert deposits are the most abundant type of recent surface deposits in Kuwait, covering more than 50 % of the surface of Kuwait. Six main types of sand deposits were recognized: (1) sand sheets, (2) sand dunes, (3) wadi fill deposits, (4) residual gravel, (5) playa deposits, and (6) desert plain deposits.

Gharib et. al. (1985), in their study on the active sand control measures in Kuwait air bases, calculated the rate of moving sand during summer months (June to September).

They stated that, a total of 6,000 m³ is estimated for Ahmed Al-Jaber Air Base in the southern area of Kuwait and 4,095 m³ for Ali As-Salem Air Base in northern area. They also stated that the sand flux intensity at Ahmed Al-Jaber Base recorded a peak of 3 m³/m in June, while it reached a peak 2.6 m³/m in the same month at Ali As-Salem Base.

Sand sheets

Sand sheets cover mostly the flat low-lying areas in the southern part of Kuwait, but also a few areas in the northern part. Two types of the sand sheets were defined: (a) smooth sand sheets and (b) active sand sheets. A rugged vegetated sand sheet (Khalaf et. al. 1984) used to occupy the shallow wide depression surrounding the ephemeral desert lake areas and mostly covered with widespread vegetated sand drifts. These deposits have been reduced because of the anthropogenic activities since the 1980s. These activities include: (1) excessive grazing, which causes the depletion of biomass, forage loss, soil trampling, and sediment destabilization, as an immediate impact; and as a long-term impact, it will result in enriching dusty and sandy particles in the storms, creeping sand expansion, vegetation cover disappearance which in turn leads to higher rate of water erosion with a subsequent decrease in the rate of soil recharge and vegetation dryness (Al-Awadhi et. al. 2003); (2) off-road vehicles and spring camping cause on-site effects comprising soil compaction, low permeability, vegetation cover destruction, breakage of armour layer of pebbles and gravel which in turn exposes underlying or in between finer sediments to wind erosion; and off-sites impacts by increasing the rate of water and wind erosion, sand sheets and drifts development, and soil fertility loss (Al-Awadhi et. al. 2003); (3) overexploitation of sand and gravel, which may immediately lead to disturbance and rupture of surface and near-surface sediments and destruction of vegetation cover; it may also increase the dust and sand in the downwind areas and disturbance of surface run-off pattern and running water loss in pits and quarries, on a long-term basis (Al-Awadhi et. al. 2003); and (4) ground entrenchment and digging for military activities that was intensified by the Iraqi invasion of Kuwait in 1990 and the associated Gulf War activities. These adversely affected the fragile balanced desert ecosystem of Kuwait, directly due to the mechanical removal of the native soil due to the heavy bombing and trench digging making the Kuwaiti desert more vulnerable to intense and frequent sandstorms. In addition, off-road vehicle use during the war caused severe compaction or top-soil loosening. Moreover, the most destructive effect of the soil and vegetation cover in the Kuwaiti desert was the crude oil lakes and pools due to oil wells burning by the Iraqi troops (Al-Awadhi et. al. 2003)

Smooth sand sheets Smooth sand sheets have relatively flat surfaces, sometimes covered with a very thin veneer of

Fig. 10 Examples of landsat images of 1990s used in the study: *Top*: Landsat image of Ras Al-Subiyah area in 1990 (Al-Hurban et. al. 2007) *Bottom*: Landsat TM bands 1, 2, and 3 color composite image of Kuwait City and its environs, February 28, 1993 (after Kwarteng and Al-Ajmi 1997)

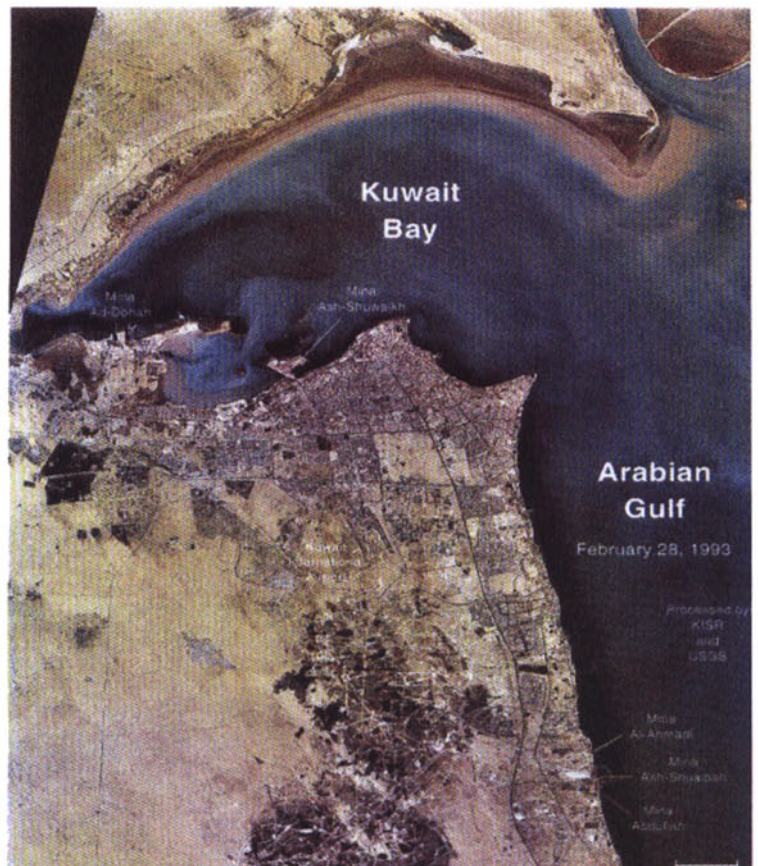
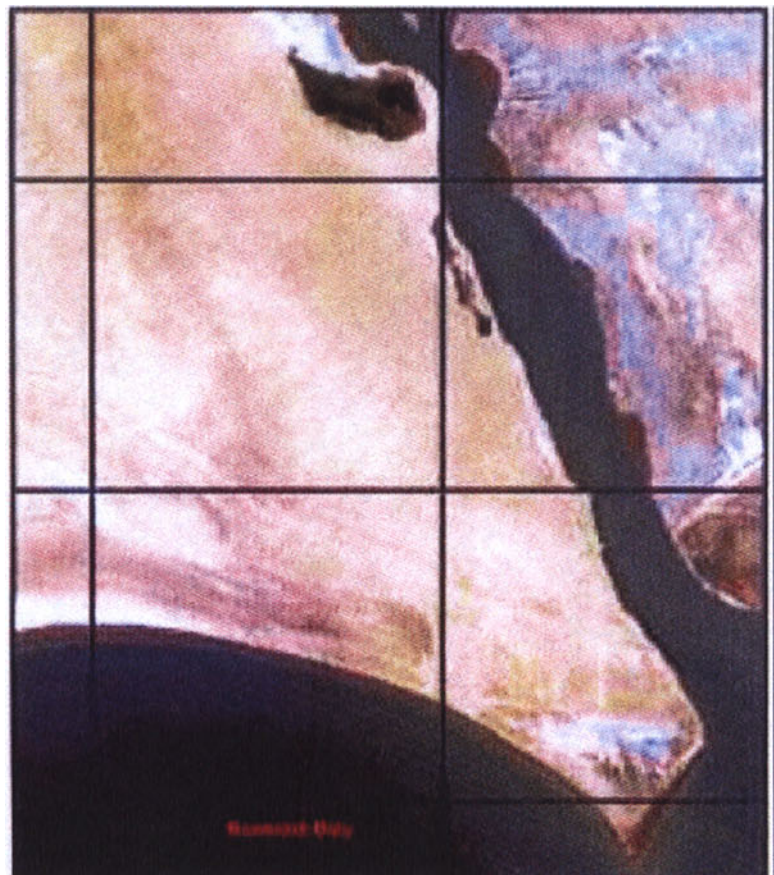
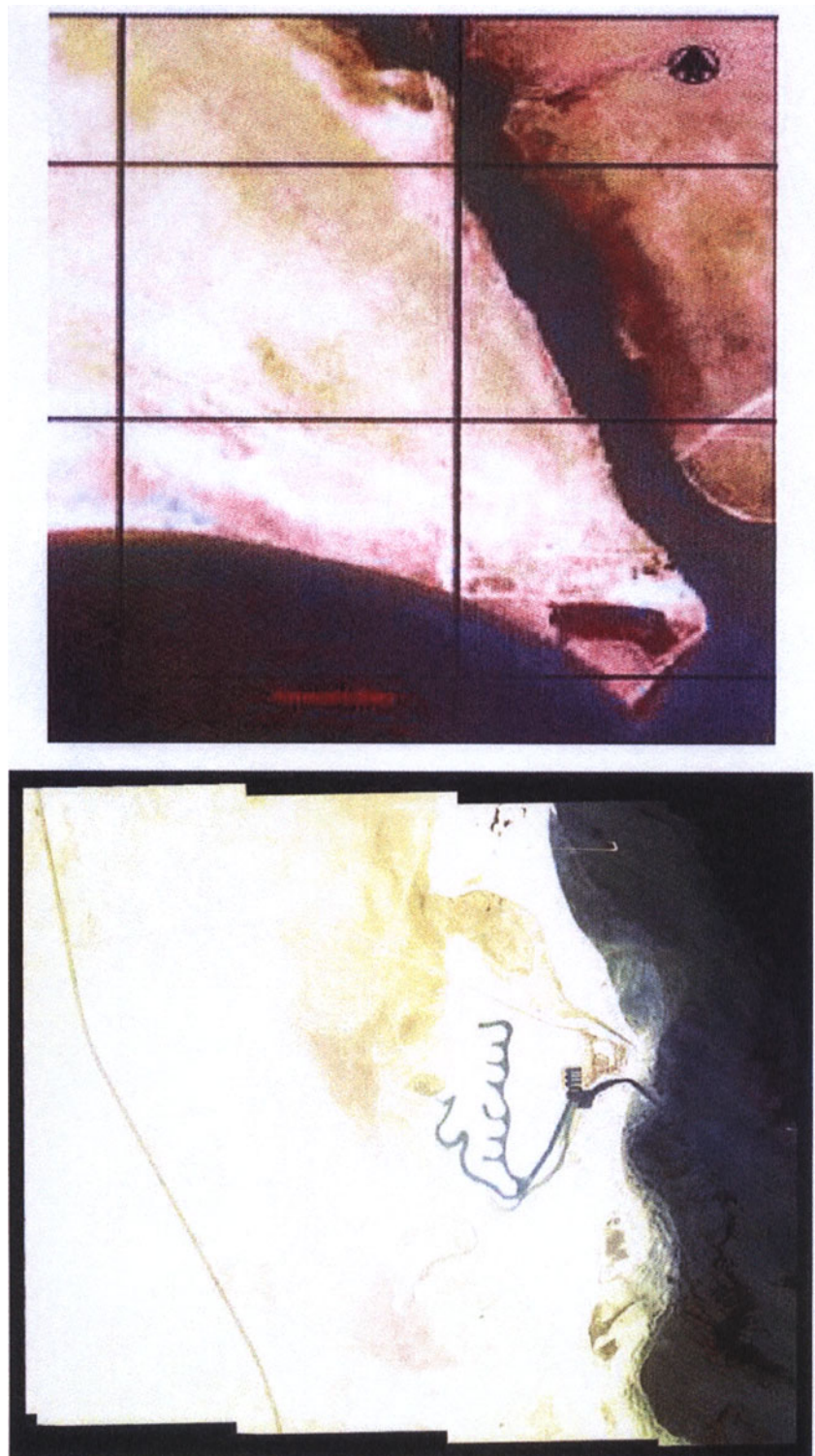


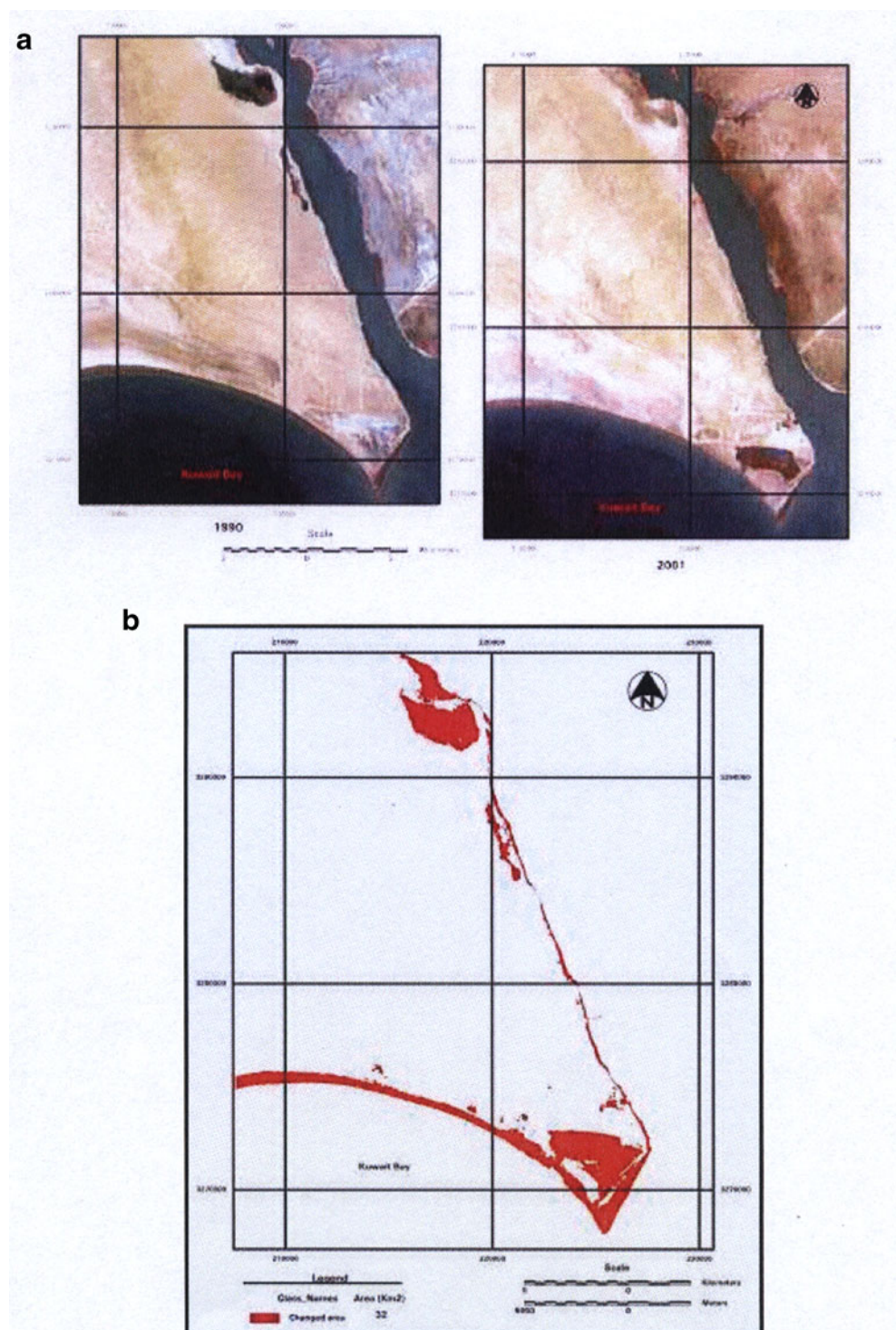
Fig. 11 Examples of landsat images of (2000–2004) used in the study: *Top*: Landsat image of Ras Al-Subiyah area in 2001 (Al-Hurban et. al. 2007) *Bottom*: Raw image of IKANOS data of Al-Khiran area 2001



residual granules. In most cases, they have a unidirectional ripple surface, indicating the northwesterly prevailing wind direction, subsequently covered with some patches of residual gravels (Fig. 16a). Bagnold (1941) suggested that the development of these sand sheets could be referred to the rapid deposition of sand under high wind velocities. Most of the southern part of Kuwait is covered with smooth sand sheets.

Active sand sheets These cover considerable areas of Kuwaiti desert occurring in the form of a thin blanket of light-colored and well-sorted sand, encroaching over other types of recent surface deposits. Their shape and way of arrangement are related to the prevailing northwesterly wind direction; some of these are associated with *barchan* dunes. The Kuwaiti desert can be divided into three main

Fig. 12 a, b Change detection in Al-Subiyah area: **a** Change detection during 1990 and 2001. **b** Change detection from 1990 until 2001



zones based on three main types of active sand sheets as follows:

Umm Negga active sand sheet It is situated in the north-eastern part of Kuwait extending from the northern border of the State towards Khor Al-Subiyah. It migrates by producing a sheet of residual gravels dissected by shallow wide valleys filled with aeolian deposits.

Al-Huwaimliyah active sand sheet This sheet is located in the northwestern part of Kuwait extending southeast from the northern borders of Kuwait to the western edge of Al-Liyah ridge. Transverse sand dunes are associated with this sheet, which migrates over residual gravel sheets that are initiated by the northwesterly wind-blowing sediments in the southern desert of Iraq. This was supported by Al-Hurban and Al-Ostad (2009)

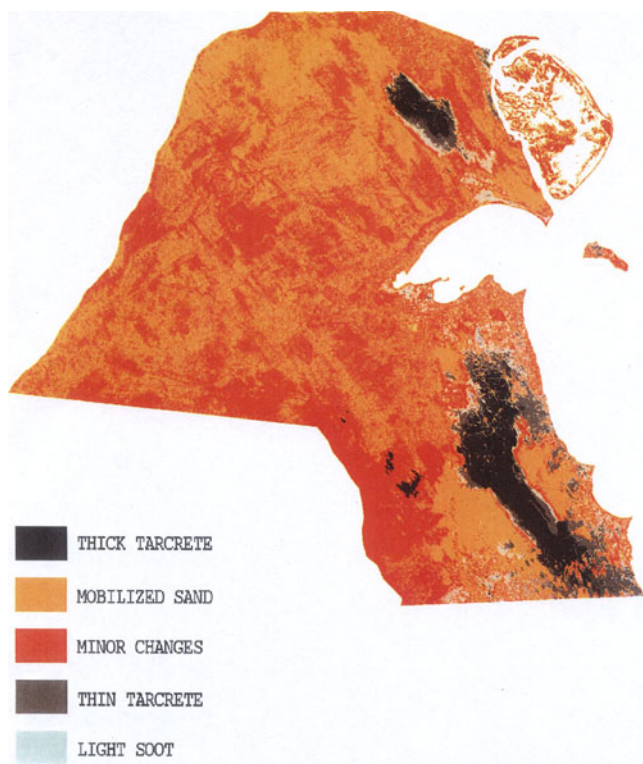


Fig. 13 Change detection map of Kuwait (after El-Baz and Al-Sarawi 2000)

who stated that, according to the heavy mineral suits, most of the desert sediments are from the Al-Dibdibba gravel deposits, which are derived from the Arabian Shield rocks during the Pleistocene period.

Al-Dabi et. al. (1997) and El-Baz & Al-Sarawi (2000) stated that the northern province of Kuwait is dominated by sand dune fields (350–500 km²), which are oriented along the main downwind direction, and receiving most of their accumulated sediments from southern Iraq, where the aeolian processes at the present time are very active in the southern Mesopotamian plain in general and in Kuwait in particular. Khalaf and Al-Ajmi (1993) indicated that among the aeolian processes, deflation removes the fine sand and mud sediment downwind, resulting in the lag deposits, known as desert pavement, particularly the pebbly lag deposits which cover the upper Dibdibba gravel ridges in northern Kuwait and the pebbly granule lag deposits covering the fluvial desert deposits in the northern flat, in the inter-ridge areas of the Al-Huaimiliya undulated plain, and the lower Dibdibba bedrock in the western calcaretic plain.

The northern part of Kuwait is characterized by flat topography. Depending on the wind data and landsat images interpretation, it appears certain that the dunes are formed where the wind energy is significantly reduced along the direction of drifting sand.

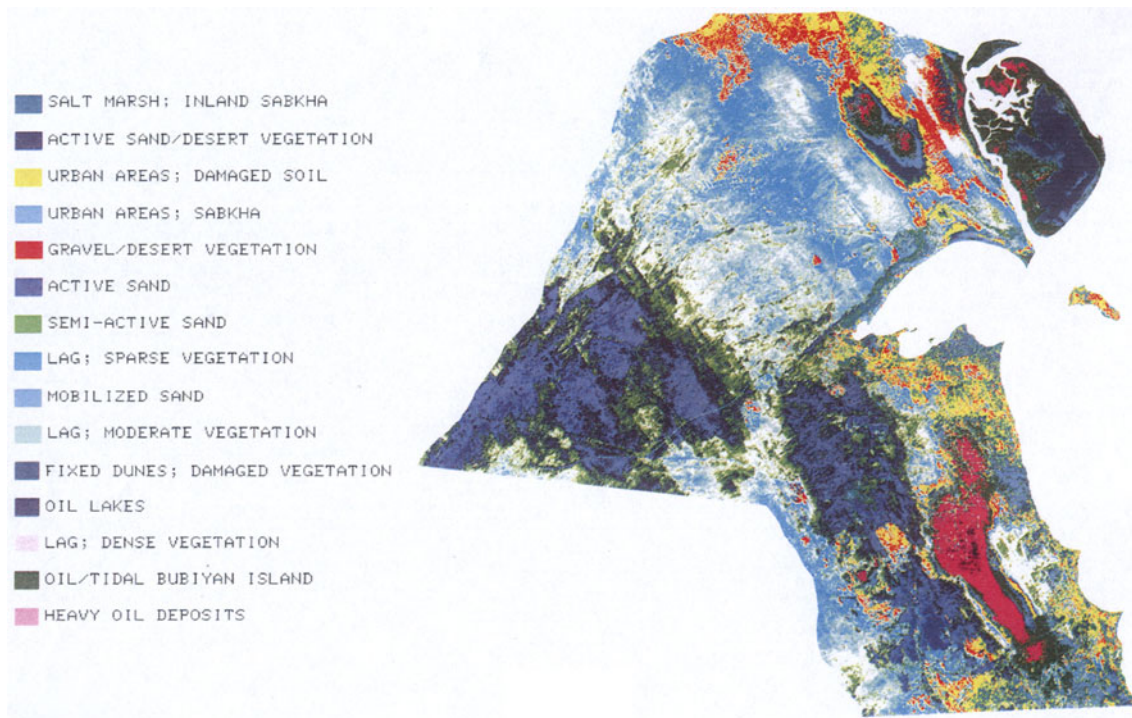


Fig. 14 An undefined thematic map of Kuwait containing 20 spectral classes that were assigned different colors using the unsupervised image classification, showing the new and additional land cover

features that were found as a direct result of the military activities and/or burning of the oil wells after the Gulf war (after El-Baz and Al-Sarawi 2000)

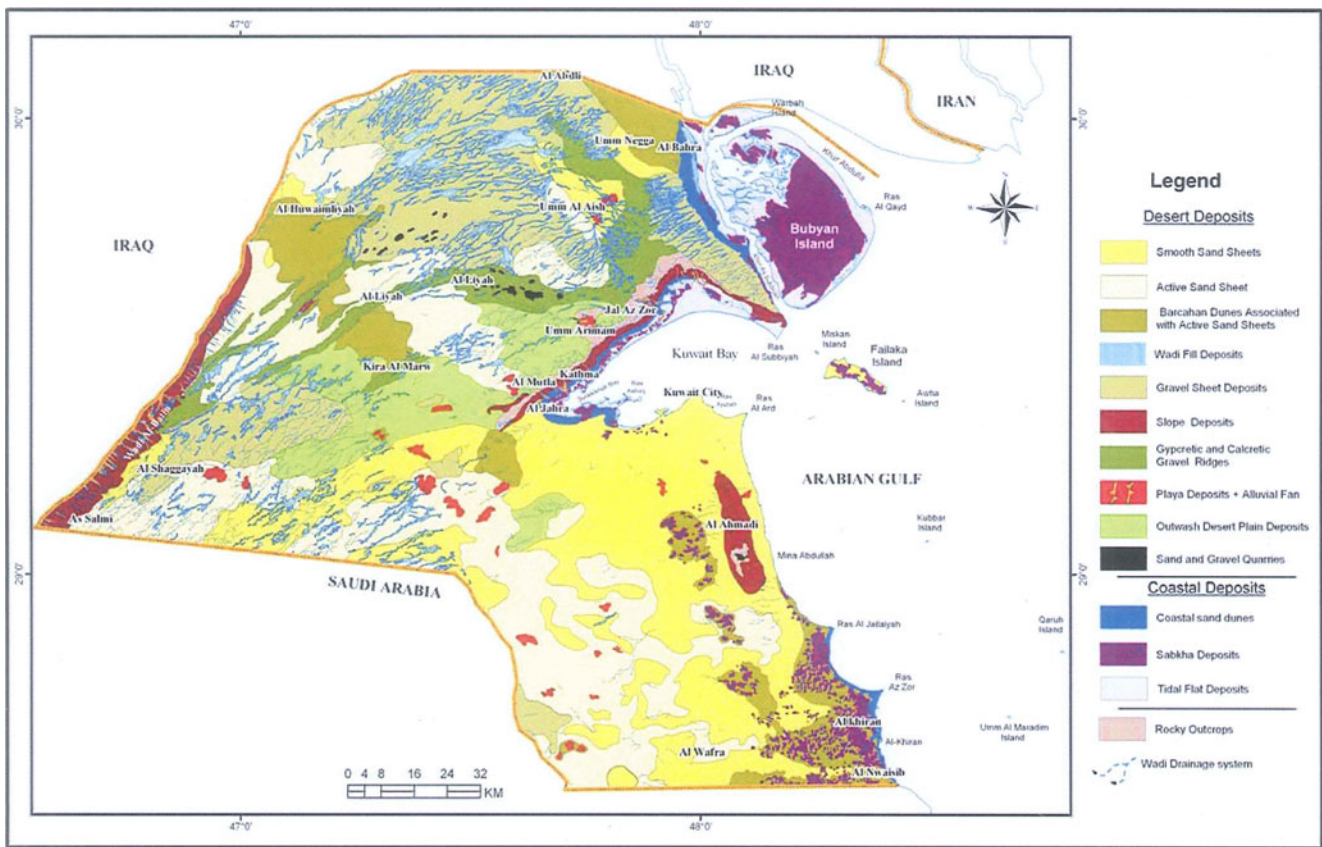


Fig. 15 Sedimentological map of Kuwait showing the major classes and subclasses of the recent surface deposits

Table 1 Distribution of surface deposits in 1980s and how they were changed during time passing due to different factors

Surface deposits	Distribution in 1980s	Major changes observed or present	Factors responsible for changes	
Desert deposits	1. Sand sheet	Rugged vegetated sand sheets were distributed	Most of the area was covered with smooth and active sand sheets	Anthropogenic activities (grazing, off-road vehicles, campaign, overexploitation of sand and gravel deposits, and military activities)
	2. Desert sand dunes	Small sizes of barchans	Barchan size increased	Transportation of active sand sheet and the area became more enclosed and less human activities
	3. Wadi fill deposits	Larger size of fill deposits	Smaller in size	Erosion, rainfall in 1990
	4. Residual gravel	Large in size and more abundant	Less abundant and smaller in size	Deflation, more exposed to anthropogenic activities
	5. Playa deposits	In different shapes and depths	Mostly covered with active sand sheets	Increase in aeolian processes due to natural and anthropogenic activities
	6. Desert plain deposits	More and larger sized pebbles with sand drift	Less pebbles and more scattered ones with smaller size	Wind erosion
Coastal deposits	1. Coastal sand dunes	Small sandy hillocks around shrubs	Larger in size and more abundant in southern areas	Geology and geomorphology of the area
	2. Sabkha deposits	Extends more in landside and wider along coastal area	Inland sabkhas are covered with sand sheets, and coastal sabkhas are narrower	Movement of active sand sheets
	3. Beach and tidal flat deposits	Narrow belt, small spits	More development of beaches, larger sized spits	High wave and current energy

The Al-Huwaimiliya belt is bordered by elevated grounds and dissected by elevated calcretic and gypsum-gravelly ridges. The low-lying areas between these ridges are desert plain, mostly covered by pebbly lag.

Southern coast active sand sheet This extends along the southern coastal area of Kuwait from Ras Al-Jailaih to Al-Nwaisib, surrounding and partially covering the inland and coastal sabkhas. The coastal drifts on the landward side are flanked by the dry sabkha and flat and the active sand sheets (Al-Hurban and Al-Ghadban 2008).

Sand dunes

Sand dunes are developed in both the desert and coastal areas of Kuwait. The sand dunes occur in two major groups: free and anchor, where the desert sand dunes existing as crescent-shaped dunes named *barchans* belong to the former class (Al-Dousari et. al. 2008; Khalaf et. al. 1984), which are usually associated with the active sand sheets (Fig. 16b) and occurring as isolated dunes or dune belts. They are the most common form of sand dunes in Kuwait, geomorphically distributed within the Atraf-Huwaimilyah zone area, Kabd, Sabbiyah, Um Al-Aish, Buhaith, and Dhubaiya (Al-Dousari et. al. 2008)

Isolated *barchans* are commonly associated with active sand sheets of Umm Negga and Al-Huwaimilyah areas.

According to their morphology and orientation, it is certain that they are migrating southeasterly. About 11 *barchans* are scattered at Umm Negga. Their axes are oriented northwest–southeast with an average width of about 150 m and an average height of approximately 10 m. Strong winds during storms resulted in the development of unidirectional asymmetrical ripples on the upwind side of the dunes, as the surface of *barchans* at Umm Negga has been a subject to partial erosion. Some small *barchans* have been completely removed from their site leaving behind a trace of thin layer indicating their past location.

The annual rate of movement or migration of the isolated dunes ranges from 8 m for the Umm Negga dunes to 50 m for the Umm Al-Aish dunes (El-Baz and Al-Sarawi 2000). Barchan chains, which prevail in Al-Huwaimilyah in the northwestern part of Kuwait, constitute three chains of 273, 230, and 107 dunes, with an average width of 36 m, average height of 3.3 m, and a rate of movement of the small dunes of 50 m/year (El-Baz and Al-Sarawi 2000). The fine sand material in the dunes near or within the Mesopotamian flood plain upwind in Iraq is more and decreases gradually downwind due to aeolian sorting and winnowing (Al-Dosari 2003). The dunes of Kuwait contain more than 40 % coarse sand, while the highest percentage of this fraction in the dunes of Iraq is 8.7 % due to the provenance sand dunes in the Mesopotamian flood plain source, as well as the increasing sediment supply increase from eroding Al-Dibdibba Formation within Kuwait (Al-Dosari 2003). Comparison

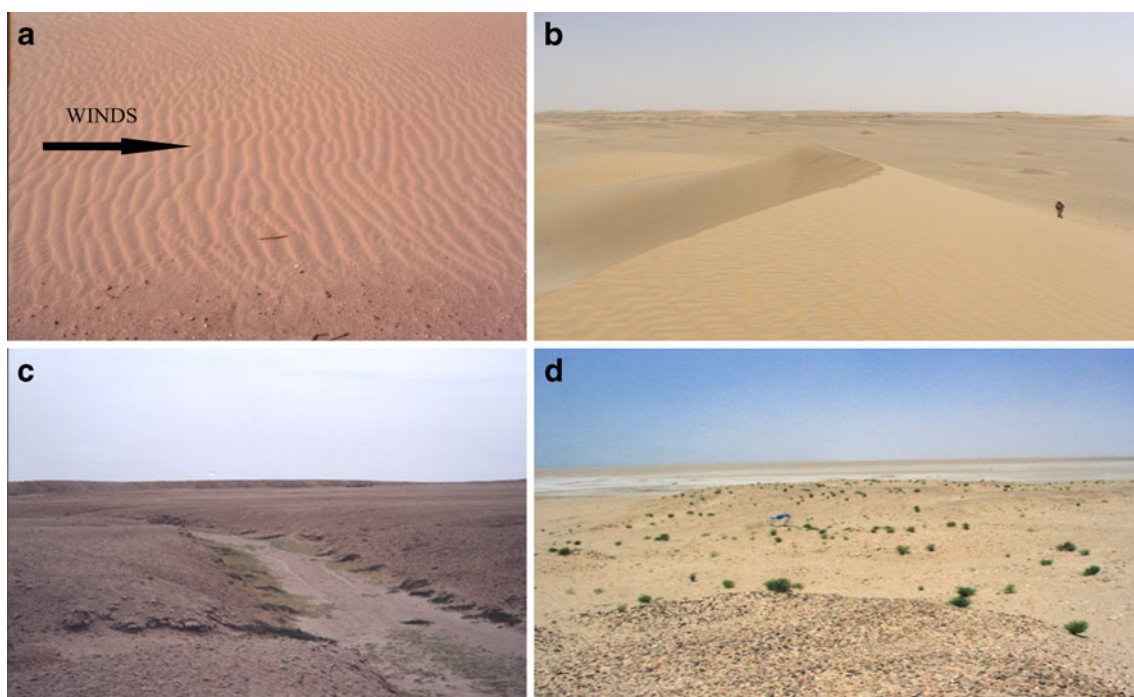


Fig. 16 a–d Field photographs showing different desert deposits: **a** Smooth ripples sand sheet in Al-Managish area. **b** A close view of one of the barchan dunes associated with active sand sheets. **c** A secondary

channel of Wadi Al-Batin (note the wadi fill deposits). **d** Residual gravel capped ridges in Al-Sabbiyah area

of the upwind and downwind aeolian deposits with those of Al-Dibdibba Formation shows similarities in the color, carbonate content, heavy and light minerals, and inclusions (Al-Dousari 2003).

Wadi fill deposits

Wadis is the Arabic term for valleys that are dry desert streams. The drainage system covering the northern part of Kuwait originated mainly from Wadi Al-Batin (east/northeast–west/southwest) parallel to Al-Dibdibba fluvialite conglomerate ridges. Along with aeolian origin of most of *wadi* fill deposits, some *wadis* are partially filled with fluvialite *wadi* fill deposits.

The different orientation of such *wadi* system to the prevailing wind direction in addition to the large aeolian sediment transport in the region allowed such *wadis* to act as sand traps (Fig. 16c).

Residual gravel

Generally, they cover most of the northern part of Kuwait, similar to *serir* deposits of the Lybian desert, occurring as dispersed blankets of a mixture of variant grain sizes including sand, silt, and clay capped with multi-sized gravels (Fig. 16d; McKee and Tibbitts 1964).

In addition to Al-Dibdibba Formation, Al-Asfoor (1980) stated that Jal Az-Zor Formation provides a clastic source for residual gravels. However, the volume of the existing residual gravels was much smaller than the volume expected to be derived from its assumed source. Therefore, it can be stated that most of the residual gravel have been removed by erosion. Moreover, Al-Asfoor (1980) also indicated that the pebbles and boulders in the residual gravels deposits are of different orientation with slope direction and that the main agent of transportation was fluvialite.

Deflation process that results in the concentration of pebbles and boulders on the surface will form a desert pavement. It was noticed that material of pavement is composed of varying size. Fuchs et al. (1968) recorded pebble diameters of 40–50 cm and proposed a westerly provenance based on proximal and distal grain sizes. According to their mode of occurrence, residual gravels of Kuwait can be subdivided into three types as follows:

Gravels sheet deposits They develop as continuous sheets, through which parallel dendritic drainage pattern traverse forming *wadi* fill deposits, and occur in most of the northern areas, especially in Khor Al-Subiyah and Al-Shaggayah areas (Al-Hurban et al. 2007).

Slope deposits Slope deposits develop as a continuous sheet covering Al-Dibdibba Formation and Jal Az-Zor ridges,

resulting in sub-parallel curved ridges that are mainly composed of Pleistocene fluvialite Al-Dibdibba conglomerates.

Gypcretic and calcretic gravel ridges These biochemical deposits constitute the hard crust of various components originated due to the chemical precipitation of minerals, either on the surfaces or within the pores of the original sediments. Gypcrete, calcrete, and partly silcrete are the most commonly developed types of duricrust in the Arabian Gulf. In Kuwait, there are well-developed gypcrete duricrusts on the desert plain sediments, over the Al-Dibdibba gravel and the calcareous sandstones of Jal Az-Zor Formation. They are of less than 1 m thick, commonly 10–30 cm. They are well developed on flat plains and mainly flat elevations on the tops of ridges.

Gypcrete is one of the observed duricrust types at or near the land surface. The main gravel source of gypcrete clasts in Kuwait is by deflation of the gypsiferous crust during dry periods, which was formed under lacustrine processes during the Pleistocene (El-Sayed 1993).

Calcretic duricrust is locally named as “Gatch,” which is partly consolidated deposits of a massive bedded calcrete observed in several parts of Kuwait. It mainly consists of quartz sands with carbonates (calcite and/or dolomite) as a dominant cement (Al-Sulaimi 1988; Al-Sulaimi et al. 1990).

Playa deposits

Playa is a terminology describing barren depressions constituting the lowest portion of a desert basin in which rainfall and sediments have accumulated periodically and developed as ephemeral lakes in arid regions (Neal 1969).

In Kuwait, playas are locally named “Khabrat” or “thamilat.” They occur in different shapes and depths in the form of small deflated depressions in the *wadi* drainage systems in the northern parts, including in the desert plain deposits. They are small, elongated, elliptical basins in the northwestern area, parallel to the prevailing drainage pattern direction (northeast–southwest). The playas associated with the desert plains are usually circular in shape, flat, and very shallow, while playas associated with *wadis* are covered with a thin mud layer of vegetated surface (Khalaf et al. 1984). Some of the playas are entirely covered with aeolian sand, and historically, they used to be surrounded by vegetated sand sheets. Deflation is considered to be the main process at work resulting in the development of the small desert depressions, especially in the northwestern part of Kuwait. Removal of sediments will lead to lowering the land surface and hence to the relief development.

The most significant and the largest playa in Kuwait is Umm Ar-Rimmam situated on the slope side of Jal Az-Zor escarpment, as it was developed in a hard calcareous land surrounded by steep rocky cliffs. It is proposed that this

feature occurred due to deflation processes accompanied by chemical weathering without any tectonic interference.

Desert plain deposits

The deposits of the desert plain or broad shallow depressions originated by the combined action of wind and water. In Kuwait, the desert plain deposits are of the Holocene age covering more than 20 % of its surface area and occurring in significant amounts in Umm Al-Aish basin, which is considered an inter-basin in Al-Rawdhatain area, enclosing the largest depression in Kuwait, Al-Mutla area and randomly distributed in the western region (Khalaf et. al. 1984). They consist of a mixture of mostly silty and clayey sand, usually with gravel admixture.

The desert plain deposits in Umm Al-Aish are usually overlain by a thin layer of gypsum, where the wind action on these deposits is obviously witnessed by the development of lag pebbles. Playas usually occupy the central part of the desert plain deposits.

Al-Rawdhatain area is covered by clayey layers from floods in earlier decades, as the area is basically a large catchment basin occupying one third of the northern part of the northern province of Kuwait. Al-Rawdhatain is characterized by the existence of a large number of fresh water wells; a production from Pleistocene pluvial deposits reaches one half million imperial gallons. Topographically, the area slopes 5–7°/km from the north towards south. The area is bounded by Jal Az-Zor escarpment to the east and the ridges of the basin and range area to the west. Comparing the sedimentomorphologic map with the other type of maps of previous studies, it is found that desert plain covers most of the area that used to be rugged sand sheet and gravel deposits, but the drainage system is from east to west. The playa in the southern corner of the area became somewhat elongated in shape due to erosional activities.

Coastal deposits

The coastal zone of Kuwait extends from seashore to the highlands, where the coastal deposits are developed. This is so because this area is thought to be submerged and covered with sea water in the earlier ages, evidently by the occurrence of Quaternary oolitic limestone coastal ridges separating the extensive and extremely flat areas (sabkhas) from the open sea. Moreover, the surface of these sabkhas is encrusted by salts, and they are vertically composed of interbedded mud layers with evaporite-rich layers, indicating that they were being occasionally flooded by seawater allowing them to be occupied by algal mats of different structures (Khalaf et. al. 1984). Furthermore, the extensive and prolonged intertidal flat sediments are partly originated in ancient projected lagoons to seawater and partly formed

in place by chemical precipitation from water (Khalaf et. al. 1984). Picha (1978) suggested that the Quaternary tectonics worked significantly in the physiographic and sedimentary development of the area forming favorable conditions for accretion and preservation of oolitic sediment and sabkhas.

There are many factors affecting this environment including coastal morphology, environment, composition of the bed rocks, physical and chemical properties of the sea water, and climate and anthropological construction. In northern Kuwait, terrestrial and marine deposits cover the coastal plain, extending from the base debris slope at Jal Az-Zor to the coastal line of Kuwait Bay. The coastal plain has a width ranging from 1 to 3 km. It has a concave profile changing to gentle convex shape at the lowest end with a slope ranging between 0 and 2°. It is approximately 10 m above sea level in height (Al-Hurban and Hersi 2008).

The coastal plain is distinguished by other fluvial depositional features such as alluvial fans, which consist of accumulated boulders, gravel, and mud deposits in the valleys' mouth at the point where the valley leaves the steep Jal Az-Zor escarpment to the gently sloping coastal plain. Lower areas of the alluvial fans witnessed the deposition of fine-grained sediments, whereas higher parts of the slope witnessed the accumulation of coarser-grained materials. The coastal deposits can be subdivided into three main subdivisions namely: coastal sand dunes, sabkha deposits, and beach and tidal flat deposits.

Coastal sand dunes

They occur as a discontinuous belt (mainly nabkhas) along the coastline, extending from the landward limit of the sabkha flat to the debris slope, height ranging from 0.2 to 2.0 m. Nabkhas are biologically anchored sand dunes attached to shrubs or bushes, and are inactive. They are small sandy hillocks around shrubs developed in the northern and southern coastal plains. The controlling factors to the extension of the coastal sand dunes, distribution, and types are geology and geomorphology of the area. The areas of coastal sand dunes can be differentiated into northern and southern areas. They are dominated by aeolian deposits with a local provenance consisting of silicic grains and rock fragments, which are mostly derived from the slope sediments of Jal Az-Zor and from other desert deposits (Khalaf et. al. 1984).

Northern area This area extends from Ras Al-Ard in the southern coast of Kuwait Bay to Ras Al-Subiyah and the northern areas. The coastal dunes frequently occur along the southern coast of Kuwait Bay decreasing to the east side, except the sabkha dunes of Sulaibikhat Bay. The sediments of the dunes in this area are mainly composed of oolitic

sands, which mostly originate from oolitic limestone coastal ridges.

In the northern coast of Kuwait Bay to Ras-Al-Subiyah, the coastal dunes occur in the form of a narrow discontinuous belt towards the slope deposits of Jal Az-Zor escarpment. These sediments are composed of silicic grains and sedimentary rock fragments indicating that these sediments originated from the slope deposits of Jal Az-Zor area.

Southern area This area extends from Ras Al-Ard to the southern coastal border of Kuwait. The types of coastal dunes are different from those in the northern area, due to the variant geology and geomorphology of the southern sector. In the northern part of the southern area, there is lack of coastal dunes due to the extensive urbanization in the area, while the southern part is distinguished by abundance of continuous coastal sand dunes that formed in low-land flat area behind the Quaternary oolitic limestone coastal ridges.

Sabkha deposits

Sabkha is the Arabic name generally used to describe the coastal flat areas extending above the high tidal level and covered by evaporite-rich clastic sediments. Such a name was coined as a result of many specialized studies on the coastal and nearshore of the southern coast of the Arabian Gulf (Evans et. al. 1964; Kinsman 1964; Kendal and Skipwith 1968; and Evans and Bush 1969).

Al-Hurban (2004) defined sabkha as “salt flat,” which is part of a landform sequence extending from the shoreline, with an inland basin through a lagoon then to the sabkha. They occupy flat surfaces involving two units: the intertidal flat and sabkha.

The coastal sabkha flats (Fig. 17a–c) occur above normal high tide level in isolated, irregularly shaped patches along the coastal plain. They are mainly flat salt marshes bare of vegetation and covered by evaporite-rich clastic sediments. The sabkhas expand further horizontally, seaward and landside.

Most of the Kuwaiti coasts are bordered by low tidal flats standing just above normal high tide level, which is usually covered by sabkha deposits. These deposits are composed of multi-sized quartz sand, mixed with carbonate mud and occasional crystals of gypsum, covered by salts and gypsum developed during rainy seasons (Al-Hurban and Gharib 2003). Two types of sabkha flats occur in Kuwait depending on the noticeable differences in the coastal line, the northern sandy sabkha flats and the southern carbonate-rich sabkha flats.

The northern sabkha flats They extend along the north coast of Kuwait Bay and Warba and Bubiyan islands. The sabkha flat at the southern coast of Kuwait Bay is bordered

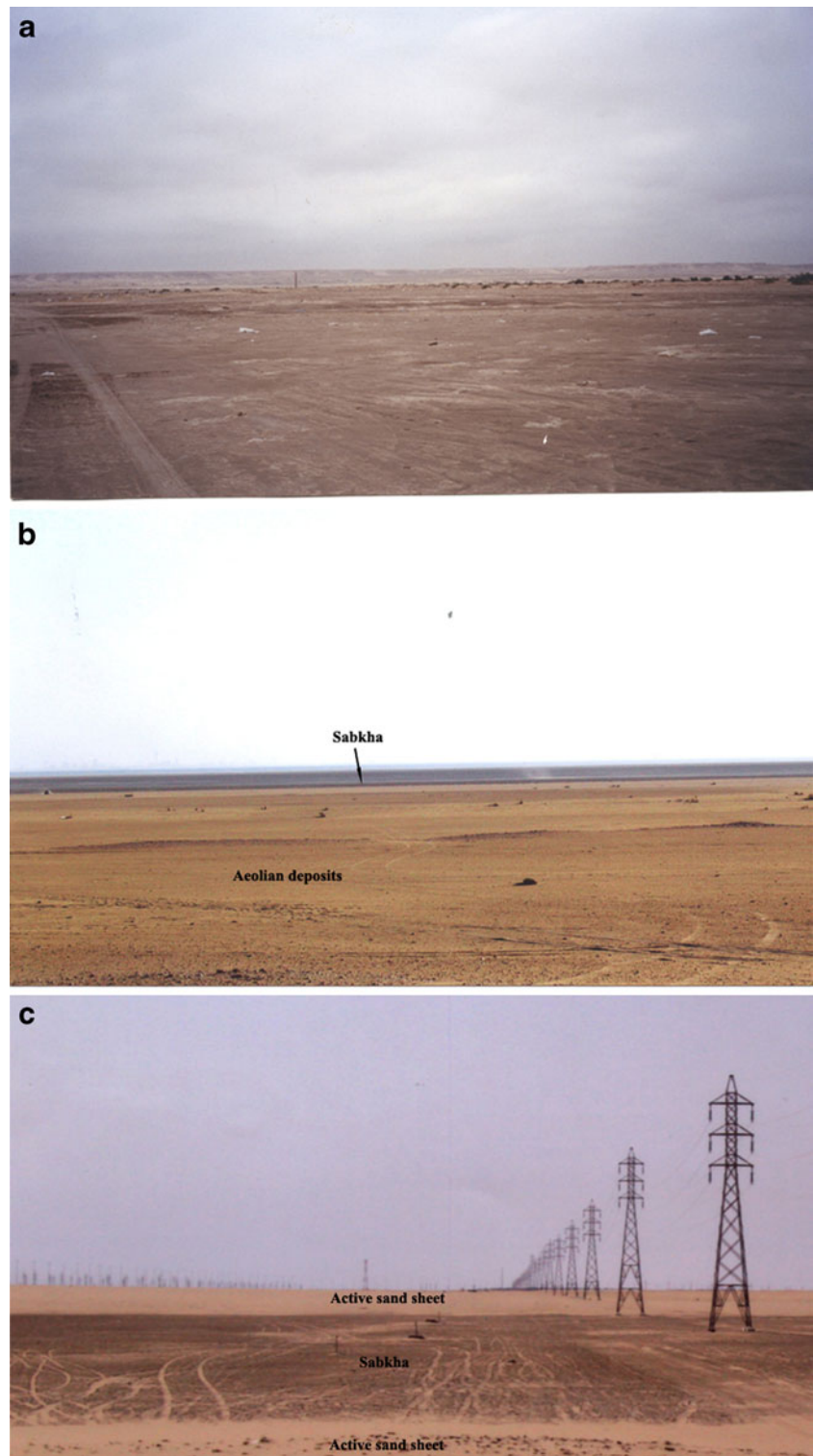
by low steep cliffs of Quaternary raised beaches on its landward side.

The northern coast of Kuwait Bay extends from Ras Kathma to Ras Al-Sabbiyah, and the sabkha flat develops and terminates near the slope and alluvial fan deposits of Jal Az-Zor escarpment. The sabkha flat takes up a narrow strip in the western area of the northern coast of Kuwait Bay with its maximum width in the central area at Al-Bahra, and develops along this coast as a continuous extension of the intertidal flat.

Some Quaternary coastal ridges separate the sabkha flat from the intertidal zone in the northern areas. The surface of sabkha flat is desiccated in most localities, and salts of sodium (halite) and calcium (calcite) are interbedded.

On the seaward side, some of these sabkhas were partly eroded, and inland shallow depressions are developed, covered with salt crusts, gypsum, and dried algal mats due to the spring tide overflowing, followed by evaporation and runoff. Furthermore, offshore Warba and Bubiyan islands are extensive tidal flats developed in the estuary of the Tigris-Euphrate delta plain. Generally, sabkha flats of these islands differ in several disciplines from those of the southern coast of the Arabian Gulf (Khalaf et. al. 1984). Warba and Bubiyan islands form a unique type of sabkhas, as they occurred by the submergence of the southern part of Shat Al-Arab estuary, representing a good example for the coastal sabkhas environment developed by the submergence of a river estuary in an arid zone (Khalaf et. al. 1984). The whole surface is considered as an extensive sabkha flat. The nature of the sediments probably has been affected by their vicinity to Shatt Al-Arab estuarine complex, their physiography, and the nature of the surrounding areas. In 1970, the whole surface of Warba and Bubiyan islands was seen to be covered with brownish marly soil with scarce vegetation (Khalaf et. al. 1984). Warba and Bubiyan islands are covered with loose silty sediments indicating their transportation along a NW direction (Khalaf et. al. 1984), as well as being characterized by abundant siliciclastic host sediments, absence of algal mat growth, and lack of recent diagenetic dolomite development (Al-Zamel and Al-Sarawi 1998). Thus, they differ from those in the southeastern Arabian Gulf, which is prevailed by calcium-rich dolomite in the muddy portions of the sabkha (e.g., the Holocene evaporitic settings of Abu Dhabi coastal area) (McKenzie 1981; Patterson and Kinsman 1982) and are associated with well-defined tidal channels. In Al-Khiran sabkha deposits in southern Kuwait, lack of dolomite is due to the composition of the underlying pre-Pleistocene substrate with hardly any dolomitic material (Picha 1978). Pilkey and Noble (1966) found no dolomite in the northern Arabian Gulf sabkha deposits, and if any dolomite is to occur is suggested to be partly transported as wind-blown dust from the subtidal and intertidal sediments.

Fig. 17 a–c Field photographs showing coastal sabkha flats in different areas of Kuwait: **a** Coastal sabkha in Jal Az-Zor area. **b** Coastal plain shows the sabkha covered with aeolian deposits in Jal Az-Zor area. **c** Sabkha deposits partially covered by active sand sheet in Al-Khiran area



The southern sabkha flats In southern area, the sabkha was essentially developed to cover a very large area around Al-Khiran tidal creeks. They are separated from the open sea by the Quaternary oolitic limestone coastal ridges extending landward to about 20 km. These sabkhas resemble those of Qatar and Abu Dhabi (Evans et. al. 1964). Aeolian sand

sediments partially cover their inland side. Their deposits are commonly of brown to light gray in color and loose or slightly consolidated, and their surfaces are encrusted by salts. Interbeddings of mud layers and evaporite-rich sand bands were revealed in the sabkha deposits through a vertical section (Al-Hurban and Gharib 2004). Sand blown by

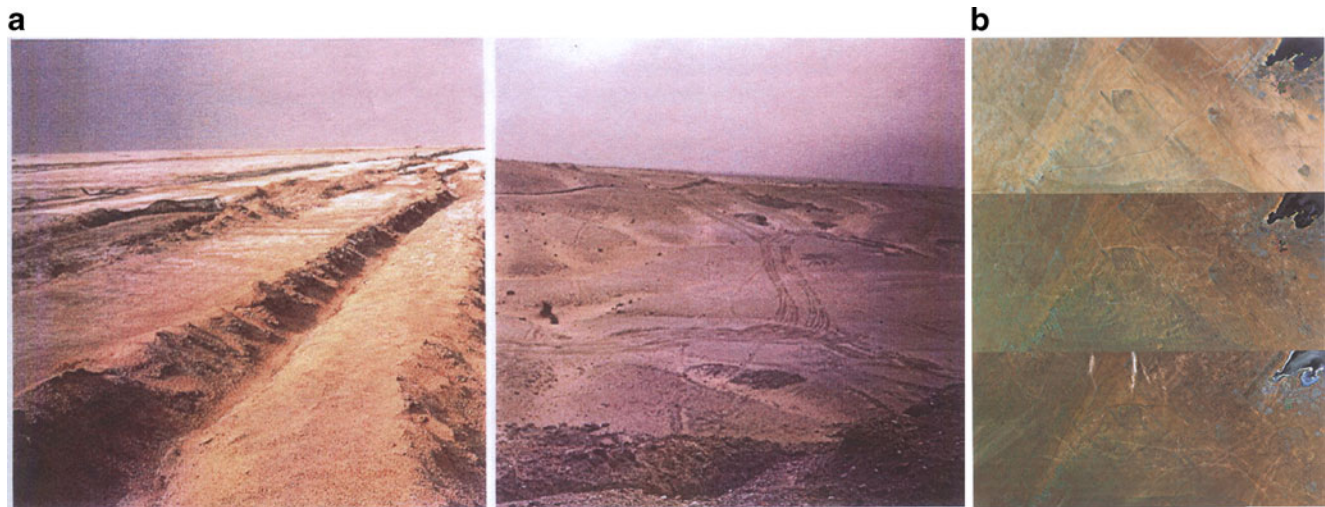


Fig. 18 **a, b** Field photographs and landsat images showing the vehicles' movement and tracks and trenches on the desert surface: **a** Vehicles' tracks and trenches on the desert surfaces. **b** Three landsat

images showing the increase of military vehicle tracks on the desert surface of the State of Kuwait (after El-Baz and Al-Sarawi 2000)

wind from desert in the vicinity played a considerable role in building the stratigraphy within the sabkha deposits.

Quaternary tectonics had contributed to the physiographic and sedimentary development of the areas including providing preferential circumference for the accretion and preservation of oolitic sediments and sabkhas (Picha 1978). Al-Hurban and Gharib (2004) reported that the southern sabkha province encompassed two main types of sabkha deposits: coastal and inland sabkhas. Some of these sabkhas were vegetated and others were barren of vegetation, depending on the groundwater salinity. The growth of salinity-tolerant plants such as *Zygophyllum*, *Calligonum*, and *Haloxylon* was witnessed in these sabkhas (Al-Hurban 1996). From a mineralogical point of view, both coastal and inland sabkhas are composed of quartz, feldspar, gypsum, and rock fragments, in addition to skeletal fragment and

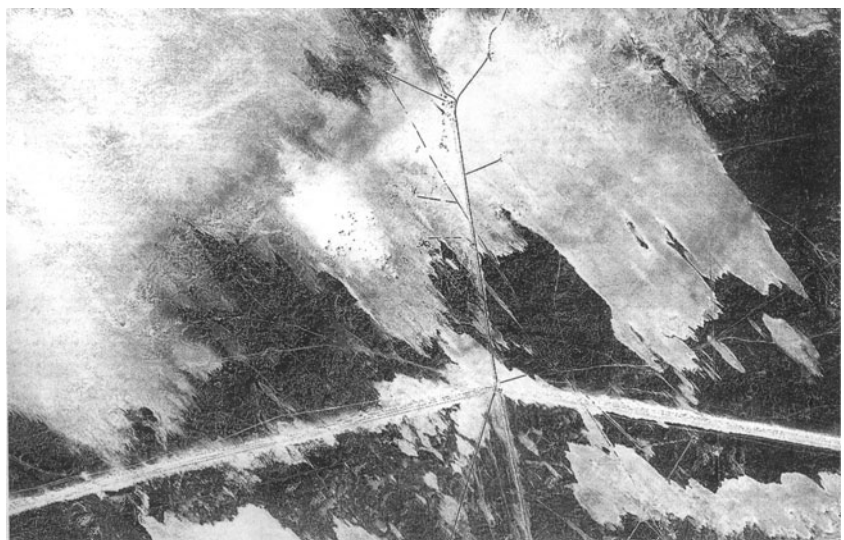
oolites only in the coastal sabkhas (Al-Hurban and Gharib 2003, 2004).

Beach and tidal flat deposits

The tidal flat area is the lowest part of the coastal plain extending from the base of the sabkha seaward between the high and low watermark. It is covered by muddy sediments with common beach deposits developed at higher elevations on the flat. It occurs as a narrow continuous belt extending along the coast of variant width from about 50 m in the southwest to about 600 m in the northeastern part.

Well-developed beaches are along the southern coast of Kuwait, where the coastal profiles are relatively steep. This can be attributed to the characteristics of the southern coastlines and the working factors in that area. Southern coastline

Fig. 19 An aerial photograph showing the effect of the sand berms built by the Iraqi troops as a protective measure on Kuwait-Saudi borders (after El-Baz and Al-Sarwai 2000)

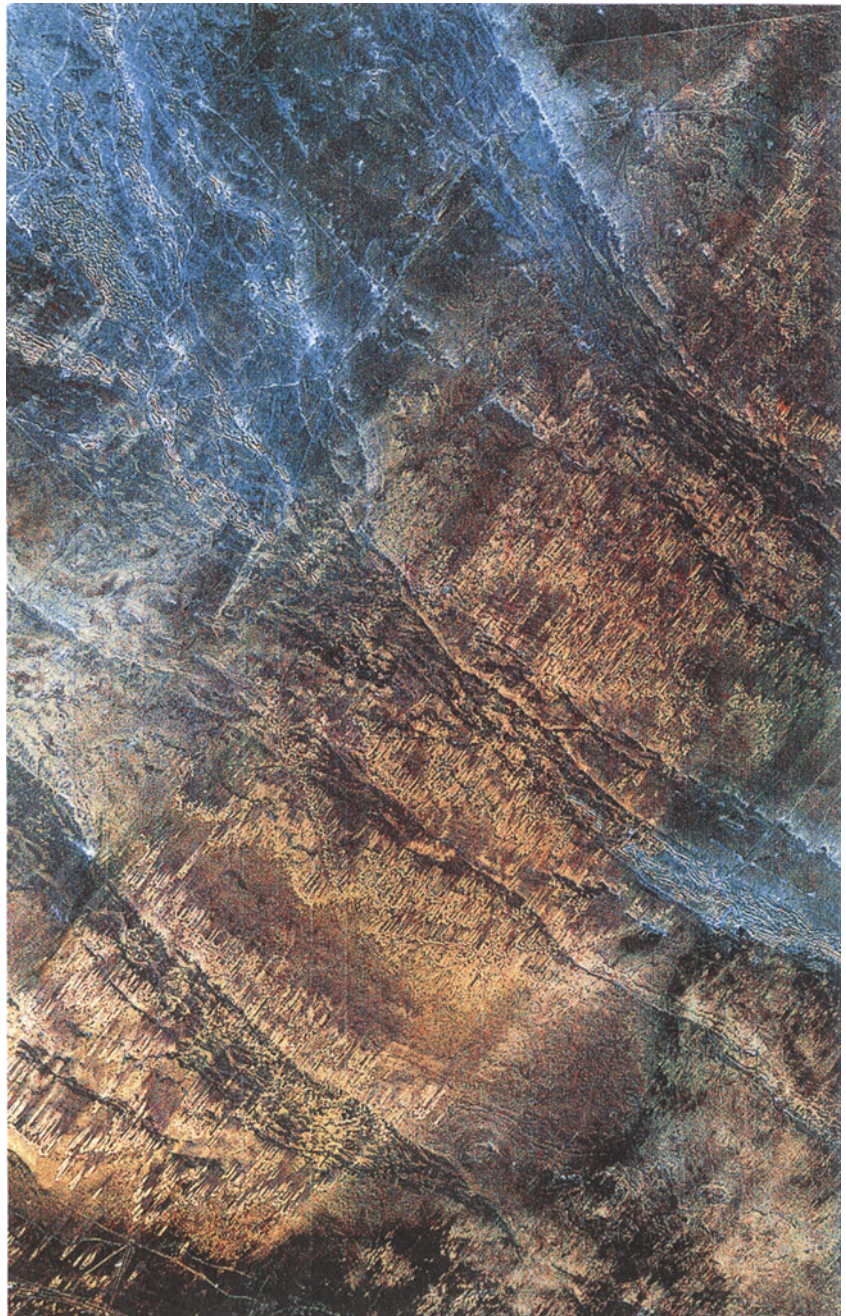


of Kuwait is distinguished by possessing a relatively steep slope beach profile, marine terraces (involving the outcropping of raised beach cliffs), cusped cove shore line bordered by headlands, energetic environment, active waves, and long shore currents. All these characteristics provide a suitable climate for the well development of beaches along the southern coastline of Kuwait. In addition, the energetic waves and currents along the southern coasts along with the exposure of relatively loose sediments are responsible for the beach sediments along the southern coastline (Khalaf et. al. 1984). Along the northern coast of Kuwait beaches are limited by the water currents in the northern area, but tidal

spits are frequently developed. Northern coastal beaches are mostly witnessing recurved sand spits, among of which is Ras Al-Subiyah, which was developed at the updrift side of Khor Al-Sabbiyah (Khalaf et. al. 1984). Moreover, there is a narrow beach zone occurring at Ras Al-Sabbiyah (Al-Hurban et. al. 2007).

The majority of the northern coastal beaches are distinguished by recurved sand spits, prominently at Ras Al-Sabbiyah and the south-eastern corner of Bubiyan island (Al-Zamel and Khalaf 1978). Such a spit has a length ranging from 2 to 4 km and a width ranging from 100 to 300 m, with a series of curving beach ridges separated by supratidal flats.

Fig. 20 A landsat image showing the considerable increase in sand dunes evolution and development, particularly in the northwestern part of Kuwait (after El-Baz and Al-Sarwai 2000)



Different features can be recognized characterizing the southern coastline. Such features include relatively steep slope beach profiles, cusped shoreline with areas fringed by headlands, high energy environment, active waves, and long shore currents. Factors affecting occurrence of beach deposits are relative high wave and current energy, and the exposure of relatively unconsolidated deposits.

Discussion and conclusion

Dust and sand storms are generated within 300 km of Kuwait, as evidenced from the thin veneer of recent surface sediments. These cover most of Kuwait's surface, which is categorized into two main classes based on their textural properties and mode of occurrence—desert and coastal deposits. The desert deposits are subdivided into: sand sheet deposits, sand dune deposits, *wadi* fill deposits, residual gravel deposits, playa deposits, and desert plain deposits, while the coastal deposits are subclassified into: coastal dune deposits, sabkha deposits, and beach and tidal flat deposits.

Aeolian sand deposits are regarded to be the most frequent type among the recent surface deposits, as they cover more than 50 % of Kuwait's surface. They occur in variant forms such as sand sheets, sand dunes, and *wadi* fill deposits. Their sand constituents could be transported from older deposits in the form of bedload, while simultaneously the finer components (silt and clay) are transported in suspension mode as dust storms. This would justify the occurrence of substantial deposits of mobile sand in Kuwait, as increasing amounts of dust are carried in suspension.

In the early 1980s within the low-lying areas, abundant small-sized *barchans* dunes (about 3 m high) were noticed to be migrating, whereas recently two types of dunes were noticed to develop namely: (a) the Al-Huwaimiliyah small barchan dunes, which were recorded in 1984, and (b) large barchan dunes, about 10–12 m high, which were not recorded until recently, but probably developed after the Gulf war, in 1990.

The movement of large tanks and mechanized vehicles on the desert surface of Kuwait, particularly the western part of the country, had adversely affected desert pavement by forcing the pebbles and cobbles covering the surface to be deep in the sand resulting in the excavation of large amounts of soil on either side of the vehicles track (Fig. 18a). In addition, those military precautions and action involving trenches and pits dug for hiding military equipment (Fig. 18b) increased the sand mobilization, as most of these trenches or pits were covered with sand shortly after the war and needed to be excavated. Among the military activities was the construction of sand walls, where the major berms were constructed along the borders with Saudi Arabia in the south and along the north and west of Jal Az-Zor in the north. The sand of the southern berm, due to the topographic

rise, was blown and deposited 1 km downwind of the berm forming sand streaks or elongated small sand dunes (Fig. 19). During the Gulf war, the Iraqi troops planted many mines particularly in the tri-border area near the western corner of Kuwait. Laying and then recovering and detonating the mines afterwards caused extensive surface disturbances headed by the mobilization of sand previously protected by wind-polished closely packed residues of pebbles and gravels. All these activities of troops movement, pits trenches digging, berms building, and mines laying and recovering caused severe damage to the desert pavement allowing an increase in the rate of aeolian sand transportation and accumulation which resulted in a considerable increase in sand dune evolution and development, particularly in the northwestern part of Kuwait (Fig. 20). Al-Dabi et. al. (1997) used satellite images taken over 4 years (1985, 1989, 1992, and 1994; Fig. 21) to compare number and distribution of the dunes with time. They found that the rate of dune formation from 1985 to 1989 was 31 dunes/year; the rate increased to 321 dunes/year from 1989 to 1992, and from 1992 to 1994, it remained high at 296 dunes/year. By field measurements, they found that the overall size of the dune field increased from 120 km² in 1985 to 220 km² in 1994.

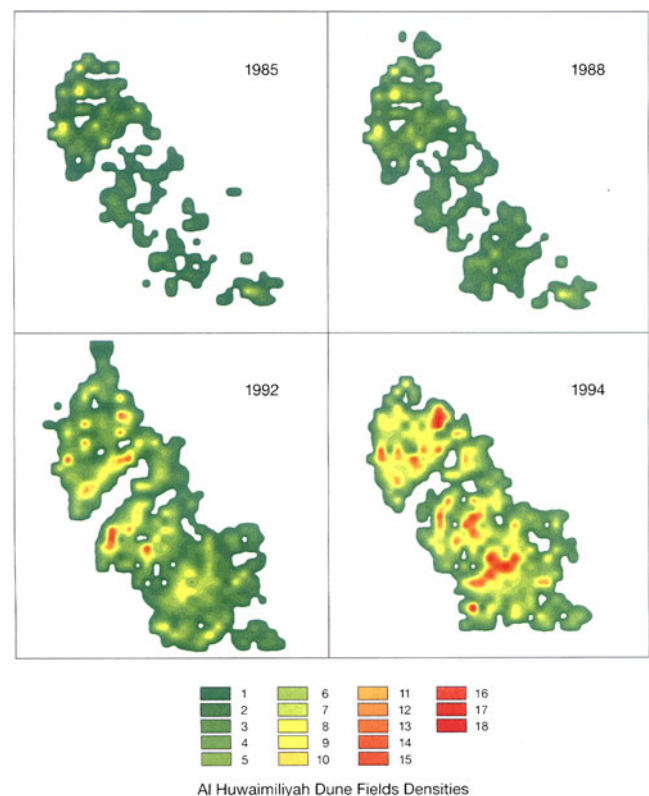


Fig. 21 GIS maps of the increase of sand dunes in Al-Huwaimiliyah region in northern State of Kuwait constructed from satellite images taken over 4 years (1985, 1989, 1992, and 1994; after Al-Dabi et. al. 1997)

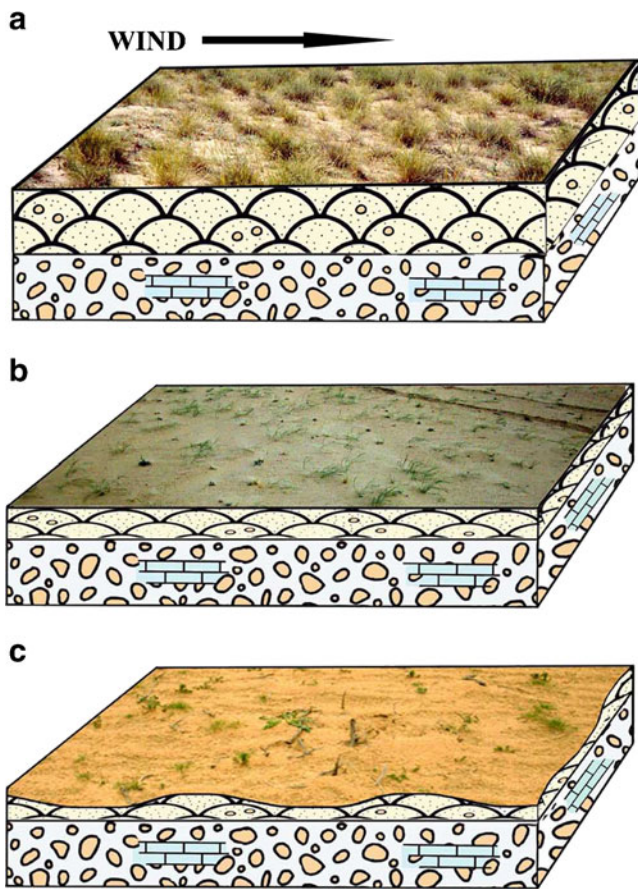


Fig. 22 a–c Block diagrams which are connected with field photographs showing changes in the lithologic units during different periods of time. **a** Rugged vegetated sand sheet (RVSS) during the 1980s. **b** Deteriorated RVSS and development of sand sheet with granule ripples recently. **c** Smooth sand sheet

Comparing the density of the vegetation cover (essentially the perennial desert shrubs), during the early 1980s and recently, reveals the severe degradation to which the landscape was subjected. Khalaf et. al. (1984) prepared a sedimentomorphologic map of Kuwait in the early 1980s, which indicated that most of the western and southern parts of Kuwait were covered by rugged vegetated sand sheets (RVSS), which were developed due to the coalescence of nabkhas. Such areas were distinguished due to their dense to moderate vegetation cover. In the present time, these RVSS are no longer evident and living desert shrubs (*H. salicornicum*) are rarely seen. The RVSS are replaced by smooth sand sheets mostly covered by granule lag (Fig 22a–c). The dense shrubs stabilizing the RVSS were desirated and died, and their remnants worked as barriers marking the original occurrence of preexisting nabkhas which were then eroded, and the bedrock was exposed (Fig. 22a–c).

Nabkhas that existed during the early 1980s were extensively eroded in the last 30 years, as the sand mounds forming them were deflated and replaced by granule residuals, mostly in the form of granule ripples. Comparing the nabkhas in the protected areas and non-protected areas, it was found that in the non-protected areas camel grazing is an extensive activity, where several permanent camel enclosures exist in the area (Fig. 6). Camels grazing in the non-protected areas is taking place irrationally, as the shepherds let the herds free to graze on the *Nitraria* shrubs during the day in considerably large numbers all feeding only on the *Nitraria* leaves. This dramatically affected the shrub’s canopy area coverage and consequently the size of nabkhas developed around them. Overgrazing by camels and sheep as well as grazing by goats which uproots plants and inhibiting the growth resulted in significant losses of plant cover;

Fig. 23 A photograph showing seasonal traditional spring campaigns in the non-protected areas, as it involves the clearance of the natural vegetation around the camps



and thus, it is thought to be a major cause of deterioration and disappearance of the RVSS.

Within Ras Al-Subiyah area, more intact *Haloxylon* stands were observed, as well as relatively dense vegetation cover in the demilitarized zone along the northern and northwestern border area between Kuwait and Iraq, where anthropogenic activities (grazing and recreational activities) are prohibited. These areas witness well-developed and flourishing *H. salicornicum* nabkhas.

The northern desert of Kuwait is mostly covered with residual gravels, which occur as a very wide blanket composed of a mixture of gravel, sand, silt, and clay which resulted from the deflation processes on the Dibdibba desert. Such a process caused the fine particles to be carried by wind leaving the coarser particles in the form of lag coarse pebbles, and boulders making a more resistant crust.

In the northwestern deserts, playa deposits used to be more abundant during the 1980s and more closely associated with drainage systems. They are proposed to be forming due to deflation processes, which resulted in the declining of the land surface that consequently filled with sediments driven by drainage. Recently, the majority of these playas are covered with aeolian sediments. Misak et. al. (2001) stated that Kuwait is suffering from prevailing drought conditions during the last two decades resulting in hypersalinity of groundwater, which in turn prohibits new growth of shrubs. Drought conditions decreased the soil moisture and humidity, and thus intensified the deflation processes in the area. As a result, fine sand particles were deflated easily as wind born particles towards the playa surfaces, where they were re-deposited.

Fig. 24 Photographs showing the off-road driving that is taking place on a daily basis, where the vehicle tracks are obvious on the sabkha surfaces, as well as on the nabkha mounds



The aggregation and accumulation of rain washed sediments of multi-sized grains in broad shallow depressions which resulted in the occurrence of desert plain deposits. Along Jal Az-Zor escarpment, the slope deposits were well developed and consist of boulders of calcareous grits with finer detritus as the alluvial fans which develop close to the slope deposits. Coastal deposits are subclassified into three types: coastal sand dune deposits, sabkha deposits, and beach and tidal flat deposits.

Conclusively, Kuwait's desert is mainly covered with aeolian sand deposits, which imply that wind had acted on the unconsolidated loose desert clastic deposits. The north-western and southern parts of Kuwait are suffering from severe land degradation. This is mainly due to the traditional anthropogenic activities (overgrazing, campaign, off-road vehicles traffic), military operations, in addition to the relevant significant role played by the aeolian processes, soil type, and climatic conditions. Overgrazing of the vegetation cover, particularly the *Nitraria* shrubs around which the major fields of nabkhas occur, by livestock of camels, sheep, and goats plays a significant role in vegetation cover deterioration and enhancement of aeolian processes in Kuwait (Fig. 6). Abundance of seasonal traditional spring campaigns in the non-protected areas, as it involves the clearance of the natural vegetation around the camps (Fig. 23), about 3,600 m² on average per camp (Misak et al. 2002). Off-road driving is taking place on a daily basis, where the vehicle tracks are obvious on the sabkha surfaces, as well as on the nabkha mounds (Fig. 24), and in association with the animal traffics, result in the severe disturbance in the surface sabkha sediments and the nabkha's sediment cover, which is devastating to sediment stability. The impacts of such anthropogenic activities along with the military activities effort in the same domain, illustrated earlier in this paper, are enhanced by the prevailing harsh climatic conditions such as drought, high temperature, high evaporation rates, high wind speed, and hypersalinity of groundwater (Khalaf and Al-Hashash 1983; Khalaf and Al-Ajmi 1993; Al-Awadhi and Misak 2001).

According to the distribution of the areas exhibiting deflation process effects and those exhibiting depositional effects, it was revealed that the northern desert of Kuwait is receiving excessive sand supply, but on the contrary, the southern desert of Kuwait is experiencing the opposite. The width of sabkha deposits increases in southern areas due to the rising sea level. The southern sabkhas of Kuwait extend to cover a very wide area around Al-Khiran tidal creeks and occupying an extensive, extremely flat area separated from the open sea by the Quaternary oolitic limestone coastal ridges and external landward for about 20 km (Khalaf and Al-Ajmi 1993). A vertical section in these sabkha deposits reveals an interbedding of mud layers and evaporite-rich sand bands which indicates that they are submerged by



Fig. 25 A photograph shows a vertical section in sabkha deposits, which reveals an interbedding of mud layers and evaporite-rich sand bands indicating that they are submerged by seawater

seawater (Khalaf and Al-Ajmi 1993; Al-Hurban 1996; Fig. 25). At present, a wide area of sabkha flat is partly covered by aeolian sand due to the migration of sand sheets over the sabkha flat, and the inter ridge of the sabkha flats is showing scattered sand drift features. The outward growth of the sabkha plains could be attributed to the extensive prolonged intertidal flat sedimentation during the periods of high sea level (transgression), as the sediment has partly originated in ancient protected lagoons to seaward and partly formed in place by chemical precipitation directly from sea water. The aeolian sediments from the surrounding desert area contributed majority of the sabkha deposits. Picha (1978) suggested that the Quaternary tectonics had a significant role in the area's physiographic and sedimentary developments, including formation of favorable conditions for accretion and preservation of oolitic sediment and sabkhas. It is worth mentioning that the recent surficial deposits map prepared by this study can be a good guide for the decision makers on the environmental aspect to take into consideration to conduct an environmental impact assessment before implementing any future developmental projects or plans (e.g., constructional and urban projects).

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