# Chapter 12
# Soil-Landform Relationships in the Arid Northern United Arab Emirates

**C.F. Pain, M.A. Abdelfattah, S.A. Shahid, and C. Ditzler**

**Abstract** The morphology and evolution of landforms, together with the materials of which they are composed, play a major role in the development and distribution of the soils in the northern United Arab Emirates, where landforms of aeolian origin in the west contrast with fluvial landforms in the east. These aeolian and fluvial landforms in turn contrast with a belt of coastal landforms along the Arabian Gulf and the Gulf of Oman. This chapter describes the landforms and soils of the Northern Emirates (NE), and shows how their form and evolution are closely related. At great group level (US Soil Taxonomy), the following soils were recognized: Torriorthents, Torripsamments, Haplocalcids, Haplocambids, Haplogypsids, Calcigypsids, Aquisalids, and Haplosalids. Twenty eight soil series were identified. Various combinations of these soil series were grouped into 42 map units, each consisting of two or more soil series and a number of minor soil types. At subgroup and family levels, these soils can be related to specific landform morphologies and processes.

**Keywords** United Arab Emirates • Aeolian soils • Alluvial soils • Arid soils • Soil-landform analysis

C.F. Pain (✉)
MED-Soil, Universidad de Sevilla, Sevilla, Spain
e-mail: colinpain@gmail.com

M.A. Abdelfattah
Faculty of Agriculture, Fayoum University, Fayoum, Egypt
e-mail: maa06@fayoum.edu.eg

S.A. Shahid
International Center for Biosaline Agriculture, Dubai, United Arab Emirates
e-mail: s.shahid@biosaline.org.ae

C. Ditzler
National Soil Survey Center, NRCS-USDA, Lincoln, NE, USA
e-mail: craig.ditzler@earthlink.net

 
J.A. Zinck et al. (eds.), *Geopedology*, DOI 10.1007/978-3-319-19159-1_12

## 12.1 Introduction

The development of landforms usually leads to the juxtaposition of different types of landforms and therefore different types of soils (Zinck 2013). This is a consequence of the influence of landforms on topography, soil parent material, and soil age. Geomorphology and geology, combined with time and climate, are the main factors that influence soil distribution. Understanding geomorphology is useful in understanding soil patterns. While the current arid climate suggests that wind erosion is the dominant factor shaping the geomorphology, this has not been always so, such as in wadis where water erosion has significant role in alluvial soil formation. At a detailed level there may be a close relationship between soil characteristics and position on a hillslope – the catena concept of Milne (1936). At a broader scale, different landform types will be formed of different materials, and be of different ages, and these factors will be reflected in the soil types present.

Soils in arid and semi-arid areas, especially those formed on depositional materials, tend to be very little modified from the original parent material (Dunkerley 2011). Nevertheless, some pedological alteration occurs. For example, dust falling on sand dunes contributes clay minerals to the material, and is found as thin clay coatings on sand grains. In other materials, especially in alluvium, calcium carbonate may form distinctive soil horizons where it cements the sediments. Near the coast, sea water intrusion introduces high salts in the soil leading to form marshlands and salt scalds locally called sabkha. The latter are devoid of any vegetation due to high salinity and near-surface water table of brine composition (Abdelfattah and Shahid 2007). Loose sandy material subject to aeolian movement creates various landforms: undulating, linear, transverse, and barchan sand dunes of different heights to over 200 m, as well as deflation plains. A number of dune formation periods probably occurred in the last 20,000–30,000 years, and older dunes now contain cores of sandstone. These aeolian processes of recent millennia have dominated the evolution of today's landscape. These and other processes tend to be controlled by materials that in turn are controlled by landforms.

The latter situation is the subject of this chapter, which introduces the Entisols and Aridisols that form the soils of the study area. It focuses on the landforms and soils of the Northern Emirates (NE), and describes the relationships between the two. It is based on data obtained during a soil survey of the area (EAD 2012).

## 12.2 Area and Methods

### *12.2.1 Regional Setting*

The United Arab Emirates (UAE) is a federation of seven emirates in the south-east part of the Arabian Peninsula and adjacent to the Arabian Gulf (Fig. 12.1). It borders Oman and Saudi Arabia. The total area of the country is about 82,880 km$^2$. The NE

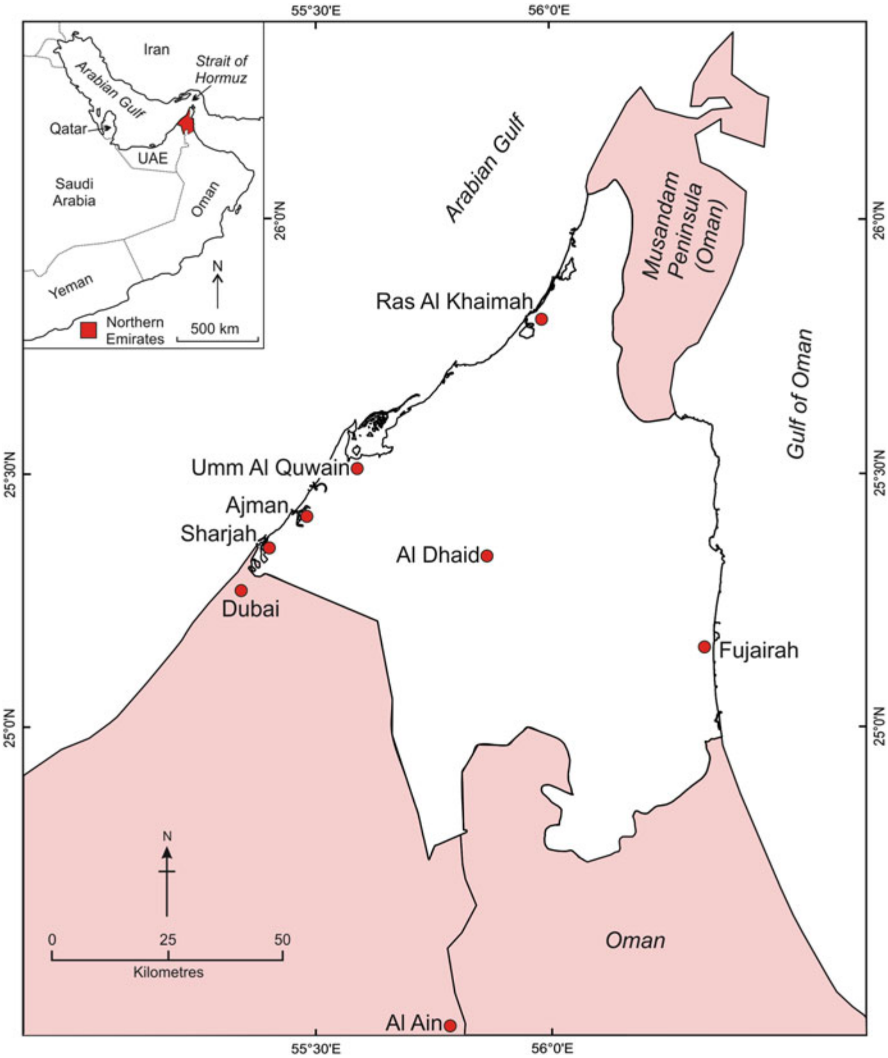


**Fig. 12.1** The Northern Emirates and their location in the regional context of the Arabian Peninsula

consists of Sharjah, Ajman, Umm Al Quwain, Ras Al Khaimah, and Fujaira Emirates, and covers 6475 $km^2$, about 8.2 % of the country's surface area. The landscape is described in EAD (2012) and Pain and Abdelfattah (2015). It ranges from small areas of level coastal plains and sabkha to undulating desert sand plains, extensive areas of linear and transverse dunes, an alluvial plain up to 15 km wide, and mountainous rock outcrops along the Hajar Mountains. In the western part of the NE, linear dunes rise up to 100 m above the surrounding landscape, interspersed with small areas of almost level deflation plains and flats (Abdelfattah 2013a, b).

The UAE is in the Arabian Desert and is one of the hottest countries in the world. It has an arid climate with harsh dry summers, when temperatures regularly exceed 50 °C, and mild to warm winters with very little sporadic rainfall (80–160 mm in the NE) (Abdelfattah and Shahid 2007; Shahid and Abdelfattah 2008). The soil climate temperature regime in the NE is hyperthermic. There is a marked excess of evaporation over rainfall.

The oldest rocks in the NE are in the Hajar Mountains, where there are Permian to Cretaceous metamorphic, ophiolite, and sedimentary rocks including limestone (Styles et al. 2006). Surficial geology is dominated by Quaternary sediments, with aeolian dunes in the west and alluvial sediments on both sides and within wadis in the Hajar Mountains. The current shoreline of the NE consists of coastal lagoons, tidal flats, and marshes. The dunes and other sandy surficial materials are nowhere more than a few 10–100 s meters thick and overlie alluvial gravel inland and coastal and marine deposits near the coast (Fig. 12.2).

### *12.2.2 Data Collection*

The study reported here was carried out during the Soil Survey of the NE (EAD 2012). Landforms were mapped from Google Earth images and a digital elevation model (DEM) derived from the Shuttle Radar Terrain Mission (SRTM), aided by reconnaissance fieldwork. Details of landform characteristics and materials were added during the soil survey, which involved detailed site and soil descriptions at 10,020 auger sites (2 m depth), 200 backhoe pits (2 m depth), and 150 drill observations (10 m depth). In sandy and silty materials augers and sand spears were used for routine observations, while in gravelly areas a Geoprobe corer was used (Geoprobe Systems, Kansas, USA http://geoprobe.com/). Soil and landscape descriptions were collected at every site and are available in the UAE Soil Information System at www.uaesis.ae (Abdelfattah and Kumar 2015). This information was used to compile final landform and soil maps.

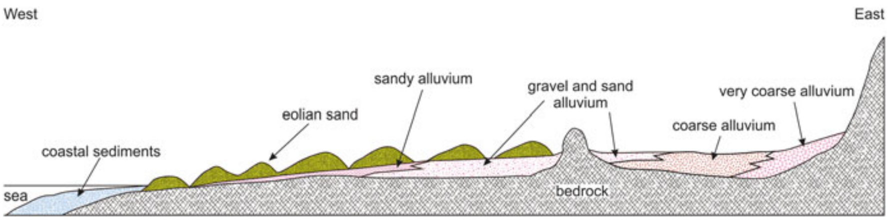


**Fig. 12.2** Schematic cross section showing the main geological and geomorphic materials between the Hajar Mountains on the east and the coast on the west (not to scale)

## 12.3 Soils of the Study Area

### *12.3.1 Taxonomic Units*

Twenty-eight soil series and one miscellaneous area (rock outcrop) were established according to the Soil Survey Manual (Soil Survey Staff 1993). They were allocated as components of 42 soil map units that make up the soil map of the Northern Emirates. The soil series are members of 2 soil orders, 6 suborders, 8 great groups, 13 subgroups, and 21 families as defined by the USDA Soil Taxonomy (Soil Survey Staff 1999). In addition to the Al Ain soil series, first identified in Abu Dhabi Emirate (EAD 2009; Shahid et al. 2013), 27 soil series were identified and described for the first time in this soil survey area. The soil orders are Aridisols and Entisols. The Aridisols are further divided into Calcids, Cambids, Gypsids, and Salids. The Entisols are divided into Orthents and Psamments (EAD 2012; Abdelfattah and Pain 2012; Abdelfattah 2013b). Most of the soils are either sandy or gravelly, but there is an important set of soils (Cambids) that are formed on fine alluvium in the area around Ras Al Khaimah. The collection of soil subgroups identified is shown in Fig. 12.3. Their relationships to landforms and parent materials are in Table 12.1.

### *12.3.2 Map Units*

While the classification of soil profiles in the USDA soil classification is based on logical and hierarchical relationships between the different kinds of soils, map units reflect associations between soils in a landscape. A map unit will almost always include soil types that do not belong to the appropriate classification unit. These different soil types occur in areas that are too small to appear on the map; for example, soils on narrow floodplains in an area dominated by soils on aeolian sand dunes.

Soils were mapped at a scale of 1:50,000 (3rd order USDA level), with 42 map units being recognized. The name of a unit reflects the dominant soil or soils found within it, together with a general landscape characteristic that enables map units with similar soils to be separated on the basis of their landscape. Each unit typically consists of two or more soil series, or map unit components, together with a number of minor soil types. Each map unit description records the estimated proportion of each soil component and briefly summarizes the relationships between the components within that unit; the estimates were made from site observations, located between 500 and 1000 m apart. The individual map unit components consist of soil series described during the field survey.

Map unit descriptions were compiled on the basis of field observations of landscape patterns and an analysis of the soil and landscape classifications at sites within units described during the routine soil survey. The most common soil or soils were used to name the unit. Users of the information should be aware that each map unit will contain a wider range of soils than those described in the report, and individual

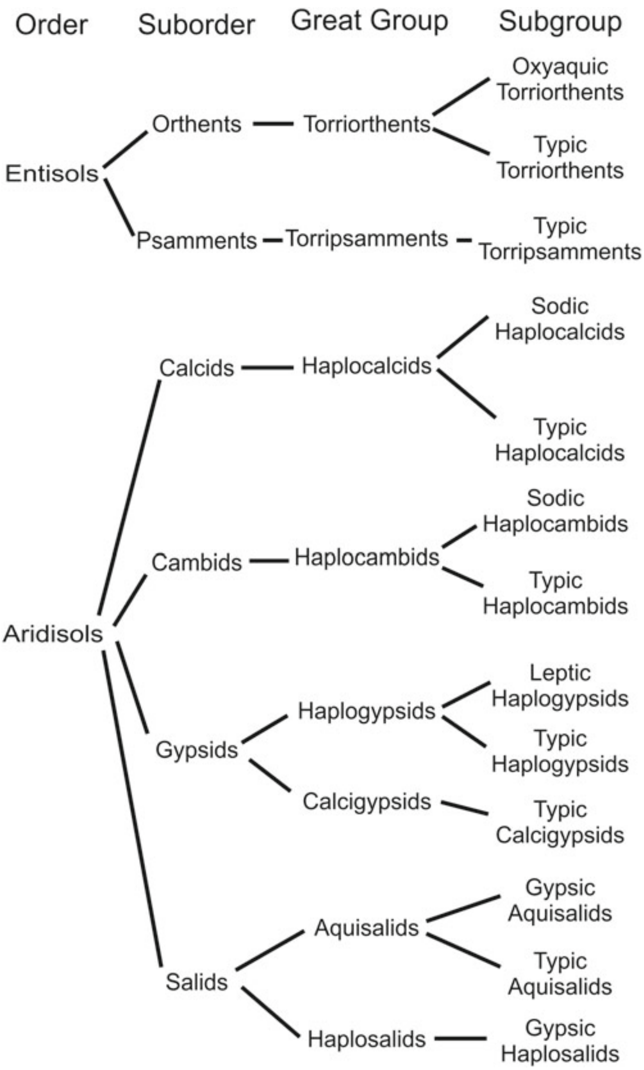


**Fig. 12.3** Soil taxa identified in the Northern Emirates

delineations of the same unit, while having similar named soils, are likely to have a slightly different composition of minor and unreported soils.

Map unit characteristics, and interpretations made for different land uses for a unit, refer to the entire distribution of that unit unless specifically mentioned otherwise. Relative proportions of the named soil series may vary between delineations of individual map units, and minor soils may occur in all or only some of the unit delineations. Thus, the map and the definitions provide users with a guide to what they are likely to find in any particular part of the NE.

**Table 12.1** Soil subgroups and their landforms and parent materials

| Subgroups | Landforms | Parent materials |
|---|---|---|
| Oxyaquic Torriorthents | Coastal landforms | Sandy marine deposits with a thin eolian sand mantle |
| Typic Torriorthents | Floodplain, terrace fan | Alluvium (loamy sand to gravel, cobbles, and stones) |
| Typic Torripsamments | Sand dunes, floodplains within dunes | Eolian sands, alluvial sands |
| Sodic Haplocalcids | Floodplain, terrace fan | Loamy and sandy alluvium |
| Typic Haplocalcids | Floodplain, terrace fan | Gravelly alluvium |
| Sodic Haplocambids | Floodplain, terrace fan | Loamy alluvium |
| Typic Haplocambids | Floodplain, terrace fan | Loamy alluvium |
| Leptic Haplogypsids | Floodplain, terrace fan | Loamy, sandy and gravelly alluvium containing gypsum |
| Typic Calcigypsids | Floodplain, terrace fan | Loamy and gravelly alluvium containing gypsum as well as secondary calcium carbonate |
| Gypsic Aquisalids | Coastal landforms | Sandy, or sandy and loamy, marine deposits |
| Typic Aquisalids | Coastal landforms | Marine deposits over a lithified dune |
| Gypsic Haplosalids | Coastal landforms | Sandy, or sandy and loamy, marine deposits |

## 12.4 Soil Forming Factors

The following sections describe the soil-forming factors that are related to geomorphology, in the context of the NE, and the processes that have contributed to the soil landscapes present today.

### *12.4.1 Parent Material*

The nature of the parent material has a significant impact on the texture, mineralogy, and chemistry of the soils. Within the NE, parent material can be divided into three categories: aeolian sand, marine deposits in low-lying coastal areas, and alluvium derived from the various rock types of the Hajar Mountains. Each of these parent materials produces different soils depending on landscape position, climatic conditions, influence of plants and animals, and the amount of time these factors have had to alter the parent material.

#### 12.4.1.1 Aeolian Sand

Pleistocene and Holocene aeolian sands occur throughout the western half of the NE in dunes and sand sheets. They consist of local coastal deposits, windblown sediments blown in from more distant areas, and older sediments derived from the then-exposed floor of the Arabian Gulf during drier glacial periods with lower sea levels. The aeolian sands of the NE are high in calcium carbonate equivalents (20 – >40 % by weight). The highest calcium carbonate contents are in the northern coastal areas, with a progressively higher proportion of silica sands and iron-oxides towards the mountains (White et al. 2001), giving the sands further inland a progressively redder color. Coastal areas are also influenced by additional windblown minerals, such as salt and gypsum, and often have an admixture of sea-shell pieces with the sand grains. The surface layers of the aeolian deposits are continuously being reworked, eroded, and re-deposited, and there is little opportunity for weathering and soil formation processes to occur, so horizons are only weakly developed. The Ajman Series (Typic Torriorthents) has formed in aeolian sands in a narrow band along the western coastal areas, while the slightly redder and coarser Sharjah Series (Typic Torripsamments) dominates the aeolian sands further inland (Fig. 12.4a).

#### 12.4.1.2 Marine Deposits

On the coastal sabkha flats, the parent material consists mostly of recent sedimentary deposits of marine origin. Soil formation has been strongly influenced by the presence of near-surface saline groundwater and the accumulation of halite (sodium chloride salt), gypsum, and other soluble minerals that are moved upward through the soil profile by evaporation and then accumulate in the upper part of the profile. The Umm Al Quwain Series (Gypsic Aquisalids) is an example of a soil that formed in the coastal marine deposits parent material (Fig. 12.4b).

#### 12.4.1.3 Alluvium

The level to gently undulating plains extending away from the Hajar Mountains are alluvial in origin, as evidenced by their stratified nature and inclusion of water-rounded pebbles. The size and amount of the pebbles are highest near the mountains (Fig. 12.4c) and decrease with distance from the mountains (Fig. 12.4d, e).

The coarsest soils formed in the gravelly and cobbly parent materials in the wadis within the mountain valleys (e.g. Bih Series – Typic Torriorthents). The plains between the mountain foothills and the edge of the aeolian sand dunes to the west also tend to be gravelly, but with fewer cobbles and smaller pebbles than in the mountain wadis (e.g. Al Dhaid Series – Typic Haplocalcids). Further east, the alluvial plain parent materials have been mostly covered by the younger aeolian sands of the dunes. In inter-dunal flats, the alluvial deposits are predominantly sandy with only a few pebbles mixed in, due to their greater distance from their mountain source.

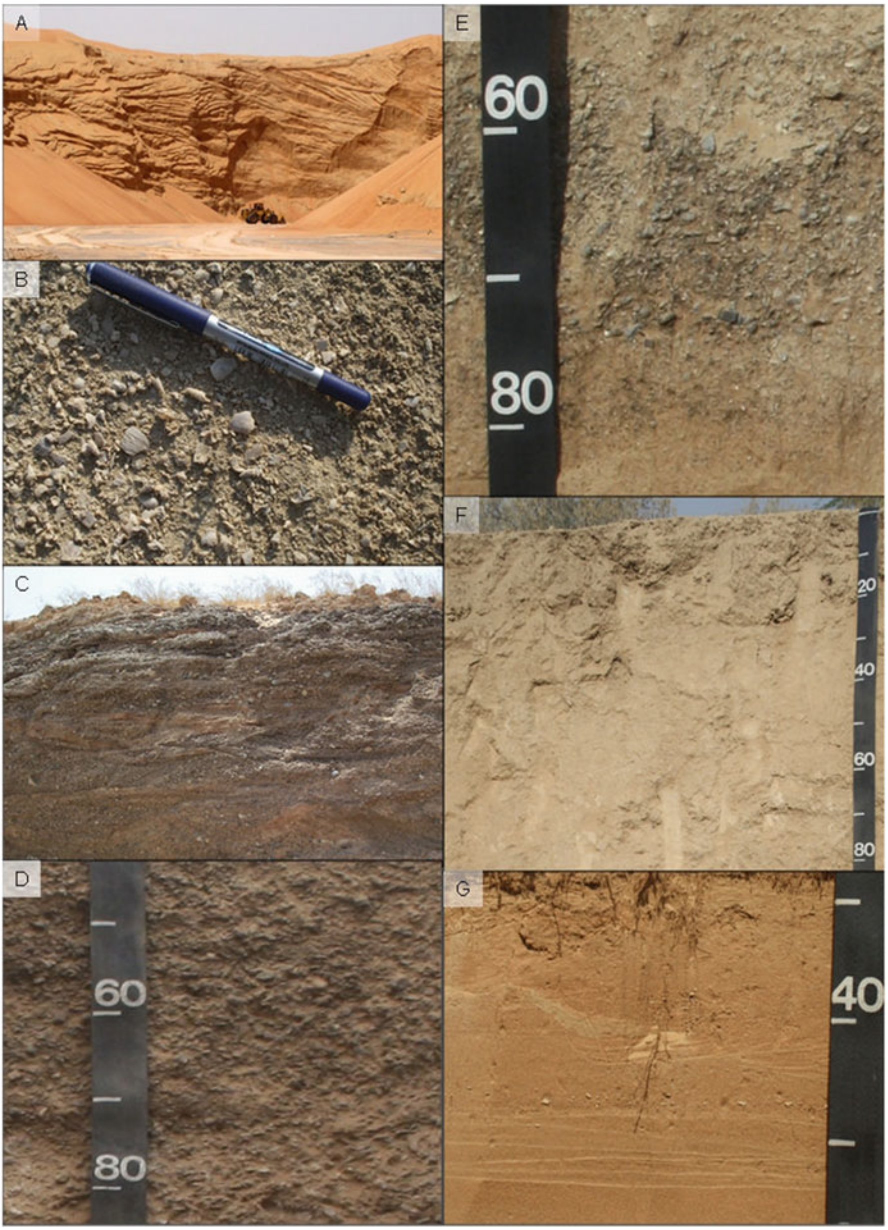


**Fig. 12.4** Examples of different parent materials in the NE. (**a**) thick aeolian sands of the Sharjah series (NE011); (**b**) marine deposits with shell fragments; (**c–e**) gravel deposits of the alluvial plains, getting finer with distance from the mountains; (**f**) fine-textured alluvium of the Ras Al Khaimah series (NE019); (**g**) fine alluvium in a wadi deposit

In the northern parts of the area, loamy alluvial sediments have been deposited in distal alluvial fans following transport from mountains upslope. These are some of the finest-textured parent materials in the NE (Fig. 12.4f) (e.g. Ras Al Khaimah Series – Typic Haplocambids). The present-day wadis extending away from the mountains and out into the desert are composed of thick, stratified, predominantly sandy parent materials of relatively recent alluvial origin. They are believed to be subject to rare flood events today (e.g. As Sirer Series – Typic Torriorthents) (Fig. 12.4g).

### *12.4.2 Climate*

In the geopedologic context, climate contributes to soil formation in the NE mainly through its influence on vegetation, and by wind. The low vegetation density means that wind has direct access to the soil surface. Calcium carbonate tends to be present in dust that falls on the soils, and the limited precipitation has the effect of moving it downward with the wetting front, where it eventually precipitates in the soil, forming calcic and gypsic horizons (e.g. Al Kabkub Series – Typic Haplocalcids). In areas where a water table is present within 200 cm, dissolved minerals, such as sodium chloride salts and gypsum, are moved upward in the profile through evaporation. They accumulate in the soil to form gypsic and salic horizons. The Hisan Series (Gypsic Haplosalids) is an example of a soil with both a gypsic and a salic horizon formed in this way.

Sands from the soil surface at one location are blown off and deposited elsewhere. The result is minimal soil development due to the rapid loss or gain of soil material. On the gravely alluvial plains, wind removes the fine soil particles over time and leaves the heavier gravel behind, forming a pavement protecting the soil from further wind erosion (Fig. 12.5a).

### *12.4.3 Relief*

Relief and topography affect soil development primarily be regulating the movement of water into and through the soil, and also by influencing the amount and intensity of sunlight that warms the soil. Convex landscape positions tend to shed water and limit infiltration, while concave positions tend to concentrate water flow and increase the potential for water infiltration. However, with the very low precipitation in the NE, these effects are limited. Slope steepness and aspect determine the amount and intensity of sunlight that hits the soil surface. South- and west-facing slopes tend to be warmer and drier than north- and east-facing slopes.


**Fig. 12.5** (**a**) desert pavement after deflation, the removal of sand by wind; (**b**) salt crust near Umm Al Quwain

### *12.4.4 Time*

Older soils tend to have more highly developed horizons relative to younger soils in similar environments. Soils in warm, arid environments, such as the NE, tend to develop horizons slowly compared to soils in other environments. Within the NE, the movement of windblown sands has not allowed any significant horizon development to occur in soils on the dunes and sand sheets, and these soils are the youngest and least developed in the area. More stable, older soils on the alluvial plains, especially those formed in loamy parent material, show more pronounced profile development, such as structure development, accumulations of salts, gypsum, and carbonates, and differences in the color of horizons.

## 12.5 Soil Forming Processes

Soil formation is the result of complex interactions of physical, chemical, and biological processes that occur in the soil over time. Despite their complexity, these processes can be generalized into the four categories of additions, removals, transfers, and transformations (Simonson 1959). These are all related to a greater or lesser extent to geomorphology. Examples of additions include the deposition of sand and calcium carbonate-rich dust by wind and the accumulation of fine sediments on the surface of the soil as a result of periodic flooding and ponding in wadis. Processes of removal include the deflation of some soil surfaces through the action of wind, which removes the finer sand particles. This removal results in the concentration of gravel on the soil surface and the formation of a desert pavement. In the arid conditions of the NE, removal of soil materials from the soil profile by leaching of water is uncommon and is generally restricted to areas under irrigation. Transfer of materials in the soil can be seen through the dissolution of calcium carbonate (decalcification) and/or gypsum in the surface layer of the profile and their downward movement with the wetting front and eventual precipitation and accumulation below in a calcic (calcification) or gypsic horizon (gypsification). Additionally, transfer of materials in the soil is evidenced by the upward movement of saline water driven by evaporation as moisture from a subsurface water table is drawn upward and salts accumulate in the upper part of the profile. Transformation of soil constituents is evidenced by the release of minerals to the soil as rock fragments slowly weather in place. Also, in the soils of the coastal sabkha that have water tables, iron has been chemically reduced and then oxidized to form reddish-colored iron-accumulations in the soils.

### *12.5.1 Salinization*

Salinization is the process responsible for the accumulation of soluble salts in the soil profile. In the NE, it occurs due to the upward movement of solutes from an underlying water table as water evaporates at the soil surface, and water rises because of capillary suction. Accumulating salts result in the formation of a salic horizon. This is a major process in soils of the coastal sabkha flats. In cases where salinization is extreme, a salt crust a few centimeters thick covers the soil surface. A polygonal pattern of soil cracking may develop in the crust as the salt crystals grow and expand, causing surface heaving of a few centimeters in height (Fig. 12.5b).

### *12.5.2 Calcification and Gypsification*

The processes responsible for the accumulation of calcium carbonate and/or gypsum in the soil are referred to as calcification and gypsification. Both calcium carbonate and gypsum are soluble in water and can therefore be relatively easily dissolved, moved, and then re-precipitated within the soil (Fig. 12.6a). This most commonly occurs on landforms such as floodplains and terraces.

## 12.5.3 Aeolian Movement of Sand

Wind-blown sands blanket much of the landscape in the form of dunes and sand sheets. Some soils, such as the Al Madam Series (Typic Calcigypsids), are formed mostly in alluvial deposits, but have a cover of recently deposited aeolian sand a few tens of centimeters thick. Other soils, such as the Sharjah Series (Typic Torripsamments), are in areas of thick sand deposits on dunes and sand sheets and are formed entirely in aeolian sands (Fig. 12.6b). Still others, such as the Al Dhaid Series (Typic Haplocalcids), have had sand blown away from the surface, leaving a concentration of gravel armoring the surface and protecting it from further erosion by wind.

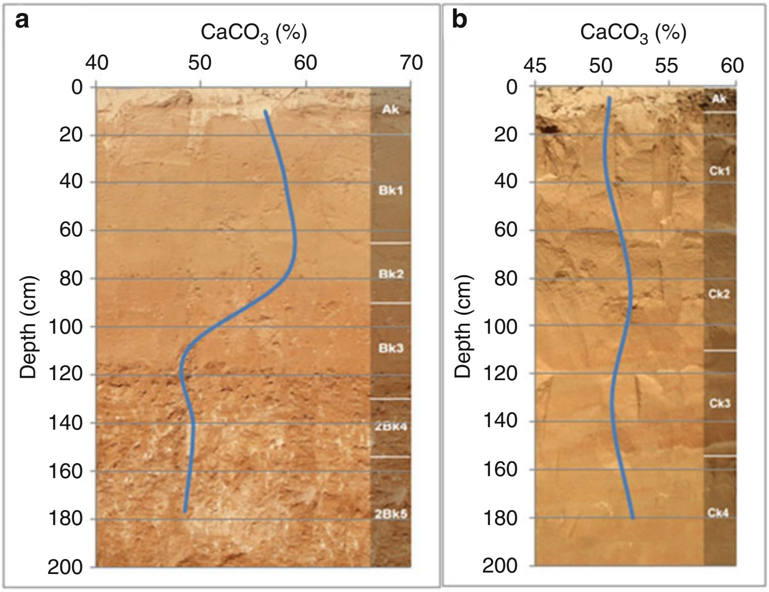


**Fig. 12.6** (**a**) soil example (Al Kihef series, Typic Haplocalcids) with carbonate concentrating in the B horizon; (**b**) soil example formed on aeolian sand (Sharjah series, Typic Torripsamments) with minimal change in carbonate content with depth, reflecting little pedogenic alteration

## 12.6 Conclusions

Different landforms in the NE have different soil classes because of the influence of pedogenic processes such as salinization, decalcification and calcification, and gypsification. Although the rainfall is scanty in the desert environment, the recognition of calcic and gypsic horizons clearly demonstrates the operation of soil forming processes over a period of time. Coastal landscapes are dominated by Salids, the sand dunes and sand sheets by Psamments, and alluvial plains by Orthents and Calcids. The map units are based largely on combinations of different soil series that occur in specific geomorphic environments.

These conclusions demonstrate that a geopedology approach is just as important in arid and semiarid environments as it is in environments where soils are more strongly developed. The approach used here can be used in other arid areas where there is as yet a lack of detailed soil information. Such an approach is also important for land use planning because it provides a convenient and efficient way of obtaining soil and landform information.

## References

Abdelfattah MA (2013a) Pedogenesis, land management and soil classification in hyper-arid environments: results and implications from a case study in the United Arab Emirates. Soil Use and Manage 29:279–294. doi:10.1111/sum.12031

Abdelfattah MA (2013b) Integrated suitability assessment: a way forward for land use planning and sustainable development in Abu Dhabi, United Arab Emirates. Arid Land Res Manage 27:41–64

Abdelfattah MA, Kumar AT (2015) A web based GIS enabled soil information system for the United Arab Emirates and its applicability in agricultural land use planning. Arab J Geosci 8:1813–1827. doi:10.1007/s12517-014-1289-y

Abdelfattah MA, Pain C (2012) Unifying regional soil maps at different scales to generate a national soil map for the United Arab Emirates applying digital soil mapping techniques. J Maps 8(4):392–405. doi:10.1080/17445647.2012.746744

Abdelfattah MA, Shahid SA (2007) A comparative characterization and classification of soils in Abu Dhabi coastal area in relation to arid and semi-arid conditions using USDA and FAO soil classification systems. Arid Land Res Manage 21:245–271. Available online: http://soils.usda.gov/technical/classification/taxonomy/. Last accessed 1 May 2015

Dunkerley DL (2011) Desert soils. In: Thomas DSG (ed) Arid zone geomorphology: process, form and change in drylands, 3rd edn. Wiley, New York, pp 101–129

EAD (2009) Soil survey of Abu Dhabi Emirate – extensive survey, vol 1. Environment Agency, Abu Dhabi

EAD (2012) Soil survey of the Northern Emirates. Three vol including soil maps. Environment Agency, Abu Dhabi

Milne G (1936) A provisional soil map of East Africa. East African Agriculture Research Station Amani Memoirs, Tanganyika Territory

Pain CF, Abdelfattah MA (2015) Landform evolution in the arid northern United Arab Emirates: impacts of tectonics, sea level changes and climate. Catena 134:14–29. doi:10.1016/j.catena.2014.09.011

Shahid SA, Abdelfattah MA (2008) Soils of Abu Dhabi Emirate. In: Perry RJ (ed) Terrestrial environment of Abu Dhabi Emirate. Environment Agency, Abu Dhabi, pp 71–91

Shahid SA, Abdelfattah MA, Othman Y, Kumar A, Taha FK, Kelley JA, Wilson MA (2013) Innovative thinking for sustainable use of terrestrial resources in Abu Dhabi Emirate through scientific soil inventory and policy development. In: Shahid SA, Taha FK, Abdelfattah MA (eds) Developments in soil classification, land use planning and policy implications: innovative thinking of soil inventory for land use planning and management of land resources. Springer, Berlin, pp 3–49

Simonson RW (1959) Outline of a generalized theory of soil genesis. Soil Sci Soc Am Proc 23:152–156

Soil Survey Staff (1993) Soil survey manual. Soil conservation service. US Department of Agriculture handbook 18. USDA National Soil Survey Centre, Lincoln, Nebraska

Soil Survey Staff (1999) Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys, 2nd edn. US Department of Agriculture, Natural Resources Conservation Service. USDA handbook 436. USDA National Soil Survey Centre, Lincoln, Nebraska

Styles MT, Ellison RA, Arkley SLB, Crowley Q, Farrant A, Goodenough KM, McKervey JA, Pharaoh TC, Phillips ER, Schofield D, and Thomas RJ (2006) The geology and geophysics of the United Arab Emirates, vol 2: geology. British Geological Survey, Keyworth, Nottingham, and Ministry of Energy, UAE

White K, Goudie A, Parker A, Al-Farraj A (2001) Mapping the geochemistry of the northern Rub' Al Khali using multispectral remote sensing techniques. Earth Surf Proc Land 26:735–748

Zinck JA (2013) Geopedology. Elements of geomorphology for soil and geohazard studies, Special lecture notes series. ITC, Enschede