GEOLOGICAL OVERVIEW

In addition to its well-known oil and gas reserves, the UAE is endowed with a number of other significant and unusual geologic features and environments that are both well exposed and readily accessible. This chapter reviews the overall geological history of the UAE and then examines in more detail the geology of the present-day sand deserts, the sabkhas and the Hajar Mountains.

A GEOLOGICAL HISTORY

Geologically, the UAE occupies a corner of the Arabian Platform, a body of continental rock that has remained relatively stable since the Cambrian Period more than 500 million years ago (Fig. 1). The Arabian Platform encompasses not only present-day Arabia but also the shallow Arabian Gulf (which is not a true ocean basin) and the rocks of the Zagros Mountains of Iran. In addition, for most of its history the Arabian Platform has been part of the larger Afro-Arabian continent, and the two have behaved as a unit in response to plate tectonic movements (Fig. 2). Only 25–30 million years ago, with the initial opening of the Red Sea, did Arabia begin to separate from the African plate.

The Precambrian history of the UAE is somewhat speculative. Precambrian rocks do not outcrop in the UAE, nor are they known from drilling information, but exposures of Precambrian sedimentary rocks in neighbouring Saudi Arabia and the Sultanate of Oman indicate that this region participated in the late Precambrian glaciations that are known from geologic evidence in many disparate parts of the present-day globe.

Figure 2: *The Afro-Arabian plate, highlighting the UAE*

Since the middle Cambrian Period, not long after the first appearance of abundant fossilisable life forms, the area that now constitutes the UAE has been generally at or near the edge of the Afro-Arabian continent, often covered by a shallow sea. Early Cambrian sediments on both sides of the Arabian Gulf, including thick accumulations of salt, suggest that the region may have been at that time the site of early-stage rifting of a larger continent to form a new ocean basin. This interpretation would account for the UAE's subsequent position at the continental margin.

Movements of the Afro-Arabian plate during the Palaeozoic caused Arabia to pass near the South Pole in the Ordovician Period, and the UAE may have become glaciated along with most of North Africa. By the mid-Palaeozoic the Afro-Arabian continent was itself part of the larger southern supercontinent of Gondwana, which began to break up in the Permian and Triassic. Since the end of the Palaeozoic, the UAE has remained in tropical or subtropical latitudes.

Despite its travels, the UAE appears to have remained tectonically relatively stable. The exception is the creation of the Hajar Mountains along its eastern margin, discussed separately below. The geological history of the country as a whole has therefore been primarily a history of the advance and retreat of the sea in response to global, rather than local, tectonic and climatic fluctuations.

THE OIL AND GAS RESERVOIRS

Over time, sediments accumulated on the continental shelf that was to become the UAE. Isolated pre-Permian exposures in the UAE reveal shallow-water terrigenous sediments (sandstones and shales). These were probably relatively thin overall and may have been largely removed by intermittent emergence and erosion. Later, in the tropical Mesozoic seas, thick sequences of carbonate rocks

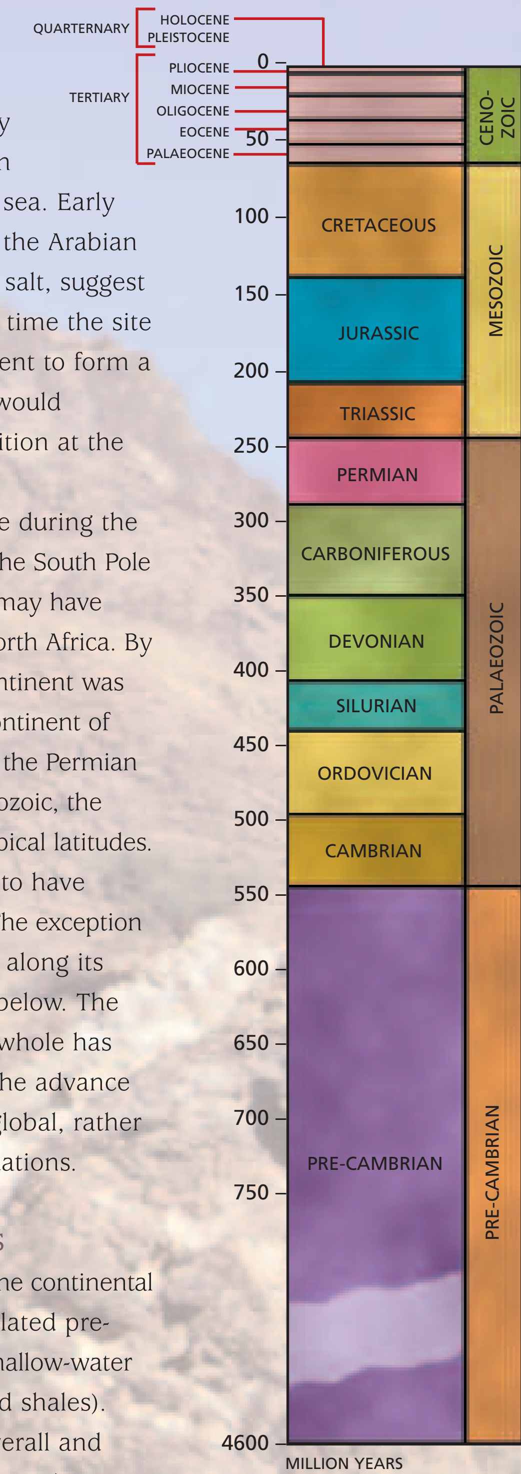


Figure 1: *The geological timescale*

Burrow casts and the enigmatic fossil Cruziana (at lower left)*, believed to be trilobite tracks, from the scarce Palaeozoic rocks of the UAE.*

– limestones ($CaCO_3$) and dolomites ($CaMg(CO_3)_2$) — were deposited. The late Permian and Mesozoic seas of the UAE were part of a major ocean that existed to the north of Arabia during that time, separating the Afro-Arabian continent from the Eurasian continent. This palaeo-ocean, known to geologists as Tethys, at one time extended westwards through the present-day Mediterranean countries and eastwards to the Himalayas (Fig. 3).

Fossiliferous limestones and dolomites of late Permian to late Cretaceous age (*ca*. 260 to *ca*. 65 million years ago) are the rocks in which the UAE's abundant hydrocarbon reserves are typically found. Some of these rocks represent depositional environments much like today's Arabian Gulf shores, but they are now buried at depths of 2,500 metres to 8,000 metres. The lower part of the Mesozoic sequence, in particular, includes many sabkha deposits indicative of a restricted shallow-water environment.

The source of the oil and gas itself was probably abundant organic material deposited in these same sediments – the remains of algae and other micro-organisms that flourished in the warm tropical seas. As they were buried deeper and deeper, insoluble organic residues were broken down by heat to form crude oil and natural gas. The fluid and relatively buoyant oil and gas then migrated upwards as the sediments were compacted, using porous rock units and fractures as pathways, until they were trapped by an impermeable layer or structural barrier.

It is ironic that these enormously important hydrocarbon reservoir rocks are almost nowhere exposed at the surface within the UAE. Apart from the rocks of the Hajar Mountains, however, there is little surface outcrop of any kind throughout eastern Arabia, and most of what is known in detail of the geological history of the Arabian Platform in this area comes from drilling and seismic information. Two persistent regional structural features recognised by petroleum geologists are a major ridge running north-east to south-west through the Qatar Peninsula and a parallel and adjacent major trough running through western Abu Dhabi and

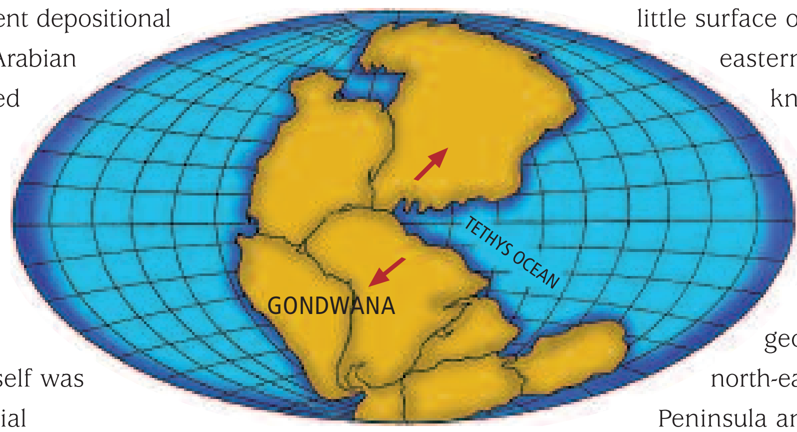


Figure 3: *The Tethys Ocean in the late Permian*

LEFT: *The author on a trail in the northernmost Hajar Mountains, called the Ru'us al-Jibal, where the thick carbonate sediments of the Tethys Ocean are well-exposed.*
RIGHT: *The mountains of Ru'us al-Jibal drop steeply to the sea.*

into the Empty Quarter. Subsurface structures may be very gentle, but gradients of as little as 2 per cent can be sufficient to permit migration and entrapment of crude oil.

Shallow-water sedimentation continued through the early Tertiary over most of the UAE, but regional uplift began in the late Oligocene (*ca*. 30 million years ago). Subsequent early Miocene sediments consist of salt and gypsum, and the area has been above sea level since the end of the Miocene (*ca*. 5 million years ago). In the west of Abu Dhabi, exposures of terrestrial deposits and vertebrate fossils of late Miocene age (*ca*. 6–8 million years ago) indicate an environment of riverine savannah at that time (as discussed by Whybrow *et al*. in the chapter *The Fossil Record*).

The sea also retreated briefly at various times throughout the earlier Mesozoic and Tertiary depositional history, intermittently exposing areas of low relief as at present. This is shown by occasional gaps in the sedimentary record and by sedimentary features indicating surface erosion, such as the development of palaeo-soils. One such example is a regional hiatus in marine sedimentation which occurs at the Cretaceous–Tertiary boundary.

Since the mid-Cretaceous (*ca*. 100 million years ago), local topographic highs (and major structural traps for petroleum) have been created by salt domes rising from the thick Cambrian salt deposits that underlie many areas of the southern Arabian Gulf at depths of some 10,000 metres. Today these salt domes form several of the UAE's offshore islands, including Sir Bani Yas, Das, Arzanah, Zirku and Sir Abu Nu'air, and the coastal hills of Jebel Dhanna. Jebel Ali, on the coast of Dubai Emirate, may be related to the mobilisation of later, Miocene, salt deposits.

The salt domes pierce and disrupt the successive overlying strata, bringing up fragments of rock units not otherwise exposed to view, although the salt itself is normally dissolved before reaching the surface. On Sir Bani Yas Island, the most well-developed salt dome in the UAE, the rising salt plug has pushed up hills to almost 150 metres high. These are littered with a medley of colourful shales, lavas and, most strikingly, specular haematite, a variety of iron oxide (Fe_2O_3), whose fine, platy crystals form a glittering carpet along narrow gulleys. Sulphur is often concentrated above salt domes by chemical processes, probably from associated gypsum ($CaSO_4$-$2H_2O$), and sulphur was mined at Jebel Dhanna, probably *ca*. the seventeenth to nineteenth centuries.

MOUNTAIN BUILDING

The exception to this generally placid but productive history lies in the Hajar Mountains in the north-east of the country and along the border with the Sultanate of Oman. There, earth movements driven by plate tectonics – and therefore ultimately by convection within the earth's mantle – caused the crust and upper mantle of the

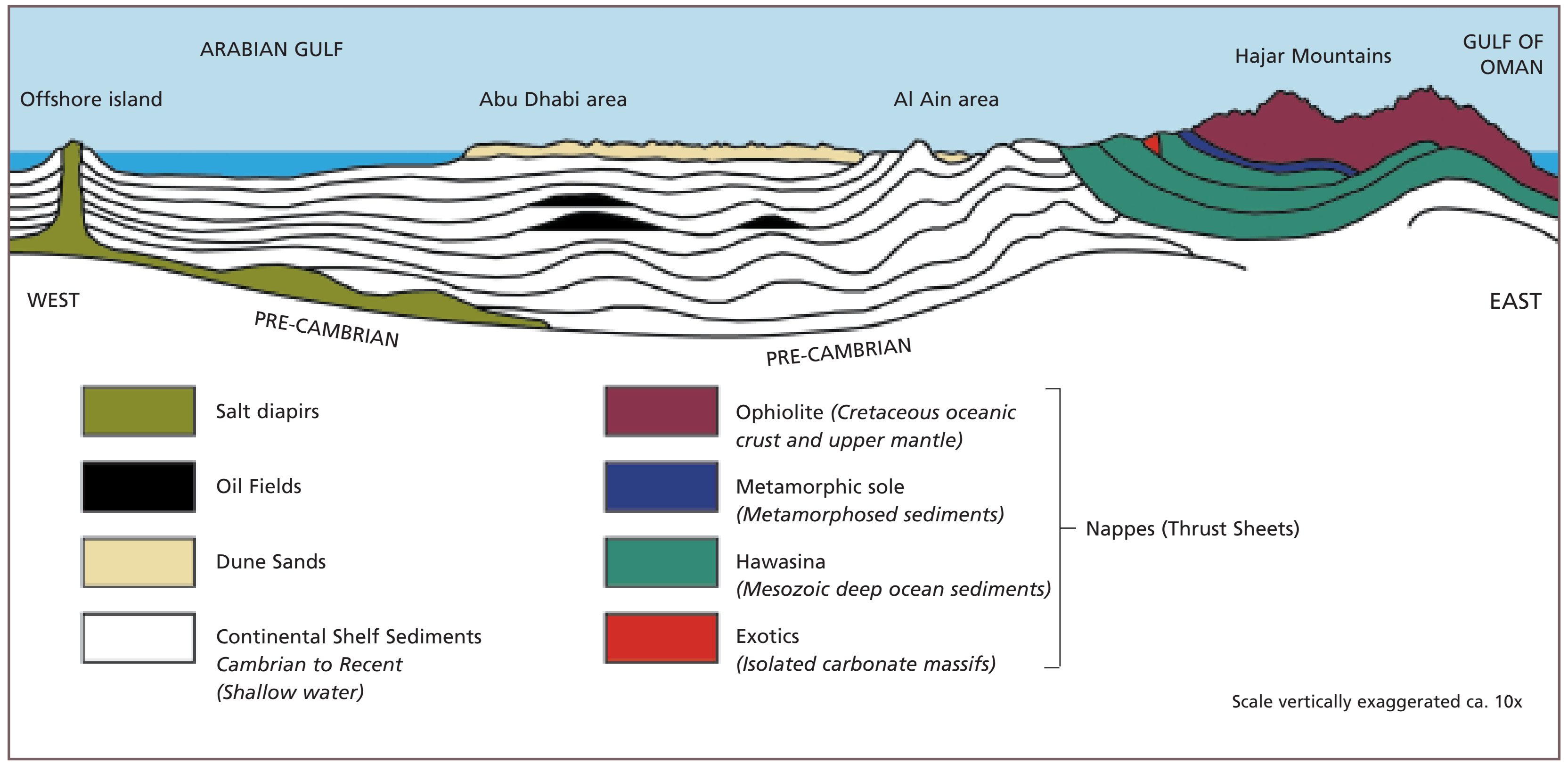
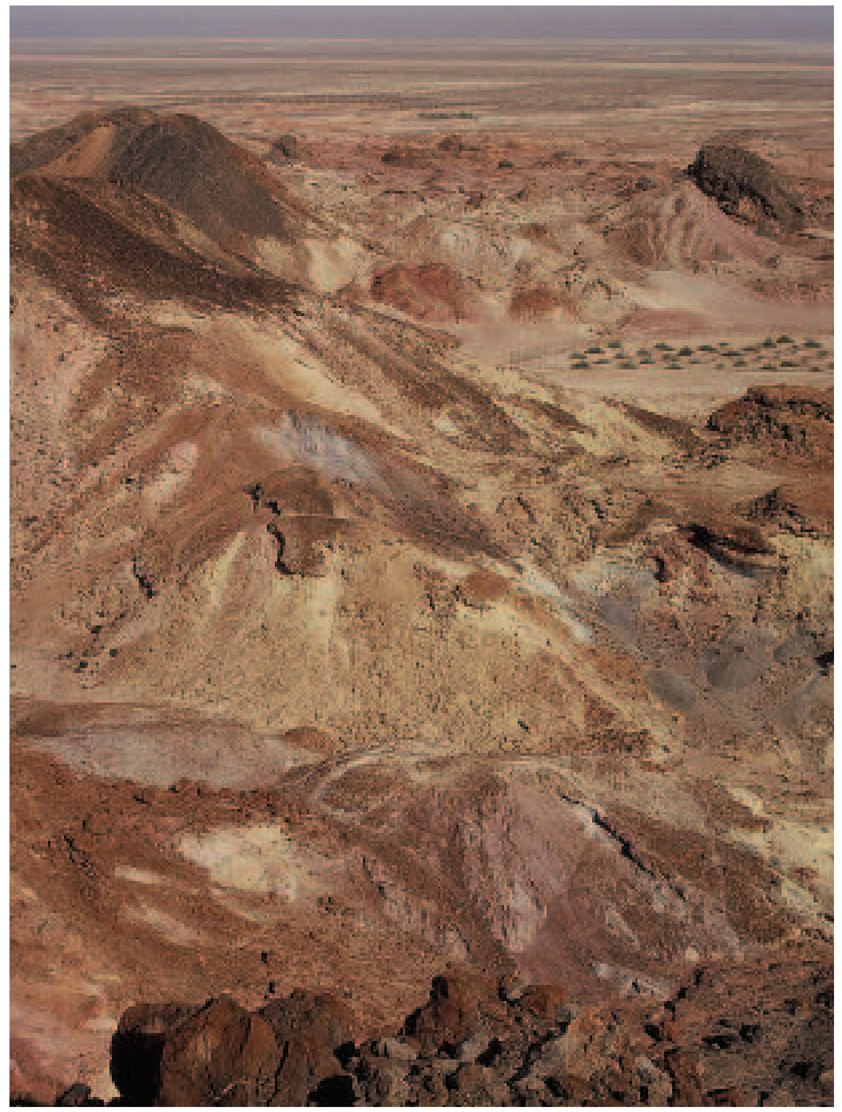


Figure 4: *Geological cross-section of the UAE*

below left: *The sediments found in the Ru'us al-Jibal correlate with the oil-bearing strata buried thousands of metres beneath the surface in the western UAE.*
below right: *The purple-brown patina known as 'rock varnish' covers ancient gravel plains. It is now known to be caused by manganese-fixing bacteria.*

top: *The wadis at the tip of the Musandam Peninsula have been flooded through a combination of tectonic subsidence and post-glacial rise in global sea level.*
below: *The salt dome at Sir Bani Yas has carried up fragments of a medley of rock units not otherwise seen at the surface.*



deep ocean, then lying to the north-east, to be forced over the edge of the Arabian Platform and its cover of shallow-water sediments. This process created a structure of massive superimposed sheets (*nappes*) of diverse rock types that now appear to have been shuffled, like cards, on a grand scale (Fig. 4). The result was fortuitous for geologists, since the Hajar Mountains today constitute the world's finest and most extensive surface exposure of rocks of the oceanic crust and upper mantle.

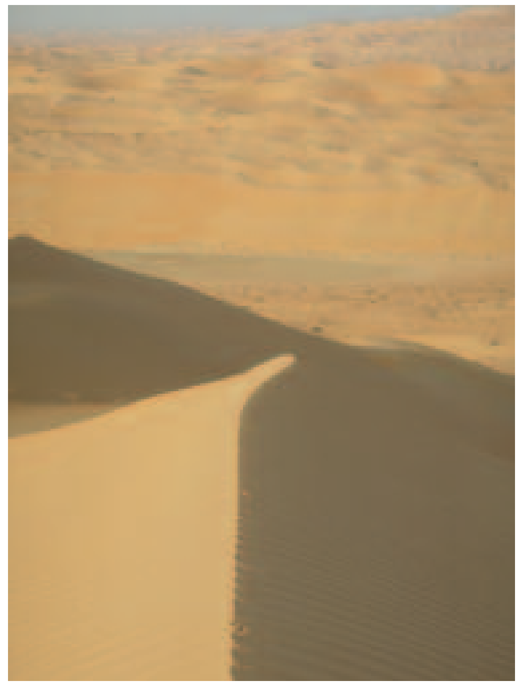
These nappes were emplaced during the late Cretaceous, from about 90–75 million years ago. In the process, the area was raised above the sea, creating a chain of rugged islands in the area of the present-day Hajar Mountains. That original relief was rapidly eroded, however, and much of the area again became a site of shallow marine deposition by the end of the Cretaceous.

The height and rugged topography of today's Hajar Mountains is the product of renewed uplift and erosion due to regional forces commencing in the late Oligocene (*ca*. 30 million years ago) and continuing to the present. This regional uplift is believed to be related to the gradual opening of the Red Sea and to the ongoing convergence of the Afro-Arabian and Eurasian plates, which is responsible for the Zagros Mountains of Iran and other mountain chains from the Alps to the Himalayas.

Geologically recent events, such as Pleistocene glaciation and its associated effects on climate and sea level, have put the finishing touches to the present-day geology of the UAE as a whole. These events are discussed in more detail by Evans and Kirkham in the following chapter, *The Quaternary Deposits*.

THE SAND DESERT

Most of the land surface of the present-day UAE is a sand desert, stretching from the Arabian Gulf coast south to the uninhabited sands of the Empty Quarter, the Rub' al-Khali, and east to the gravel outwash plains bordering the Hajar Mountains. The desert is a geologically recent feature, the result of prolonged subaerial erosion and re-deposition in an arid environment. The sands overlie the thick, oil-rich sedimentary strata of the Arabian Platform which constitute the bedrock of most of the UAE, but most of the oil- and gas-producing rocks are not exposed at the surface, and are known only from drilling.



The wind sculpts desert features on many scales.

The desert sands vary in both composition and form. Near the coast they consist mostly of calcium carbonate ($CaCO_3$) material derived from the carbonate sediments, seashells and coral reefs of the coast. Further inland, the sand consists predominantly of quartz grains. Quartz (SiO_2) is the most common rock-forming mineral and is a stable end-product of the chemical weathering of most rock types other than carbonates. However, even the well-weathered and well-winnowed quartz grains of the desert sands normally contain intra-crystalline impurities or acquire fine surface coatings or which may impart different colours.

In many areas near the coast, especially in the Northern Emirates, the sand is stabilised by plant growth, although the natural vegetation has been altered in recent times by extensive grazing of domesticated animals. Further inland the sands may be quite barren, as few plants can successfully colonise the mobile dunes.

DUNE PATTERNS

Sand dune formation is controlled by a combination of wind strength and direction, and sediment supply. In detail, however, the formation of dune patterns remains poorly understood. Within a given area the dune pattern may be quite regular, but also intricate. Physical features are typically created on several different scales – giant sand ridges on a scale of hundreds of metres to a few kilometres, sand dunes measured in metres to tens of metres, and ripples on a scale of centimetres to a metre or more. This hierarchy can be readily observed in the deserts of the UAE.

Because dune patterns vary with wind direction, seasonal or occasional variations in wind direction introduce new elements into the overall pattern. These elements may reinforce or cancel each other, in the same manner as ocean waves. In addition, because sand dunes cannot move or change as quickly as ocean waves, past history may play a significant part in what we see today. Despite relatively consistent prevailing wind directions in the present-day UAE, dune morphology and alignment differ considerably from one area to another (Glennie 1991; 1996; 1997) and the overall mosaic is complex and nuanced. Many elements have become apparent only with the aid of satellite imagery (Fig. 7).

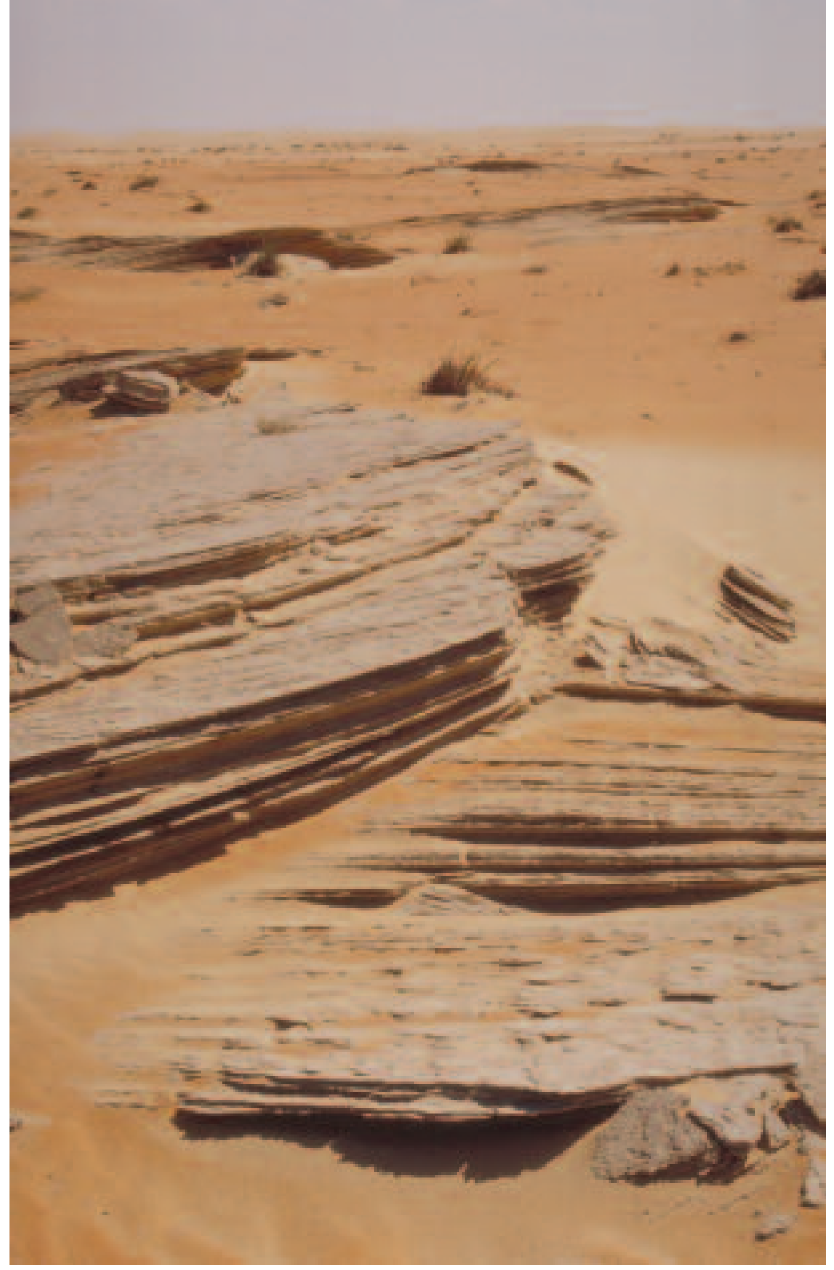
In an attempt to find order among these phenomena, geologists have recognised certain basic types of dune forms. Many of these are well-illustrated in the UAE, although hybrid or intermediate forms are perhaps equally or more common. *Barchan dunes* are the simplest. These are individual crescent-shaped dunes, convex in the upwind direction, having a relatively gentle upwind slope but a steep slip face downwind. They tend to form in areas where the sediment supply is limited and are most often seen atop gravel plains or salt flats. They may form fields of up to several dozen, advancing across the flats.

Transverse dunes are elongated sand ridges that form perpendicular to the prevailing wind direction. Most of the active dune fields in the UAE are of this general type. Typically they occur in parallel arrays with elongated troughs between, but they may be quite variable. The crestlines may be relatively straight, or sinuous or cuspate (in which case they may be called *barchanoid*), and oblique elements are often present. Like barchans, transverse dunes are asymmetrical, having relatively gentle upwind slopes and steep slip faces on the downwind side.

In the UAE, very large transverse dune ridges are developed in and to the south of the Liwa oasis. The main ridges reach heights of up to 150 metres above the adjacent basin floor. The Liwa dune ridges are cuspate or barchanoid in plan view, and in satellite images the individual arcs resemble short, asymmetrical barchans that have coalesced with each other. The Liwa dunes also exemplify the so-called *aklé* pattern, in which the cusps of adjacent ridgelines are 'out of phase' by half a wavelength, so that the trough between them is divided into a discontinuous chain of more or less equi-dimensional basins separated by narrow sandy gaps. Smaller, subsidiary dune patterns are developed on the main ridges.

Linear dunes, also called *longitudinal* or *seif dunes*, are oriented parallel to the prevailing wind direction. Their mode of formation is not well understood and various explanations have been proposed, including, *inter alia*, consistent high wind velocities, a bi-directional wind regime and helical air flow along the troughs between the dunes.

In the UAE, active linear dunes are well developed today only in the remote south-west, where they were remarked on by the explorer Sir Wilfred Thesiger ('a succession of dune chains, each

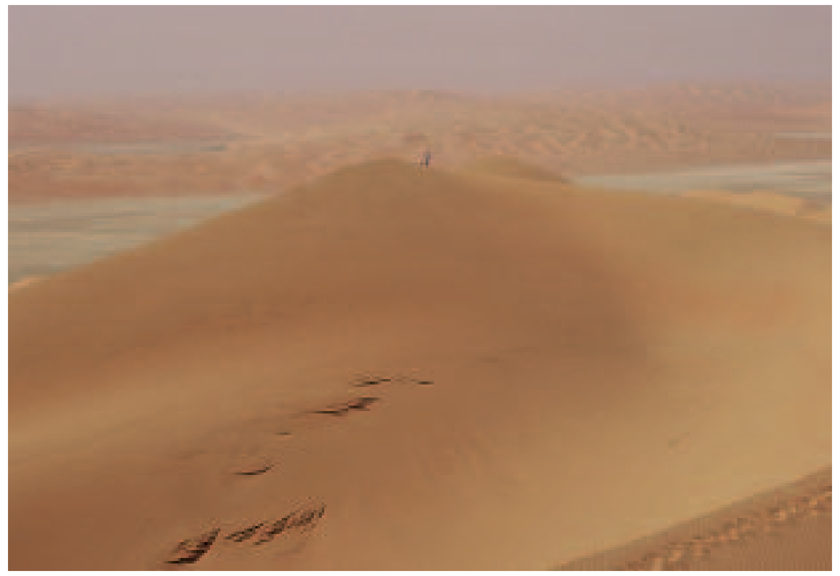


LEFT: *'Fossil' dune sands were cemented at a time when groundwater levels were higher than today.*
BELOW: *An inland sabkha lake after rains at Qaraytisah, in the Eastern Desert.*

of which, when approached from the west, showed up in turn as a wavy silver-blue wall, three to four feet high, running out of sight to north and south along the top of an orange-red slope a mile wide'). The limited observations permitted in that area are consistent with the formation of such dunes by the asymmetric development of small barchans formed atop an older ridge, perhaps under the influence of a consistent, oblique, subsidiary wind direction. However, linear dunes having the same alignment continue across the UAE border for hundreds of kilometres south-south-west into the Empty Quarter, where they are much larger and more extensively developed (as they are elsewhere in the world), with well-developed slip faces on both sides. For this a more comprehensive explanation is obviously required.

Whatever their mode of origin, linear dunes are thought to have been a more prominent feature of the UAE landscape in the past. The sand deserts of the central and eastern UAE are characterised by a pattern of large relict dune ridges aligned in a more or less west–east orientation (from WNW to ESE in the south to WSW to ESE in the north-east). These were once considered the remains of transverse dunes, but are now interpreted to have formed as linear dunes (Glennie 1991; 1996; 1997), probably aligned with stronger and more consistent winds prevailing during

RIGHT: *Giant dune ridges and sabkha flats at Liwa*
BELOW: *Between Abu Dhabi and Liwa, tongues of pale sand resembling a choppy sea of dunes are advancing along broad troughs between higher, flatter ridges of red sand.*



the last Ice Age. In the central UAE, north of Liwa, the former dune ridges have been heavily eroded, as discussed below. In northern Abu Dhabi and the Northern Emirates, a more recent pattern of small linear east-west ridges has been superimposed on the remains of broad older ridges trending WSW to ENE.

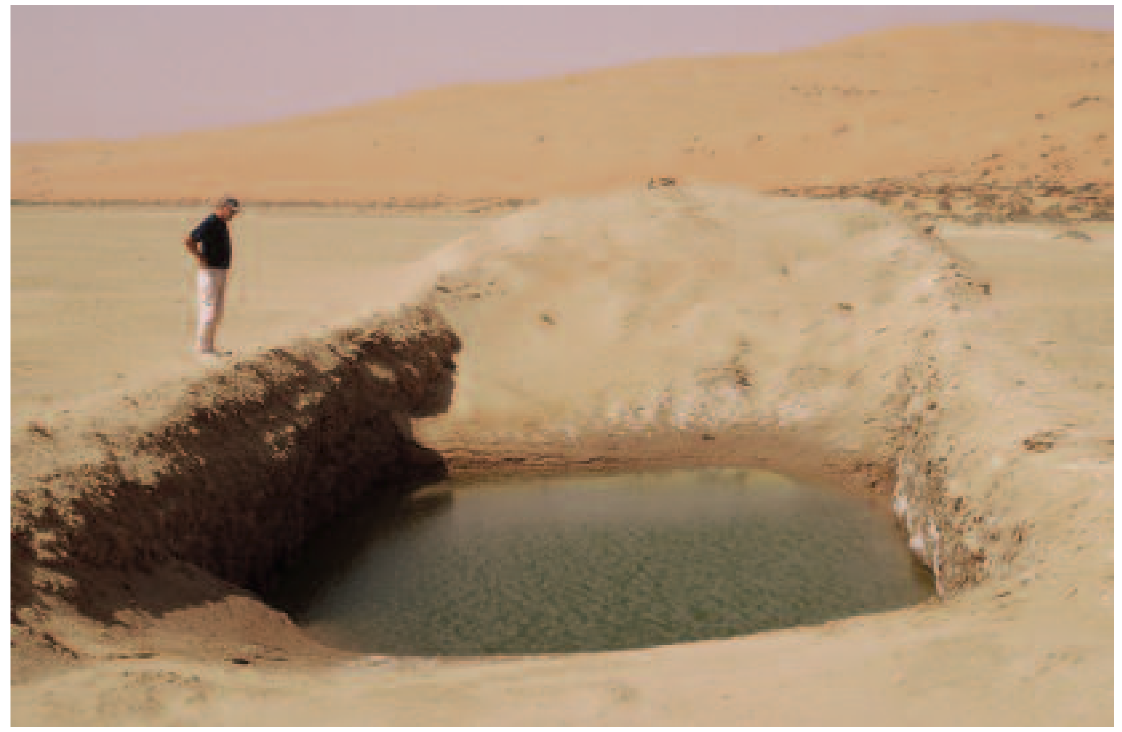
In the Manadir area in the extreme south-east of the country, along the border with Oman, large, elongated sand ridges remain well developed. They are locally called *'irqs* ('ergs') and many are individually named. The dune ridges of Manadir rival those of Liwa in size but are straight overall and are separated by elongated, continuous sabkha flats. The Manadir ridges are now interpreted as linear in origin. However, this is most evident only on a large scale, since their surfaces have been extensively reworked by present-day winds. In the field, the Manadir ridges exhibit the directional asymmetry typical of transverse dunes, e.g., those of the Liwa area.

THE EFFECTS OF CLIMATIC CHANGE

The largest dune features of the present-day UAE, including the major dune ridges of Liwa and Manadir and the eroded dune ridges of central Abu Dhabi and the Northern Emirates, are generally considered to have formed during the most recent glacial period, which reached its climax about 18,000 years ago. Glaciation in northern latitudes contributed to sand dune development in the UAE in two ways. First, glaciation compressed the width of the climatic zones between the ice front and the equator, leading to stronger global winds. Second, glaciation caused a fall in global sea level which emptied the Arabian Gulf and thus exposed a tremendous volume of loose sediment to serve as source material for the dunes (Glennie 1991; 1996; 1997). A glacial period origin for the major dune features is consistent with the fact that they do not seem to be aligned with today's prevailing winds.

The present-day wind regime appears to be transporting material from the coast inland and reworking the surface of the major earlier structures without, so far, removing or reorienting them. For example, one can observe between Abu Dhabi and the Liwa oasis that extensive tongues of pale sand resembling a choppy sea of transverse dunes (aligned north-east to south-west) are filling in broad troughs between higher, flatter ridges of red sand (aligned WNW to ESE). The latter are interpreted as the eroded cores of large linear dunes. Satellite images indicate the pervasive development of small-scale linear alignments, oriented NNW to SSE, on many of these ridges in the area north of Liwa. Further inland, the major dune ridges of Liwa and Manadir also do not appear to be in motion, nor are they being deflated at the present time, although, as noted above, the dune ridges of Manadir have taken on many of the characteristics of transverse dunes.

The crests of active dunes are normally very sharp, but after rain they may be flattened or rounded. The prevailing wind direction in the UAE today is from the north-west, so that most active dune crests are aligned north-east to south-west, with their steep faces to the south-east. The major subsidiary wind direction, however, is from the south-east. Occasional strong south-east winds have the effect of creating temporary 'reverse' crests at the tops of dunes otherwise oriented to north-west winds. This phenomenon causes particular difficulty to drivers of vehicles in the dunes.



LEFT: *The water table is never far below the sabkha surface, even deep within the Liwa region.*

In addition to changes in wind regime, the UAE deserts have experienced changes in annual rainfall at various times in the past. This is indicated by the widespread occurrence of outcrops of lightly cemented, cross-bedded dune sands. These were cemented by the precipitation of calcium carbonate and other salts from groundwater at a time when the water table was much higher than it is today. Other evidence of higher rainfall in the past includes playa lake sediments, horizons containing abundant fossil roots and burrows, fossil reeds, crocodile bones, freshwater mollusc shells and trails, and fragments of ostrich eggshell. Coarsely cemented horizons, called 'calcrete' or 'gypcrete,' are sometimes preserved preferentially as caps on low, flat-topped hills or *mesas*, and represent precipitation from groundwater at the shallow water table beneath former interdunal sabkhas.

Many of these features may be attributable to the alternation of so-called pluvial (wet) and inter-pluvial (dry) periods recognised elsewhere in the region and believed to correlate with the stages of Pleistocene glaciation, pluvials generally corresponding to warm inter-glacial periods. Arid conditions in the UAE predated Pleistocene glaciation, however. The widespread Miocene deposits of the Baynunah Formation (*ca*. 6–8 million years old) in the west of Abu Dhabi are interpreted as a major river system that watered a semi-arid, subtropical savannah. The Baynunah Formation contains the fossilised remains of early relatives of elephants, hippopotamus, horses, bovids, crocodiles, turtles and other animals (Whybrow and Hill 1999; Whybrow *et al.*, this volume). The intervening Pliocene is generally thought to be unrepresented in the UAE, but was a period of aridity in both East Africa and the Mediterranean.

Paradoxically, the dune sands of the UAE have facilitated human habitation in the desert. This is because the porous sands act as a reservoir for what little rain does fall, allowing it to collect above impermeable bedrock or subsurface crust, thus protecting it from evaporation. Where the resulting water table is close to the surface, wells may be dug and small-scale agriculture may be possible (Fig. 5). The best example in the UAE is the Liwa oasis, which was a seasonal home to many Abu Dhabi families until the discovery of oil.

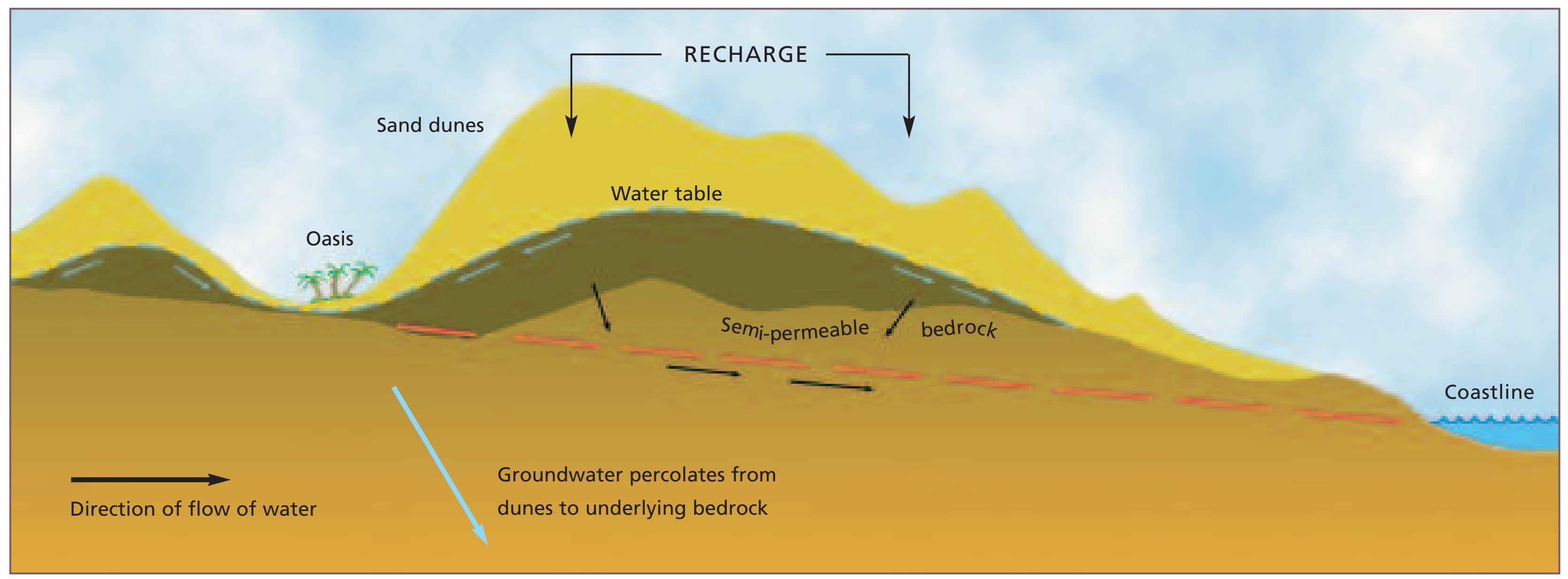


FIGURE 5: *Cross-section of an oasis*

SABKHA ENVIRONMENTS

Sabkha is the Arabic term adopted by geologists for low-lying salt flats subject to periodic inundation. Three general types have been recognised, based on their environment of formation. All are found in the UAE. Coastal sabkha, as the name implies, forms at or near the marine shoreline. Fluvio-lacustrine sabkha is formed in association with river or lake drainage systems in arid areas. Inland or interdunal sabkha is found in low-lying basins within the sand desert.

All sabkhas share certain characteristics. Although they are restricted to hot, arid regions, the sabkha surface is always very close to the local water table, usually within about a metre, and, in fact, the existence of the sabkha is dependent on that proximity. Groundwater is drawn towards the surface by capillary action and evaporates in the upper subsurface in response to the high temperatures. There it deposits dissolved salts, including calcium carbonate ($CaCO_3$), gypsum ($CaSO_4$-$2H_2O$), anhydrite ($CaSO_4$) and sodium chloride or halite (NaCl), which precipitate in that order. These salts typically create a hard, often impermeable crust within a zone about half a metre below the surface. This crust, along with high salinity, discourages all plant growth. The crust also impedes the drainage of surface water, so that after rains the sabkhas flood. The surface water then evaporates over time, often leaving behind a dazzling white crust of salt.

Various surface phenomena are characteristic of sabkha. An irregular, puffy crust of loosely cemented salts and fine sediment is common on dry sabkha. Expansion due to the crystallisation of salts may create raised polygonal patterns, whereas shrinkage due to desiccation may create polygonal 'mud cracks.' On coastal sabkha, the growth of dark mats of cyanobacteria (formerly called blue-green algae) gives rise to a distinctive wrinkled surface. In each case, subsequent deposition of salt or wind-blown sediment takes place among or atop these surface irregularities. The flat sabkha surface itself resists erosion by wind (*deflation*) due to dampness and the cementation of surface grains by precipitated salts.

When dry, the sabkha can be firm and suitable for vehicle transportation, but after rains it is notoriously treacherous. Sabkha is not quicksand, however, and the subsurface crust will ultimately support the weight of humans, animals and ordinary vehicles, although this may be small comfort to one who is mired in it. In 1948, Thesiger relied on this knowledge to cross the Sabkha Matti in the western UAE by camel after a week of rain.

Mats of cyanobacteria (formerly called blue-green algae) form on coastal sabkha at the upper limit of normal high tides.

COASTAL SABKHA

The UAE is famous worldwide for its coastal sabkha, which dominates the coastline from the area of Abu Dhabi Island westwards. Here the sabkha may extend more than 15 kilometres inland. The coastal sabkha is extremely flat but most of the surface is, nevertheless, above the level of normal high tides, so that it is flooded only by a combination of storm surge and spring tides, or by heavy rains.

Cross-sections through the sabkha show a characteristic sequence (from top to bottom) of halite, anhydrite, gypsum, calcareous mud, and bacterial layers, all above dune sands (Fig. 6) (Evans *et al.* 1969; Kirkham 1997). This sequence reflects the growth of the coastal sabkha. Gelatinous mats of cyanobacteria develop in the high intertidal zone and trap fine calcareous sediment brought in by the tides. The sediment itself is the product of precipitation of calcium carbonate – both primary precipitation in warm surface waters and organic precipitation as the shells of macroscopic and microscopic marine organisms. The rate of intertidal and shallow subtidal sedimentation in the Arabian Gulf is believed to be as high as anywhere in the world, and carbonate sediments such as these represent an important 'sink' for atmospheric carbon dioxide.

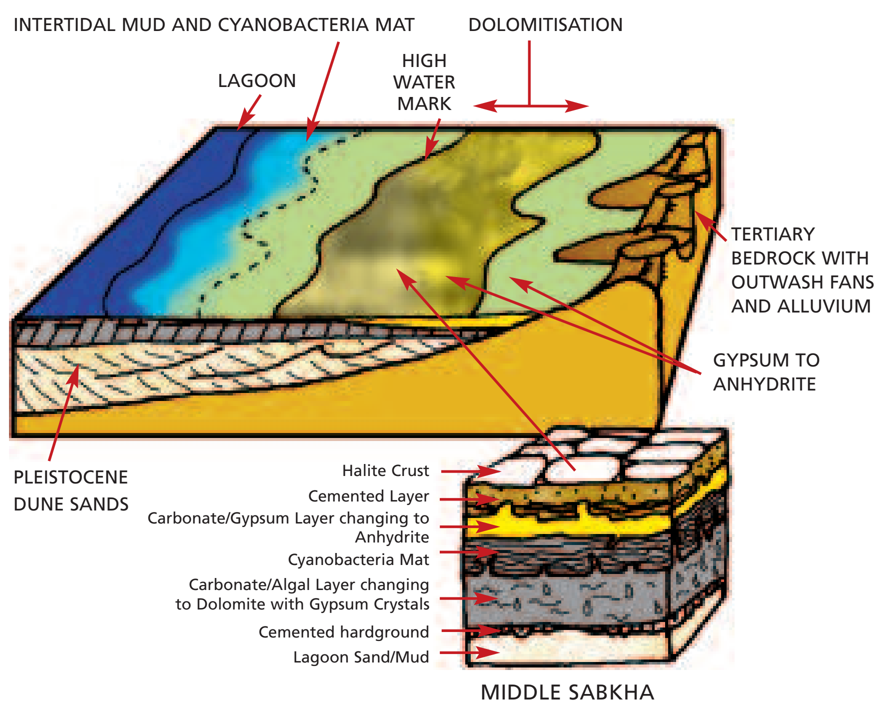


FIGURE 6: *Cross-section of coastal sabkha*

ABOVE LEFT: *Rain or storm surge may flood sabkha for several kilometres above normal high tides.*
ABOVE RIGHT: *Salt polygons form by surface evaporation and capillary action.*
RIGHT: *Wrinkled sabkha surface in the Manadir area of the Eastern Desert.*

Within the carbonate sediments, gypsum crystals form at the water table as vertically-oriented discs, and anhydrite may form just above the water table if the temperature within the sediment is high enough, the crystallisation of both causing slight expansion of the sediment (Kirkham 1997). Little by little, all of the foregoing processes raise the level of the land surface and thereby help to maintain the flat coastal sabkha against erosion by the sea.

Study of the coastal sabkha of Abu Dhabi has also yielded an answer to the 'dolomite problem.' *Dolomite* or calcium magnesium carbonate ($CaMg(CO_3)_2$) is known from the geologic record as a common mineral, sometimes the dominant mineral, in carbonate rocks of shallow water origin. Because primary deposition of dolomite is virtually unknown in present-day environments, it was long assumed that dolomite was the product of early post-depositional alteration of calcium carbonate or limestone ($CaCO_3$), which was widely deposited by precipitation in warm seas. The problem was that there were also no present-day environments known in which alteration to dolomite was taking place. Now it is recognised that dolomitisation occurs extensively in the sabkha environment, beginning above the normal high-tide zone, where magnesium present in seawater is concentrated in brines. Further inland the upper sabkha carbonate sediments may be entirely replaced by finely crystalline dolomite.

Additional details of the geochemistry, surface dynamics and evolution of sabhka environments in the United Arab Emirates are described by Evans and Kirkham in the following chapter, *The Quaternary Deposits*.

THE SABKHA MATTI

The Sabkha Matti is a large and infamous sabkha located in the extreme west of the UAE, extending more than 100 kilometres inland (Fig. 7). Until recently it was the bane of overland travellers. The Sabkha Matti is here classified as a fluvio-lacustrine sabkha because it is situated at what has been identified as the probable confluence and estuary of several rivers which drained the Empty Quarter in earlier, wetter times (Goodall 1994; Whybrow *et al.*, this volume). Groundwater percolating in buried watersheds may help to account for the location and extent of the present-day sabkha there. During the last glaciation the

Sabkha Matti was covered by sand dunes, but these have been mostly removed by the prevailing north-west winds after the rising post-glacial sea level cut off northerly sediment sources.

INTERDUNAL SABKHA

The UAE's best example of interdunal sabkha occurs in the Liwa area, where the sinuous giant dune ridges enclose myriad sabkha flats. Although these flats are generally drier than other UAE sabkha, after heavy rains they may remain flooded for weeks or months, and their existence testifies to the historical proximity of groundwater. Deep within the Liwa area, traditional wells are preserved, and new troughs have been bulldozed, in which the water level remains within 2 metres below the surface. Within the Liwa oasis, however, residents report that the water table has dropped to 10 metres or more as a result of increasing agricultural demand.

The Liwa area is one of several noted for its *sand roses*. These are attractive natural formations resembling stone flowers. They consist of interlocking flat discs of gypsum-cemented sand, formed by subsurface precipitation at the water table. Typically, layers of sand roses are found weathering out of low dunes somewhat above the present day sabkha surface. The remnants of more extensive layers of gypsum-cemented sand, originally formed in the same way, cap occasional low mesas within the Liwa area.

The elongated parallel sabkhas of the Manadir area, in the extreme south-east of the country (Fig. 7), are larger than those of Liwa and are probably intermediate between interdunal sabkha and fluvio-lacustrine sabkha, since it is likely that their hydrology is at least partly controlled by surface and subsurface runoff from the Hajar Mountains to the east. As in Liwa, some of these sabkhas are now being filled with sweet sand in preparation for agricultural use.

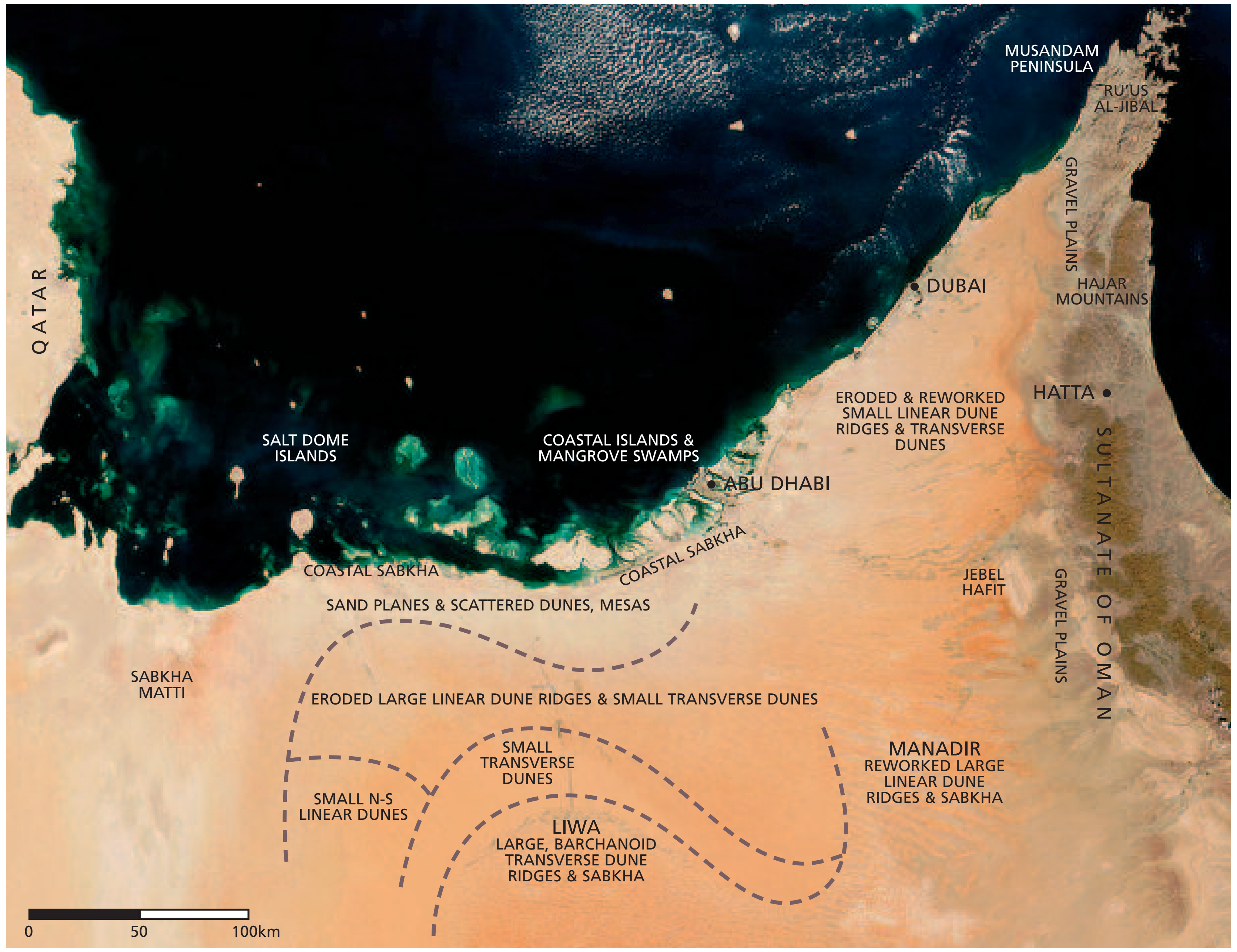


FIGURE 7: *Satellite image of the UAE, showing the distribution of diverse environments*

THE HAJAR MOUNTAINS

The Ru'us al-Jibal at sunset: this area has been uplifted by more than 3,000 metres in the past 30 million years.

The Hajar Mountains parallel the east coast of the UAE and continue south-eastward into Oman, along the UAE border. Within this area they are divided geologically into two main ranges. In the north, the mountainous Musandam Peninsula, most of which lies within the Musandam province of the Sultanate of Oman, is traditionally called the *Ru'us al-Jibal* (literally 'the heads of the mountains') because of its high peaks, which reach just over 2,000 metres. The Ru'us al-Jibal exposes a thick sequence of Mesozoic carbonate sediments that correlates with the principal oil-bearing strata that lie deeply buried to the south-west.

To the south of the Ru'us al-Jibal, the Hajar Mountains are somewhat lower, with major summits from *ca*. 800–1,600 metres. Here they consist of a distinctive complex of igneous rocks that represents the upper mantle and oceanic crust of an ocean that once lay to the north-east. Originally formed deep within the earth beneath a zone of sea-floor spreading, these rocks now lie atop contemporaneous shallow water sedimentary rocks of the Arabian Platform. They are also associated with highly deformed sediments deposited on the former deep ocean floor. The rocks of the mantle and oceanic crust, exposed together at the surface in this way, are collectively called *ophiolite*. The ophiolite of the Hajar Mountains constitutes the world's best preserved and most extensive such exposure, stretching some 500 kilometres from Dibba in the UAE to south-east of Muscat in Oman. For this reason it is of tremendous interest to geologists.

Ophiolites are found in many major mountain belts, but typically as relatively small, isolated and highly-deformed units that represent one of the telltale signs of the presence of a former ocean basin, since consumed by subduction and, ultimately, the collision of two continental masses. It is the often shiny, greenish-black appearance of such typical, pervasively deformed or *tectonised* ophiolites that earned them their name, which means 'snake rock.' The Hajar Mountain ophiolite, however, is unlike most other ophiolites by virtue of its extent, its thickness and its relative lack of deformation, both macroscopically and microscopically.

The distinctive geology of the Hajar Mountains is best understood by reviewing the plate tectonic history of the area. In simplified form, this consists of five principal stages described below. Figures 8a–e depict these stages and Figure 9 shows the present distribution of the principal rock units. The text on pages 60–62 describes in

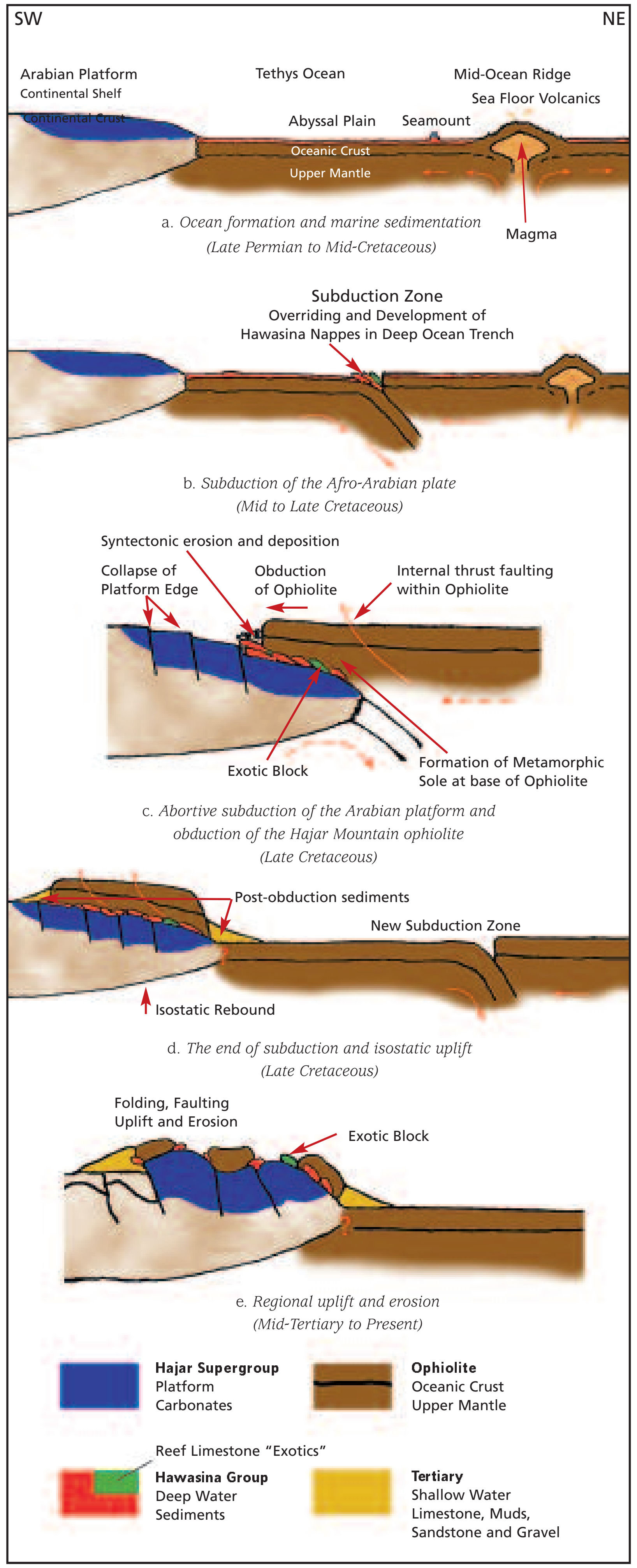


FIGURE 8: *The plate tectonic history of the Hajar Mountains*

Pillow lavas are formed when lava erupts in deep water, typically at mid-ocean ridges where new oceanic crust is formed.

more detail the resulting structural and stratigraphic sequence, the formal geological nomenclature, and the kinds of rocks and minerals that can be found in the Hajar Mountains today.

RENEWED OCEAN FORMATION AND MARINE SEDIMENTATION
(Late Permian to Mid-Cretaceous) (Fig. 8a)

The Tethys Ocean had existed between Gondwana and Asia since Late Palaeozoic time. In the Late Permian, a new axis of sea-floor spreading was initiated within the Tethys, at or near the margin of Arabia. To the north of the Ru'us al-Jibal area, this spreading caused the rifting of several *microcontinents* from the north-east edge of Arabia (Glennie 1997). These microcontinents were destined to cross the Tethys and become, in time, parts of Turkey, Iran and Afghanistan. The 'new' ocean basin left in their wake is sometimes called Neo-Tethys. Rifting of these microcontinents may account for the restricted circulation indicated by the Late Permian and Triassic shelf carbonates of the Ru'us al-Jibal.

To the south of the Ru'us al-Jibal, the rifting was centred offshore along a mid-ocean ridge situated to the north-east of the Arabian Platform, although it may have caused block faulting and minor vulcanism at the continental margin. Along the rift, new oceanic crust was created as adjacent plates of the lithosphere separated. This crust consisted of a suite of related igneous rocks formed at various depths under the mid-ocean ridge by fractional melting of mantle rock, the formation of magma chambers, the injection of vertical dykes, and the extrusion of volcanics on the ocean floor.

As the Tethys continued to open, marine sediments accumulated on the continental shelf, slope and rise of the Arabian Platform, and on the abyssal plain of the new ocean. The deep ocean sediments included radiolarian cherts, fine muds and, nearer the Arabian Platform, intermittent beds of coarser material deposited by submarine landslides and dense, sediment laden flows called 'turbidity currents,' originating on the continental shelf edge and slope and generally mobilised by earthquakes or severe storm

activity. Isolated limestone banks or coral atolls were developed offshore on seamounts (extinct subsea volcanoes) and on foundered ridges created in association with the early stages of ocean rifting.

SUBDUCTION OF THE AFRO-ARABIAN PLATE
(Mid- to Late Cretaceous) (Fig. 8b)

In the mid- to late Cretaceous, about 110 million years ago, a subduction zone formed in the Tethys Ocean between the mid-ocean ridge and the margin of the Arabian Platform, lying some 400 kilometres or more to the north-east of the present day coast. This subduction zone dipped to the north-east. Here the plate carrying the Afro-Arabian continent began to be subducted beneath the oceanic crust of the Tethys at a deep ocean trench. At depth within the subduction zone, the upper mantle and oceanic crust of the Afro-Arabian plate, plus a thin veneer of deep ocean sediments, were re-assimilated into the deeper mantle.

At a subduction zone, not all of the descending plate is subducted and assimilated, however. At least part of the veneer of deep ocean sediments is normally scraped off and piled up in front of the overriding plate as an *accretionary wedge*. The effect of continued under-thrusting and scraping off of sediments in the subduction zone was to create a wedge of overlapping sheets of deep-water sediments, with those formed nearest to the Arabian Platform (south-west) at the bottom and those formed farthest away (north-east) on top.

ABORTIVE SUBDUCTION OF THE ARABIAN PLATFORM AND OBDUCTION OF THE HAJAR MOUNTAIN OPHIOLITE
(Late Cretaceous) (Fig. 8c)

The subduction process proceeded routinely until enough of the Afro-Arabian plate had been subducted to bring the Arabian Platform itself into the subduction zone. Subduction cannot accommodate the relatively light (i.e. less dense) rocks that constitute continental crust, and the arrival of the Arabian Platform therefore caused the subduction zone to 'jam.' The situation was ultimately resolved by the formation of a new, parallel subduction zone further to the north-east, beneath the present-day Indian Ocean coast of Iran and Pakistan, an area called the Makran, in order to accommodate the continuing global convergence of the adjacent plates (Glennie 1997). However, in the process of trying and failing to subduct the edge of the Arabian Platform, the distinctive geology of the Hajar Mountains was created.

In the final stages of the abortive subduction, the leading edge of the Arabian Platform was forced under the edge of the overriding plate. Correspondingly, the overriding plate, consisting of upper mantle and oceanic crust, was forced over the edge of the Arabian Platform and over the overlapping layers of deep ocean sediments that had accumulated in the trench. Those sediments deformed plastically and seem to have acted as a lubricating layer. The phenomenon of thrusting of a sheet of oceanic crust onto the adjacent continent at a subduction zone is called

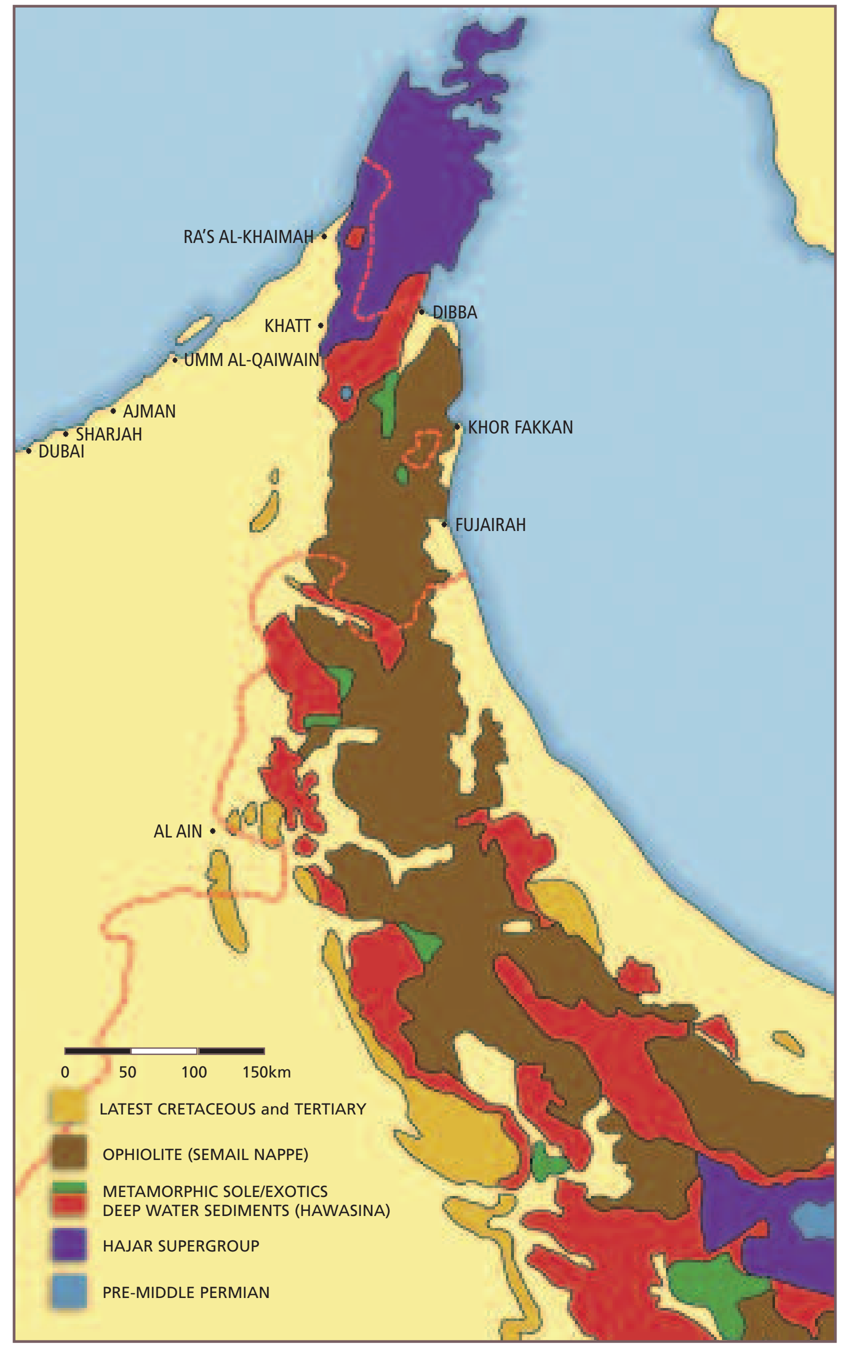


FIGURE 9: *Geologic map of the northern Hajar Mountains*

obduction. The process of obduction of the Hajar Mountain ophiolite began approximately 90 million years ago and was completed by about 75 million years ago.

The emplacement of the ophiolite nappe, originally some 15 kilometres thick, involved considerable shearing along its base, which is today exposed along most of the western front of the mountains. In addition, the mantle rocks were invaded by hydrothermal fluids both in their initial environment beneath the mid-ocean ridge and during their subsequent transport and emplacement. This has resulted in extensive veining and pervasive alteration of the mantle rocks to a mineral group called *serpentine* – fibrous to platy, greenish-white to yellow-brown minerals related to talc and asbestos.

It should be noted that the preceding description is over-simplified in a number of ways. Among other things, the ophiolite of the Hajar Mountains represents a piece of oceanic crust that originally

The colourful deep ocean sediments of the Hawasina basin are thrust against the grey carbonates of the Ru'us al-Jibal in Wadi Khabb.

contained within itself major lateral offsets like those of the present-day mid-Atlantic ridge, known as *transform faults*. Those offsets are preserved today as transverse structural alignments that mark several of the major wadi systems that cross the Hajar Mountains, including the Hatta area and the so-called Dibba Zone along the southern edge of the Ru'us al-Jibal. Both of those areas are structurally very complex, with many different rock units exposed chaotically along them.

The Dibba Zone constitutes a particularly significant discontinuity. Most importantly, it separates the shelf sediments of the Ru'us al-Jibal from the ophiolite to the south. To the north of the Dibba Zone, the Ru'us al-Jibal area may have been affected by the rifting of microcontinents from the continental margin in the Late Permian. The Ru'us al-Jibal may also have escaped being overridden by the ophiolite nappe in the Late Cretaceous. Seismic evidence shows that the elevated trend of the Ru'us al-Jibal continues north-eastwards under the Straits of Hormuz (Ricateau and Riché 1980), but the postulated geological connection with the Zagros Mountains of Iran, a classic folded mountain belt only 100 kilometres to the north, remains enigmatic.

The mechanics of obduction of the ophiolite are not well understood. Oceanic crust and mantle are significantly denser than continental crust, so that the emplacement of a slab of ophiolite 15 kilometres thick on top of the Arabian Platform poses a particular geophysical challenge. Yet the ophiolite appears to have been emplaced without geologically significant heat or pressure, since there has been relatively little metamorphism of the rocks immediately beneath it. Because sediments were deposited in front of the ophiolite as it was obducted, we know that the process occurred below sea level, and one explanation is that the forces involved caused buckling of the crust in front of the ophiolite, creating a trough into which it could advance more easily. At a later stage, uplift and gravity sliding may have played a role.

The Hajar Mountain ophiolite is chemically somewhat different from typical oceanic crust, as revealed by modern oceanographic studies. Also, the age of the ophiolite rocks (90–100 million years) indicates that they were formed only shortly before they were obducted. As a result, the majority of researchers now believe that the Hajar Mountain ophiolite originated not from sea-floor

LEFT: Serpentinised peridotite is the most common rock type found within the ophiolite. The dark peridotite, originally formed in the upper mantle, has been extensively altered to a pale green fibrous mineral called serpentine.
BELOW: Blocks of white limestone called 'exotics' often cap hills within the deep ocean Hawasina basin sediments.

spreading at a normal mid-ocean ridge, but by means of a smaller-scale version of that same process, called marginal basin spreading, which takes place in the overriding plate close to the subduction zone. Marginal basin spreading is hypothesised to result from physical tension in the overriding plate caused by rapid descent of the subducted plate (Glennie 1997), accompanied by high heat due to friction along the descending slab and release of water vapour from the subducted crust and sediments, all of which would facilitate fractional melting in the overriding plate. Young oceanic crust would be hotter and therefore more buoyant, and marginal basin crust is typically somewhat thinner than normal oceanic crust. Both of these characteristics would ease to some extent the mechanical difficulties of obduction.

The fact remains that the obduction of the Hajar Mountain ophiolite constitutes an exceptional phenomenon and it may yet prove necessary to invoke an exceptional explanation, perhaps including a unique array and interaction of plate tectonic elements.

THE END OF SUBDUCTION AND ISOSTATIC UPLIFT
(Latest Cretaceous) (Fig. 8d)

After initial obduction of the ophiolite nappe, subduction finally ceased in this area and a new subduction zone was established further to the north-east, under the Makran coast, where subduction continues to the present day. Freed from the downward pull of subduction, the thick pile of superimposed rocks that had been accumulated by subduction and obduction at the edge of the Arabian Platform rose isostatically at a rapid rate, since the column of rocks involved is less dense than the underlying mantle. This uplift completed the detachment of the obducted ophiolite slab and probably also caused additional movement of the nappes in response to gravity.

Isostatic uplift raised the Hajar Mountain area above sea level, possibly with considerable relief, but it was rapidly eroded in a wet tropical climate (Nolan *et al*. 1990). Shallow-water sediments from the latest Cretaceous and early Tertiary drape the western flank of today's mountains, indicating that some if not all of the region was again submerged at that time. Latest Cretaceous and early Tertiary sediments found near Al Ain and Jebel Faiyah are known for their abundant and diverse shallow-water marine fossils, including rudists (large, solitary, bivalve molluscs), echinoids (sea urchins and sand dollars), gastropods (snails) and nummulites (large, disc-shaped foraminifera). These are described in more detail by Whybrow *et al*. in the chapter on *The Fossil Record*.

REGIONAL UPLIFT AND EROSION
(Mid-Tertiary to Present) (Fig. 8e)

The Hajar Mountains, as we know them today, are the result of deformation in the late Oligocene and early Miocene (*ca*. 30–20 million years ago), followed by uplift and erosion under generally arid or semi-arid conditions, continuing to the present day. This deformation and uplift are presumed to be related to the slow-motion collision (i.e. tectonic convergence) of the Eurasian plate with the Afro-Arabian plate and other marginal plates, coupled with the opening of the Red Sea. Those interactions have been responsible for mountain building from the Alps to the Zagros to the Himalayas during the same time period. The Hajar Mountains, however, are situated relatively far from the relevant plate boundaries and no conceptual model has yet been proposed which fits this mid-Tertiary phase of activity more precisely into our evolving understanding of plate tectonics and its relationship to mountain building. Nevertheless, certain generalisations can be made.

A bench or terrace cut by the sea into the mountain front near Ra's al-Khaimah has since been uplifted.

Whereas the original emplacement of the ophiolite involved a substantial component of horizontal movement, amounting to hundreds of kilometres, the mid-Tertiary phase of deformation is generally considered to have involved mainly internal compression, which was accommodated by relatively open folding and faulting. Those features are well displayed in the massive carbonate strata of the Ru'us al-Jibal. On the other hand, evidence of more dramatic local tectonics can be seen or inferred in sedimentary strata along most of the western mountain front. In Wadi Haqil, near Ra's al-Khaimah, the Ru'us al-Jibal carbonates are thrust westwards for a minimum of several kilometres. To the south, locally severe compression is reflected in the tight folding of prominent outlying anticlinal ridges such as Jebel Faiyah, Jebel Hafit and Jebel Rawdhah, where the surface and subsurface deformation of the Tertiary strata is complex and involves high-angle thrusting to the east (Kirkham 1998). Subsurface drilling has confirmed the existence of low-angle westerly thrust faults on a scale of up to 30 kilometres in these same areas (Dunne *et al.*, in Robertson *et al.* 1990). Some interpretations find deep-seated thrusting to be a more fundamental factor in the mid-Tertiary deformation overall (Hanna 1990).

At the end of the Miocene, about 5 million years ago, the Arabian Platform began its collision with Asia, pushing up the Zagros Mountains along its leading edge and creating behind them the shallow downwarping that today contains the Arabian Gulf, which is nowhere more than 100 metres deep. During much of its life the Gulf has not been a marine basin but a broad river valley, draining Mesopotamia and, in wetter times, the Empty Quarter.

The Hajar Mountains as a whole have continued to rise slowly since the mid-Tertiary. In the south and central Ru'us al-Jibal, uplift since the Oligocene is estimated at more than 3,000 metres. A wave-cut terrace of undetermined age along the mountain front south-east of Ra's al-Khaimah now lies at an elevation of *ca.* 100–200 metres above sea level. An exception is the very tip of the Musandam Peninsula, which is estimated to have subsided rapidly by as much as 60 metres in the past 10,000 years (Vita-Finzi 1979), perhaps due to its approach to the subduction zone beneath the Makran. This subsidence has flooded the major wadis north of Khasab, creating the unique arid fjords of that area. The Gulf of Oman, which is a true ocean basin, has continued to subside throughout the Tertiary and has accumulated a thick sequence of sediments eroded from the east flank of the Hajar Mountains.

Erosion of the Hajar Mountains has produced the broad gravel plains that border the mountains on both east and west, and the gravel terraces that fill major wadis. Within the mountains themselves, erosion has proceeded by alternation of cutting and filling. At present we are in a phase of cutting down, so that in virtually any mountain wadi south of the Ru'us al-Jibal, one can observe that the current wadi bed is bordered intermittently by the steep walls of higher gravel terraces (up to as much as 30 metres higher) representing former base levels. These wadi walls provide excellent cross-sections for the study of sedimentary processes in the wadi environment, processes that continue today. Much of the surface area of the gravel terraces has remained undisturbed for a long time, and the gravel pavement now displays a deep purple-brown patina known as *rock varnish* (also known as desert varnish), for which a primary role has been attributed to manganese-fixing bacteria (Dorn 1998).

The alternating phases of cutting and filling could be due in part to variations in the rate of regional uplift, but it seems evident that the role of climate has been paramount. Erosion of the mountains and deposition of gravels has been greatest when the climate has been wettest. Precipitation levels known from historical times are not sufficient to account for outwash gravels of the size and scale that exist. For this, the best explanation may lie in the climatic vicissitudes of the Quaternary Period.

Direct dating of uplift and erosional phenomena in the mountains of the UAE, for example, terrace levels or wet and dry periods, has so far not been systematically undertaken. The recent discovery of an extensive cave and cave deposits at the present-day summit of Jebel Hafit, but presumptively formed originally at or near ground level (Fogg *et al.* 2002), may contribute to more precise estimates of the timing of climatic events and erosion and uplift rates.

THE QUATERNARY PERIOD

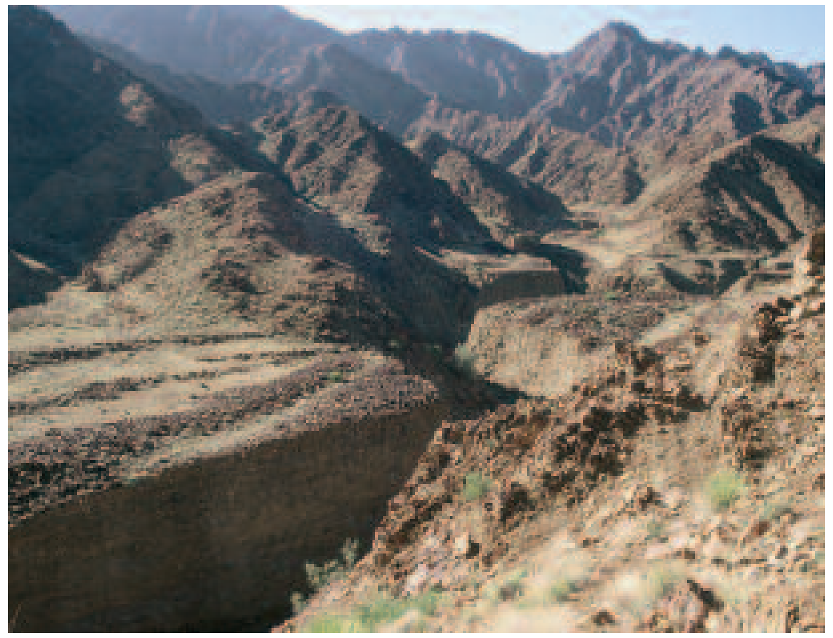
The final episode in the geologic history of the UAE is the events of the past 1.8 million years called the Quaternary Period, consisting of the alternation of Pleistocene glacial and inter-glacial periods and in particular the latest, current inter-glacial period that geologists call the Holocene or Recent (measured from 10,000 years ago to the present). In the UAE these climatic variations were experienced as pluvial and inter-pluvial periods, with pluvials corresponding generally to inter-glacials.

At the peak of the last glaciation, about 18,000 years ago, global sea level was approximately 120 metres lower than today, due to the large amount of surface water stored in polar icecaps and massive continental glaciers. The Arabian Gulf was dry, and the waters of the Tigris and Euphrates emptied directly into the Gulf of Oman. As the glaciers waned thereafter, sea level rose, reaching its present level (and probably a metre or so higher) some 4,000–6,000 years ago. Raised beaches on the East Coast appear to reflect previous inter-glacial sea stands several metres higher than today.

In the sand deserts of the UAE, inter-glacial conditions sometimes created rivers and lakes, while glacial periods emptied the Gulf and brought strong winds and sand to build the great dune systems. Along the coast, changing sea levels and changing climate formed the backdrop not only for sabkha and shoreline development, but also for the first evidence of human inhabitation of the UAE. The oldest UAE archaeological sites, some 7,500 years old, are found on what are today offshore islands, and many later settlements appear closely linked to the contours of former shorelines. Still earlier evidence is likely hidden beneath the waters of today's Arabian Gulf.

The effect of Quaternary events on the geology and geography of the UAE is described in more detail by Evans and Kirkham in the following chapter, *The Quaternary Deposits*.

Gary Feulner



Hajar Mountain wadis bear witness to multiple episodes of cutting and filling.

STRUCTURAL UNITS AND ROCK TYPES OF THE HAJAR MOUNTAINS *FROM TOP TO BOTTOM OF STRUCTURAL SEQUENCE*

Fossiliferous latest Cretaceous limestone at Jebel Rawdhah

Sheeted dykes near Wahala

Gabbro near Hiluw

POST-OBDUCTION SEDIMENTS

This unit consists of shallow-water sediments deposited after emplacement of the ophiolite nappe. Various subunits are recognised, both in the field and from drilling. They range in age from latest Cretaceous to Miocene and include both clastics (sandstones and shales) and carbonates. These sediments were deposited unconformably on top of the underlying units and have themselves been folded or tilted and eroded by deformation and uplift in the late Oligocene and early Miocene. This can be observed at Jebel Faiyah, Jebel Buhais or Jebel Rawdhah in the Northern Emirates, or at Jebel Hafit or Fossil Valley (Jebel Huwayyah), near Al Ain. These sediments are known for their abundant shallow-water marine fossils, including rudists (large, reef-forming bivalve molluscs), echinoids (sea urchins and sand dollars), gastropods (snails) and nummulites (large, disc-shaped foraminifera).

UNCONFORMABLE SEDIMENTARY CONTACT

OPHIOLITE NAPPE

At the top of the main structural sequence lies the ophiolite nappe, often called the *Semail nappe* by geologists. This nappe consists of a sheet of the upper mantle and oceanic crust dated at *ca*. 90–100 million years old. The total original thickness of the ophiolite nappe was some 15 kilometres, including more than 10 kilometres of upper mantle.

Oceanic Crust

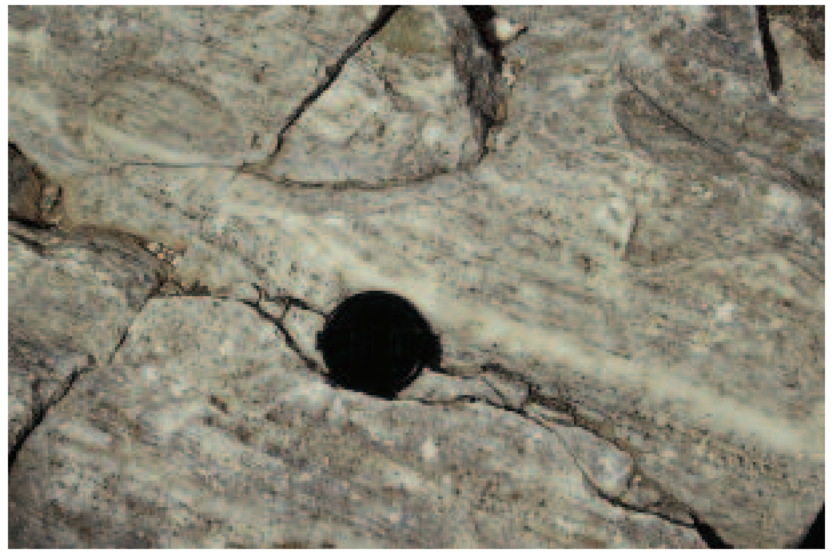
At the top of the ophiolite, the rocks of the oceanic crust normally occur in a regular sequence, from top to bottom, as follows:

(a) *Lavas and pillow lavas:* These are usually basalts and were extruded at a mid-ocean ridge or sea-floor spreading centre. Pillow lavas are lavas erupted under deep water, which cool quickly at their surface while flowing, forming distinctive pillow-like lobes. Occasionally, deep-water sediments (usually cherts or thin-bedded limestones) are associated with the pillow lavas (see photo on page 54).

(b) *Sheeted dykes:* These are sets of parallel intrusive 'walls' of diabase or diorite (a medium-grained igneous rock also of basaltic composition) which were emplaced vertically and served as feeders for lavas at the mid-ocean ridge.

(c) *Gabbro and layered gabbro:* These are coarsely crystalline rocks which solidified in magma chambers under the mid-ocean ridge or sea-floor spreading centre. They are composed principally of calcic feldspar and pyroxene, having a range of chemical composition equivalent to basalt. Gabbro is relatively low in silica (SiO_2), but not as low as mantle rocks.

Gabbro is common along the East Coast and in Wadi Hiluw, but in the UAE the top of the ophiolite nappe has generally been eroded and the rocks of the upper oceanic crust are therefore absent. Sheeted dykes are found only at the mouth of Wadi Hiluw and pillow lavas are known only from isolated outcrops. Both sheeted dykes and pillow lavas are common, however, along the neighbouring Batinah coast of Oman.



Anorthosite in Wadi Sahanna

Copper mineralisation near Hiluw

Serpentine (lizardite)

Upper Mantle

The compositional transition from oceanic crust to upper mantle has long been recognised seismically. The abrupt change in seismic velocities that occurs at this horizon is known as the Mohorovicic discontinuity or 'Moho.' In the Hajar Mountains it is possible to walk below the Moho.

Mantle rock is distinctively low in silica and high in magnesium and iron, relative to ordinary rocks. The primary constituent of the upper mantle is a dark rock called (generically) *peridotite*, which is made up of the mineral *olivine* and one or more types of *pyroxene*, with minor trace minerals such as *chrome spinel*. The precise composition (and therefore the technical name) is variable. The most common peridotite in the Hajar Mountains is called *harzburgite*, but *lherzolite* and *wehrlite* are also found.

Like ophiolites elsewhere, the ophiolites of the UAE contain localised deposits of *copper* ore. Many of these were mined in antiquity and can now be recognised by the presence of slag from nearby smelting. Mantle peridotites may also contain occasional pods of relatively pure olivine or of relatively pure *chromite*. The latter has been mined in the modern era.

Mantle peridotites are well exposed along the road from Dhaid to Masafi and from Masafi to Dibba, as well as in the area south of Hatta, but alteration to *serpentine* minerals (fibrous green *chrysotile*, greasy white *lizardite* or platy, yellow-brown *bastite*) is common. In many places near the base of the ophiolite nappe, along the western front of the mountains, the mantle peridotites have been extensively fractured and veined with fibrous serpentine and occasionally with white, chalky *magnesite* ($MgCO_3$), which weathers to look like styrofoam. From Al-Ghail south to Shawkah, the base of the ophiolite has been pervasively silicified and altered almost beyond recognition.

TECTONIC/METAMORPHIC CONTACT

METAMORPHIC SOLE

At various sites the emplacement of the ophiolite nappe was accompanied by localised contact metamorphism of the rocks at its base, involving both the underlying sediments and the ophiolite itself. Metamorphism was sometimes sufficient to produce garnet schists or amphibolites. This *metamorphic sole* is well exposed as silver-white rocks along the main road north of the town of Masafi. The rocks exposed there are principally schists and marbles, the metamorphic products of clastics and carbonates, respectively, in the underlying sediments.

TECTONIC/METAMORPHIC CONTACT

Magnesite boulder near Hatta

Mica schist near Masafi

Turbidite sediments near Dibba

HAWASINA NAPPES

This unit consists of the deep ocean sediments that were deposited in the Tethys Ocean, stacked or imbricated at the subduction zone, and finally thrust ahead of the advancing ophiolite. They are late Permian through mid-Cretaceous in age, and are therefore contemporaneous with the shallow-water carbonates of the Arabian Platform, which they now overlie. A number of individual subunits have been identified and mapped, but the internal structure is often very complex due to the movement and deformation that these rocks have undergone.

The Hawasina sediments include red and green cherts (sometimes composed of radiolarians), thin-bedded mudstones and carbonates, fissile shales, turbidites, continental slope and rise clastics (including conglomerates of slumped and redeposited shelf limestones), and occasional volcanic rocks. These sediments are often very colorful and are best seen in the UAE in the so-called Dibba Zone along the southern border of the Ru'us al-Jibal, between Dibba and Tawiyan. They can also be observed just over the Oman border in the area of Wadi Sumayni.

At the top of the Hawasina sediments, in certain places, are large blocks of white reef limestone, sometimes turned to marble, called *exotics*, which are resistant and tend to form the summits of large or small peaks (see photo on page 57). They are typically associated with volcanic rocks and are thought to represent limestone banks or coral atolls that formed atop seamounts or submarine ridges. No major exotics occur within the UAE, but good examples can be seen just over the Oman border at Jebel Ghaweel and near the villages of Shiyah and Shuwayhah, all just off the road from Jebel Rawdhah to Mahdhah.

Within the Hawasina nappe, sediments representing the continental slope and rise are often distinguished as the *Sumayni Group*, and the exotics and their associated volcanics as the *Haybi* or *Umar Group*.

TECTONIC CONTACT

ARABIAN PLATFORM

The lowest unit observed, structurally, is the Arabian Platform itself, represented in the UAE by the thick late Permian to mid-Cretaceous shallow-water carbonates (limestones and dolomites) exposed in the Ru'us al-Jibal. These are known collectively to geologists as the *Hajar Supergroup* and include numerous subunits. They can be correlated with the principal oil-bearing strata that lie deeply buried to the west. Various horizons throughout the Hajar Supergroup contain shallow-water marine fossils, including abundant bivalves and gastropods, rarer brachiopods, crinoids and cephalopods, and locally abundant pipe corals and trace fossils.

The pre-Permian basement of the Arabian Platform is known in the UAE only from localised and fragmentary outcrops of Paleozoic shallow-water clastics near Jebel Qamar South and the village of Al-Ghail, which have been collectively called the *Rann Formation*. Scarce fossils have indicated ages ranging from Ordovician to Devonian. The carbonates of the Ru'us al-Jibal are presumed to have been deposited unconformably above the pre-Permian basement.

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