Evolution of The Emirates’ Land Surface: an Introduction

K.W. Glennie

Introduction

With the exception of the Omani territory in the north-eastern Ru’us al-Jibal (Musandam peninsula) and north-central Oman Mountains, the United Arab Emirates (UAE) occupies a broad strip of land flanking the southern shores of the Arabian Gulf between the Qatar peninsula and the Gulf of Oman. Much of that land consists of relatively low-lying rolling dunes and interdune areas forming the north-eastern limit of the Rub al-Khali (Empty Quarter of Saudi Arabia), which reach 150 m above sea level in the region to the north of Al Liwa. In the northern emirates, the dunes extend up to the Oman Mountains. To the south-east, however, the eastern limit of the dunes coincides approximately with the Oman border, where they overlie the *deflated* (wind eroded) surface of sub-horizontal fluvial sediments that had earlier been transported westward from the mountains (Fig. 1).

A general lack of rainfall ensures that most of Arabia is a desert. Summer temperatures can approach 50°C on the Gulf coast of the Emirates, where relative humidity averages between 50 and 60 per cent. Inland, however, temperatures can exceed 50°C and relative humidity be less than 20 per cent (United Arab Emirates University). Over the western lowlands of the Emirates, annual rainfall is mostly less than 40 mm. In Al Ain the mean annual rainfall is 96 mm and yet the potential yearly evaporation is over 3000 mm (*op.cit.* Plate 44). With a high rate of evaporation and an annual rainfall over the Oman Mountains that rarely reaches 200 mm, this highland area, which has elevations within the Emirates of over 1500 m, must also be classified as desert; its desert status is emphasized by its surface of almost continuous barren rock and a sparse vegetation confined mostly to the floors of wadis.

With the exception of the south-western Ru’us al-Jibal, the rocks exposed within the mountains of the Emirates differ markedly from those that contain deeply buried oil and gas fields in the west and beneath the southern Gulf. Also, the extensive plains of fluvial sediments that flank the mountains are evidence of a former, much wetter, climate than is indicated by the younger dune sands and salt-covered *sabkha*s that overlie their extremities. The history of deposition and deformation of these rock units, the much more recent evidence of rapid changes in climate from very humid to hyper-arid, together with the geological processes that culminated in today’s desert surface, form the topic of the following pages.

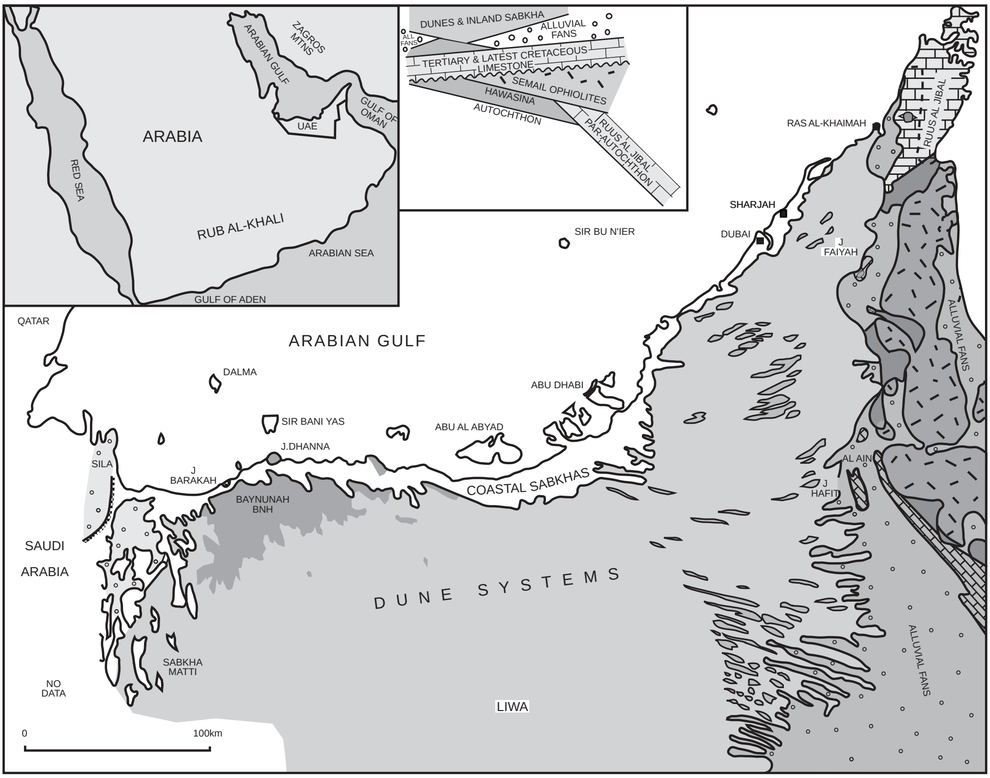


Fig. 1. Simplified geological map of the United Arab Emirates. Inset diagram indicates some of the complex geometrical relationships between rock units of the mountains and flanking areas. See also Table 1.

Mountain and Subsurface Geological Framework

The subsurface

The oldest exposed rocks underlie the whole of the Emirates except the Oman Mountains and immediate flank areas; they are seen at only two localities on the mainland, Jebel Ali south-west of Dubai and Jebel Dhanna in the western part of Abu Dhabi, but also occur on several offshore islands (e.g. Sir Bani Yas, Sir Abu Nu'air: Fig. 1). These jebels and islands are dome-shaped at the surface and are cored by Hormuz Salt (named after similar salt on Hormuz Island in the Straits of Hormuz). The salt was deposited almost 600 million years ago on the floor of an almost enclosed sea when evaporation resulted in its water becoming super-saturated with respect to *halite* (common salt) (see also Glennie 1987: Fig. 12a). About 20 million years before the present (20 Ma BP), the Red Sea was also floored by salt in a similar way. Salt can flow and, unlike the sedimentary rocks that overlie it, cannot be compacted with increased depth of burial. For this reason, the salt is now less dense than most of its overburden and, using any vertical weakness, penetrates upward *(diapirism)* through the overlying rock sequence to form *salt domes* at the surface. In the south-eastern Gulf, the source of the diapiric Hormuz salt now lies at a depth of some 10 km (Beydoun 1991). *Hydrocarbon source rocks* of similar age occur in Oman, and may be present in the Gulf area, but because of deep burial must long since have generated their oil and gas. Several of the offshore salt domes are associated with the occurrence of oil and gas where *reservoir rocks* have been deformed by the rising salt to create a *trap* (e.g. Umm Shaif, Zakum).

Arabia, as part of the megacontinent *Gondwana,* was located south of the Equator throughout the Palaeozoic era (Table 1). Initially it was geometrically 'up-side-down' (Fig. 2) relative to the poles as Gondwana moved south across the south pole (and came up the other side the 'right-way up') under the influence of *plate-tectonic* processes (see below). Because Arabia's southern traverse was undertaken largely in temperate latitudes, most of the Palaeozoic rocks comprise sandstones and shales, a small exposure of which occurs in Jebel Rann, south-west of Dibba. Hydrocarbon source rocks of Silurian age are known in both Oman and Saudi Arabia, and might be viable for the generation of oil also in western Abu Dhabi.

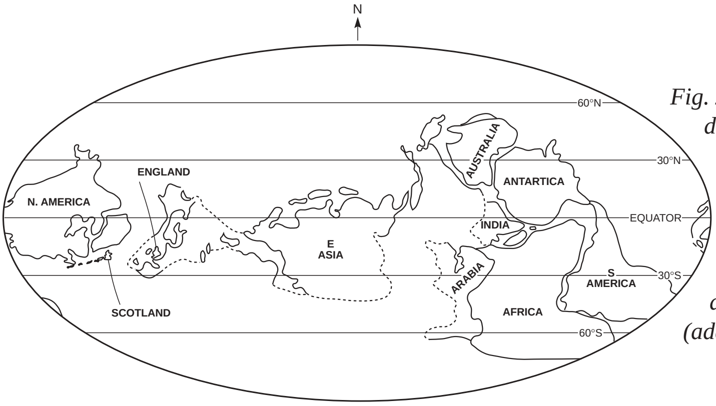
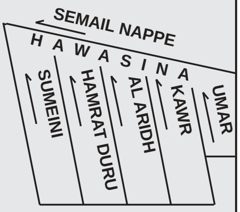


Fig. 2. Distribution of continental plates during the early Palaeozoic. Arabia then formed part of a megacontinent called Gondwana, which included Australia, Antarctica, India, Africa and South America. Gondwana was separated from eastern Asia by an ancient ocean called Tethys (adapted from Smith et al., 1981).

In complete contrast, between the Late Permian (about 260 Ma BP) and Late Miocene (part of Neogene on Table 1; about 5–10 Ma BP), Arabia slowly drifted northwards across the Tropics, where warm, shallow, tropical seas were ideal for the growth of corals and other shallow-marine creatures with calcareous shells; their accumulation after death led to the formation of varieties of *limestone.* Depending partly on a water depth that varied with time, the sea floor was intermittently covered by a variety of rocks that included organic-rich muds, mostly of Jurassic and Cretaceous age, but also some Triassic formations, which later became the source of hydrocarbons (oil and gas) now stored in porous carbonate rocks (limestones and *dolomites)* (see Table 1). Reservoir rocks range in age from the Late Permian (Khuff Formation) to the Jurassic, where the Arab reservoirs are important, and Cretaceous (Shuaiba, Mauddud and Mishrif), to the Lower Tertiary (Pabdeh Formation). Seals, preventing the relatively buoyant hydrocarbons from escaping to the sea floor, cap the reservoirs. The best of these are *evaporites* such as *gypsum* and *anhydrite* inter-bedded with the different Arab reservoir horizons, or the overlying latest Jurassic Hith Formation (Al Silwadi et al. 1996). These seals were probably deposited on extensive coastal *sabkha*s similar to those now found along the shore and on the offshore islands of Abu Dhabi (Alsharhan & Whittle 1995).

For source rocks to become *mature* and give up their oil, they need to be buried to a depth where the temperature approaches that of boiling water (about 3 km, depending on the local *temperature gradient* through the underlying rock sequence). At a depth of around 4 km, it starts to become mature for gas production but post-mature for the generation of oil, and by

AGE Ma	PERIOD			① PLATFORM AREA		② MUSANDAM PENINSULA (PARAUTOCHTHONOUS)	③ OMAN MOUNTAINS (ALLOCHTHONOUS)
				GROUP	FORMATION		
2	CENO-ZOIC	QUATERNARY NEOGENE PALEOGENE		FARS PABDEH	PABDEH (G)	ERODED/ NOT DEPOSITED	
65	MESOZOIC	CRETACEOUS	HSG	ARUMA WASIA THAMAMA	LAFFAN (S) MISHRIF (O) MAUDDUD (O) SHUAIBA (S/O)	MUSANDAM	
145		JURASSIC		SAHTAN	ARAB (O) DIYAB (S) ARAEJ (O) MARRAT (O)		
208		TRIASSIC		AKHDAR	JILH (S) KHUFF (G)	ELPHINSTONE ← RUUS AL JIBAL	
251	PALAEOZOIC	PERMIAN				THRUST OVER ARUMA & HAWASINA	
290		CARBONIFEROUS		MAJOR HIATUS			
360		DEVONIAN					
410		SILURIAN					
440		ORDOVICIAN					
500		CAMBRIAN		?			
540	PRECAMBRIAN			HORMUZ SALT			
				?			
700				CRYSTALLINE BASEMENT FIRST FORMED AROUND 950 Ma B.P.			
800							

NOTES:

1. Autochthonous rock units - Geological groups in L.H. column. R.H. column lists some important source rocks (S) and oil- (O) & gas- (G) bearing formations. Note Basal Cambrian Hormuz Salt.
2. Parautochthonous rocks of Musandam Peninsula are similar to those of the platform area but have been thrust short distance over Aruma and Hawasina covering deeper platform rocks, probably at end of Paleogene.
3. South of the Musandam Peninsula, the Hawasina comprises an imbricate sequence of continental slope (Sumeini) and ocean floor sediments (Hamrat Duru to Umar groups). They are overlain by the Semail Nappe comprising former oceanic crust. Obduction of both Hawasina & Semail took place during time span of deposition of the Aruma Group on the Arabian Platform.

← indicates sense of thrusting

HSG = Hajar Supergroup

Table 1. Rock units of the United Arab Emirates. *A simplified outline emphasizing differences between the Oman Mountains and subsurface of the desert plains. Some important oil and gas horizons within the autochthonous Hajar Super Group of the Arabian Platform are shown (R= reservoir rock; S= source rock and C= cap rock or seal). Note that the Hawasina and Semail Nappes were obducted onto the Arabian continental margin during the Late Cretaceous.*

6 km, the temperature is so high (around 180°C) that even gas generation ceases (post-mature for gas). Newly generated oil is squeezed out of its source bed and migrates (usually upward) into a porous reservoir rock (e.g. sandstone, dolomite). The oil or gas can be retained in the reservoir rock only if it is kept in by an impervious *cap rock* or *seal*, and the reservoir/seal couplet forms a trap. Structural deformation of the reservoir/seal couplets, preventing the formation of traps, can occur in a variety of ways; these can include fault movement at basement level, which affects all overlying rocks, differential compaction of underlying sands and shales and, most prominently in the southern Gulf area, diapiric uplift of the Eo-Cambrian

Hormuz salt and its sideways withdrawal from the deep salt horizon to feed that diapirism (Fig. 3). A simple outline of the maturation and migration of hydrocarbons from source rock to reservoir and trap is given in Glennie (1995). For a general discussion of Arabian petroleum geology, see Beydoun (1991) and more specifically for the Emirates, Alsharhan (1989).

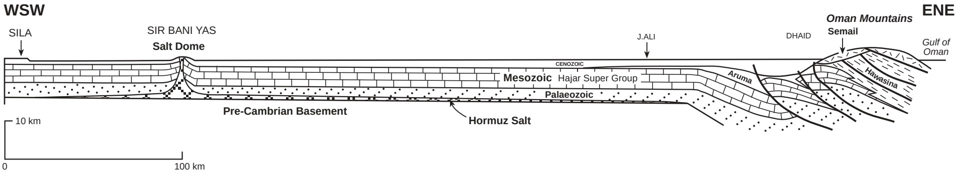


Fig. 3. Schematic W-E geological cross-section through the United Arab Emirates. Deformation leading to the creation of hydrocarbon traps within the Hajar Super Group resulted from movements associated with basement faults and the Hormuz salt (small diapir at J. Ali not shown) generally too small to show at scale of section. The nappes of the Oman Mountains were obducted when the eastern margin of Arabia and adjacent ocean floor attempted to underthrust oceanic crust now represented by the Semail Nappe.

The Oman Mountains

The origin of the subsurface rocks that underlie the greater part of the Emirates has been told in relatively simple terms, but that of the mountains is much more complex and its interpretation is not without controversy (Robertson and Searle 1990; Glennie 1995). Its presentation thus requires more space.

The creation of the Oman Mountains is closely connected with the plate-tectonic processes mentioned above. This hypothesis is based on two observations:

- The continents are composed of relatively thick (20–70 km), light and buoyant crust (*continental crust)*, while the oceans are floored by a thinner (4–10 km), denser crust (*oceanic crust*); both 'float' on a slightly plastic *mantle* that is capable of flowing as a slow-moving convection current under the influence of radioactive heat generated in the core of the Earth.
- New oceanic crust is created from molten *magma* filling tension gashes within existing crust and extruded as lava on the ocean floor at *mid-ocean ridges*, while a similar amount of older crust is carried back down into the Earth's mantle at arcuate oceanic trenches (*subduction zones)*; thus the Earth's circumference remains more or less constant as the continents and adjacent oceanic crust move away from the 'spreading' oceanic ridges and converge elsewhere at subduction trenches.

Perhaps the clearest example of the above processes is seen today on either side of the Americas. In the Atlantic Ocean, depending on location, the Americas have been moving away from Europe and Africa at an average rate of about 5 cm a year for the past 60 to 100 million years (60–100 Ma) or more, the axis of spreading being the submarine Mid Atlantic Ridge; while at the western margin of South America, oceanic crust of the Pacific Plate is being *subducted* beneath the Andes (see e.g. Glennie 1992, 1995).

For much of the Palaeozoic era, Gondwana was separated from Asia by a major ocean known as Tethys (Fig. 2). In the Late Permian, some 260 or 270 Ma BP, a continental block comprising Anatolia, Central Iran, Helmand (south Afghanistan) and perhaps Tibet, separated from the Arabian-Indian margin of Gondwana to form a *microcontinent* (Glennie 1995: Fig. 16).

The intervening area became floored by a relatively narrow spreading ocean called Neo-Tethys 1 (sequentially, there were two), which probably was rather like the modern Red Sea. Although there are some doubts about the oceanic nature of its underlying crust (it may have been 'thinned' and volcanically ruptured continental crust (Béchennec et al. 1988, 1990)), Neo-Tethys 1 seems to have had a spreading life of probably less than 50 Ma, for, in the Late Triassic, the newly formed microcontinent was itself split into two by a new axis of spreading and the creation of another ocean (Neo-Tethys 2: Fig. 4) that was to exist for over 100 Ma. Neo-Tethys 1 ceased to spread from then on. The southward narrowing microcontinent between the two oceanic areas, Neo-Tethys 1 and 2, comprised Anatolia, the Sirjan-Sanandaj zone of Iran (Glennie et al. 1990; Glennie 1995), and possibly a number of mountain-size 'fragments' of shallow-marine limestone and marble within the Hawasina Series referred to as 'Exotics' (Al-Aridh and Kawr groups of Table 1); exotic because these whitish marbles look out of place in their surroundings of the much darker rocks of the adjacent *Semail Napp*e (former oceanic crust) and the deep-water sediments (limestone and red-brown *chert;* see below) of the *Hawasina Series.*

The Hawasina comprises sequences that vary in thickness from about 1000 to 200 m and range in age from the Triassic (locally mid Permian) to the mid Cretaceous. The thinner and, more particularly, the uppermost parts of the sequences are commonly distorted and tightly folded. Furthermore, a large part, or even the total sequence, is commonly repeated in an imbricate fashion (like a row of books on a shelf, all leaning in one direction) as they partly overlie each other. A simplified picture of sedimentation on the ocean floor can be deduced by reconstructing the imbricate pile back into their original positions relative to each other (Glennie et al. 1973, 1974, 1995 Fig.8).

When Neo-Tethys 1 formed, its floor was covered with sediments derived from the edge of the Arabian continental shelf; at the continental shelf edge, shallow-marine organisms, including calcareous grasses, thrived in well-oxygenated waters, and shells or, in the case of the grasses, lime mud, accumulated when they died. The shells were partly fragmented by wave action and also by burrowing organisms. The whole formed a metastable mass of sediment that could be dislodged by the shock of an earthquake or even a violent storm. Such dislodged sediment would slide down the continental slope and develop into a relatively high-velocity flow called a *turbidity current*, which finally deposited its entrained sediment over the lower *continental rise* and *abyssal plain* of the ocean as a bed called a *turbidite.* Turbidity currents have been recorded in modern environments at speeds of up to 70 km/hour (Holmes 1978), and their momentum carries them far across the abyssal plain.

At depths greater than some 3000 to 4000 m, calcium carbonate is unstable. The fine calcareous muds that settle out from suspension in the oceanic waters are especially susceptible to replacement by silica to form reddish brown cherts (a rock rather like flint), which are characterized by the siliceous framework of very small unicellular creatures called radiolaria (i.e. they form radiolarian cherts). Turbidites and radiolarian cherts make up much of the Hawasina sedimentary sequence. The volumetrically greater calcareous turbidites dominated deposition closest to the Arabian continental shelf edge, while the much thinner red cherts were in the deepest water farthest from the shelf edge (Glennie et al. 1973, 1974; Glennie 1995).

In complete contrast to the turbidites and cherts, the 'Exotics' form large blocks of white shallow-marine limestone, commonly recrystallized to marble (a process that destroyed many

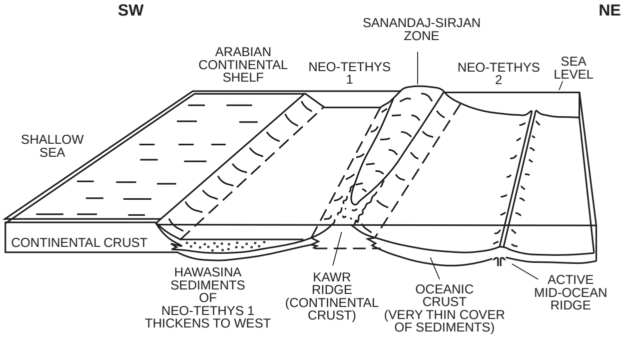


Fig. 4. Block diagram to illustrate the spatial relationships between the Arabian continental margin, Neo-Tethys 1 and 2, and the intervening Sirjan-Sanandaj-Kawr microcontinent during the Jurassic and Early Cretaceous.

of the fossils that may have been present initially). The 'Exotics' seem to have been derived from the far side of Neo-Tethys 1 relative to the Arabian continental margin (Kawr Ridge on Fig. 4). Most 'Exotics' are underlain by an association of a red siltstone and *pillow lavas* formed by extrusion of lava at the sea floor. At Jebel Rann, south-west of Dibba, however, 'exotic' limestone overlies Ordovician sandstone, which indicates the presence of continental crust. These observations suggest that the 'Exotics' probably formed as the outcome of continental break-up and the creation of a new intervening ocean. The largest known 'Exotic' in the mountains is Jebel Kawr, in Oman, which is almost 1000 m thick and over 25 km across.

The Anatolia-Sirjan-Sanandaj microcontinent that separated Neo-Tethys 1 and 2 narrowed southward (Fig. 4), and along much of the Oman coastline of Arabia was probably represented by little more than the 'Exotic' Limestones (Kawr Ridge). As the Kawr Ridge had little or no exposure above sea level, it generated no sediment by erosion other than carbonate fragments; thus this part of Neo-Tethys 2 was deprived of sediment other than a rain of the finest clay-size particles settling out of suspension in the oceanic waters and eventually forming radiolarian chert (Umar Group, Table 1).

Sedimentation in the relatively narrow Neo-Tethys 1 took place from the Late Permian to the mid Cretaceous, and, in Neo-Tethys 2, from the Late Triassic until the mid or Late Cretaceous. As Neo-Tethys 2 continued to widen, so the Africa-Arabian and adjoined South American portions of Gondwana moved to the west or south-west away from the Neo-Tethyan axis of spreading. Sometime during the Early Cretaceous, however, Africa and South America began to separate to create the intervening South Atlantic Ocean (Glennie et al. 1990; Glennie 1995). South America continued to move to the west, but Afro-Arabia had to reverse its sense of motion and move away from the South Atlantic spreading axis. With Neo-Tethys 2 continuing to spread, very strong compressional stresses soon developed. These were relieved by the creation of an easterly-dipping trench down which the oceanic crust of first the western part of Neo-Tethys 2 and then Neo-Tethys 1 was subducted. During that process, the sediments covering the floor of both Neo-Tethys 1 and 2 were scraped off the down-going oceanic plate to form the *accretionary wedge* of imbricate sequences of the Hawasina mentioned above (Glennie et al. 1990; Glennie 1995).

Subduction zones are of two types (see Fig. 6 in Glennie 1995):

- Andean Type: oceanic crust at the eastern edge of the Pacific Plate is currently being subducted beneath the Andes mountain range. As the sedimentary cover is scraped off the down-going oceanic crust, the Andes are elevated a little more. The uppermost sediments being subducted are considerably younger than the overlying rocks of the Andes mountains; moisture associated with the descending plate lowers the melting point of rock and causes volcanic activity (together with the intrusion at depth of granite) in the overlying Andes.

- Ocean-ocean subduction: the oceanic crust of Neo-Tethys 2, when initially subducted, was possibly up to 100 Ma old and had therefore had enough time since its formation at a spreading ridge to cool down. The old and cold crust was relatively dense, and preferred to descend steeply rather than at a gentle angle; this, in turn, caused the axis of bending to roll back away from the subduction trench, thereby creating crustal tension in a geological structure that had developed initially because of crustal compression. Crustal tension inevitably leads to volcanic activity and the creation of new oceanic crust; this new oceanic crust became the Semail Nappe of the Oman Mountains (see Lippard et al. 1986).

Because the new axis of spreading developed behind the subduction trench, the newly created oceanic crust is said to have resulted from *back-arc spreading.* It is noteworthy here that the newly formed oceanic crust was younger than most of the ocean-floor sediments that were being subducted nearby.

Subduction of the oceanic crust and the growth of an *accretionary wedge* of ocean-floor sediments beneath the future Semail Nappe began some 110 Ma BP (Lippard et al. 1986). The difficulty of trying to ‘swallow’ the thick ‘exotic limestones’ down the subduction trench can be imagined from the amount of recrystallization and fracturing that affected the limestones; they were sheared from their mixed continental and ocean-margin substrate. When, later, the even thicker continent margin of Arabia reached the subduction trench, it could neither be sheared off nor ‘swallowed’; it became jammed within the upper part of the subduction zone, and subduction ground to a halt.

The South Atlantic Ocean continued to widen, however, and the back-arc spreading axis just east of the subduction trench was still active. Compressional stresses built up until another subduction trench formed further to the east. In the Oman Mountains, the Late Cretaceous timing of nappe emplacement (*obduction)* can be dated by the fossil content of the Aruma Group sediments (Table 1) being deposited adjacent to the nappes being emplaced. In the Inner Makran of Iran, the presence of volcanic bombs in slightly younger Late Cretaceous marine sediments indicates that a new subduction process had already been in progress there for a few million years (Glennie et al. 1990). The Makran subduction trench is still active today, and has built an accretionary wedge of marine sediments that extends to the present southern coastline of Iran east of the Straits of Hormuz.

When the new subduction trench formed in Iran, compressive stresses in the Oman Mountains sector were removed, allowing the leading edge of the Arabian continent to rise isostatically (like a piece of wood being released under water), causing the separation of what now became the Semail Nappe from its formerly contiguous oceanic crust of back-arc type. This uplift caused the accretionary wedge of Hawasina sediments, together with the Semail Nappe, to slide a little further onto the essentially immovable *autochthonous* continental shelf sequence, the whole process being known as *obduction.* At this time (end Cretaceous), the Hawasina and Semail did not form a high mountain range, but rather an island chain, the flanks of which were covered by Early Cenozoic shallow-marine limestones that extended westward across the rest of the Emirates.

Uplift into the present mountain range did not begin until about the end of the Paleogene or early Neogene, possibly as a result of continental collision between Arabia and Iran associated with the opening of the Red Sea and perhaps of other plate movements including that of India. As part of this event, the highland area of Ru'us al-Jibal (Fig. 1) was pushed westward slightly and compressed along a series of reverse faults, and now at the mountain edge locally overrides Paleogene strata in the subsurface (Fig. 3); other examples of the structural style can be found in Boote et al. 1990 and Dunne et al. 1990. This compression is clearly expressed by the steep western flank of the coastal mountain just north of Sha'am. East of Ra's al-Khaimah, in the Hagil *Window* just north of the exit of Wadi Bih, the shallow-marine rocks of the Ru'us al-Jibal and Elphinstone groups can be seen to overlie units of the Hawasina with a thrust contact. The amount of horizontal over-thrusting is believed to have been no more than a few kilometres and does not extend south of Dibba.

The surface of Jebel Hafit, just south of Al Ain, consists of Lower Cenozoic limestones and marls that have now been deformed into a sharp, steeply flanked anticline whose axis plunges to both north and south. The time of its deformation is believed to have coincided with uplift of the Oman mountains, possibly by reactivation of one of the underlying thrust planes within the Hawasina. Further north, Jebel Faiyah forms a similar structure that has been dissected sufficiently to expose underlying rocks of the Semail Nappe. Cenozoic rocks are also exposed along the mountain edge to the east and north-east of Jebel Hafit (e.g. Jebel Qamar).

Along the coast of Oman in the vicinity of Muscat, and to the south-east almost as far as Sur, are a number of elevated horizontal wave-cut terraces, up to 150 m above present sea level, which indicate that the Oman Mountains have continued to rise during the past few million years or so. A similar terrace in the northern Emirates has been cut into the western edge of the southern Ru'us al-Jibal, south of the exit of Wadi Bih (due east of Ra's al-Khaimah). In contrast, the northern extremity of the Oman Mountains is being depressed below sea level as its offshore continuation across the Straits of Hormuz is subducted beneath the Makran coast. According to Vita Finzi (1979), the northern tip of the Musandam peninsula is subsiding at the very rapid rate of about 6 mm per year.

The rate of horizontal closure between Arabia and Asia is not known. That it continues to do so, even if relatively slowly, is attested by the many violent earthquakes experienced in Iran as the outer edge of the Arabian Plate (north-east edge of the Zagros Mountains) grinds against the adjacent Sanandaj-Sirjan Zone; geologists have aptly named this earthquake-prone contact the Crush Zone.

Miocene Terrestrial Sediments of Western Abu Dhabi

At the time of continental collision between Arabia and Asia during the early Miocene (early Neogene), shallow-marine sedimentation was replaced by terrestrial conditions over much of the Gulf region. In western Abu Dhabi, the Shuwaihat Formation comprises deformed evaporitic sediments that are replaced upwards by dune sands which, like those of today, were deposited under the influence of a northern (*shamal*) wind; the sands are riddled with the moulds of plant roots (Glennie and Evamy 1968), which indicate the former proximity of the water table at fairly shallow depth. Among other places, such sediments are exposed on Shuwaihat island, at Jebel Dhanna and south of Sila (Fig. 1).

With an erosional interval representing several million years, the dune sands are overlain by fluvial gravels and sands of the Baynuna Formation (Fig. 1), which contain a wide variety of vertebrate fossils of both terrestrial and aquatic types: crocodile, turtle, hippopotamus, an early type of elephant, buffalo and ostrich, as well as smaller mammals (Whybrow and Hill 1999). The change from arid dune and *sabkha* to the more humid conditions needed for the hippopotamus and crocodile to thrive requires a considerable change in climate, a change that seems to have taken place repeatedly during the past million years or so. The erosional time gap between the Shuwaihat and Baynuna formations is possibly the result of a considerable fall (100 m?) in global sea level when Antarctica used that volume of water to form its thick cover of ice.

Quaternary Sediments of the Emirates

The influence of high latitude glaciations on Arabian deserts

During the past million years or more, one event has repeatedly affected global climate, including that of tropical deserts. With a cyclicity of around 100 ka (100,000 years), the whole of Scandinavia and the northern half of North America, including Greenland, suffered a repeated slow build-up of an ice cover up to two or three kilometres thick, which then melted very rapidly (Shackleton 1987; Boulton 1993); because global temperatures were lower during glaciations, many highland areas became the sites of mountain glaciers, whereas the ice cap over Antarctica, which had been a permanent feature of the southern hemisphere from at least the Miocene onward, only expanded and contracted in size.

Apart from lowering global temperatures, these glaciations affected climate in two other ways:

- Because the ice caps became the centres of very large areas of high atmospheric pressure, all other air-pressure belts around the globe were squeezed towards the low-pressure equatorial area. With isobars much closer together than is the case today, global winds will have been much stronger and more persistent than any we now experience.
- So much water went into building the ice caps that global sea level at the last glacial maximum, about 20 ka BP, was some 120 or 130 m lower than today's. Since the floor of the Arabian Gulf is everywhere less than 120 m deep, during glacial maxima the exposed floor of the Gulf would have been the site of sand dunes migrating southward and across the Emirates into the Rub' al-Khali under the influence of the northern (*shamal)* wind; the only sign of water in the Gulf area would have been in the combined Tigris-Euphrates river, which derived its water from the wetter Anatolian highlands and reached the open sea south of the Straits of Hormuz.

The high-latitude glaciations took some 80 to 100 ka to reach their maximum extent; the last then melted within little more than 10 ka to produce a global sea level similar to the present one by about 6 ka BP; thus sea level rose at an average rate of about 1 cm per year but possibly exceeded 4 cm/year for short periods (Boulton 1993). This flooding is thought to have been the origin of the biblical story of 'Noah's Flood', perhaps around 9 ka BP (Teller et al. 2000). Noah is thought to have lived in an area now covered by the Arabian Gulf. Over the almost flat floor of the Gulf, any continuous rise in sea level would have been noticed by the people living there. Noah's family possibly lived in the drier environment of a gentle rise to escape the effects of a rainfall that was considerably higher than any experienced today. As sea level rose in the Gulf, Noah's slightly elevated pasturage would have been cut off from the mainland and then be seen to shrink in area, leading to the need for a barge or raft if he and his family and flocks were to survive the encroaching sea; necessity is the mother of invention.

Many desert areas, including much of the Sahara, had a higher rainfall between about 10 and 6 ka BP. This induced the growth of much more vegetation, which fed abundant game, leading to the term 'Climatic Optimum'; since then, most topical deserts have become more arid again (e.g. Petit-Maire 1994).

Flooding of the Gulf had a profound effect on the Emirates. Instead of sand dunes migrating freely into the area from the north, the supply of wind-driven sand was progressively cut off by the increasing extent of sea water. The wind continued to blow, however, so that in areas close to the expanding sea, sand was deflated (removed by wind action) down to the level of the water table, which was rising in concert with the rising sea level. The resulting moist surface developed into *sabkhas*, which are described later.

Fluvial sediments

When there is sufficient rainfall, fluvial gravels and sands are transported down the mountain sides and across the valley floors within the mountains; today, such rainwater reaches the sea about once in every ten years in the northern emirates, but south of Jebel Faiyah it always dissipates within the sand dunes that block the lower reaches of the wadis and never reaches the sea.

West of the mountains is a broad sheet of fluvial sands and gravels that spread for a considerable distance beneath the present cover of dune sands. In south-east Oman, the same spread of *alluvial fans* reaches as much as 200 km south of the mountains; in the north, they extend beneath the floor of the Arabian Gulf. The time of deposition of some of the younger gravels now exposed in incised wadi banks have been dated at around 30,000 and 70,000 thousand years before present (30 and 70 ka BP), while others, in Wadi Dhaid for instance, coincided with the Climatic Optimum (Sanlaville 1992). The fans have been subjected to repeated deflation, however, and near-surface sediment has been dated at over 400 ka, while the degree of alteration of some ophiolite-rich fluvial sediment suggests deposition up to a million or more years ago. The extent of these sediments, and the size of the pebbles and boulders found in them, indicate that at the time of their deposition there was much more rainfall over the area than is experienced today. The surfaces of such alluvial fans are exposed between some of the large linear dunes of the eastern emirates (Fig. 1).

Quaternary fluvial sediments are rarely exposed between the dune cover of most of the western emirates. Along the western side of Sabkha Matti, however, at the western limit of Abu Dhabi, another sequence of fluvial gravels is exposed at the surface. The attitude of the bedding laminae indicates that there, an ancient river flowed towards the north or north-east. The types of rock (e.g. limestone, volcanic lava) represented by the pebble content of the gravels point, in this case, to a source in the south-western highlands of Saudi Arabia. The time of their deposition has been dated at over 200 ka BP (Goodall 1995), which obviously was another period of higher rainfall than now.

Sabkhas

Sabkhas are flat areas of sand, silt or clay that are covered by a crust of salt (halite) for at least a part of the year. *Coastal sabkhas* may be flooded by the sea during storm and spring high tides, whereas the inland variety has no direct marine influence but derives its moisture from rare rainfall and the proximity of the water table at shallow depth, within *capillary* reach of the surface.

Coastal sabkhas and lagoons

As already mentioned above, coastal *sabkhas* formed when the supply of wind-driven sand from the north was cut off during the post-glacial flooding of the Gulf and deflation removed dry sand down to the level of the water table. Water evaporates from the damp surface, especially during the hot summer months, which becomes saturated with halite (common salt) that crystallizes to form a hard crust. Beneath the surface, calcium sulphate also becomes concentrated and forms a mush of gypsum crystals about 50 cm below the surface. At ground temperatures greater than about 42°C, the water of crystallization is driven from the gypsum crystal lattice to create anhydrite. Shinn (1983) has many illustrations of *sabkhas* in the emirates and other areas of the Gulf.

Perhaps the most characteristic feature of a coastal *sabkha* is a widespread mat of thin, black, algae. Most of the time, this *algal mat* is dry, and commonly cracked and curled up at the edges like flakes of mud in a dried-out pond. During high spring tides, however, or when storm winds drive sea water over the almost horizontal *sabkha* surface, the algae spring to life and regenerates into a slimy, wrinkly, rubbery layer. The slimy surface traps fine calcareous particles carried over the surface by the waves, and when it cracks and curls, wind-blown sand and silt can be trapped beneath its edges; with time, the *sabkha* again acquires a crust of halite.

When halite crystallizes, it does so by growing horizontally rather than by increasing its thickness vertically. A space problem ensues, which is resolved by the salt sheets over-thrusting each other if thin, or by forming polygons (ideally hexagons) as it grows thicker.

Coastal *sabkhas* cover the surfaces of much of the extensive system of low islands south-west and just to the north-east of Abu Dhabi island. Along the coast, especially of Umm al-Qaiwain and Ra’s al-Khaimah, however, the development of longshore bars has resulted in the creation of a series of shallow lagoons, which have tidally formed deltas at their mouths (Glennie 1970: Figs 98–100). Wave action builds the longshore bars into beaches, from which sands (mostly the wave-broken remains of shells and carbonate skeletons of sea grasses) are blown into the lagoon behind. In addition, as small carbonate-shelled creatures die, they leave their shells on the lagoon floor, which becomes shallower and eventually builds up to, or even above, normal high-tide level, and then acquires its own cover of coastal *sabkha* including a mat of black algae. North of Ra’s al-Khaimah town, the longshore bars formed the sites of small fishing communities, which progressively moved seaward as each site became separated from the sea by the next bar to extend northward.

Inland sabkhas

Inland *sabkhas* differ from the coastal variety in having no direct marine influence on their development. Their supply of water comes from rare rainfall and the presence of a water table within capillary reach of the surface; a balance is achieved between evaporation and deflation at the surface and the supply of water from below which can trap wind-blown sediment, both being affected seasonally. Algae may be present, but extensive algal mats are not well developed; like coastal *sabkhas,* gypsum crystals form a layer below the surface.

Within the Emirates, extensive inland *sabkhas* are found in three areas: at the landward margins of the coastal *sabkhas* beyond the reach of storm tides and extending into some adjacent interdune areas; in the large broad interdune areas between the huge dunes of Al Liwa; and in Sabkha Matti, a low lying area in the far west of Abu Dhabi, about 60 km across and extending south from the coast for almost 150 km, much of it being within Saudi Arabia. The surface of Sabkha Matti is still no more than 40 m above sea level some 100 km south of the coast.

In the Liwa area, small flat-topped hills (*mesas)* are capped by a gypsum-cemented layer indicative of former *sabkha* conditions. Lightly cemented dune sand, whose bedding attitudes indicate sand transport towards the south south-east (the same as today) is exposed in the flanks of these mesas; similar dune sands can be seen in pits dug below the gypsum-cemented surface of the interdune *sabkhas*, which are at an elevation of some 80 to 90 m above sea level. The time of deposition of the dune sands has been dated as 12 ka (in pits) and 40 and 141 ka BP in the mesas, thereby indicating that both dune and *sabkha*-producing conditions have been repeated in the area; the younger dune sands were preserved by the rise in the level of the water table during the melting of the last high-latitude ice caps. In Sabkha Matti, the deflated relics of former dunes surrounded by damp *sabkha* indicate that, prior to the last rise in the level of the water table, this area also was the site of dunes migrating southward away from the present Arabian Gulf. Both the Sabkha Matti and Liwa *sabkhas* are products of the present high water table, which is associated with the current interglacial high sea level. During glaciations, *sabkhas* occurred in neither inland nor current coastal areas.

The *sabkha* is a dangerous place and chances should never be taken with one, its salt-encrusted surface often looking deceptively firm. Beneath the thin crust of the coastal *sabkha* the algal mat and underlying mush of gypsum crystals and clay-size carbonate has little bearing strength. Unwary humans are likely to break through the surface and sink to their knees, especially if the crust is new, while narrow-tyred vehicles can become a total loss. Inland *sabkhas* are little safer. A bedouin tribesman in search of fresh pastures after rain, is likely to test the feasibility of crossing a suspect surface by sending first sheep and goats in the care of young light-weight children, followed in turn by himself with the heavier camels, and then his wife driving a laden Toyota Landcruiser pickup truck.

Sand dunes

Away from the Oman Mountains and the Abu Dhabi coastline, the surface of the Emirates is dominated by the presence of sand dunes. *Dunes* migrate in the direction of the sand-transporting wind. With a *linear dune,* this is achieved by the movement of sand along the dune flanks and deposition (causing elongation) at its down-wind end; if the up-wind supply of sand ceases for any reason (e.g. flooding of the Gulf), that end of the dune 'shrivels' and the dune shortens as sand is removed and not replaced. The same principle applies to *transverse dunes*, but because their long axes are at right angles to the wind, sand is transported over the top of the dune to its leeward side (where it forms an *avalanche slope* with a maximum inclination of 34°) rather than around its flanks. Where the supply of sand is limited, crescent-shaped *barchans* are formed; here, in addition to the movement of sand over its crest to the avalanche slope, sand is also readily transported along the dune flanks, which are drawn out into the long 'horns' that point down wind. On a much smaller scale, the axes of *ripples* are always at right angles to the wind that formed them, so their distribution gives an indication of the pattern of wind flow over and around the dune.

Across central Abu Dhabi, a broad belt of large, partly eroded (deflated) north-west to south-east trending linear dunes skirt the north-east margin of the Liwa, and lose their linear character as the Oman border is approached; this is re-established where the dunes overlie the alluvial fans that flank the Oman Mountains (Fig. 1). To the north of Jebel Hafit, the dune axes swing towards the north-east as the mountains are approached (Besler 1982). These variable trends are thought to outline the fairly constant direction of dune-forming winds at, or shortly after, the peak of the last glaciation; since that time, the outlines of the dunes have been modified but the basic plan is still recognizable. Fitting into the same wind pattern are the giant *barchanoid* dunes (up to 150 m above the interdune *sabkhas*) of the Liwa. The axes of these dunes are also transverse to the dune-forming wind, which blew towards the south south-east. Travelling further to the west, the modern (and perhaps also the ancient) winds blow increasingly towards the south, eventually to veer south-westward across the central Rub al-Khali towards the mountains of Yemen. This semi-circular pattern is typical of what are known as *trade wind deserts* (following the same sort of path as the trade winds sought by sailing ships heading westward to the Americas) such as the Sahara or, in the southern hemisphere, the Australian desert.

The broad pattern of large dunes outlined above has been modified by the effects of changing sea level in the Gulf. When sea level rose at the end of the last glaciation, the supply of aeolian sand from the north was stopped. Although the wind still blew, its direction was out of equilibrium with the geometry of the existing dunes, so their shape became modified; these modifying winds apparently were not so strong as formerly, so the new resulting dune forms were smaller than the pre-existing large dunes. This can be seen by the belt of small transverse dunes that drape the northern and north-eastern margins of the Liwa.

Over the course of recent history, the trade winds have not been so constant in direction as one might imagine. Today's strongest sand-transporting wind (the northern *shamal*) at Abu Dhabi airport has shifted about 30° to the north relative to its Glacial equivalent, and the winds are more variable than they used to be. This variability is indicated by small west-east trending linear dunes that cross the interdune areas of the Awir oasis in southern Dubai, for instance, and other similar areas further north; it is also indicated south-west of Jebel Hafit by star-shaped peaks on some of the large linear dunes, which form when winds blow in more than one direction. Today's more variable dune pattern is thought to be a product of a wind system that is weaker than it was in Glacial time.

Every time the Arabian Gulf was flooded by the sea, shallow-marine organisms flourished and eventually died, many leaving the evidence of their former existence on the sea floor in the form of calcareous shells. When the Gulf floor was exposed to the wind during sub-polar glaciations, the smaller of these shells were transported southward to the Emirates where they formed carbonate dunes. Similar dunes near the coast of north-western India are known as 'miliolite' after their content of miliolid foraminifera, and the same name has been applied in south-eastern Arabia. Inland from the coast, miliolite is widely exposed, in many cases within the core of, or adjacent to, modern dunes (e.g. draping exposures of the Baynuna Formation in western Abu Dhabi, from Silmiya south to Hameem,at the eastern end of the Liwa, or the Abu Dhabi – Al Ain road south-east of Bani Yas). Along the Hameem road, two sequences of miliolite are separated by evidence of a wetter climate; the lower sequence has a depositional age of 99 ka BP and the upper of 64 ka BP, times when the sea surface was about 25 and 80 m, respectively, below the present level of the Arabian Gulf. A study of the bedding attitudes of the miliolite indicates variations in wind direction similar to those deduced for the modern dunes (Glennie 1994).

It is clear that the dune systems of the Emirates have been controlled not only by global shifts in wind direction, but also by glacially controlled changes in exposure of the Gulf floor, which in turn have controlled the distribution of both coastal and inland *sabkhas*. Those dunes and *sabkhas* are still reacting to today's climate and associated wind directions.

Brief History of the Quaternary in the Emirates

The early Quaternary history of the Emirates is very poorly known. The limited evidence from sparsely dated alluvial fans suggests that it was probably a time of much higher rainfall than now. By about a million years ago, or perhaps as late as half a million years BP, near-polar glaciations led, in the Gulf area, to cyclic repetitions of lower sea level and stronger winds that caused sand dunes to migrate southward, with the warmer interglacials giving higher rainfall and less active dunes. For the past 5000 years, we seem to have been heading slowly in the direction of increased aridity associated in the long term (80,000 years later?) with another full glaciation in high-latitude areas.

Conclusion

By extrapolation from elsewhere, the geological history of the Emirates and adjacent areas of Arabia over the past 600 million years or so seems to have been mostly one of relative stability. Following tropical shallow-marine conditions of sedimentation in the late Precambrian, the area was largely terrestrial during much of the succeeding Palaeozoic time span. Deep erosion preceded the Permian separation of a microcontinent from the eastern margin of Arabia; the following marine transgression was associated with the successive creation of Neo-Tethys 1 and 2. Throughout most of the Mesozoic era, the Emirates was the site of shallow-marine sedimentation except in the two branches of Neo-Tethys, where deep-marine deposition took place. This situation was brought to an end by closure of Neo-Tethys 1 and 2, and the obduction of deep-oceanic sediments and a slice of newly formed back-arc oceanic crust onto the Arabian continental margin to form an island arc. The succeeding shallow-marine limestone deposition was terminated in the east when the Oman Mountains began to be uplifted into a high range some 30 Ma BP, but stable conditions of sedimentation continued over the bulk of the Emirates until major glaciations began to induce lower global sea levels perhaps some two to five million years ago and created the present land surface. Near-polar glaciations have controlled sea level in the Arabian Gulf for at least the last 500,000 years, thereby also controlling the supply of dune sand from the north or the cutting off of that supply, with the resulting widespread deflation and creation of *sabkhas*.

Glossary of Geological Terms

abyssal plain: the almost horizontal floor of an ocean between the continental slope and mid-ocean ridge, commonly found at depths in excess of 4000 m.

accretionary wedge: a wedge of sedimentary rocks that was scraped off the surface of a down-going plate during subduction.

aeolianite: a consolidated sedimentary rock formed of wind-deposited sand; commonly, but not necessarily, rich in carbonate grains.

algal mat: a sheet of rubbery algae that covers the coastal *sabkha* surface after flooding.

allochthonous: term implying derivation or transport from elsewhere; the Hawasina and Semail are allochthonous because they did not originate where now found.

alluvial fan: a fan-like spread of fluvial distributary channels, commonly at the junction of mountain and plain; fans coalesce along the length of the Oman Mountains.

anhydrite: an evaporite mineral composed of calcium sulphate, $CaSO_4$, found in some sedimentary rocks. Often derived from *gypsum* by losing its *water of crystallization.*

autochthonous: a term implying an origin where now found, i.e. not transported from elsewhere. Noun: “autochthon”.

avalanche slope: also known as **slip-face.** The slope that forms when wind-blown sand from the windward side of a dune passes into the calm air of the leeward side. The sand will start to slip if further deposition would result in the maximum angle of repose for dry sand of 34° being exceeded.

back-arc: the arcuate area ‘behind’ the hanging wall of a subduction zone; it may be subjected to either compression or extension.

back-arc spreading: the process of creating new oceanic crust in the back-arc area behind a subduction trench.

barchan: see **dune.**

barchanoid dunes: see **dune.**

BP: abbreviation of Before Present, often given in Ka, thousands (K) of years (a).

capillary: resembling a hair; of very small bore. If a tube of very small bore is immersed in water, the water will rise up within the tube as a result of capillary attraction.

cap rock/seal: an impervious rock (seal) overlying a fluid-bearing reservoir.

carbonate: general term for calcium and magnesium carbonates (limestones and dolomites).

carbonate-compensation depth: the depth below which most carbonate particles become unstable and slowly dissolve.

chert: beds of finely crystalline deep-water silica.

Climatic Optimum: the state of an ideal climate; inferred for existing desert regions to have had sufficient annual rainfall to render the area an ideal place for man to live. Such conditions are thought to have prevailed over much of the Saharan and Arabian deserts between about 9000 and 6500 years ago.

continental crust: the lighter (less dense) of the two main types of the Earth’s crust, which forms most land masses but may extend below shallow seas.

continental shelf: that part of the sea floor between the coast and the marked change in slope at the shelf edge, whose depth averages about 120 m. Continental shelves vary in width from a few kilometres to over 1000 km.

continental slope & rise: the two form the slope (upper part, to perhaps 1500 m) of the ocean floor between the continental shelf edge and the abyssal plain at depths of about 4000 m or more.

convection current: the transfer of heat from one part of a fluid or gas to another by flow of the fluid or gas from the hotter parts to the colder. A fluid will rise if heated from below because, through expansion, it becomes less dense than the cold.

deflation: the blowing away of dry fine-grained rock material (sand and dust), by the wind. A form of aeolian erosion at work chiefly in deserts.

diapir, diapirism: salt (halite) is less dense than most other rocks and is easily deformed. When buried at depth, salt is more buoyant than overlying rocks; it may then withdraw sideways to create a vertical bulge (salt pillow) that deforms overlying strata into anticlines and, by breaking through them, create salt domes and even salt walls. This process is known as diapirism; the product of diapirism is a diapir.

dolomite: a calcium-magnesian limestone, commonly formed by alteration of shallow-marine limestone.

dune: accumulation of wind-blown sand that possesses one or more slipfaces. Its size is dependent on the availability of sand and the ability of the wind to carry sand to the top without removing it again. The finest sand grains are usually found at the crest. There are several types of dune but only those common in eastern Arabia are described here.

> **barchan:** crescent-shaped sand dune, which migrates downwind in the direction of its horns. It has a gentle windward slope and a slipface on its lee slope. Barchans sometimes unite laterally to form rather irregular *barchanoid dunes.*
>
> **barchanoid dunes:** cross between a *barchan* and a *transverse dune.*

linear dune: dune whose long axis is parallel to the prevailing dune-forming wind; it grows by extending downwind. Avalanche slopes, where present, are almost parallel to the axis of the dune and can face towards either flank. May occur as a swarm of parallel dunes as in the Rub al Khali or the Wahiba.

megadune: any large dune whose height exceeds about 60 m and has a crestal spacing of about 500 m or more. Most are thought to have formed during the last major glaciation.

star dune: a roughly star-shaped pyramidal dune with three or more radiating arms with slip faces. Thought to form where seasonal winds are strongly oblique to each other. May result also by modification of older transverse or longitudinal dunes.

transverse dune: a dune whose long axis is at right angles to the prevailing dune-forming wind. Likely to break up into barchanoid and then barchan dunes if the supply of sand is not maintained.

evaporites: minerals, mostly anhydrite, gypsum or halite (common salt), that are typically formed in areas where the rate of evaporation exceeds that of rainfall or fluvial influx (i.e. in desert areas).

Gondwana: an ancient mega-continent named after the Gond tribe of northern India. Comprised Antarctica, Australia, India, Afro-Arabia and South America. It began to split up into its modern components in the later Mesozoic.

gypsum: an *evaporite* mineral, Calcium Sulphate ($CaSO_4$.- 2(H_2O)), typically found just below the surface of coastal and inland *sabkhas.* Alters to *anhydrite* when it loses its *water of crystallization.*

Hawasina: an imbricate wedge of sediments of mid Permian to mid Cretaceous age that were deposited over the floor of Neo-Tethys 1.

hydrocarbons: any organic compound comprising carbon and hydrogen, usually refers to oil and gas.

Ka: abbreviation for thousands (**K**) of years (**a).**

limestone: calcium carbonate ($CaCO_3$), mostly of biogenic origin, and largely formed in shallow seas.

linear dune: see **dune.**

Ma: abbreviation for millions (**M**) of years (**a**).

magma: molten rock when still within the Earth's crust or mantle.

mantle: the part of the Earth, nearly 3000 km thick, that underlies crust of both continental and oceanic type.

maturation, maturity: the process of 'ripening' a source rock to the state where it generates oil or gas; the state of a source rock with respect to its ability to generate oil or gas. Considered to range from immature, before any oil or gas has been generated, through mature to post-mature, when no additional oil or gas can be generated from it.

megadune: see **dune.**

mesa: a mesa is a flat-topped plateau bounded on at least three sides by steep, commonly cliffed slopes. The bedding is normally horizontal. A **butte** is a very small mesa. Both are found in the Miocene strata of western Abu Dhabi.

microcontinent: a sub-continent or continental sliver calved from a major continental plate by processes of crustal separation and spreading.

mid-ocean ridge: a (mostly) submarine ridge that transects an oceanic area and is a locus of generation of new oceanic crust.

migration: the passage of a newly generated oil or gas out of a source rock (primary migration), and its movement via rock conduits to other locations, including hydrocarbon traps (secondary migration).

nappe: a large sheet-like rock unit that has been tectonically emplaced (thrust) over a dominantly sub-horizontal or low-angle floor (e.g. Semail Nappe of Oman Mountains); at the contact, older rocks overlie younger rocks, which is the reverse of what happens during deposition of normal sedimentary sequences.

nappe emplacement (obduction): the placing of a nappe above another (usually autochthonous) rock unit without implying whether this relationship was the result of over-thrusting or underthrusting.

Neo-Tethys I: that part of the ancient ocean Tethys formed when the Sirjan-Sanandaj microcontinent separated from the eastern (Arabian) margin of Gondwana.

Neo-Tethys 2: the ocean that separated Central Iran from Siran-Sarandaj.

obduction: the process by which former oceanic crust or a wedge of oceanic sediments comes to lie upon crust of continental type.

oceanic crust: the type of crust that characteristically underlies the Earth's oceans; it is denser than continental crust.

ophiolite: obducted oceanic crust, now separated from previously contiguous crust of oceanic type.

parautochthonous: a rock unit that is not quite autochthonous, and has undergone some (thrust) transport; e.g. the Ru'us al-Jibal rock units.

pillow lava: the pillow-like masses of rock that form when magma is extruded below water and chilled rapidly.

plate: one of the major areas of the Earth's crust, normally comprising continental and contiguous oceanic crust.

plate tectonics: the processes by which the Earth's crustal plates are formed and interact with each other.

porosity: the pore spaces within a rock; in oil fields, these pores are filled with oil or gas.

reservoir, reservoir rock: any rock that can contain moveable fluids in its pore spaces.

ripple: a surface undulation, generally of unconsolidated sand, whose wavelength depends on wind strength and is constant with time. The ripple axis is always transverse to the wind. The coarsest grains are found at the crest.

The ripple height depends on the range of grain sizes present and the wind strength.

sabkha**:** a flat area of clay, silt or sand, commonly with crusts of salt. Subdivided into:

1) **coastal *sabkha*:** a coastal flat at or just above the level of normal high tide. Its sediments consist of sand, silt or clay and its surface is often covered with a salt crust formed by the evaporation of water drawn to the surface by capillary action or from occasional marine inundations. The coastal *sabkha* is characterized by the presence of algal mats and the occurrence of gypsum and anhydrite within its sediment. It is subject to *deflation* down to the water table.
2) **inland *sabkha*:** a flat area of clay, silt or sand, commonly with saline encrustations, that is typical of desert areas of inland drainage and some interdune areas. Their salts may be formed by evaporation of surface water, or of water drawn to the surface from the water table by capillary action.

salt dome: a dome-shaped structure caused by the upward penetration of a circular plug of salt, commonly 1-2 km in diameter, through overlying strata; the plug may also give strata through which it fails to penetrate a domal shape.

Semail Nappe: the name given to the huge ophiolite nappe of the Oman Mountains.

Semail ophiolite: the huge ophiolite slab of the Oman Mountains typically comprising peridotites and harzburgites, partly serpentinized, gabbros and basaltic pillow lavas.

shamal**:** Arabic word for north: applied to north or northwest wind that blows down the Arabian Gulf and clockwise across the Rub al-Khali.

star dune: see **dune.**

source rock: a rock rich in organic matter which, if heated sufficiently, will generate oil or gas.

subduction: the process at a plate margin of crustal consumption down a subduction zone.

subduction zone: a sloping linear zone down which crust and overlying sediment of mostly oceanic type passes into the mantle beneath the edge of another plate, commonly but not exclusively of continental type.

temperature gradient: the change in temperature measured over a given distance; usually measured in °C/km. Often used to calculate depth at which source rocks become mature.

thrust: a reverse fault or slide plane, on which older rocks have been emplaced over younger ones.

thrust sheet: a sheet of rock that has been tectonically emplaced over a younger rock sequence, the two units commonly being separated by a relatively low-angle thrust plane: a nappe.

Trade Wind Desert: a term sometimes applied to those deserts in subtropical land areas that are crossed by the *trade winds*.

transverse dune: see **dune**.

trap: any deformation (fold, fault, wedge-out) of a reservoir rock/seal couplet that can cause hydrocarbons to be trapped as they migrate from their source rocks.

turbidite: the sedimentary deposit that settles out from a turbidity current; its sediment is commonly graded from coarse at the base to fine at the top.

turbidity current: high velocity current of relatively dense turbid sediment and water that occasionally flows across the floor of some ocean basins from a site usually high on the adjacent continental slope.

wadi: desert watercourse, dry except after rain, or a valley where water may continue to flow intermittently.

water of crystallisation: the water present in hydrated compounds such as gypsum ($CaSO_4.2H_2O$). If the temperature of the gypsum crystal is raised above about 50°C, either by deep burial or by near-surface heating in a desert, it loses its water of crystallisation ($2H_20$) and becomes the anhydrous mineral *anhydrite (*$CaSO_4$).

window: an area where erosion has cut down through a thrust plane to expose the underlying rocks: e.g. Hagil Window in the south-west Ru’us al Jibal.

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