Late Miocene Palaeoenvironments in Arabia: A Synthesis

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Faunal interchange, along with biotic interaction in situ, is viewed as a significant process in the evolution and differentiation of terrestrial mammalian communities during the Neogene (Barry et al., 1985, 1990; Flynn et al., 1991; Janis, 1993; Barry, 1995; Opdyke, 1995; Vrba, 1995). The timing and location of these intercontinental migratory events are mediated to an extent by climatic and tectonic events, which can facilitate dispersal by the formation of “corridors” in regions where interchange was previously restricted by geographical or ecological barriers. As barriers are transgressed, speciation and extinction occur as introduced fauna interact with novel ecosystems. Major faunal turnovers in terrestrial successions have been linked with the creation of corridors formed by low sea-level stands or by the tectonic reshuffling of landmasses (Barry et al., 1985; Thomas, 1985). Alternatively, the formation of barriers can separate previously continuous populations, resulting in speciation by vicariance.

Continental plate movement, in addition to controlling the configuration of connections between landmasses (Rögl, 1999—Chapter 35) and development of potential orogenic barriers (Partridge et al., 1995), can contribute to climatic variability, which provides an additional filter to faunal migration. Alteration of the arrangement of marine basins and hence ocean circulation patterns, generation of topographic highs, and formation of volcanic fronts erupting volcanic debris into the atmosphere can all have profound effects on climatic conditions and atmospheric circulation patterns. Shifts in climatic filters that influence dispersal can occur independently of plate tectonic events as a result of orbital perturbations (Milankovitch, 1930; Imbrie and Imbrie, 1980) or meteoric impacts (Hut et al., 1987). Climatic variation influences dispersal by changes in sea level associated with increasing or decreasing glaciation, altering the structure and composition of plant communities and affecting weather conditions or seasonality patterns.

The primary and most obvious means of documenting faunal migrations in the past is by comparing fossil faunal assemblages from sites of various ages and regions (Thomas et al., 1982a; Bernor et al., 1987; Le Loeuff, 1991; Bonis et al., 1992). This approach, however, is complicated by taphonomic effects (Hill, 1987), discrepancies between researchers in assigning taxonomic identification to extinct faunas, and in general by a paucity of information (see Hill and Whybrow, 1999; Hill, 1999—Chapters 2 and 29). Palaeobiogeographical reconstructions benefit greatly from an understanding of the potential dispersal routes and the existence or development of palaeoecological or palaeogeographical obstacles. In this regard, the Arabian Peninsula and the area immediately to the north (the remaining part of the Arabian Plate) is pivotal in assessing faunal interchange in the Old World during the late Miocene. This region forms the intersection of three continents and it is likely to have had a significant role in the movement of fauna between Africa, South Asia, and Europe. Notable palaeontological events in this part of the Old World during the late Miocene include the establishment of the modern East African fauna, which involved the replacement of more archaic middle Miocene forms by taxa more closely related
to extant species (Hill, 1995), a series of significant synchronous first and last appearances in the fossil record of the Siwalik succession in Pakistan (Barry et al., 1990; Barry, 1995), the spread of grassland-adapted fauna (Gabunia and Chochieva, 1982; MacFadden and Cerling, 1994), and the origin of the human lineage (Hill and Ward, 1988; Hill, 1994).

By late Miocene Baynunah times, palinspastic (palaeogeographic) reconstructions of the region place the Arabian Plate roughly in its modern configuration relative to the African and Eurasian Plates (Briggs, 1995). Connections between the Eastern Paratethys and the Indo-Pacific had been severed permanently by the Afro-Arabian Plate impinging onto the Eurasian continent 12–14 million years (Ma) ago (Lyberis et al., 1992; Rögl, 1999—Chapter 35). Development of the modern-day extension of the Red Sea, Arabian Gulf, and Gulf of Aden was incomplete during the mid- to late Miocene and did not form the geographic barriers they do today along the margins of the Arabian Peninsula (Coleman, 1993). No consensus exists regarding the initial stages of rifting in the Red Sea but evidence for extension and widespread volcanism extends back to at least the early Miocene, at which time the structural shape of the Red Sea depositional basin was defined (Coleman, 1993). Although there is evidence that the Red Sea trough occasionally contained deep-water sediments during the Miocene (Crosley et al., 1992), extensive evaporitic sequences throughout this interval suggest episodic batch filling of the basins followed by evaporitic draw-down and shallow-water evaporation associated with sabkhas.

**Present Climate**

Considering that the regional geographic and tectonic setting of the Arabian Peninsula has remained consistent over the past 15 Ma, the modern climate represents a valuable model for attempts to understand the palaeoclimatic patterns that may have influenced the region in the past. Presently lying between 12° and 38° N, the Arabian Peninsula straddles the subtropical high-pressure belt and much of the area is today climatically arid or semiarid, dominated by subtropical deserts. Several major climatic regimes interface in this region and the climate and weather of the Arabian Peninsula are influenced by a complex variety of seasonal combinations of high- and low-pressure systems superimposed on annual solar variations. These include the year-round equatorial lows, ridges of the Azores High and seasonal anticyclones, the regional highs lying over the Armenian Plateau in the cool half of the year, summer depressions over Pakistan and the Arabian Gulf, winter lows from the Mediterranean Sea, and depressions from the Sudan in the transition seasons (Hastenrath, 1985; Roberts and Wright, 1993; Schneider, 1996). The Yemen highlands in the extreme southern portion of the Arabian Peninsula manage to intercept some of the moisture borne by the southwestward South Asian monsoon summer winds. An important factor mediating the interplay between these circulation systems is the relief of the region, characterised by a northeastward inclination with considerable altitude along the western and southern margins. The meridional mountains of Lebanon effectively block the influence of the Mediterranean and the westerly circulation in the winter, most of which travels well north of the Arabian Peninsula anyway, while the Kurdistan and Zagros Mountains check the southward flow of winter air.

The northern portion of the peninsula receives most of its precipitation during the winter half of the year in association with middle- to high-latitude westerly depressions whose tracks are steered by the subtropical jet stream (Wigley and Farmer, 1982). Most of the precipitation falls to the north but occasionally moist air masses penetrate to the interior of the peninsula. Central African depressions lie over the western part of the Arabian Peninsula from October to April but are usually too shallow to bring precipitation. Occasionally, depressions from northern Egypt reach the Arabian Peninsula where they affect the weather along the Red Sea as far as the Kamaran Island and possibly even as far as Bahrain. In the interior of the Arabian Peninsula,
rainfall is typically no greater than 50–100 mm and in the Rub' al Khali and along the Gulf of Aden it is even less. Exposed to the minimal influence of the Indian monsoon, the Arabian Sea coast receives little more than 50 mm of rainfall while the Yemen Mountains get 200–400 mm. The interior averages less than 10 rain days a year while the monsoonal part of the Arabian Peninsula coast exceeds 25 days. Mean surface temperatures over the central Arabian Peninsula average 15 °C during the winter with variation associated with elevation (Schneider, 1996).

The thermal low centred over the Arabian Gulf effectively influences the weather and its constancy in summer. The beginnings of this low are felt in April and it is at its deepest in July and August. During the summer, the rather dry northerly and northwesterly etesian winds dominate this region. Thermal stratification in the tropical trade-wind circulation zone does not promote cloud formation between May and November. Very low evaporation also accounts for the considerable cloud cover and rainfall. Over 80–90% of days in Iraq are clear and clouds appear on only 35–40 days in winter. Around the Gulf of Oman and Arabian Gulf, the monsoon increases the relative humidity to over 50–60%. While the mean surface temperature during the summer is 34 °C, the mean maximum surface temperature can reach 45 °C.

Dust storms are characteristic of the arid and semi-arid zones. They are associated both with strong convection along a cold front and with strong, constant winds that transport dust and sand. In the Arabian Peninsula, these storms can affect immense areas, from the Syrian Desert to the Rub' al Khali. They pass over the eastern, less-elevated half of the peninsula, directed from the west by mountains over 1000 metres high. In the south their progress is restricted by the mountains near the Arabian Sea, and in summer by the presence of the intertropical convergence zone and the southwest monsoons associated with it. A prominent physiographic feature of the peninsula is large sandy deserts referred to as sand seas or ergs.

Acolian sands cover 770,000 km² or almost 90% of the peninsula’s land surface (Whitney et al., 1983).

**Past Climates**

As the Miocene terrestrial palaeoenvironmental record remains poorly known, interpretations of climatic trends in tropical (low-latitude) terrestrial regions during the past 20 Ma have been drawn heavily on global events recorded in the marine record, and to a limited extent from terrestrial sequences elsewhere. This period of time incorporates several major fluctuations in worldwide climate and the onset of Milankovitch mid-latitude northern hemisphere glaciation (deMenocal and Rind, 1993). All of these probably had profound effects on the evolution of the Arabian fauna and flora. In the long-term evolution of global climate, Neogene climatic conditions appear to reflect a continuation of the general trend documented for the past 100 Ma, characterised by a shift from the mid-Cretaceous thermal maximum to a world dominated by bipolar ice sheets. Antarctic and Southern Ocean cryospheric development occurred throughout the Cenozoic while northern hemisphere glaciation developed in the latest Neogene (Miller et al., 1987). This sequential cooling and cryospheric development did not occur uniformly but rather as a series of abrupt shifts representing threshold events (Kennett, 1995). Accompanying this cooling trend was a presumed increase in aridity in low latitudes (Shackleton and Kennett, 1975a). Explanations for the trend are incomplete but research so far suggests that several processes are involved in this long-term evolution of climate. They include shifting orbital parameters, changes in continent–ocean distribution, ocean heat transport, orography, and atmospheric CO₂ levels (Crowley and North, 1991; Prell and Kutzbach, 1992). The following discussion provides an overview of global and continental Miocene climatic trends and changes that may be relevant for interpreting the evolution of landscapes in Arabia during this period.
Early to Middle Miocene (23–12 Ma)

Before the final establishment of the east Antarctic Ice Sheet in the mid- to late Miocene, the early Miocene (23–15.6 Ma) global climate was relatively warmer, and global ice volume was low as is indicated by $\delta^{18}O$ values of planktonic and benthic marine foraminifera (Haq, 1980). $\delta^{18}O$ values between 19.5 and 15 Ma are the lowest in the Neogene, reflecting the climax of Neogene warmth. Antarctica apparently became thermally decoupled from the north, and Antarctic waters continued to cool (Grobe et al., 1990; Kennett and Barker, 1990). Haq (1980) hypothesized that warming of the Atlantic would have been favourable for the existence of widespread lowland forest in Africa. Andrews and Van Couvering (1975) also suggested a homogeneous landscape like the modern Congo Basin across much of eastern and central Africa during the early Miocene. They postulated that as rifting was in its initial stages, orographic barriers associated with crustal doming did not yet exist to prevent moist air masses from the Atlantic reaching the East African plateau, and possibly the Arabian Peninsula. Based on an examination of habitat and ecological diversity spectra, Van Couvering (1980) and Nesbit Evans et al. (1981) also suggested widespread equatorial rainforest communities in eastern Africa at 23–17 Ma. Axelrod and Raven (1978), however, proposed a more complex vegetational history for eastern Africa during this period, in which grassland and woodland communities were established as early as 23 Ma based on microfossil and macrofossil floras from the Ethiopian Highlands that indicate dry-adapted vegetation.

Following this interval of climatic amelioration in the early to middle Miocene was the onset of significant cooling at about 15 Ma. This reflects major expansion of the east Antarctic ice sheet (Kennett and Barker, 1990), renewed cooling at high latitudes and deep oceans, and important changes in deep oceanic circulation (Flower and Kennett, 1994). This dramatic shift to colder climates reflects a critical threshold in climate evolution during the Cenozoic (Kennett, 1995) and represents the onset of climatic and oceanic circulation patterns that characterise and dominate the late Neogene. The expansion of grasslands and of grazing-adapted faunas has been described in South America (Pascual and Juareguizar, 1990), Australia (Stein and Robert, 1985), and North America (MacFadden and Cerling, 1994). The Afro-Arabian Plate converged with the Asian Plate in the middle Miocene bringing to an end the moderating influence of the Tethys Sea on the climate of the Africa/Arabian continent. As the warm Tethys Sea with its associated moist air masses was disrupted, drier conditions and extremes of temperature may have increased over lowland areas of Africa and Arabia (Axelrod and Raven, 1978; Williams, 1994). Although the palaeobotanical record of Africa is poor for the Miocene after about 17 Ma, the current consensus is for a spread of savannah, deciduous forest, thorn forest, and sclerophyllous vegetation at the expense of rainforests (Axelrod and Raven, 1978; Van Couvering, 1980; Bonnefille, 1984; van Zinderen Bakker and Mercer, 1986; ). Carbon and oxygen isotopic analyses of palaeosol carbonates and organic matter from various localities in East Africa, however, suggest that while there may have been a gradual increase in C$_4$ grasses and aridity over the past 20 Ma, Serengeti-type grasslands are a relatively recent phenomena (Cerling, 1992; Kingston et al., 1994).

Late to Terminal Miocene (12–5.5 Ma)

The late Miocene (12–6.5 Ma) represents a prolonged period of cool climate, with average $\delta^{18}O$ values consistently higher than the early Miocene, punctuated by two distinct cooling events recorded in the marine record. The earliest occurred between 12.5 and 11.5 Ma and the second between 11 and 9 Ma. This latter event was manifested by major growth of the Antarctic Ice Sheet (Shackleton and Kennett, 1975a,b), 4–5 °C cooling of deep-ocean bottom water (Miller et al., 1987), and a worldwide temperature drop of 7 °C (Tiwari, 1987). Expansion of polar ice may have caused the dramatic drop in sea level recorded at 11–10 Ma (Moore et al., 1987). Vincent and Berger (1985) suggested that this event was related to a draw-
down of atmospheric CO₂ caused by changes in upwelling that increased the removal of carbon from the oceanic sink into sediments. This event was followed by a period of relative warmth during the middle part of the late Miocene, 9–7 Ma (Haq, 1980; Kennett, 1982).

Associated with these Miocene changes was a significant increase in aridity documented by an increase in aeolian deposition throughout the late Cenozoic (Rea et al., 1985), high-latitude shifts in vegetation to more seasonal and arid-adapted flora (Wolfe, 1985), and a hypothesised general transition from forested environments to habitats with abundant grasses (Potts and Behrensmeier, 1992; Williams, 1994). Such shifts have been documented in both western North America (Axelrod and Raven, 1985) and Australia (Tedford, 1985). At 7.4–7.0 Ma, Quade et al. (1989) detected a dramatic shift from vegetation dominated by C₃ plants (forest/grassland) to one dominated by C₄ (grassland) plants in the Siwalik sediments of Pakistan, possibly correlated with inception or strengthening of monsoonal conditions due to uplift of the Tibetan Plateau or to declining atmospheric pCO₂ (Cerling et al., 1993). In India, humid forest taxa rapidly retreated eastwards to areas of moister climate during this period (Prakash, 1972). Fossil macroflora from the southwestern Cape of South Africa indicate replacement of subtropical rainforest by the present “fynbos” or macchia (Coetzee, 1978) and the transition to a Mediterranean type of climate. Evidence of vegetation in East Africa during this period does not support the widespread replacement of forests by grasslands but rather a persisting heterogeneous landscape (Cerling, 1992; Kingston et al., 1994).

The terminal Miocene to early Pliocene (6.5–5.5 Ma) is characterised by extensive climatic variation, which resulted in significant changes in the size of the polar ice sheet. At the Miocene–Pliocene boundary (5.5 Ma) the Antarctic Ice Sheet may have exceeded its glacial maximum extent by as much as 50% (Shackleton and Kennett, 1975b; Denton, 1984), resulting in an appreciable drop in global sea level of up to 50 metres. The drop in sea level coupled with the closure of the Straits of Gibraltar, due to tectonic impingement of the African Plate against Europe, resulted in the Messinian Salinity Crisis (Hsu et al., 1977; Stein and Sarnelet, 1984; Hodell et al., 1986), which involved the isolation and eventual desiccation of the Mediterranean Sea. The thickness of evaporative sequences in the Mediterranean Basin suggests that the cycle of evaporation must have been repeated about 40 times in the latest Miocene. Climatic deterioration manifested as increasing aridity in low latitudes may have had a significant influence on the African and Arabian flora as the Red Sea Basin was also dry during this interval (van Zinderen Bakker and Mercer, 1986).

**Miocene Palaeoenvironments of the Arabian Peninsula**

**Early to Middle Miocene**

Known empirical evidence of terrestrial environments on the Arabian Peninsula during the early to middle Miocene is limited to continental sediments and associated fossil fauna and flora exposed in four areas of eastern Saudi Arabia (Powers et al., 1966; Hamilton et al., 1978; Thomas et al., 1978; Thomas, 1982; Whybrow et al., 1982; Whybrow, 1984; Whybrow, 1987; Whybrow et al., 1990) and the western part of the Emirate of Abu Dhabi (Whybrow et al., 1990; Whybrow et al., 1999—Chapter 4; Bristow, 1999—Chapter 6). These deposits have been divided into the late early Miocene Hadrukh Formation (c. 19–17 Ma), the overlying late early Miocene Dam Formation (c. 17–15 Ma), and the middle Miocene Hofuf Formation in Saudi Arabia and the middle Miocene Shuwaihat Formation in Abu Dhabi.

Table 27.1 presents a compilation of palaeoenvironmental data derived from lithofacies studies and analyses of fossil material recovered from these sequences. In general, the data indicate that this portion of the early to middle Miocene Arabian Peninsula was dominated by more open environments than during the Eocene (As-Saruri et al., 1999—Chapter 31) and Oligocene (Thomas et al., 1999—Chapter 30). Interpretations of the fauna
<table>
<thead>
<tr>
<th>Basis of reconstruction</th>
<th>Formation</th>
<th>Site</th>
<th>Age</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eocene of Wadi Rayan, and Fayum of Egypt</td>
<td>Fossil fruits and seeds, family ?Nymphaeaceae</td>
<td>Kaninah</td>
<td>Kaninah, southern Yemen</td>
<td>Middle Eocene</td>
</tr>
<tr>
<td>Tropical lowland evergreen forests</td>
<td>Family Anonaceae</td>
<td>Kaninah</td>
<td>Kaninah, southern Yemen</td>
<td>Middle Eocene</td>
</tr>
<tr>
<td>Strongly seasonal climate with marked rainy season</td>
<td>Sedimentary lithofacies (lack of evaporites, the presence of siliciclastics, and of broad permanent lakes with carbonate sedimentation)</td>
<td>Ashawq (Shizar Member)</td>
<td>Taqah, Oman</td>
<td>c. 33 Ma</td>
</tr>
<tr>
<td>Semi-arid climate</td>
<td>Erycine snake and embithropod <em>Arsinotherium</em></td>
<td>Ashawq (Shizar Member)</td>
<td>Taqah, Oman</td>
<td>c. 33 Ma</td>
</tr>
<tr>
<td>Open savannah</td>
<td>Bovids</td>
<td>Hadrukh</td>
<td>Eastern Province of Saudi Arabia</td>
<td>Late early Miocene</td>
</tr>
<tr>
<td>Dry rather than arid (freshwater environment containing dissolved solutes probably concentrated by evaporation)</td>
<td>Fossil fruits (<em>Midravalva arabica</em> of the family Potamogetoneae—pondweeds and ditch grasses—and sediments)</td>
<td>Hadrukh</td>
<td>Jabal Midra ash-Shamali, Eastern Province of Saudi Arabia</td>
<td>Late early Miocene</td>
</tr>
<tr>
<td>Palm wood</td>
<td>Fossil wood</td>
<td>Hadrukh/Dam</td>
<td>Ad Dabtiyah, Saudi Arabia</td>
<td>19–17 Ma</td>
</tr>
<tr>
<td>Woodland habitat</td>
<td>Rhinoceroses</td>
<td>Hadrukh/Dam</td>
<td>Ad Dabtiyah, Saudi Arabia</td>
<td>19–17 Ma</td>
</tr>
<tr>
<td>Environment</td>
<td>Fossil or Microfauna</td>
<td>Location</td>
<td>Site Details</td>
<td>Date</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
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<td>------------</td>
</tr>
<tr>
<td>Forest</td>
<td><em>Dorcattherium</em></td>
<td>Hadrukh/Dam</td>
<td>Ad Dabtiyah, Saudi Arabia</td>
<td>19–17 Ma</td>
</tr>
<tr>
<td>Forest if okapi is used as modern analogue, savannah if giraffe is used</td>
<td><em>Canthumeryx</em></td>
<td>Hadrukh/Dam</td>
<td>Ad Dabtiyah, Saudi Arabia</td>
<td>19–17 Ma</td>
</tr>
<tr>
<td>Tropical to subtropical near-shore environment, tidal flats, and a large estuarine system</td>
<td>Vertebrates (general)</td>
<td>Hadrukh/Dam</td>
<td>Ad Dabtiyah, Saudi Arabia</td>
<td>19–17 Ma</td>
</tr>
<tr>
<td>More open type of woodland and bushland</td>
<td>Microfauna</td>
<td>Dam</td>
<td>As Sarrar, Saudi Arabia</td>
<td>17–15 Ma</td>
</tr>
<tr>
<td>More forested</td>
<td>Dominance of browsing vertebrate fauna</td>
<td>Dam</td>
<td>As Sarrar, Saudi Arabia</td>
<td>17–15 Ma</td>
</tr>
<tr>
<td>Mangroves—tropical climate</td>
<td>Fossil roots</td>
<td>Dam</td>
<td>Dawmat al 'Awdah, Saudi Arabia</td>
<td>17–15 Ma</td>
</tr>
<tr>
<td>Palm wood</td>
<td>Fossil wood</td>
<td>Dam</td>
<td>South of Jabal Dawmat al 'Awdah, Saudi Arabia</td>
<td>17–15 Ma</td>
</tr>
<tr>
<td>Open milieu</td>
<td>Vertebrate fauna</td>
<td>Hofuf</td>
<td>Al Jadidah, Saudi Arabia</td>
<td>c. 14 Ma</td>
</tr>
<tr>
<td>Open environment with marked aridity</td>
<td>Vertebrate fauna</td>
<td>Hofuf</td>
<td>Al Jadidah, Saudi Arabia</td>
<td>c. 14 Ma</td>
</tr>
<tr>
<td>Alternating interdune and coastal type sabkhas, transverse and barchanoid dunes, and river systems; evidence of marine sediments within the basin</td>
<td>Sedimentary lithofacies</td>
<td>Shuwaithat</td>
<td>Abu Dhabi, UAE</td>
<td>Miocene</td>
</tr>
</tbody>
</table>

**Notes:**
- Middle Miocene (unconformably underlying the Baynunah Formation)
from the Dam Formation at As Sarrar as browser-dominated (Thomas et al., 1982b), and selected taxa from the Hadrukh/Dam Formation at Ad Dabtiyyah as forest dwellers (Gentry, 1987a,b), suggest limited existence of more closed habitats, possibly along river or lake margins. As pointed out by Whybrow and McClure (1981), Whybrow (1984), and Thomas (1982), the suggestion of widespread and persisting aridity during the early to middle Miocene in this region (Kortlandt, 1972; Sen and Thomas, 1979; Thomas, 1979; C. T. Madden, USGS written communication, in Whitney et al., 1983) is unsupported. But aeolian lithofacies reflecting large-scale transverse and barchanoid dunes interbedded with sabkha facies in the middle Miocene Shuwaihat Formation (Bristow, 1999—Chapter 6) indicates that arid to hyperarid conditions existed locally if not extensively at times. These dune forms are characteristic of very dry inland desert regions where vegetation is sparse, sand supply is limited, and winds almost unidirectional (Pye and Tsoar, 1990). An evaporitic sequence 2 metres thick at the top of the Dam Formation, Qatar (Whybrow, 1984) also supports intermittent arid conditions.

In contrast to interpretations of widespread equatorial rainforest in Africa (Andrews and van Couverying, 1975; Nesbit Evans et al., 1981; Van Couverying, 1980) and more forested conditions in the Siwaliks of Pakistan (Quade and Cerling, 1993; Morgan et al., 1994) during the early Miocene, environments of the early Miocene of the Arabian Peninsula appear to have been dominated by more open woodland or bushland ecosystems. Postulated increasing low-latitude aridity during the middle Miocene may be reflected in the dune and sabkha facies of the Shuwaihat Formation.

Late Miocene

The Baynunah succession (8–6 Ma) provides the only late Miocene evidence for palaeoenvironments on the Arabian Peninsula. As the late Miocene terminates with the Messinian Salinity Crisis, there has been speculation that the Arabian Peninsula was characterised by increasingly arid conditions during the time leading up to this event. Noting an increase in aeolian sedimentation in deep-sea cores (Leinen and Heath, 1981; see also Rea et al., 1985), Whitney et al. (1983) suggested that the late Miocene in Arabia may be more arid and/or experienced greater wind intensities than at present. Also citing evidence for xerophytic vegetation in central Africa in the late Miocene based on pollen studies (Maley, 1980), Whitney et al. (1983) hypothesised that the Arabian Peninsula was also arid as it lies within the same climatic belt. Research on sand seas (ergs) on the Arabian Peninsula led Brown (1960) and Holm (1960) to suggest that the sand bodies formed during a dramatic increase in aridity near the end of the Tertiary or Quaternary. In evaluating the data presented by Whybrow and McClure (1981), C. T. Madden (USGS written communication, in Whitney et al., 1983) interpreted the sediments as having been deposited in a hot arid to semi-arid climate. Although these scenarios do not seem unreasonable in the context of apparent global climatic trends during the late Miocene, available evidence from the Baynunah Formation does not corroborate these notions of aridity.

Information bearing on the palaeoenvironment of Baynunah times is summarised in table 27.2 and indicates environments ranging from grassy woodlands to wooded grasslands. As these deposits are primarily fluvial, much of the data provides information about conditions within the river system (Friend, 1999; Jeffery, 1999; Forey and Young, 1999; Lapparent de Brin and Dijik, 1999; Rauhe et al., 1999—Chapters 5, 10, 12, 13, and 14), indicating a major drainage system comprised of diverse microhabitats ranging from deep open bodies of water, to moderately fast-moving currents, to quiet, shallow water. Although the ancient river system undoubtedly had great significance for the regional flora and fauna, these reconstructions do not provide direct information relating to terrestrial environments distal to the ancient river system. The river may have been flowing through an arid region or alternatively more humid, tropical ecosystems. Terrestrial fauna associated with the river system, however, include a wide range of taxa such as large boids, suids, elephantids, equids, carnivores, and a cercopithecid (Whybrow et al., 1990). These suggest communities relying on extensive resources in
a region dominated by wooded grasslands, rather than being confined to a riparian forest isolated within a desert-like region. Isotopic analyses of palaeosol carbonates, herbivore enamel (Kingston, 1999—Chapter 25), and ratite eggshells (Ditchfield, 1999—Chapter 7) support such an interpretation. Interpreted adaptations of pulmonate gastropods (Mordan, 1999—Chapter 11) and species of Clarias (Forey and Young, 1999—Chapter 12) hint at the possibility of seasonality in precipitation during Baynunah times.

**DISCUSSION**

In contrast to the apparently more open environments of the Arabian Peninsula during the Miocene, limited environmental data from the Eocene and Oligocene indicate that the region may have supported more forested habitats. Components of an assemblage of fossil fruits and seeds recovered from the middle Eocene Kaninah Formation, in the southern part of the Republic of Yemen, suggest affinities to modern tropical lowland evergreen forests (As-Saruri et al., 1999—Chapter 31). Aspects of the palaeoflora are similar to those described from the Eocene and Oligocene of Egypt. Terrestrial sediments with a diverse vertebrate record indicate a marginal–littoral depositional environment along the Oligocene coast of Oman (Thomas et al., 1999—Chapter 30) at the site of Taqah. Despite interpretations of a semi-arid palaeoclimate based on calcareous crusts and the presence of an euryne carinate and of the embithroloid Arioithiterium (Thomas et al., 1991), overall sedimentological criteria suggest a strongly seasonal climate with a marked rainy season (Thomas et al., 1999—Chapter 30) (see table 27.1). Emphasis is placed on the resemblance of the Taqah faunal assemblage to that of the Oligocene Jebel Quatrani Formation of the Fayum in Egypt (Thomas, 1999—Chapter 30), which has been interpreted as possibly representing a forest assemblage (Fleagle, 1988). Any comprehensive understanding of phytogeographic trends during the Tertiary in this region is compromised by the limited data relating to palaeohabitats, but available information is consistent with the possibility of a transition from forested to more open habitats during the late Oligocene/early Miocene.

Climatic information deciphered from deep-sea cores (Prell et al., 1992) and general circulation models (Ruddiman and Kutzbach, 1989; Prell and Kutzbach, 1992) suggest that the climatic conditions of the Arabian Peninsula have varied considerably in the past. Although most of the peninsula today lies beyond the influence of the South Asian and African monsoon systems, the origin and dynamics of the monsoons had a direct if not indirect effect on the evolution of climate there. Appre- ciable uplift of the Tibetan Plateau about 8 Ma (Molnar et al., 1993) has been linked to an intensification of monsoonal patterns recognised by changes in marine microfossils in the Arabian Sea and western Indian Ocean (Kroon et al., 1991; Prell et al., 1992). This uplift continued intermittently during the Miocene and affected the development of the easterly jet stream that today brings dry subsiding air to the Arabian Peninsula. Major shifts in the fauna and flora from the Siwalik succession of the Potwar Plateau have been linked to climatic change resulting from this uplift (Barry et al., 1990; Quade and Cerling, 1995). Changes in orbitally induced solar radiation associated with this modification of atmospheric circulation patterns no doubt affected environments of the Arabian Peninsula during the late Miocene as did conditions associated with the onset of the Messinian Salinity Crisis.

High-resolution studies of Pleistocene lacustrine deposits in the Arabian Peninsula (McClure, 1978; Kuzmbach et al., 1993; Roberts and Wright, 1993) reveal a series of changes in lake levels that reflect shifts in climatic regimes possibly driven by changes in the intensity of the monsoons. Assuming that the complexity of factors controlling the climate and environments of the modern Arabian Peninsula existed in the past, minor perturbations in the circulation patterns across Africa, the Indian Ocean, the Mediterranean, or regions to the north during the Miocene could have had major effects on the habitats present in this region.
Table 27.2. Palaeoenvironmental reconstructions of the Baynunah Formation

<table>
<thead>
<tr>
<th>Palaeohabitats</th>
<th>Basis of reconstruction</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diverse river system with large, deep, and open bodies of water (either lakes or slow- to fast-moving rivers) with shallow banks indicated by the [i]avialis specimens; <em>[Crocodylus]</em> has the ability to negotiate river sections with steep banks</td>
<td>Crocodylidae</td>
<td>Rauhe et al., 1999 (this vol., Chapter 14)</td>
</tr>
<tr>
<td>Grassy woodland/bushland vegetational physiognomy associated with the fluvial deposits with possibly more open grasslands distal to the river system</td>
<td>Stable carbon isotopic analysis of palaeosol carbonate and hervibore enamel</td>
<td>Kingston, 1999 (this vol., Chapter 25)</td>
</tr>
<tr>
<td>Aeolian sands in arid environment</td>
<td>Plant root moulds</td>
<td>Glennie and Evamy, 1968</td>
</tr>
<tr>
<td>Fluvial deposition with no evidence of marine influence; gravels containing transported bones deposited by currents flowing with speeds of tens of centimetres (per second?); rivers appear to have been variable in flow, probably 3–10 metres deep during flood stage, and braided in the sense that they contained many sediment bars, and channels of varied size and form; palaeosols indicate periodic subaerial exposure</td>
<td>Lithology of the lower Baynunah Formation</td>
<td>Friend, 1999 (this vol., Chapter 5)</td>
</tr>
<tr>
<td>Dietary reliance on both C3 and C4 vegetation (wooded grassland and grassy woodland)</td>
<td>δ13C of ratite eggshells</td>
<td>Ditchfield, 1999 (this vol., Chapter 7)</td>
</tr>
<tr>
<td>Adapted to life in moderately fast-moving streams and rivers rather than lakes or slow-moving rivers</td>
<td>Two species of unionoids (swan mussels)</td>
<td>Jeffery, 1999 (this vol., Chapter 10)</td>
</tr>
<tr>
<td>Genera within the Pseudonapacentai are characteristic of rather xeric habitats, but tend to occur in situations where there is regular seasonal humidity, whether in the form of precipitation at high elevations or lower down close to water at the base of wadis; suggests wetter than present and perhaps seasonal conditions</td>
<td>Pulmonate gastropods</td>
<td>Mordan, 1999 (this vol., Chapter 11)</td>
</tr>
<tr>
<td>Palaeohabitats</td>
<td>Basis of reconstruction</td>
<td>Reference</td>
</tr>
<tr>
<td>-------------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>Prefer quiet, shallow waters and/or swamp conditions and can withstand intermittent periods of drought</td>
<td><em>Clarias sp.</em></td>
<td>Forey and Young, 1999 (this vol., Chapter 12)</td>
</tr>
<tr>
<td>Found in a variety of freshwater habitats but most are bottom dwellers in relatively slow-moving waters</td>
<td><em>Bagridae</em></td>
<td>Forey and Young, 1999 (this vol., Chapter 12)</td>
</tr>
<tr>
<td>Generalised, inhabiting a wide range of habitats</td>
<td><em>Barbus sp.</em></td>
<td>Forey and Young, 1999 (this vol., Chapter 12)</td>
</tr>
<tr>
<td>Terrestrial tortoise is an intertropical form inhabiting savannas, open forests, and even deserts and can endure aridity; some of the aquatic tortoises prefer flowing wide river systems whereas others are less-good swimmers and prefer muddy waters</td>
<td><em>Chelonia</em></td>
<td>Lapparent de Broin and Dijk, 1999 (this vol., Chapter 13)</td>
</tr>
<tr>
<td>Similar and possibly ancestral to <em>Gulo</em>, which has been considered as indicative of boreal forest or woodland; wolverines are also animals of open tundra and can indicate grassy and open habitats</td>
<td><em>Plesiogulo</em></td>
<td>Barry, 1999 (this vol., Chapter 17)</td>
</tr>
<tr>
<td>Relatively deep mandibular ramus suggest hypsodonty = tough food; short and broad muzzle = grazing; deep ectoflexids on some premolars are interpreted as poor adaptation to abrasive foods</td>
<td><em>Hipparion abudhabiensis</em></td>
<td>Eisenmann and Whybrow 1999 (this vol., Chapter 19)</td>
</tr>
<tr>
<td>Fossil wood</td>
<td><em>Acacia</em></td>
<td>Whybrow and Clements 1999 (this vol., Chapter 23)</td>
</tr>
</tbody>
</table>
**Summary**

Although the Baynunah Formation and associated fossil material are limited, temporally and spatially, when viewed in the context of late Miocene palaeoenvironments of the Arabian Peninsula, they provide significant evidence that the region did not present a continuous ecological barrier to intercontinental exchange. Analyses of lithofacies and associated fauna and flora indicate an open woodland environment adjacent to a major river system. Habitats distal to the river may have been more open, perhaps even grasslands. While conceivable, it is unlikely that the Baynunah sediments, representing the only known window into the late Miocene of this area, record a moderate environment set within a region and time interval dominated by arid to semi-arid climatic patterns. Unlike the widespread semi-arid to hyperarid conditions that dominate the Arabian Peninsula today, the environment during the late Miocene may have been more varied and supported a number of different types of habitats. In this case it would be unreasonable to extrapolate the interpreted environments for western Abu Dhabi to a regional scale.

It remains difficult to link global climatic trends and events documented in the marine record with the evolution of terrestrial communities, primarily because of a lack of sites and resolution in continental sediments. Although it is tempting to correlate climatic shifts with faunal interchange, local and regional effects of global shifts on terrestrial ecosystems are intricate and basically unknown. Late Cenozoic cooling at high latitudes clearly had an aridifying effect on low latitudes but the timing and magnitude of these changes on the continents varied greatly depending on buffering by regional and local atmospheric circulation patterns.

**References**


