13

Cenozoic stratigraphy of the Arabian Peninsula and Gulf

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ABSTRACT

The lithostratigraphy of the Cenozoic of the Arabian Peninsula and Gulf is discussed in relation to regional and, where possible, global biostratigraphy (and hence absolute chronostratigraphy).

A provisional sequence stratigraphy is erected. Four megasequences are defined on the basis of bounding regional unconformities. These megasequences are discussed in ascending stratigraphic order (that is, in the form of a geological history). The discussion concerns age, geological setting, and source, reservoir and caprock development, with particular emphasis placed on petroleum geology aspects. Comments on subdivision of the sequences, and on their correlation with global sequences, are added as appropriate.

13.1 INTRODUCTION

The Cenozoic stratigraphy of the Arabian Peninsula and Gulf has been the subject of detailed study ever since the first petroleum reservoired in Cenozoic sediments (Oligocene–Miocene carbonates of the Asmari Formation) was discovered at Masjid-i-Suleiman in Iran (then Persia) in 1908. Cenozoic reservoirs currently produce prolifically not only elsewhere in Iran but also in Iraq (e.g., Kirkuk Field, Oligocene Kirkuk Group reservoir), in the Kuwait–Saudi Arabia Divided [Neutral] Zone (e.g., Wafra Field, Palaeocene–Eocene Umm Er Radhuma and Dammam Formation reservoirs), in the offshore Arabian Gulf (e.g. Abouzar, Bahrehgansar and Doroud Fields, Miocene Ghar Formation reservoir) and in the Yemeni sector of the Gulf of Aden (Sharmah-1, Eocene Habshiya Formation reservoir).

This chapter is concerned with the Cenozoic stratigraphy of the area bounded to the north by

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the Sinai Peninsula, the Levant States, Turkey and the Zagros Suture, to the east by the Gulf of Oman and Arabian Sea, to the south by the Gulf of Aden and Socotra Island, and to the west by the Red Sea and Gulf of Suez (Figure 13.1).

General aspects of the Cenozoic stratigraphy of the study area are discussed by, among others, Henson (1938, 1951), Lees (1950), Dunnington (1958, 1967), Kamen-Kaye (1970), Beydoun and Dunnington (1975), Murris (1980, 1981), Adams, Gentry and Whybrow (1983), Beydoun (1986, 1988, 1991), and Eva *et al.* (in prep.).

Following comments on palaeoenvironmental interpretation and age-dating, the detailed lithostratigraphy of the following regions is discussed in turn below: Eastern Syria and Northern Iraq; southwest and offshore Iran; southern Iraq, Kuwait, Saudi Arabia, Qatar and the United Arab

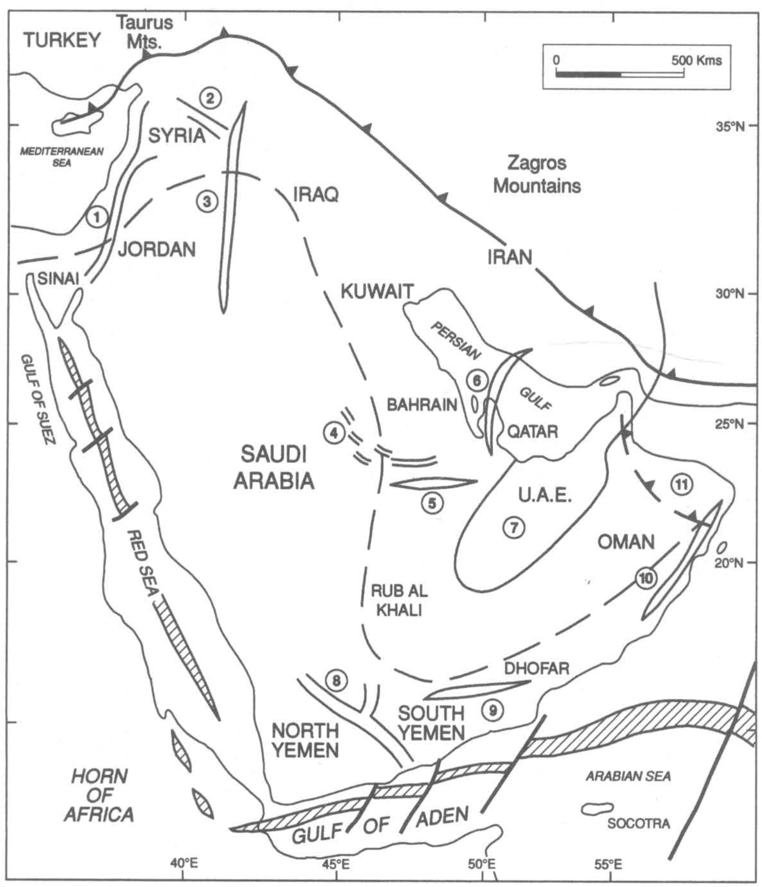

Figure 13.1 Location map illustrating principal structural elements (simplified after Beydoun, 1988).
Dashed line indicates boundary between essentially undisturbed cratonic areas to the south and west and folded belt to north and east. Toothed line (Zagros Suture) indicates boundary between external fold belt (broad basins and swells) and internal fold and thrust belt (orogen). 1 = Levant Fracture System; 2 = Euphrates Graben; 3 = Hail Arch; 4 = Central Arabian Graben; 5 = Central Arabian Arch; 6 = Qatar Arch; 7 = Rub Al Khali Basin; 8 = Marib-Jawf Graben; 9 = Hadhramaut Arch; 10 = Huqf Axis; 11 = Semail Thrust.

Emirates; southern Oman and Yemen; northern Oman.

13.2 PALAEOENVIRONMENTAL INTERPRETATION

Palaeoenvironmental interpretation in this chapter is based partly on published information and partly on our unpublished interpretations of observed bio- and lithofacies. The following comments on biofacies are generally applicable:

13.2.1 Carbonate environments

Low-energy ('back-reef') carbonate environments are characterized by green algae, porcellaneous-walled symbiont-bearing 'larger' benthonic foraminifera (soritids, alveolinids) and 'smaller' benthonics (miliolids); higher energy ('reef' and 'fore-reef') carbonate environments by red algae and hyaline-walled symbiont-bearing larger benthonics (rotaliids, miogypsinids, nummulitids, discocyclinids, lepidocyclinids) (e.g., Buxton and Pedley, 1989; Racey, in prep. (and references therein)).

13.2.2 Clastic environments

Non-marine clastic environments are characterized by fresh-water ostracods and charophyte oogonia. Foraminifera are absent.

Marginal and shallow marine clastic environments are characterized by particular types of smaller benthonic foraminifera (discorbids, eponidids, asterigerinids, elphidiids).

Deeper marine clastic and pelagic environments are characterized by different types of smaller benthonics (cancrisids, alabaminids, chilostomellids) and planktonics (globigerinids, globorotaliids).

13.2.3 Evaporitic environments

Evaporitic environments are characterized either by the total absence of microfauna or by the development of low abundance and diversity assemblages of smaller benthonic foraminifera tolerant of hypersalinity (e.g., miliolids, elphidiids, rotaliids) together with certain types of ostracod.

13.3 AGE-DATING

The regional lithostratigraphy of this paper has been calibrated against regional and, where possible, global biostratigraphy (and hence absolute chronostratigraphy) (Figure 13.2).

13.3.1 Regional biostratigraphy

The regional (Pan-Tethyan) biostratigraphic zonation schemes adopted herein are those of Schaub (1951, 1981) and Adams (1970) (the latter not strictly a biozonation scheme). These larger benthonic foraminiferal schemes can be calibrated against either the global planktonic foraminiferal scheme of Blow (1969) or the global calcareous nannoplankton scheme of Martini (1971) (Figure 13.3). Note in this context that the established calibration of Adams' 'zones' (and incidentally those of Smout (1954), Sander (1962) and El-Khayal (1974)) against Blow's zones has been revised herein on the basis of new evidence as to the true stratigraphic significance of some purportedly Palaeocene species (see discussion under Saudi Arabia below). Reinterpreted ranges of selected larger benthonic foraminifera are given in Figure 13.4. Additional nummulitid ranges are given by Racey (this volume), and additional alveolinid ranges by White (this volume).

Schaub (1951, 1981), based on a virtual lifetime's work, recognized five parallel Cenozoic larger benthonic foraminiferal biozonation schemes, each comprising 11–15 individual biozones and corresponding to a particular lineage of *Nummulites*, *Assilina* or *Alveolina* (see also Hottinger (1977) on the nummulitids, and Hottinger (1962), Gaemers (1978) and White (1992) on the alveolinids). Schaub's schemes have most widespread applicability in the platform carbonates of Western Tethys, though they can be confidently used at least as far east as Oman (Racey, this volume; White, this volume).

Adams (1970) recognized 12 Cenozoic 'zones', each broadly corresponding to one of the former Dutch East-Indian 'Letter Stages' as defined by van der Vlerk and Umbgrove (1927). Adams' scheme has most widespread applicability in the platform carbonate province of the Indo-West

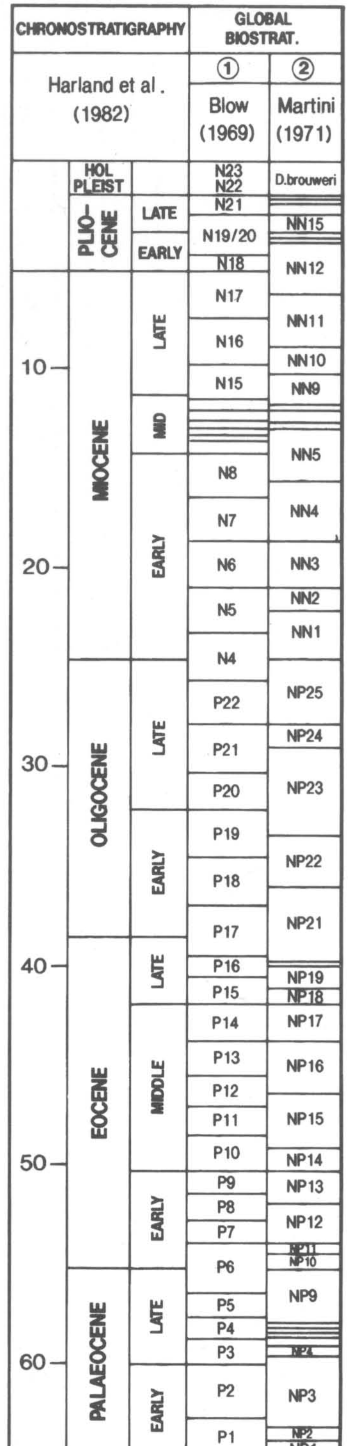

Figure 13.2 Cenozoic chronostratigraphic time-scale and global biostratigraphic zonation schemes (after Harland *et al.*, 1982, 1990). 1 = Planktonic foraminifera; 2 = Calcareous nannoplankton.

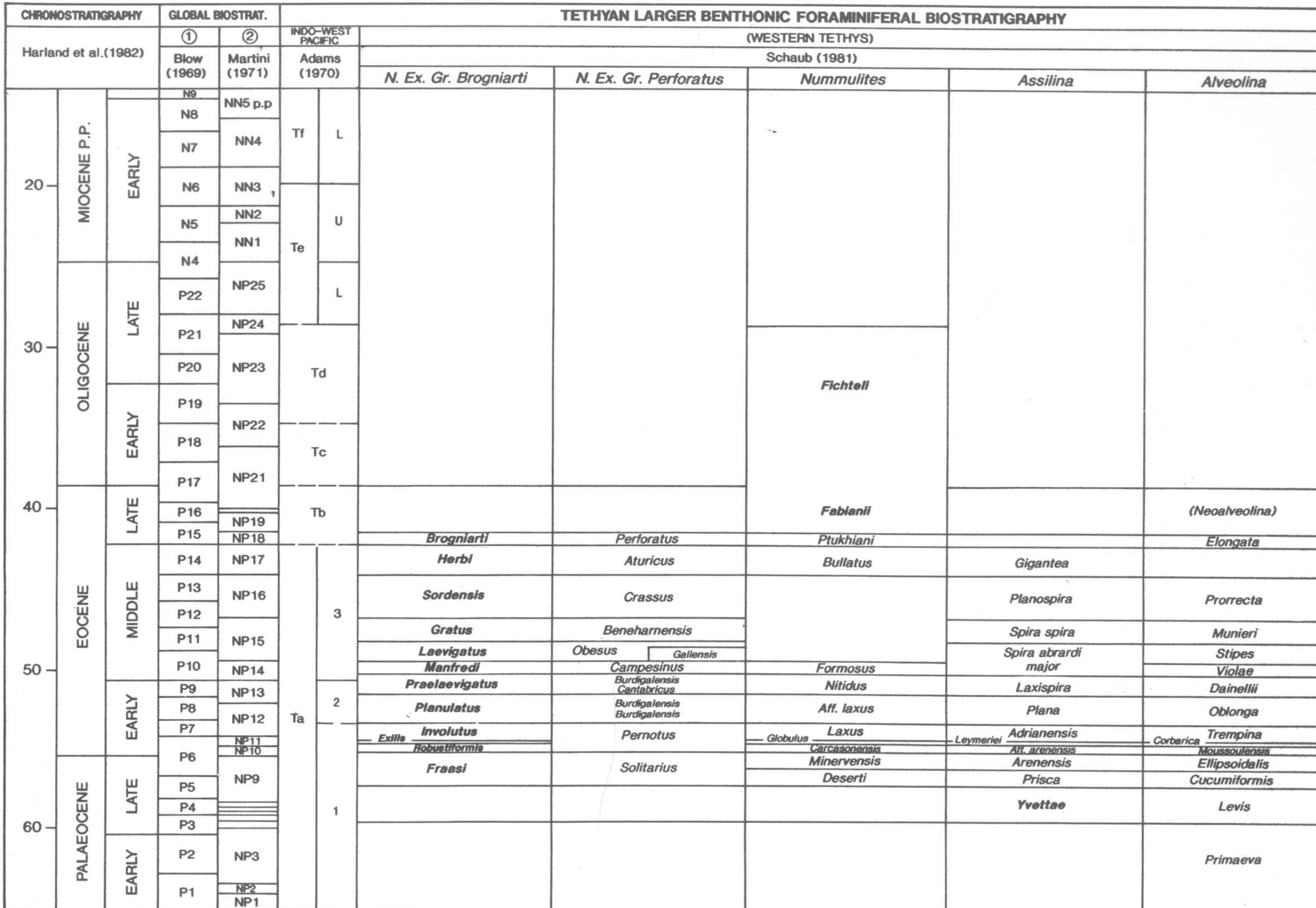

Figure 13.3 Cenozoic chronostratigraphic time-scale and Tethyan larger benthonic foraminiferal biostratigraphic zonation schemes. 1 = Planktonic foraminifera; 2 = Calcareous nannoplankton. Schaub's Danian stage calibrated against Martini's Zones NP1–NP4, Thanetian against NP5–NP9, Ilerdian against NP9–NP12, Cuisian against NP12–NP14, Lutetian against NP15–NP17, Biarritzian against NP18 and Priabonian against NP19–NP21. Zones indicated in bold type have stratotypes.

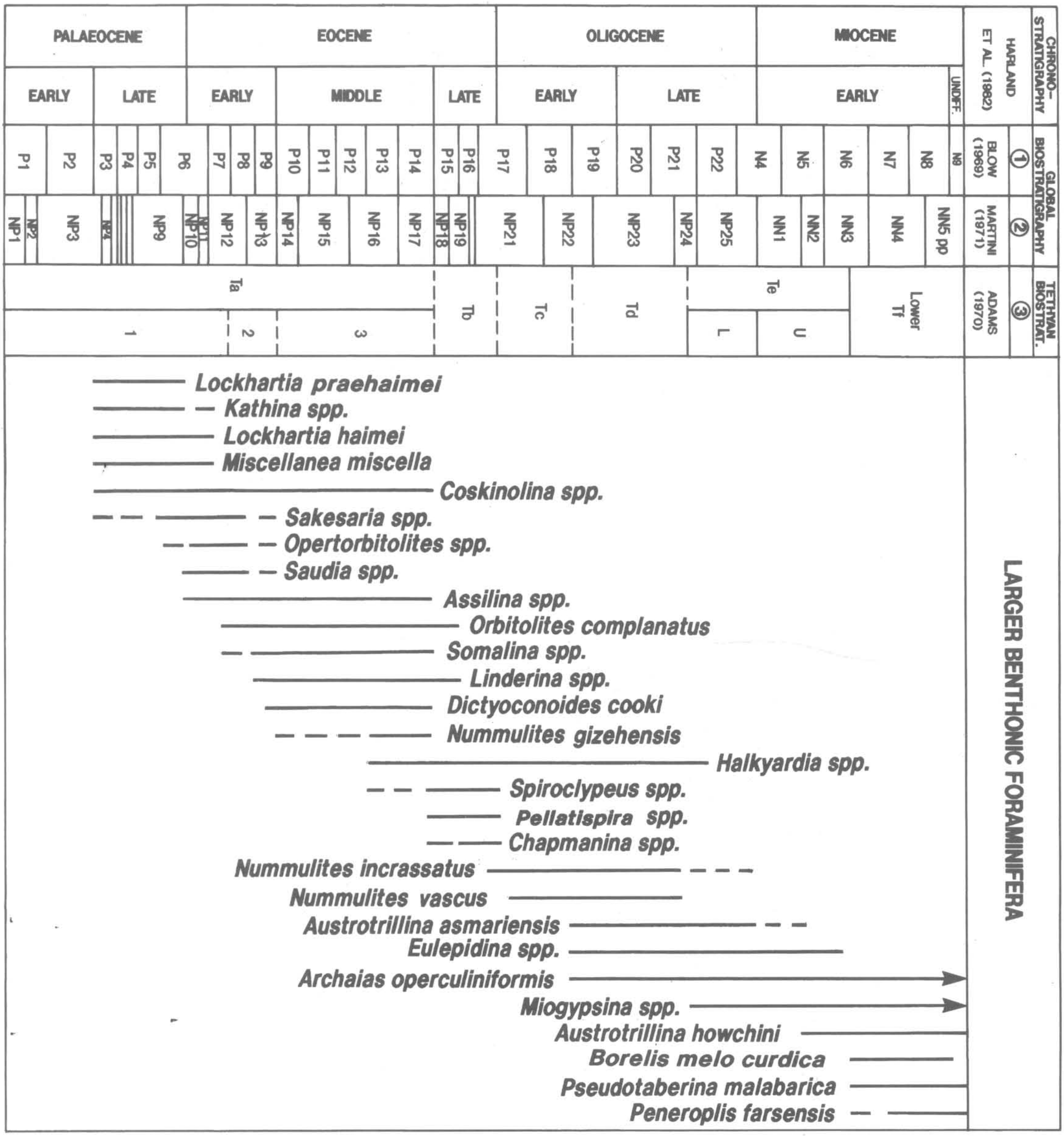

Figure 13.4 Stratigraphic range chart for selected larger benthonic foraminifera. 1 = Planktonic foraminifera; 2 = Calcareous nannoplankton; 3 = Larger benthonic foraminifera.

Pacific, though it can be confidently used at least as far west as southwest Iran.

13.3.2 Global biostratigraphy

The global biostratigraphic zonation schemes adopted herein are those of Blow (1969) (see also Blow, 1979) (planktonic foraminifera) and Martini (1971) (calcareous nannoplankton) (Figure 13.2). These schemes are applicable in the pelagic carbonate and open marine clastic lithofacies of the study area.

13.3.3 Absolute chronostratigraphy

The absolute chronostratigraphy adopted herein is that of Harland *et al.* (1982).

It is necessary to record that there are a number of differences of interpretation between Harland *et al.* (1982) and other authors. Some of the more important of these are discussed below.

1. Harland *et al.* (1982) place the Early–Middle Eocene boundary at the boundary between planktonic foraminiferal biozones P9 and P10 of Blow (1969) or at what they regard as an equivalent level between calcareous nannoplankton biozones NP13 and NP14 of Martini (1971). Other authors (including Haq, Hardenbol and Vail, 1987) calibrate the planktonic foraminiferal and calcareous nannoplankton biozones differently, such that the boundary between planktonic foraminiferal biozones P9 and P10 (and hence the Early–Middle Eocene boundary) falls within calcareous nannoplankton biozone NP14.
2. They place the Eocene–Oligocene boundary within planktonic foraminiferal biozone P17 of Blow (1969) or calcareous nannoplankton biozone NP21 of Martini (1971). Other authors either place it lower (at the top of NP20) or higher (at the top of P17).
3. They place the Early–Late (Rupelian–Chattian) Oligocene boundary at the top of planktonic foraminiferal biozone P19 or at an equivalent level within calcareous nannoplankton biozone NP23 of Martini. Other authors (including Haq, Hardenbol and Vail, 1987) place it within calcareous nannoplankton biozone NP24 of Martini (1971) or at an equivalent level within planktonic foraminiferal biozone P21 of Blow (1969). The latter placement better honours recent data on the age of the Rupelian stratotype (Vinken, 1988).
4. They place the Early–Middle Miocene boundary at the base of planktonic foraminiferal biozone N9 of Blow (1979) (the *Orbulina* First Appearance Datum). Harland *et al.* (1990) place it at the base of N8 (the *Praeorbulina* First Appearance Datum), and Haq, Hardenbol and Vail (1987) place it within N8.
5. They place the Middle–Late Miocene boundary within planktonic foraminiferal biozone N15 of Blow (1979). Other authors either place it at the top of N14 or at the top of N15.
6. They place the Miocene–Pliocene boundary at the boundary between planktonic foraminiferal biozones N17 and N18 of Blow (1979). Haq, Hardenbol and Vail (1987) place it within N18. Other authors place it at the boundary between N18 and N19.

13.4 REGIONAL LITHOSTRATIGRAPHY OF EASTERN SYRIA AND NORTHERN IRAQ

13.4.1 Introduction

Papers on the Cenozoic stratigraphy of these areas include those of Henson (1937), Dubertret (1940), van Bellen (1956), Al-Naqib (1959), Dunnington *et al.* (1959), Daniel (1963), Weber (1963), Ejel and Nouet (1966), Krasheninnikov *et al.* (1967), Ponikarov (1967), Wolfart (1967), Ejel (1969), Al-Sayyab and Al-Saddiki (1970), Kukal and Saddallah (1970), Ctyroky and Karim (1971), Kassab (1972, 1976, 1978), Ctyroky, Karim and van Vessem (1975), Dunnington (1975), Lateef (1976), Bolli and Krasheninnikov (1977), Karim (1978, 1985), Prazak (1978), Ibrahim (1979), Buday (1980), Al-Senjery (1984), Mohammed (1984), Al-Hashimi and Amer (1985, 1986), Al-Shibaini, Al-Qayim and Salmin (1986), Kassab, Al-Omari and Al-Safawee (1986), Majid and Veizer (1986), Abawi and Maroof (1988) and

Abawi (1989). Papers on the Cenozoic stratigraphy of adjacent Jordan include those of Bayliss (1973) and Futyan (1976).

The formations of eastern Syria and northern Iraq can be dated biostratigraphically with varying degrees of confidence and accuracy (Figures 13.5, 13.11).

13.4.2 Aaliji, Sinjar, Khurmala and Kolosh Formations

The Aaliji Formation comprises pelagic carbonates, the Sinjar 'fore-reef' (shelf margin) carbonates, the Khurmala 'back-reef' (tidal flat and lagoonal) carbonates and the Kolosh flysch-type clastics (see, for instance, Al-Hashimi and Amer, 1985; Majid and Veizer, 1986).

The Aaliji Formation contains planktonic foraminifera indicating a Palaeocene to Early Eocene age (P2–P8) (van Bellen, 1956; Kassab, 1978).

The lower part of the Kolosh Formation contains planktonic foraminifera indicating a Palaeocene age (P2–P3) and the upper part contains larger benthonic foraminifera also indicating an undifferentiated Palaeocene age (Kassab, 1976).

The Sinjar and Khurmala Formations are correlative (Dunnington *et al.*, 1959).

13.4.3 Jaddala Avanah, Pila Spi and Gercus Formations

The Jaddala Formation comprises pelagic carbonates, the Avanah 'fore-reef' (bank margin) carbonates, the Pila Spi 'back-reef' carbonates and the Gercus marginal to non-marine clastics (Al-Hashimi and Amer, 1985; Majid and Veizer, 1986).

The Jaddala Formation contains planktonic foraminifera indicating a Middle–Late Eocene age (P10-P16) (van Bellen, 1956).

The Avanah, Pila Spi and Gercus Formations are correlative (Dunnington *et al.*, 1959).

13.4.4 Kirkuk Group and Chilou Formation

The Kirkuk Group comprises the Shurau, Sheikh Alas, Palani, Bajawan, Baba, Tarjil, Anah, Azkand and Ibrahim Formations. The Palani, Tarjil and Ibrahim Formations comprise pelagic carbonates, the Sheikh Alas, Baba and Azkand Formations 'fore-reef' carbonates and the Shurau, Bajawan and Anah Formations 'reef' and 'back-reef' carbonates (van Bellen, 1956). Various of these formations contain larger benthonic and planktonic foraminifera indicating an Oligocene age (P18–P22/N3) (van Bellen, 1956; Al-Hashimi and Amer, 1985, 1986).

The Chilou Formation of eastern Syria is presumed correlative with the Kirkuk Group. It also contains planktonic foraminifera indicating an Oligocene age (RWJ's unpublished observations).

13.4.5 Euphrates, Dhiban and Serikagni Formations

The Euphrates Formation comprises platform and 'peri-reefal' carbonates, the Dhiban Formation evaporites and the Serikagni Formation pelagic carbonates (Al-Hashimi and Amer, 1985).

The Euphrates Formation contains planktonic foraminifera indicating an Early Miocene age (N8) (Prazak, 1978; Abawi, 1989).

The Serikagni Formation also contains planktonic foraminifera indicating an Early Miocene age (N8) (Prazak, 1978).

The Dhiban Formation lacks age-diagnostic fossils (Prazak, 1978).

13.4.6 Jeribe Formation and unnamed correlative

The Jeribe Formation comprises platform and 'peri-reefal' carbonates and its unnamed correlative pelagic carbonates (Al-Hashimi and Amer, 1986; RWJ's unpublished observations). The Jeribe Formation can be assigned a Middle Miocene (N9) age (Prazak, 1978).

13.4.7 Fars Group

The Fars Group comprises the Lower, Middle and Upper Fars Formations. The Lower and Middle Fars comprise essentially marginal marine carbonates, evaporites and fine clastics, the Upper Fars Formation essentially non-marine coarse clastics.

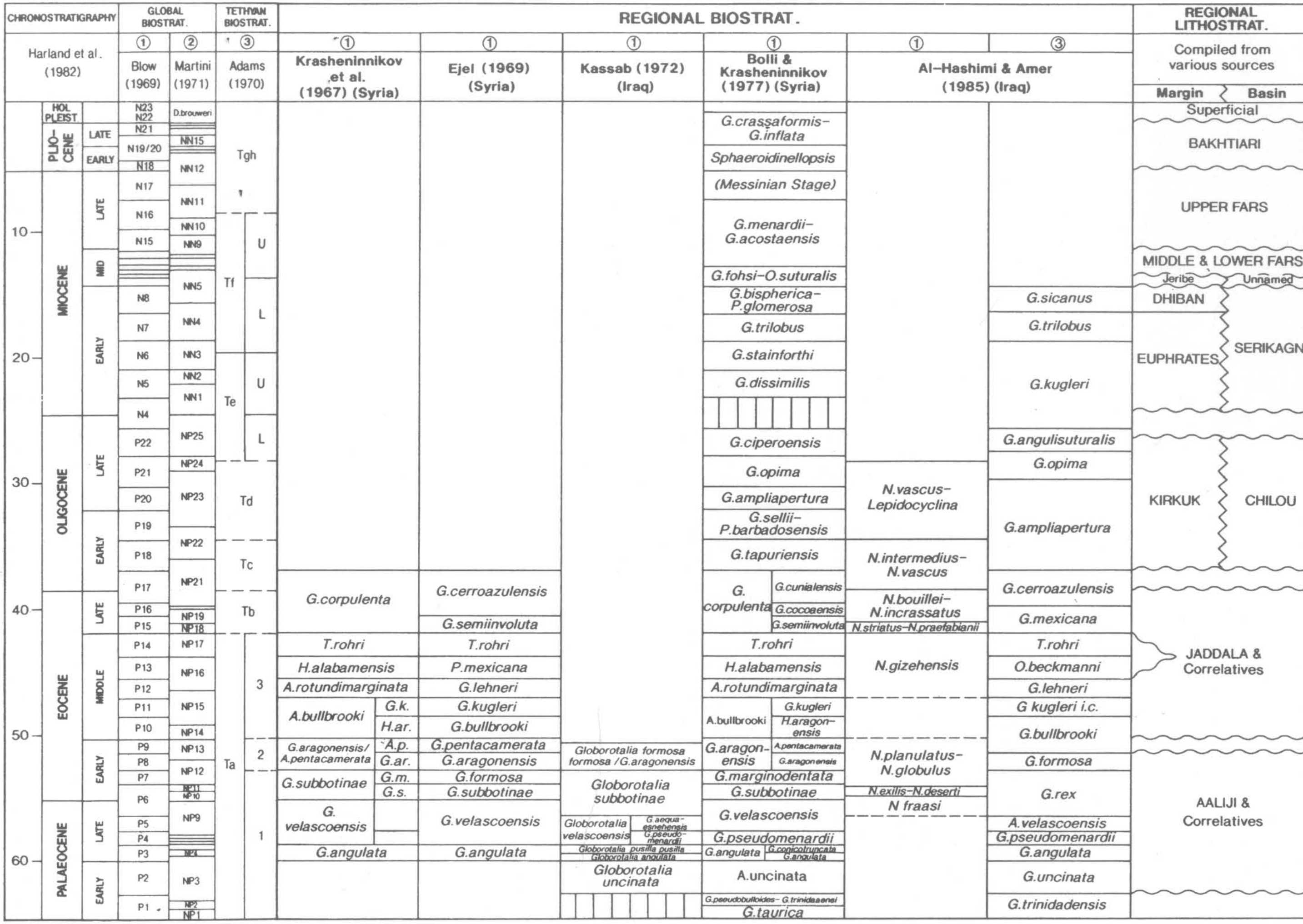

Figure 13.5 Summary stratigraphy of eastern Syria and northern Iraq. 1 = Planktonic foraminifera; 2 = Calcareous nannoplankton; 3 = Larger benthonic foraminifera.

The Lower and Middle Fars Formations locally contain markers for Middle Miocene (N13) (Prazak, 1978). The Upper Fars Formation is essentially non-marine and lacks age-diagnostic fossils. It is assigned a Late Miocene age on regional considerations (Dunnington *et al.*, 1959).

13.4.8 Bakhtiari Formation

The Bakhtiari Formation comprises essentially non-marine coarse clastics. It lacks age-diagnostic fossils and is assigned a Pliocene age on regional considerations (Dunnington *et al.*, 1959; Lateef, 1976).

13.4.9 Superficial deposits

These are essentially non-marine coarse clastics which lack age-diagnostic fossils.

13.4.10 Unconformities

Data presented by Kassab (1978) indicate the presence of an unconformity in several wells at the base of the Aaliji Formation, with part of the Early Palaeocene unrepresented. Data presented by Kassab *et al.* (1986) indicate that this unconformity is also present in well Sasan-1. Further data presented by Al-Shibaini, Al-Qayim and Salmin (1986) indicate that it is present in the Dokan Area.

Data presented by van Bellen (1956) indicate the presence of unconformities in well Kirkuk-109 between the Aaliji and Jaddala Formations (with part of the Early Eocene unrepresented), within the Jaddala Formation (with part of the Middle Eocene unrepresented) and between the Jaddala Formation and Kirkuk Group (with part of the Late Eocene unrepresented).

Data presented by Al-Hashimi and Amer (1986) indicate the presence of unconformities between the Palani and Azkand Formations (Kirkuk Group) (with part of the Oligocene unrepresented), and between the Ibrahim and Serikagni Formations (again with part of the Oligocene unrepresented) in well Ibrahim-1.

Field relationships indicate additional unconformities between the Dhiban and Jeribe Formations, between the Jeribe and Lower Fars Formations, between the Middle and Upper Fars Formations, between the Upper Fars and Bakhtiari Formations, and between the Bakhtiari Formation and unnamed superficial deposits.

13.5 SOUTHWEST AND OFFSHORE IRAN

13.5.1 Introduction

Papers on the Cenozoic stratigraphy of these areas and of the adjoining Arabian Gulf include those of Thomas (1950, 1952a, b), BP (1956), Falcon (1958), Bozorgnia (1964), Bozorgnia and Kalantari (1965), James and Wynd (1965), Wynd (1965), Mina, Razaghnia and Paran (1967), Sampo (1969), Hull and Warman (1970), Kalantari (1972, 1986), Stocklin and Setudehnia (1972), Rahaghi and Schaub (1976), Rahaghi (1978, 1980, 1984), Stampfli, Jan du Chene and Herb (1978), Kashfi (1980), Mojab (1982) and Ross, Uchupi and White (1986).

The formations of southwest and offshore Iran can be dated biostratigraphically with varying degrees of confidence and accuracy (Figures 13.6, 13.11).

13.5.2 Amiran Formation

The Amiran Formation comprises a variety of clastic lithologies. It contains the index taxa of *Globorotalia–Globigerina–G. daubjergensis* and *Miscellanea–Kathina* Zones, indicating a Palaeocene age (Wynd, 1965).

13.5.3 Sachun Formation

The Sachun Formation comprises a variety of coarse clastic, carbonate and evaporite lithologies. It contains the index taxa of the *Miscellanea–Kathina* and *Opertorbitolites* Zones, indicating a Palaeocene–Early Eocene age (Wynd, 1965).

13.5.4 Taleh Zang Formation

The Taleh Zang Formation comprises platform carbonates. It contains the index taxa of the *Miscellanea–Kathina*, *Opertorbitolites*, *Somalina*

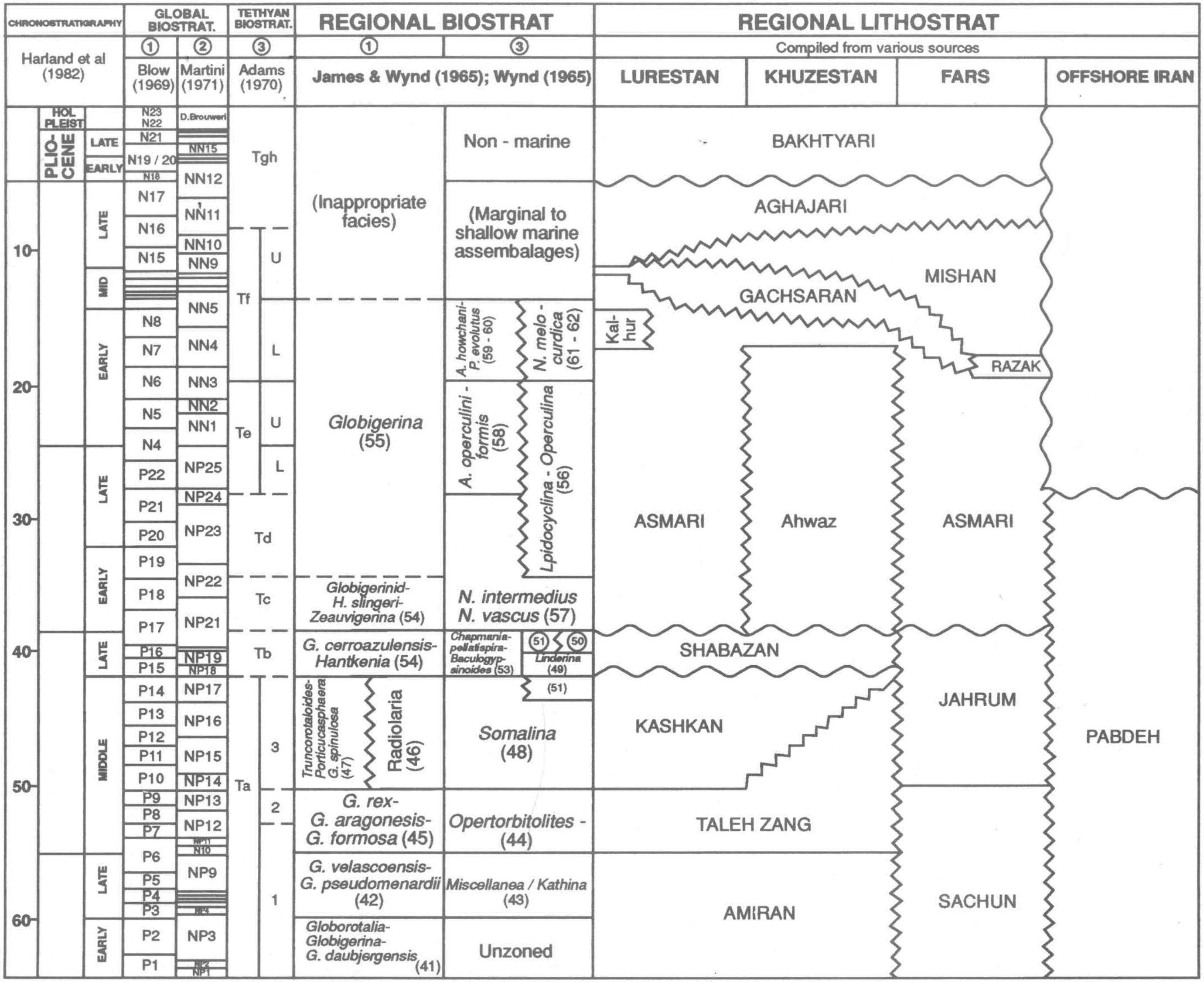

Figure 13.6 Summary stratigraphy of southwest and offshore Iran.
1 = Planktonic foraminifera; 2 = Calcareous nannoplankton; 3 = Larger benthonic foraminifera; 50 = *Dictyoconus–Coskinolina–O. complanatus*; 51 = *Nummulites–Alveolina*.

and *Nummulites–Alveolina* Zones, indicating a Palaeocene–Middle Eocene age (Wynd, 1965). Its top appears to be diachronous (Wynd, 1965).

13.5.5 Pabdeh Formation

The Pabdeh Formation comprises pelagic carbonates. It contains the index taxa of the *G. velascoensis–G. pseudomenardii*, *G. rex–G. aragonensis–G. formosa*, *Truncorotaloides–Porticulasphaera–G. spinulosa*, *G. cerroazulensis–Hantkenina* and Globigerinid–*H. slingeri–Zeauvigerina/Lepidocyclina–Operculina* Zones, indicating a Palaeocene–Early Oligocene age (Wynd, 1965).

13.5.6 Kashkan Formation

The Kashkan Formation comprises a variety of clastic and evaporite lithologies. It contains the index taxa of the Radiolaria Zone, indicating a Middle Eocene age (Wynd, 1965). Its base appears to be diachronous (Wynd, 1965).

13.5.7 Jahrum Formation

The Jahrum Formation comprises platform carbonates. It contains the index taxa of the *Somalina*, *Linderina*, *Dictyoconus–Coskinolina–O. complanata* and *Nummulites–Alveolina* Zones, indicating a Middle–Late Eocene age (Wynd, 1965).

13.5.8 Shahbazan Formation

The Shahbazan Formation also comprises platform carbonates. It contains the index taxa of the *Nummulites–Alveolina* and *Chapmanina–Pellatispira–Baculogypsinoides* Zones, indicating a Late Eocene age (Wynd, 1965).

13.5.9 Asmari Formation

The Asmari Formation comprises platform and 'peri-reefal' carbonates, with subordinate clastics (Ahwaz Sandstone Member) and evaporites (Kalhur Member). It contains the index taxa of the *Nummulites intermedius–N. vascus*, *Globigerina* spp., *Austrotrillina howchini–Peneroplis* and *Neoalveolina (Borelis) melo curdica* Zones, indicating an Oligocene–earliest Middle Miocene age (Wynd, 1965) (see also Thomas, 1952a). Its top appears diachronous (Wynd, 1965).

The Ahwaz Sandstone Member contains the index taxa of the *N. intermedius–N. vascus* and *A. howchini–P. evolutus* Zones, indicating an age in the range Oligocene–earliest Middle Miocene (Wynd, 1965). Stratigraphic relationships (the presence of overlying strata of an age in the range latest Early–earliest Middle Miocene age) probably restrict its age to within the range Oligocene–Early Miocene.

The Kalhur Member contains the index taxa of the *Globigerina* spp. Zone, indicating an age in the range Oligocene–earliest Middle Miocene (Wynd, 1965). Stratigraphic relationships (the presence of underlying and overlying strata of ages within the range latest Early–earliest Middle Miocene age) probably restrict its age to Early Miocene.

13.5.10 Gachsaran Formation

The Gachsaran Formation comprises fine clastics and evaporites. It is difficult to date biostratigraphically, as it contains mostly undiagnostic benthonic foraminifera. However, a local age in the range latest Early–earliest Middle Miocene can be assigned on the basis of the occurrence of the index taxa of the *A. howchini–P. evolutus* and *N. melo curdica* Zones (Wynd, 1965). Both the base and top of the Gachsaran Formation appear to be diachronous (Wynd, 1965).

13.5.11 Razak Formation

The Razak Formation comprises fine clastics. It is correlative with the lower part of the Gachsaran Formation (Wynd, 1965; Stocklin and Setudehnia, 1972).

13.5.12 Mishan Formation

The Mishan Formation comprises fine clastics with subordinate carbonates (Guri Limestone Member). It is difficult to date biostratigraphically as it contains mostly undiagnostic benthonic foraminifera. However, it locally contains the larger benthonic foraminifera *Flosculinella bontangensis* (Rutten, 1912) and *Taberina* [*Pseudotaberina*] *malabarica* (Carter, 1853), indicating a latest Early–earliest Middle Miocene age (Lower Tf of Adams, 1970). Both the base and the top of the Mishan Formation appear to be diachronous (Wynd, 1965).

13.5.13 Agha Jari Formation

The Agha Jari Formation comprises essentially non-marine coarse clastics. It is impossible to date biostratigraphically as it lacks age-diagnostic fossils (Wynd, 1965). Its base appears to be diachronous (Wynd, 1965).

13.5.14 Bakhtyari Formation

The Bakhtyari Formation comprises essentially non-marine coarse clastics which lack age-diagnostic fossils (James and Wynd, 1965).

13.5.15 Unconformities

Data presented by Wynd (1965) indicate the presence of unconformities at the base of the Pabdeh Formation (with part of the Early Palaeocene unrepresented), between the Kashkan and Shahbazan Formations, between the Shahbazan and Asmari Formations and between the Agha Jari and Bakhtyari Formations.

Analogy with northern Iraq (see above) indicates an intraformational unconformity within the Asmari Formation and unconformities between the Asmari and Gachsaran Formations, between the Mishan and Agha Jari Formations and between the Bakhtyari Formation and unnamed superficial deposits.

13.6 SOUTHERN IRAQ, KUWAIT, SAUDI ARABIA, QATAR AND THE UNITED ARAB EMIRATES

13.6.1 Introduction

Papers on the Cenozoic stratigraphy of these areas and of the Divided (Neutral) Zone include those of Smout (1954), Thralls and Hasson (1956), Al-Naqib (1959), Dunnington *et al.* (1959), Sander (1962), Powers *et al.* (1966), Nelson (1968), Powers (1968), Cavelier (1970), Kukal and Saddallah (1970), Ctyroky and Karim (1971), Al-Hashimi (1974), El-Khayal (1974), Ctyroky, Karim and van Vessem (1975), Sugden and Standring (1975), Al-Furaih (1977, 1980, 1983a, b, 1984), Karim (1978), Ibrahim (1979, 1983), Buday (1980), Al-Furaih and Siddiqui (1981), Al-Rawi and Sadik (1981), Siddiqui and Al-Furaih (1981), Thomas *et al.* (1981), Whybrow and McClure (1981), Whybrow *et al.* (1982), Brunet and Heintz (1983), Abu Zeid and Boukhary (1984), Breton *et al.* (1984), Cherif and El-Deeb (1984), Whybrow (1984), Al-Hashimi and Amer (1985), Hasson (1985), Whybrow and Bassiouni (1986), Bou-Rabee and Birke (1987), Whybrow, McClure and Elliot (1987), Danielli (1988), El-Nakhal (1988), Alsharhan (1989) and El-Nakhal and El-Naggar (1989). Papers on the Cenozoic stratigraphy of the northwesternmost part of Saudi Arabia abutting the Sinai Peninsula include those of Dullo, Hotzl and Jads (1983) and El-Naggar and Kamel (1988). Srivastava and Binda (1991) discuss the depositional history of the Early Eocene Shumaysi Formation in the Mekkah area of western Saudi Arabia.

The formations of southern Iraq, Kuwait, Saudi Arabia, Qatar and the United Arab Emirates can be dated biostratigraphically with varying degrees of confidence and accuracy (Figures 13.7, 13.11).

13.6.2 Umm Er Radhuma Formation

The Umm Er Radhuma Formation comprises platform carbonates. It contains in its lower part (among other species) the larger benthonic foraminifer *Lockhartia praehaimei* Smout, 1954, in its middle part *L. haimei* (Davies, 1927) and *Miscellanea miscella* (d'Archiac and Haime, 1854) (Letter Stage Tal of Adams, 1970), and in its upper part *Nummulites globulus* Leymerie, 1846 (Ilerdien Moyen-Superieur of Schaub, 1981 = NP11–NP12) (Sander, 1962; Powers *et al.*, 1966; Powers, 1968; El-Khayal, 1974; El-Nakhal and El-Naggar, 1989).

El-Khayal (1974) recognized ten larger benthonic foraminiferal faunizones within the Umm

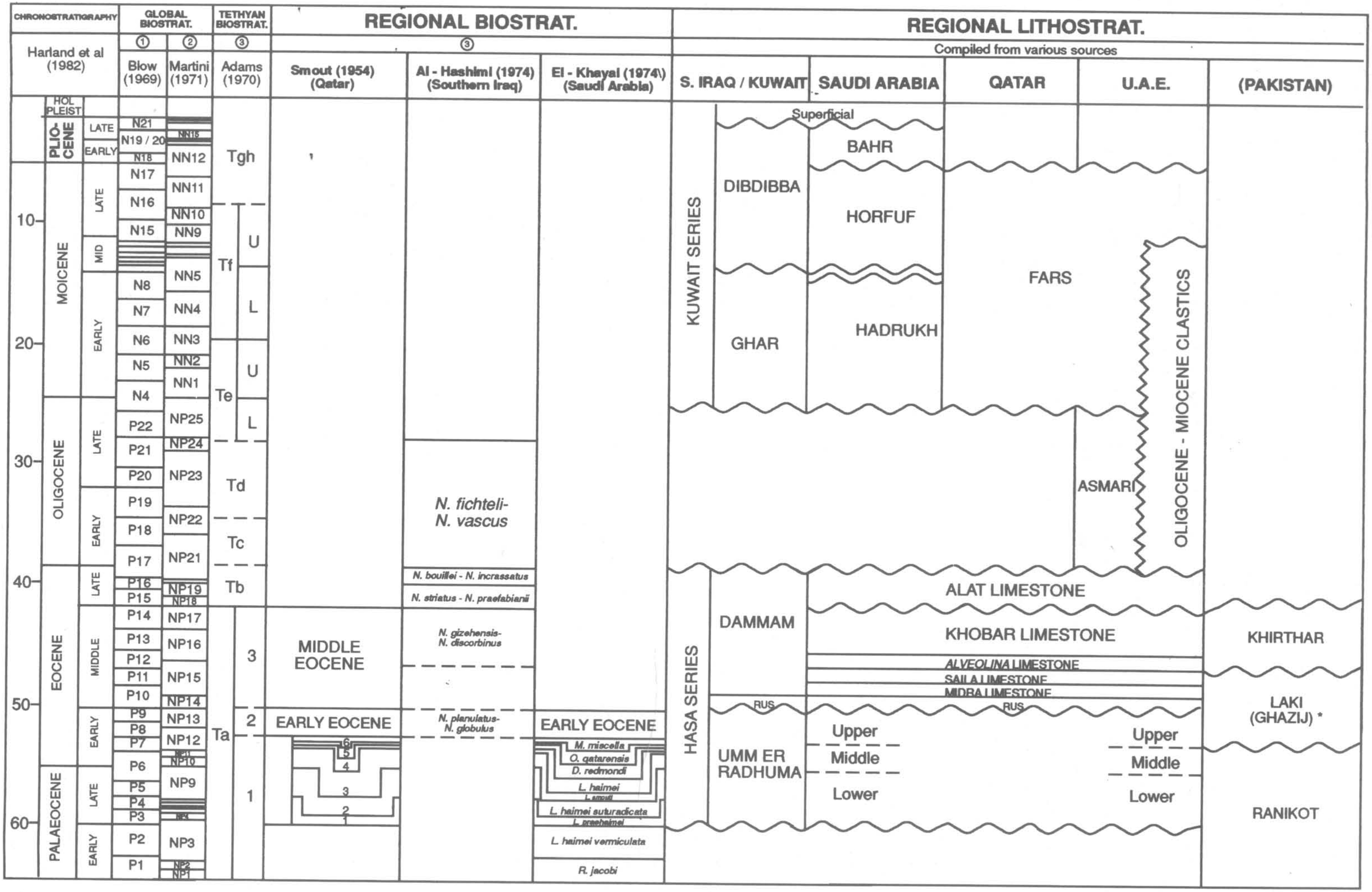

Figure 13.7 Summary stratigraphy of southern Iraq, Kuwait, Saudi Arabia, Qatar and the United Arab Emirates.
* Uppermost part (Baska Shale Formation) contains assiline larger benthonic foraminifera of the latest Early?–?earliest Middle Eocene (Cuisien Supérieur–Lutetien Inférieur of Schaub, 1981 = NP14–NP15 (RWJ's unpublished observations). 1 = Planktonic foraminifera; 2 = Calcareous nannoplankton; 3 = Larger benthonic foraminifera.

Er Radhuma Formation of eastern Saudi Arabia. The lowest three (with *Lockhartia praehaimei*) probably correspond to the lower faunal division of Powers *et al.* (1966) and Powers (1968) (Palaeocene), the middle six (with *L. haimei* and *Miscellanea miscella*) to the middle faunal division (interpreted at the time as Palaeocene) and the upper one to the upper faunal division (Early Eocene). El-Khayal (1974) also recognized two planktonic foraminiferal faunizones within the mid-part of the Umm Er Radhuma Formation (*Discocyclina redmondi* larger benthonic foraminiferal faunizone) in the El-Alat well in eastern Saudi Arabia. These were a lower *Globorotalia pusilla pusilla* Zone and an upper *G. pseudomenardii* Zone (equivalent to Blow's (1979) Late Palaeocene Zones P3 and P4 respectively).

Hasson (1985) subsequently recorded several stratigraphically significant planktonic foraminifera from both ditch-cuttings and side-wall core samples from the mid-part of the Umm Er Radhuma Formation in five wells in the Rub Al Khali Basin. These included *Globorotalia (Morozovella) formosa formosa* Bolli, 1957, the nominate taxon for Early Eocene Zone P7 of Blow (1969) (Zone P8a of Blow, 1979). Hasson's positive identification of this species calls into question the earlier findings of purportedly Palaeocene planktonics from effectively the same interval.

Significantly, Hasson's Early Eocene planktonic foraminifera occurred below *Lockhartia haimei*, *Miscellanea miscella* and other larger benthonic foraminifera regarded as of Palaeocene age by Smout (1954) (Qatar) and such subsequent workers as Sander (1962) and El-Khayal (1974) (Saudi Arabia) and Adams (1970) (Indo-West Pacific Province).

Hasson's (1985) findings necessitate a reappraisal of the stratigraphic significance of the larger benthonic foraminiferal zonation schemes of these earlier workers (see Figures 13.3, 13.4, 13.7). Note in this context that *Lockhartia haimei* and *Miscellanea miscella* also occur in association with Early Eocene planktonic foraminifera (*Globorotalia rex* Zone) in the classical Ranikot Series (traditionally regarded as Palaeocene) in the Rakhi Nala area of the Sulaiman Ranges in what is now Pakistan (Latif, 1961; Samanta, 1973).

In offshore Abu Dhabi, the Umm Er Radhuma Formation contains in its lowermost part ('basal shale member' of authors) the larger benthonic foraminifera *Lockhartia altispira* Smout, 1954, *L. conditi* (Nuttall, 1926), *L. praehaimei, Rotalia hensoni* Smout, 1954 and *Rotalia trochidiformis* (Lamarck, 1804), together with the smaller benthonic foraminifer *Alabamina dubifera* (Haque, 1960) and the planktonic foraminifera *Globigerina (Subbotina) triloculinoides* Plummer, 1926 (P1–P4), *Globorotalia (Morozovella) angulata* (White, 1928) (P3–P5), *G. (M.) conicotruncata* (Subbotina, 1947) (P3–P7) and *G. (Morozovella) pseudobulloides* (Plummer, 1926) (P1–P3), in its middle part the larger benthonics *Alveolina (Alveolina)* aff. *aramaea* Hottinger, 1962 (Ilerdien Inferieur of Schaub, 1981 = NP9–NP10), *Daviesina langhami* Smout, 1954 et spp., *Dictyokathina simplex* Smout, 1954, *Fabularia, Kathina delseota* Smout, 1954, *K. major* Smout, 1954, *K. selveri* Smout, 1954, *Lockhartia altispira, L. conditi, L. conica* Smout, 1954, *L. diversa* Smout, 1954, *L. haimei, L. hunti* Ovey, 1947, *L. hunti pustulosa* Smout, 1954, *L. tipperi* (Davies, 1926), *Miscellanea meandrina* (Carter, 1861), *M. miscella* (Letter Stage Tal of Adams, 1970), *Nummulites soerenbergensis* (Schaub, 1951) (Ilerdien Superieur–Cuisien Basal of Schaub, 1981 = NP11–NP12) et spp., *Operculina, Sakesaria cordata* (Smout, 1954), *S. cotteri* Davies, 1937 and *S. ornata* Smout, 1954 together with the planktonics *Globigerina (Subbotina) triloculinoides, Globorotalia (Morozovella) angulata, G. (M.) conicotruncata, G. (M.) pseudobulloides, G. (M.)* cf. *uncinata* Bolli, 1957 (P2–P3), *G. (Planorotalites)* cf. *compressa* Plummer, 1926 (P1–P4) and *G. (P.) pseudoscitula* Glaessner, 1937 (P8–P14), and in its upper part the larger benthonics *Dictyoconoides cooki* (Carter, 1861) (Letter Stages Ta2–Ta3 of Adams, 1970 = Early–Middle Eocene) and *Nummulites* together with the planktonics *Globigerapsis* (P9–P17), *Globorotalia (Acarinina) bullbrooki* Bolli, 1957 (P9–P14), *G. (A.)* ex gr. *pentacamerata* Subbotina, 1947 (P8–P12) and *Truncorotaloides rohri* Brönnimann and Bermúdez, 1953 (P9–P14) (RWJ's unpublished observations). The overall age-range represented is Palaeocene to Early Eocene. The Early Palaeocene appears absent or condensed.

13.6.3 Rus Formation

The Rus Formation comprises evaporites and subordinate carbonates. It lacks age-diagnostic foraminifera and is assigned a basal Middle Eocene age on regional evidence. Records of the Early Eocene larger benthonic foraminifer *Nummulites globulus* are probably spurious.

13.6.4 Dammam Formation

The Dammam Formation comprises platform carbonates with subordinate fine clastics and, locally, pelagic carbonates.

Over most of Kuwait and Saudi Arabia, it contains in its lower and lower middle parts (Midra and Saila Shale Members) no age-diagnostic foraminifera, in its middle part (*Alveolina* Limestone Member) the larger benthonic foraminifera *Alveolina (Alveolina) elliptica* var., *Dictyoconoides, Linderina* and *Nummulites,* in its upper middle part (Khobar Limestone Member) *Coskinolina [Daviesiconus] balsilliei* Davies, 1930, *Dictyoconoides cooki* (Letter Stages Ta2–Ta3 of Adams, 1970 = Early–Middle Eocene), *Halkyardia, Linderina and Nummulites somaliensis* Nuttall and Brighton, 1931, and in its upper part (Alat Limestone Member) *Dictyoconus* (El-Nakhal and El-Naggar, 1989). The overall age-range represented is Middle Eocene (Khobar Limestone Member) to Late Eocene (Alat Limestone Member). Records of the Early Eocene larger benthonic foraminifer *Nummulites globulus* are probably spurious.

In the Western Desert of southern Iraq, it contains in its middle part the larger benthonic foraminifera *Nummulites discorbinus* (Schlotheim, 1820) (Lutetien-Biarritzien of Schaub, 1981 = NP15–NP18) and *N. gizehensis* (Forskal, 1775) (Lutetien Moyen-Superieur of Schaub, 1981 = NP15– NP17) together with the planktonic foraminiferab *Globorotalia ('Hasterigerina') bolivariana* (Petters, 1954) (P9–P11), *G. (Morozovella) lehneri* (Cushman and Jarvis, 1929) (P11–P14), *G. (M.) spinulosa* (Cushman, 1927) (P9–P14), *Truncorotaloides rohri* (P9–P14) and *T. topilensis* (Cushman, 1925) (P9–P14), and in its upper part the age-diagnostic larger benthonics *Nummulites striatus* (Bruguière, 1792) (Biarritzien–Priabonian of Schaub, 1981 = NP18– NP21) et spp. and the planktonics *Globigerina ampliapertura* Bolli, 1957 (no older than P16) and *Globorotalia (Turborotalia) cerroazulensis* (Cole, 1928) (no younger than P17) (Al-Hashimi, 1974). The age-range represented is Middle–Late Eocene.

In offshore Abu Dhabi, it contains the larger benthonic foraminifera *Assilina, Chapmanina* cf. *gassinensis* Silvestri, 1905 (Letter Stage Tb of Adams, 1970 = Late Eocene), *Dictyoconoides cooki* (Letter Stages Ta2–Ta3 of Adams, 1970 = Early–Middle Eocene), *Halkyardia, Nummulites beaumonti* d'Archiac and Haime, 1853 (Lutetien Moyen–Biarritzien of Schaub, 1981 = NP15–NP18, *N. discorbinus* (Lutetien Inferieur–Biarritzien of Schaub, 1981 = NP15–NP18), *N. gizehensis* (Lutetien Moyen–Superieur of Schaub, 1981 = NP15–NP17), *N. ptukhiani* Kacharava, 1969 (Biarritzien of Schaub, 1981 = NP18), *N. striatus* (Biarritzien–Priabonian of Schaub, 1981 = NP18–NP21) and *Operculina* together with the planktonic foraminifera *Globigerapsis* (P9–P17), *Globorotalia* (*Acarinina*) *bullbrooki* (P9–P14), *G. (A.)* ex gr. *pentacamerata* (P8–P12) and *Truncorotaloides rohri* (P9–P14) (RWJ's unpublished observations). The age-range represented is Middle–Late Eocene.

A correlation with the classical Kirthar (Khirthar) Series of Pakistan is indicated not only on foraminiferal evidence (White, 1989; RWJ's unpublished observations) but also on ostracod evidence (presence of *Anommatocythere*) (Al-Furaih and Siddiqui, 1981).

13.6.5 Ghar and Dibdibba Formations

The Ghar and Dibdibba Formations of southern Iraq and Kuwait comprise essentially marginal to non-marine coarse clastics which lack age-diagnostic fossils.

13.6.6 Hadrukh, Dam, Hofuf and Bahr Formations

The Hadrukh Formation of Saudi Arabia comprises coarse clastics presumed correlative with those of the Ghar Formation of southern Iraq and Kuwait (see above). The Dam Formation of Saudi Arabia comprises carbonates and evaporites presumed correlative with the Jeribe Formation of northern Iraq (Whybrow, 1984). The Hofuf and Bahr Formations of Saudi Arabia comprise coarse clastics presumed correlative with those of the Dibdibba Formation of southern Iraq and Kuwait. All of these formations lack age-diagnostic fossils.

13.6.7 Asmari Formation, Fars Group and undifferentiated Oligocene–Miocene clastics

The Asmari Formation of the U. A. E. comprises platform and 'peri-reefal' carbonates similar to those of southwest Iran (see above). It contains in its lower part *Nummulites fichteli* Michelotti, 1841 (Oligocene Inferieur of Schaub, 1981) and in its upper part *Austrotrillina asmariensis* Adams, 1968 (Letter Stages Td–Lower Te (?-Upper Te) of Adams, 1970 = 'Middle' Oligocene–Early Miocene) (RWJ's unpublished observations).

The Fars Group of Qatar and the U.A.E. comprises essentially marginal to non-marine coarse clastics and associated evaporites similar to those of southwest Iran and northern Iraq (see above). It contains *Peneroplis* spp. (RWJ's unpublished observations).

The undifferentiated Oligocene–Miocene clastics of Qatar and the U.A.E. are presumed to correlate in part with the Asmari and in part with the Fars.

13.6.8 Uncomformities

Data indicate the presence of unconformities at the base of the Umm Er Radhuma Formation (with the Early Palaeocene, at least locally, unrepresented), at the base of the Asmari Formation (with the Late Eocene unrepresented) and at the base of the Ghar or Hadrukh Formations or Fars Group (with the late Eocene and Oligocene unrepresented).

Analogy with northern Iraq (see above) indicates uncomformities within the Asmari Formation and Fars Group, between the Ghar and Dibdibba Formations, between the Hadrukh and Dam Formations, between the Dam and Hofuf Formations, and between the Hofuf and Bahr Formations.

13.7 SOUTHERN OMAN AND YEMEN

13.7.1 Introduction

Papers on the Cenozoic stratigraphy of southern Oman and Yemen include those of Morton (1959), Beydoun (1960, 1966, 1970), Geukens (1966), Greenwood and Bleackley (1967), Tschopp (1967), Beydoun and Greenwood (1968), Beydoun and Bichan (1970), Hawkins, Hindle and Strugnell (1981), Hughes Clarke (1988), Platel and Roger (1989), Roger *et al.* (1989), Haitham and Nani (1990) and Paul (1990).

The formations of these areas can be biostratigraphically dated with varying degrees of confidence and accuracy (Figures 13.8, 13.11).

13.7.2 Hadhramaut Group (Umm Er Radhuma, Jeza, Rus, Habshiya, Dammam and Aydim Formations)

The Umm Er Radhuma Formation of southern Oman and Yemen comprises platform carbonates, and the Jeza Formation of Yemen also comprises carbonates. The Umm Er Radhuma Formation contains Palaeocene–Early Eocene larger benthonic foraminifera including *Alveolina (Alveolina) oblonga* d'Orbigny, 1826 (Cuisien Inferieur of Schaub, 1981 = NP12–NP13), *Daviesina langhami*, *Lacazina*, *Lockhartia haimei*, *Miscellanea meandrina*, *M. miscella* (Letter Stage Ta1 of Adams, 1970), *Nummulites globulus* (Ilerdien Moyen–Superieur of Schaub, 1981 = NP11–NP12), *Operculina*, *Orbitolites* and *Sakesaria dukhani* Smout, 1954 (Roger *et al.*, 1989; RWJ's unpublished observations). The Jeza Formation contains Early Eocene *Lockhartia hunti*, *L. hunti pustulosa*, *L. tipperi*, *Rotalia trochidiformis* and *Sakesaria cotteri* (RWJ's unpublished observations).

The Rus Formation comprises evaporites and subordinate carbonates. It lacks age-diagnostic fossils.

The Dammam Formation of the western part of southern Oman (Mahra and Dhofar) and the equivalent Habshiya Formation of Yemen essentially comprise platform carbonates. The lower part of the Dammam Formation (Andhur Member) contains *Dictyoconoides cooki* (Letter Stages Ta2–Ta3 of

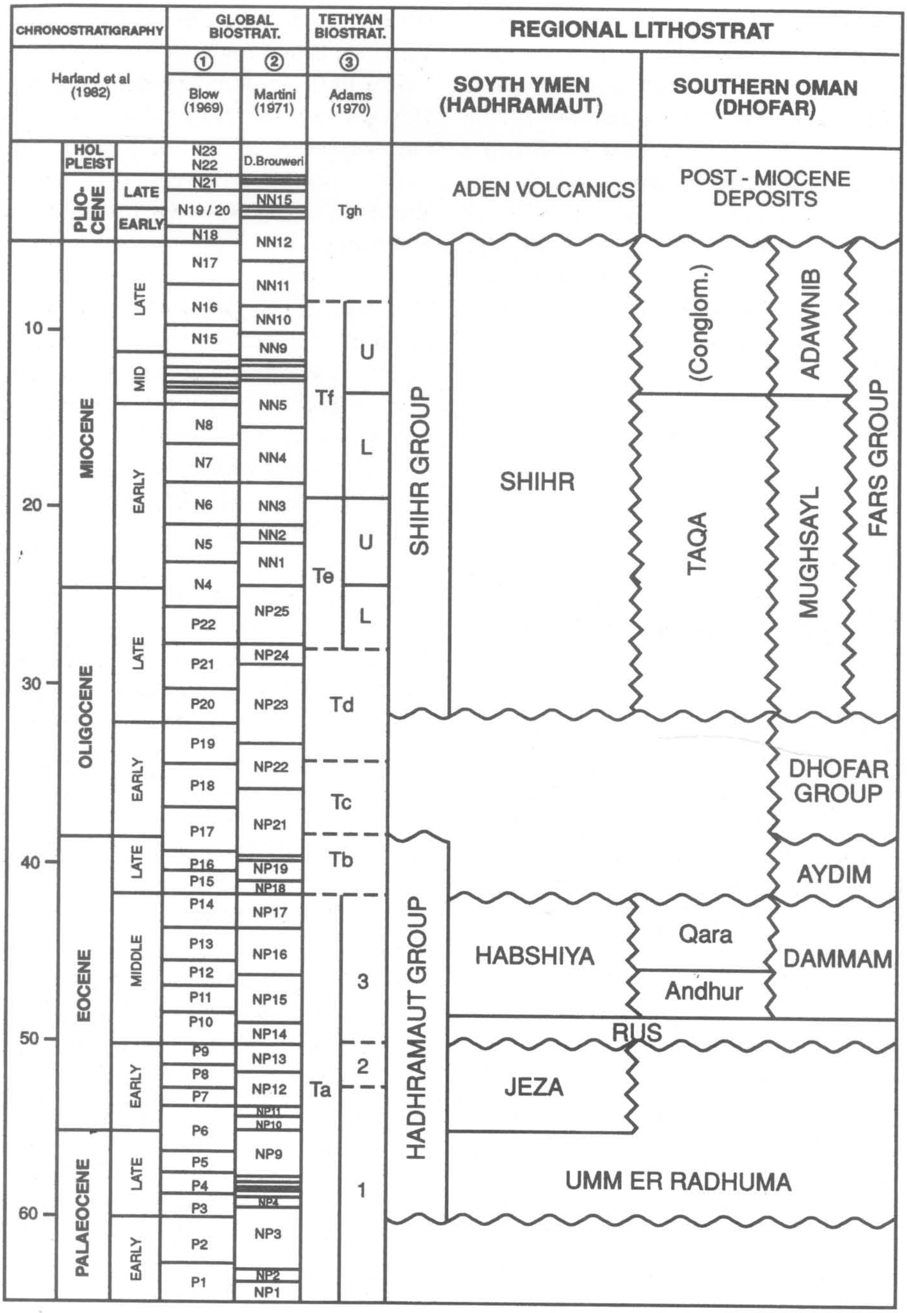

Figure 13.8 Summary stratigraphy of southern Oman and Yemen. 1 = Planktonic foraminifera; 2 = Calcareous nannoplankton; 3 = Larger benthonic foraminifera.

Adams, 1970 = Early–Middle Eocene) together with *Linderina* and *Nummulites* (Roger *et al.*, 1989); the upper part (Qara Member) the early Middle Eocene species *Alveolina (Alveolina)* ex gr. *frumentiformis* Schwager, 1883 (Lutetien Inferieur of Schaub, 1981 = NP15) together with the late? Middle Eocene (Bartonian) species *Nummulites somaliensis*. The Habshiya Formation contains Middle? Eocene species of *Dictyoconus* and *Linderina*.

The Aydim Formation of Mahra and Dhofar comprises platform carbonates. It contains the Late Eocene species *Nummulites fabianii* Prever, 1905 (Priabonien of Schaub, 1981 = NP19–NP21) together with *Dictyoconoides* and *Orbitolites* (Roger *et al.*, 1989).

13.7.3 Dhofar Group (Zalumah and Ashawq Formations)

The Dhofar Group of the central part of southern Oman essentially comprises platform carbonates. Its upper part (Ashawq Formation) contains the Early Oligocene *Nummulites fichteli* (Oligocene Inferieur of Schaub, 1981) (Roger *et al.*, 1989).

13.7.4 Shihr Group, Ghaydah Formation, Mughsayl and Adawnib Formations and Fars Group

The Shihr Group of the western part of southern Oman (Mahra and Dhofar) and Yemen (Hadhramaut) comprises mixed carbonates and clastics with associated evaporites. One of its constituent formations (the Taqa Formation of Dhofar) contains the larger benthonic foraminifera *Eulepidina* (which ranges no older than Oligocene (Letter Stage Td of Adams, 1970) and no younger than Early Miocene (Upper Te (Te5 of Wonders and Adams, 1991)) and *Miogypsina* (no older than Early Miocene (Upper Te (Te5)) and no younger than Middle Miocene (Upper Tf)). The equivalent Ghaydah Formation of Yemen (south of the Hadhramaut Arch) also comprises mixed lithologies. It contains Lepidocyclinidae of Oligocene–Miocene aspect.

The Mughsayl and Adawnib Formations of the central part of southern Oman essentially comprise carbonates (Roger *et al.*, 1989). The Mughsayl Formation is developed in open oceanic facies and contains planktonic foraminifera of Oligocene–Early Miocene aspect. The Adawnib Formation is developed in marginal marine facies and lacks age-diagnostic fossils.

The Fars Group of the eastern part of southern Oman comprises marginal to non-marine clastics and evaporites and lacks age-diagnostic fossils.

13.7.5 Post-Miocene Deposits and Aden Volcanics

The Post-Miocene Deposits of southern Oman also comprise clastics which lack age-diagnostic fossils.

The Aden Volcanics of Yemen lack fossils. They appear to be essentially Post-Miocene in South Yemen (the former Peoples Democratic Republic of Yemen), but occupy the whole Cenozoic in North Yemen (the former Yemen Arab Republic).

13.7.6 Unconformities

Data indicate the presence of unconformities at the base of the Hadhramaut Group, at the base of the Dhofar Group, at the base of the Shihr or Fars Group or equivalent, and at the base of the Post-Miocene Deposits.

13.8 NORTHERN OMAN

13.8.1 Introduction

Papers on the Cenozoic stratigraphy of northern Oman (the Oman Mountains) include those of Glennie *et al.* (1974), Montenat *et al.* (1977), Racz (1979), Hughes Clark (1988), Keen and Racey (1991), Racey (this volume) and White (this volume).

The formations of northern Oman can be dated biostratigraphically with varying degrees of confidence and accuracy (Figures 13.9, 13.11).

13.8.2 Jafnayn Formation

The Jafnayn Formation comprises platform carbonates. It contains in its lower part index taxa for the *Alveolina primaeva* Zone of Schaub (1981)

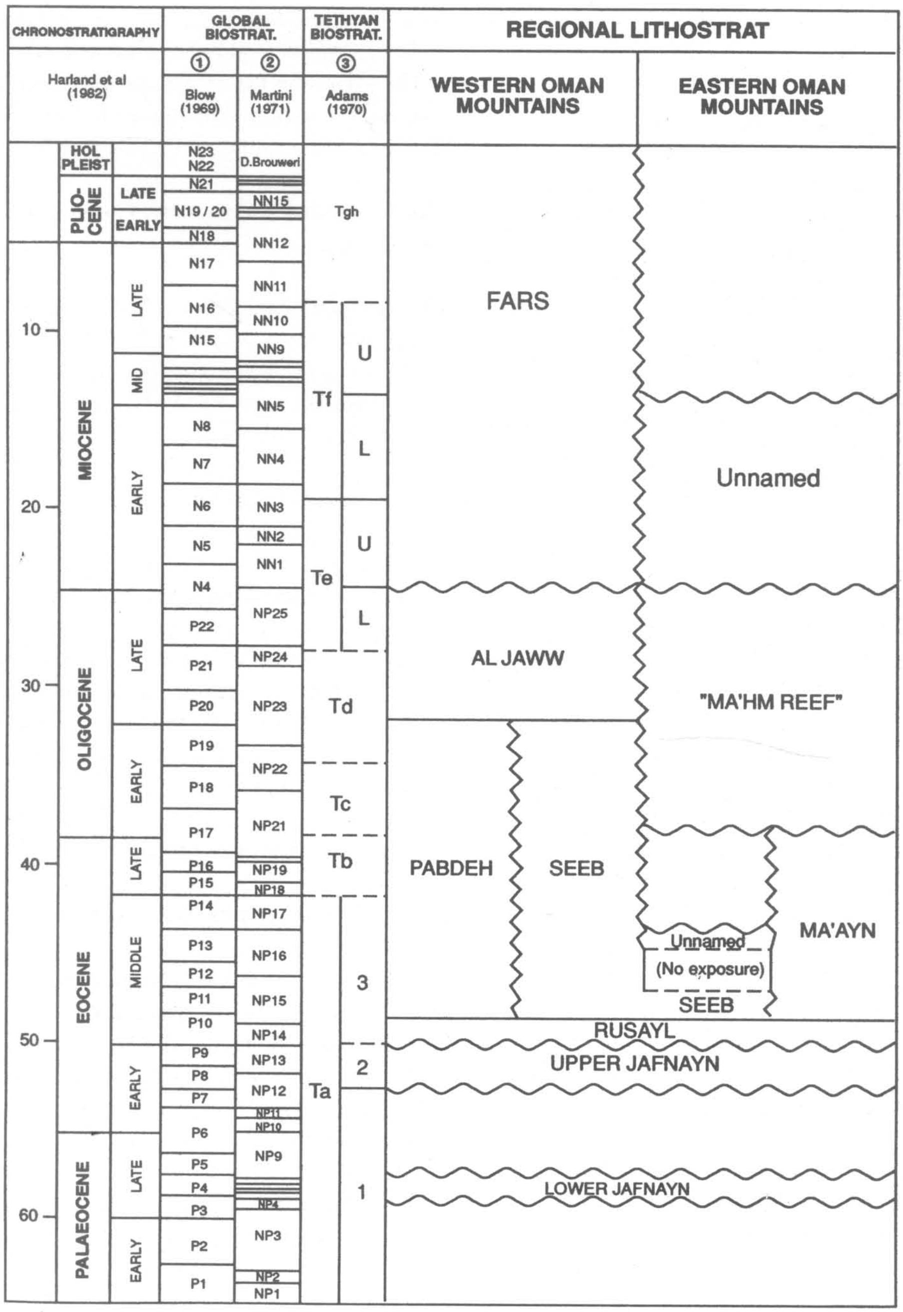

Figure 13.9 Summary stratigraphy of northern Oman. 1 = Planktonic foraminifera; 2 = Calcareous nannoplankton; 3 = Larger benthonic foraminifera.

(Thanetien Inferieur = NP5–NP8) and in its upper part index taxa for the *Alveolina oblonga* and *Assilina plana* Zones of Schaub (1981) (Cuisien Inferieur = NP12–NP13).

13.8.3 Rusayl Shale Formation

The Rusayl Shale Formation comprises clastics and subordinate carbonates. The lower marly member lacks age-diagnostic foraminifera but does contain questionably Early Eocene ostracods and miospores. The middle limestone member contains probable Middle Eocene larger benthonic foraminifera including *Somalina*; the upper sandstone and marl member contain definite Middle Eocene larger benthonic foraminifera including *Linderina rajasthanensis* Singh, 1953 (Lutetien Inferieur of Schaub, 1981 = NP15).

13.8.4 Seeb Limestone Formation, Unnamed Eocene Carbonates, Ma'ayh Beds and Pabdeh Marl

The Seeb Limestone Formation comprises carbonates. In the Eastern Oman Mountains, it contains the index species of the Middle Eocene *Nummulites obesus* and *Assilina spira abrardi* Zones of Schaub (1981) (Lutetien Inferieur = NP15), and, at one locality only (Al Khawd, 30 km from Wadi Rusayl), the index species of the Late Eocene *N. perforatus* Zone (Biarritzien = NP18). In the Western Oman Mountains, it is of Middle Eocene to Early Oligocene age.

Unnamed Eocene Carbonates crop out along the Batinah Coast. They contain the 'Auversian' species *Silvestriella tetraedra* (Gümbel, 1870), together with *Borelis vanderschmitti* (Schweighauser, 1952) and Eocene representatives of *Spiroclypeus*. Aubry (1985, 1986) gives the age of the stratotypical Auversian as Middle Eocene (NP16).

The Ma'ayh Beds are deep-water sediments of Middle–Late Eocene age.

The Pabdeh Marl of the Western Oman Mountains comprises pelagic carbonates of Middle Eocene to Early Oligocene age.

13.8.5 'Ma'hm Reef' and Al Jaww Formation

The 'Ma'hm Reef' of the Eastern Oman Mountains contains various nummulitids and lepidocyclinids of Early, Middle and Late Oligocene age.

The Al Jaww Formation of the Western Oman Mountains comprises carbonates of Late Oligocene age.

13.8.6 Unnamed Miocene Carbonates and Fars Group

The Unnamed Miocene Carbonates of the Eastern Oman Mountains are probably Early Miocene.

The Fars Group of the Western Oman Mountains comprises coarse clastics and evaporites of Neogene age.

13.8.7 Unconformities

Data indicate unconformities at the base of the Jafnayn Formation (with the Early to earliest Late Palaeocene unrepresented), within the Jafnayn Formation (with the latest Palaeocene to earliest Eocene unrepresented), between the Jafnayn and Rusayl Shale Formations, between the Rusayl Shale and Seeb Limestone Formations, between the Unnamed Eocene Carbonates and 'Ma'hm Reef' (with the late Middle of Late Eocene unrepresented), and at the base of the Fars Group or its correlatives.

13.9 SEQUENCE STRATIGRAPHY

A provisional sequence stratigraphy is erected below. Four megasequences are defined on the basis of biostratigraphically or otherwise detectable bounding regional unconformities (see above; see also Figure 13.11). They are termed APC (Arabian Peninsula Cenozoic) 1–4.

The APC1–4 unconformities are discussed in ascending stratigraphic order (i.e. in the form of a geological history). The discussion concerns age, geological setting, and source, reservoir and caprock development, with particular emphasis placed on petroleum geological aspects. Comments on the subdivision of the sequences, and on their correlation with global sequences, are added as appropriate.

The broader geological context (geological history/sequential development of Tethys) has been reviewed recently by, among others, Dercourt *et al.* (1985, 1986).

13.10 SEQUENCE APC1 (PALAEOCENE–EOCENE)

13.10.1 Definition

Base defined by regional unconformity at base of Palaeocene, top by regional unconformity at base of Oligocene.

13.10.2 Age

Palaeocene–Eocene.

13.10.3 Geological setting

The Early Palaeocene appears to have been a period of non-deposition or erosion associated with major inversion. The Late Palaeocene–Eocene saw the development of a foreland basin (in response to a collision between the Arabian and Eurasian Plates). Flysch- and arguably molasse-type coarse clastics, fine clastics and pelagic carbonates were deposited in the north and northeast, and platform carbonates everywhere else. Evaporites were deposited over wide areas during the early Middle Eocene. Regional uplift and erosion at the end of the Eocene may have been caused by isostatic rebound following earlier thrust-loading (in the north and east), or by Red Sea rifting (in the south and west) (Figures 13.12, 13.13).

13.10.4 Source, reservoir and caprock development

Although the principal sources of the Middle East petroleum accumulations are Jurassic to Cretaceous in age, there is some recently published evidence to indicate that the Palaeocene to Early Oligocene Pabdeh Formation, which belongs in part to this megasequence, is locally source-prone (Ala, Kinghorn and Rahman, 1980; Bordenave and Burwood, 1990).

Proven reservoirs are developed in Palaeocene to Eocene carbonates of the Umm Er Radhuma

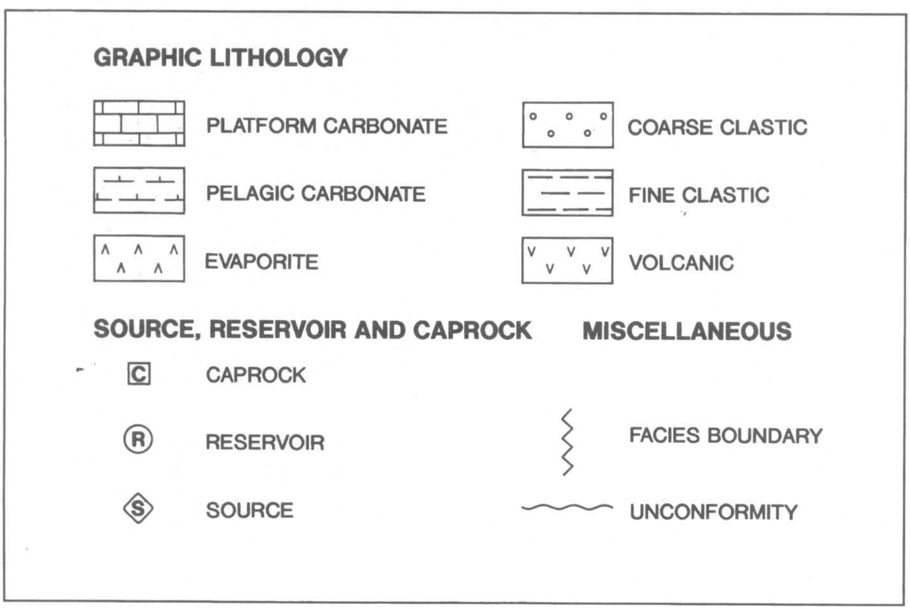

Figure 13.10 Legend for Figures 13.11–13.17

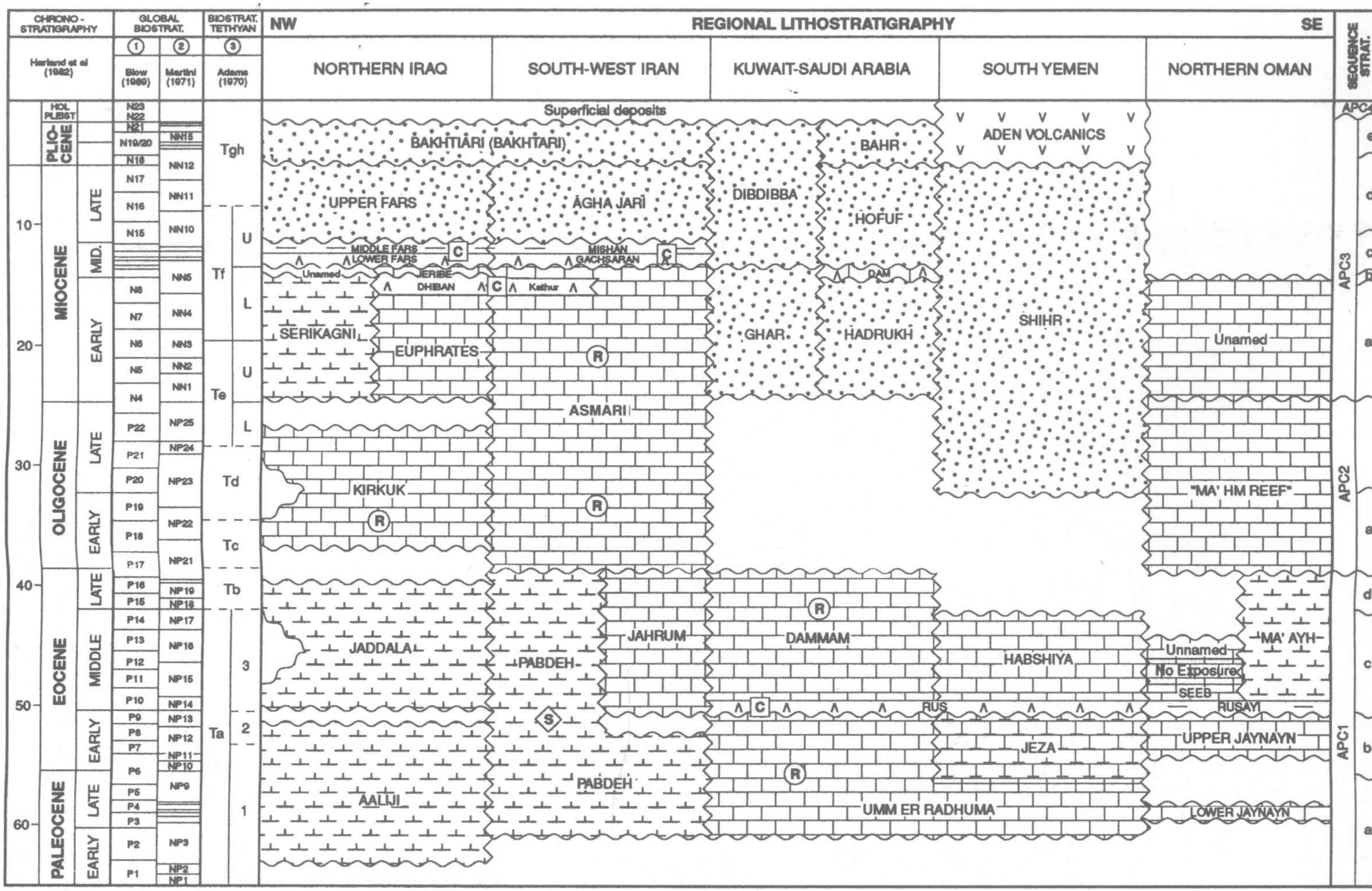

Figure 13.11 Regional stratigraphic summary. (For legend refer to Figure 13.10)

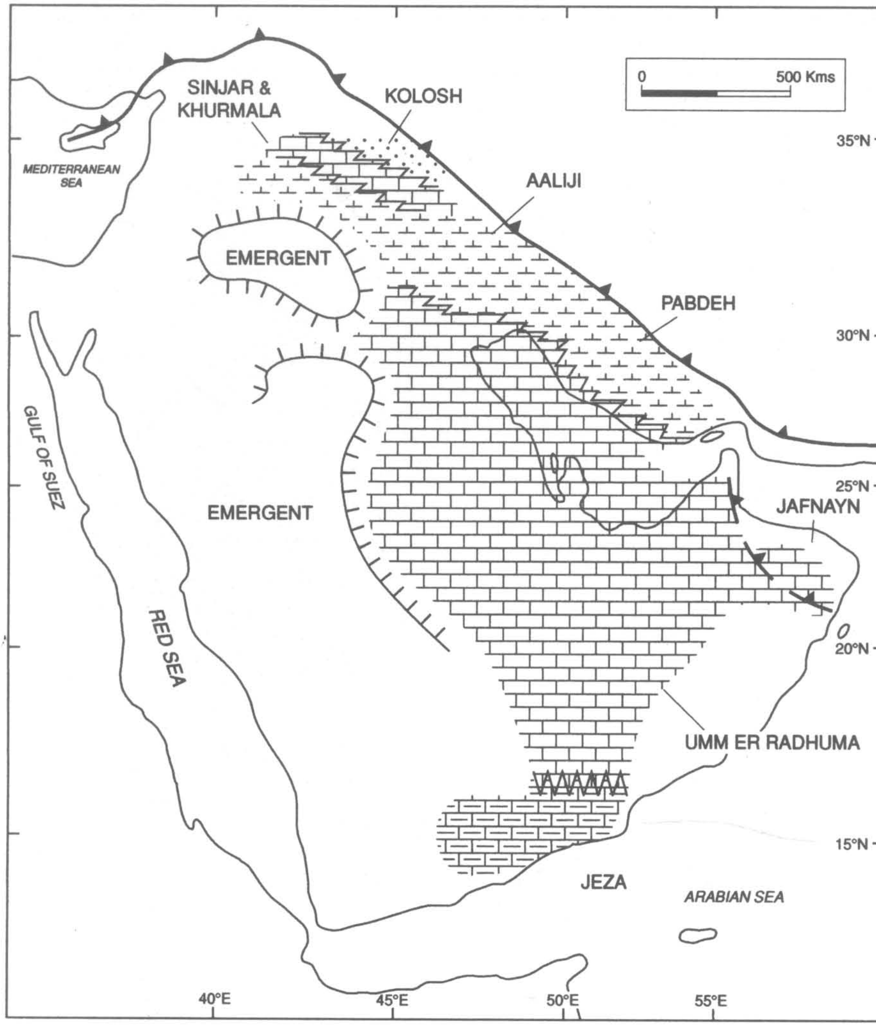

Figure 13.12 Palaeocene–Early Eocene (Sequences APC1a–APC1b) palaeogeography and facies distribution. (For legend refer to Figure 13.10.) See also Dunnington (1958), Ponikarov (1967), Buday (1980), Murris (1980, 1981), Nolan *et al.* (1986, 1990), Beydoun (1991), May (1991), Bott *et al.* (1992) and Hughes and Beydoun (1992).

and Dammam Formations (e.g., Wafra Field, Kuwait–Saudi Arabia Divided Zone (Nelson, 1968; Danielli, 1988)), and in Eocene carbonates of the Jahrum Formation (e.g., Binak Field, southwest Iran (Beydoun, 1988) and Habshiya Formation (e.g. Sharmah-1, Yemeni sector, Gulf of Aden (Haitham and Nani, 1990)). Potential reservoirs include the Sinjar and Avanah Formations of Iraq.

Evaporitic caprocks are widely developed in the Rus Formation and in overlying megasequences. Intraformational seals are locally developed within the Dammam Formation.

13.10.5 Comments

Local unconformities at the Palaeocene–Eocene boundary, at the end of the Early Eocene and within

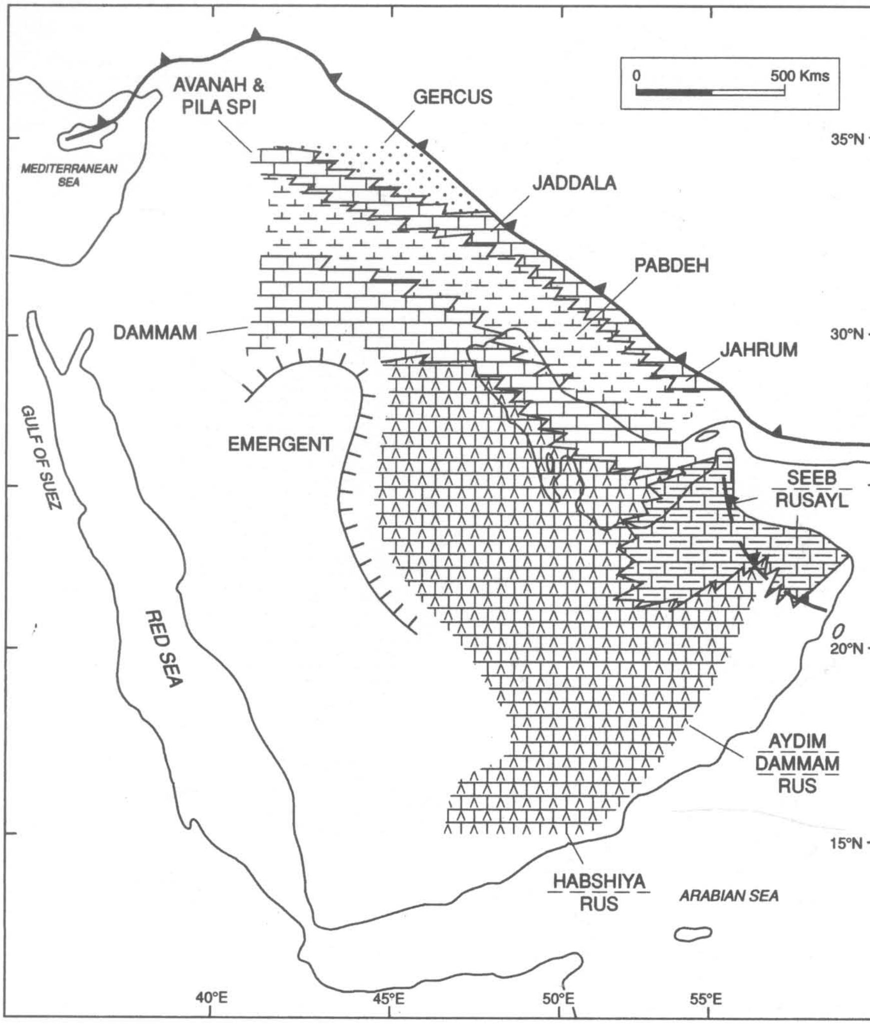

Figure 13.13 Middle–Late Eocene (Sequences APC1c–APC1d) palaeogeography and facies distribution. (For legend refer to Figure 13.10.) See also Dunnington (1958), Ponikarov (1967), Buday (1980), Murris (1980, 1981), Nolan *et al.* (1986, 1990), Beydoun (1991), May (1991), Bott *et al.* (1992) and Hughes and Beydoun (1992).

the Middle Eocene provide the basis for the subdivision of this megasequence into four sequences (APC1a, Palaeocene; APC1b, Early Eocene; APC1c, early Middle Eocene; APC1d, late Middle–Late Eocene). These sequences and their constituent bio- and lithostratigraphic units are shown on Figure 13.11. APC1a is equivalent to global third-order (eustatically-mediated) sequences TA1.2–2.3 of Haq, Hardenbol and Vail (1987), APC1b to TA2.4–2.9, APC1c to TA3.1–3.4 and APC1d to TA3.5–4.3.

13.11 SEQUENCE APC2 (OLIGOCENE)

13.11.1 Definition

Base defined by regional unconformity at base of Oligocene, top by regional unconformity at base of Miocene.

13.11.2 Age

Oligocene.

13.11.3 Geological setting

Uplift at the end of the Eocene (see above) brought about the contraction of the 'Tethyan Seaway' connecting the Indian Ocean to the east with the Mediterranean to the west. Oligocene sediments ('peri-reefal' and pelagic carbonates) are essentially confined to a narrow linear belt running through the Arabian Gulf, Iran, Iraq and Syria (the area of the former starved basin), though there are also isolated outcrops in southern Oman and Yemen. They are absent elsewhere owing either to non-deposition or to uplift and erosion associated with Red Sea rifting at the end

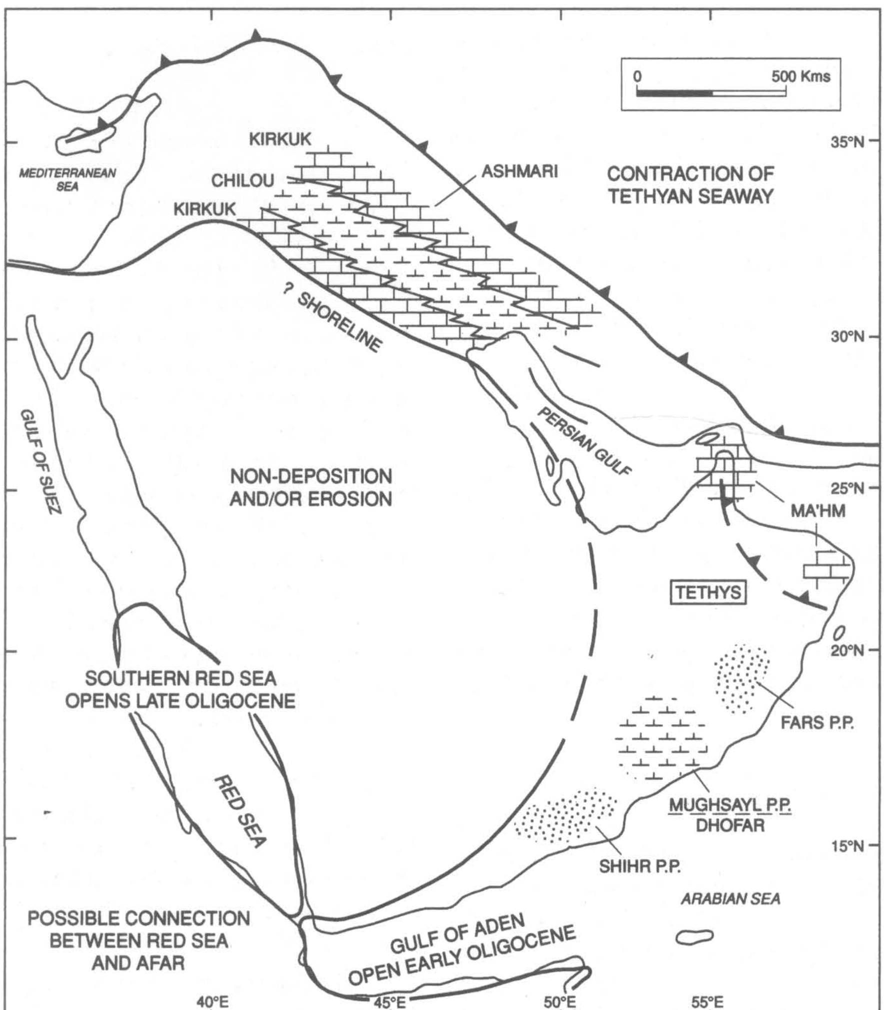

Figure 13.14 Oligocene (Sequences APC2a–APC2b) palaeogeography and facies distribution. (For legend refer to Figure 13.10). See also Dunnington (1958), Ponikarov (1967), Buday (1980), Murris (1980, 1981), Whybrow (1984), Beydoun (1991), Bott *et al.* (1992) and Hughes and Beydoun (1992).

of the Oligocene (see, for instance, Adams, Gentry and Whybrow (1983), Hughes, Varol and Beydoun (1991), Crossley *et al.* (1992) and Hughes and Beydoun (1992)) (Figure 13.14).

13.11.4 Source, reservoir and caprock development

The Palaeocene to Early Oligocene Pabdeh Formation, which belongs in part to this megasequence, is locally source-prone (Ala, Kinghorn and Rahman, 1980; Bordenave and Burwood, 1990).

Proven reservoirs are widely developed in Oligocene carbonates of the lower part of the Asmari Formation of southwest Iran (e.g., Agha Jari, Bibi Hakimeh, Gachsaran, Haft Kel, Karanj, Lali, Marun, Masjid-i-Suleiman, Naft-i-Shah(r), Naft Safid, Pazanan and Rag-e-Safid Fields) (Thomas 1950, 1952a, b; Hull and Warman, 1979; Beydoun, 1988), and of the Kirkuk Group of northern Iraq (e.g., Kirkuk, Bai Hassan and Jambur Fields) (van Bellen, 1956; Majid and Veizer, 1986; Beydoun, 1988). Oligocene–Miocene clastics, belonging in part to this megasequence, are also locally productive in southwest Iran (e.g., Ahwaz and Mansuri Fields), the Arabian Gulf (e.g., Abouzar, Bahregansar and Doroud Fields), and the Gulf States (e.g., Ratga Field, Kuwait). Much of the oil in the carbonate reservoirs remigrated there from Cretaceous reservoirs breached at the time of the Zagros Collision (Dunnington, 1958).

The caprocks to the Asmari and Kirkuk accumulations are developed in the overlying megasequence.

13.11.5 Comments

A local unconformity within the Oligocene provides the basis for the subdivision of this megasequence into two sequences (APC2a, Early Oligocene; APC2b, Late Oligocene). These sequences and their constituent bio- and lithostratigraphic units are shown on Figure 13.11. The APC2a sequence is equivalent to global third-order (eustatically-mediated) sequences TA4.4–4.5 of Haq, Hardenbol and Vail (1987) and APC2b to TB1.1–1.3.

13.12 SEQUENCE APC3 (MIOCENE–PLIOCENE)

13.12.1 Definition

Base defined by regional unconformity at base of Miocene, top by regional unconformity at base of Pleistocene.

13.12.2 Age

Miocene–Pliocene.

13.12.3 Geological setting

Tectonic activity during the Oligocene–Miocene (see also above) brought about the emergence of the 'Western Arabian Highlands', and a further contraction of the 'Tethyan Seaway' (ultimately resulting in the closure of its western (Mediterranean) end). The Miocene witnessed the widespread deposition of predominantly and increasingly marginal and non-marine sediments (especially evaporites and coarse clastics) both in the east (where the Ahwaz/Ghar Delta developed) and in the west, with marine sediments restricted to the 'Tethyan Seaway'. The Red Sea remained at least intermittently connected (possibly by way of what is now the Afar Depression) to the Gulf of Aden and Indian Ocean throughout the Miocene, as indicated by the occurrence there of the Indo-Pacifica benthonic foraminiferal genera *Ammonia* and *Pseudorotalia* (RWJ's unpublished observations). During the Pliocene, essentially continental sedimentation continued over most of the study area, while fully marine sedimentation resumed in the Red Sea (following the break-in unconformity and opening of the Bab el Mandeb Strait). The final Zagros Collision took place at the end of the Pliocene, causing extensive folding and faulting of earlier sediments (Figures 13.15, 13.16).

13.12.4 Source, reservoir and caprock development

Proven reservoirs are widely developed in carbonates of the upper part of the Asmari Formation of

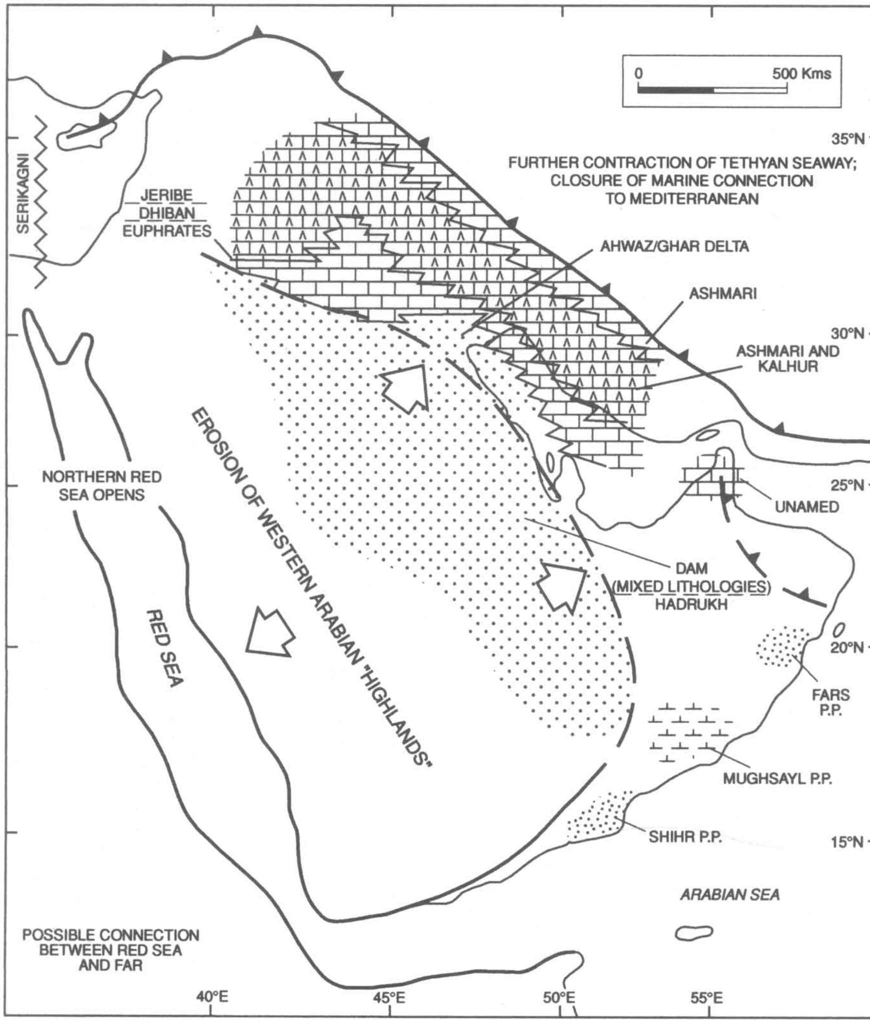

Figure 13.15 Early–earliest Middle Miocene (Sequences APC3a–APC3b) palaeogeography and facies distribution. (For legend refer to Figure 13.10). See also Dunnington (1958), Ponikarov (1967), Buday (1980), Murris (1980, 1981), Whybrow (1984), Beydoun (1991), Bott *et al.* (1992) and Hughes and Beydoun (1992).

southwest Iran and in correlative clastics. Potential reservoirs include the Euphrates Formation of northern Iraq and eastern Syria.

Evaporitic caprocks are widely developed in the Dhiban, Gachsaran and Lower Fars Formations and in the Kalhur Member of the Asmari Formation. Fine clastic caprocks are developed in the Middle Fars and Mishan Formations.

13.12.5 Comments

Local unconformities at the Early–Middle Miocene boundary, within the Middle Miocene, at the Middle–Late Miocene boundary and at the Miocene–Pliocene boundary provide the basis for the subdivision of this megasequence into five sequences (APC3a, Early Miocene; APC3b, early Middle Miocene; APC3c, late Middle Miocene;

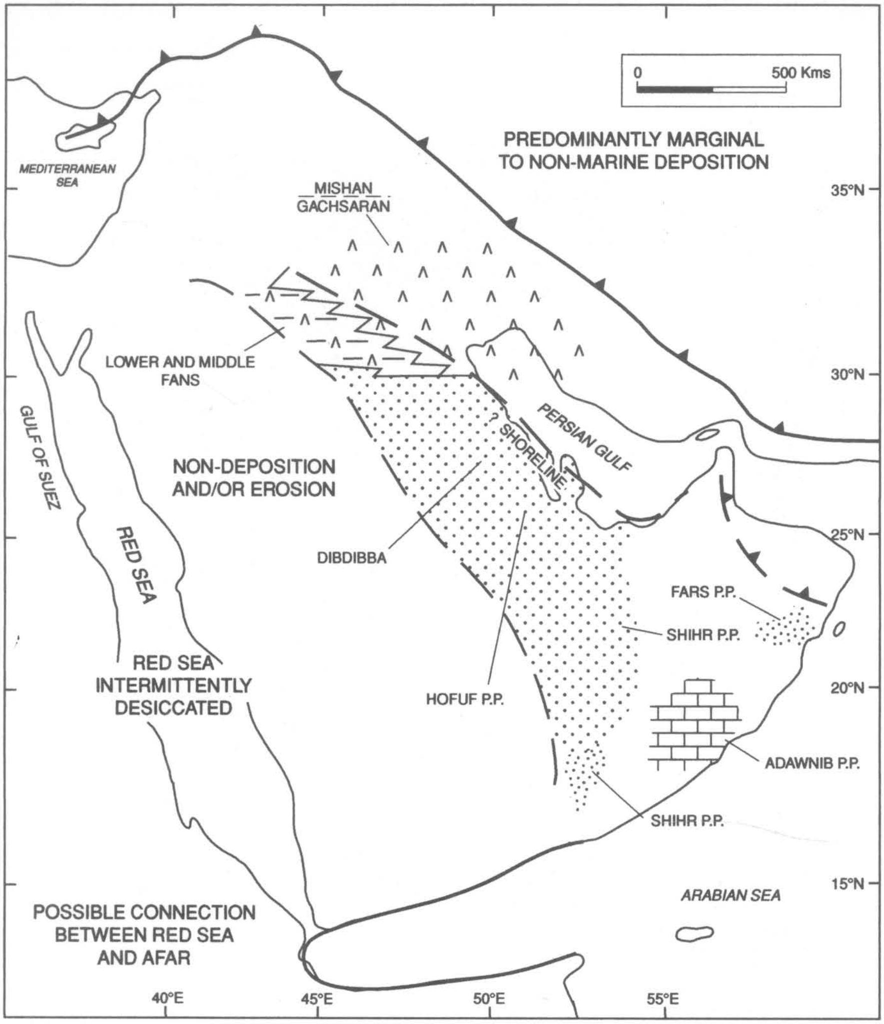

Figure 13.16 Latest Middle Miocene (Sequence APC3c) palaeogeography and facies distribution. (For legend refer to Figure 13.10.) See also Dunnington (1958), Ponikarov (1967), Buday (1980), Murris (1980, 1981), Whybrow (1984), Beydoun (1991), Bott *et al.* (1992) and Hughes and Beydoun (1992).

APC3d, Late Miocene; APC3e, Pliocene). These sequences and their constituent bio- and lithostratigraphic units are shown on Figure 13.11. The APC3a sequence is equivalent to global third-order (eustatically-mediated) sequences TB1.4-2.3 of Haq, Hardenbol and Vail (1987), APC3b to TB2.4, APC3c to TB2.5-2.6, APC3d to TB3.1–3.3, and APC3e to TB3.4-3.8.

13.13 SEQUENCE APC4 (PLEISTOCENE–HOLOCENE)

13.13.1 Definition

Base defined by regional unconformity at base of Pleistocene.

13.13.2 Age

Pleistocene–Holocene.

13.13.3 Geological setting

The final Zagros Collision at the end of the Pliocene (see also above) resulted in uplift, erosion and the deposition of a suite of essentially continental clastics over most of the study area. Marine sediments became restricted to the Arabian Gulf in the east and to the Red Sea in the west (Figure 13.17).

13.13.4 Comments

The APC4 sequence is equivalent to global third-order (eustatically-mediated) sequences TB3.9–3.10 of Haq, Hardenbol and Vail (1987).

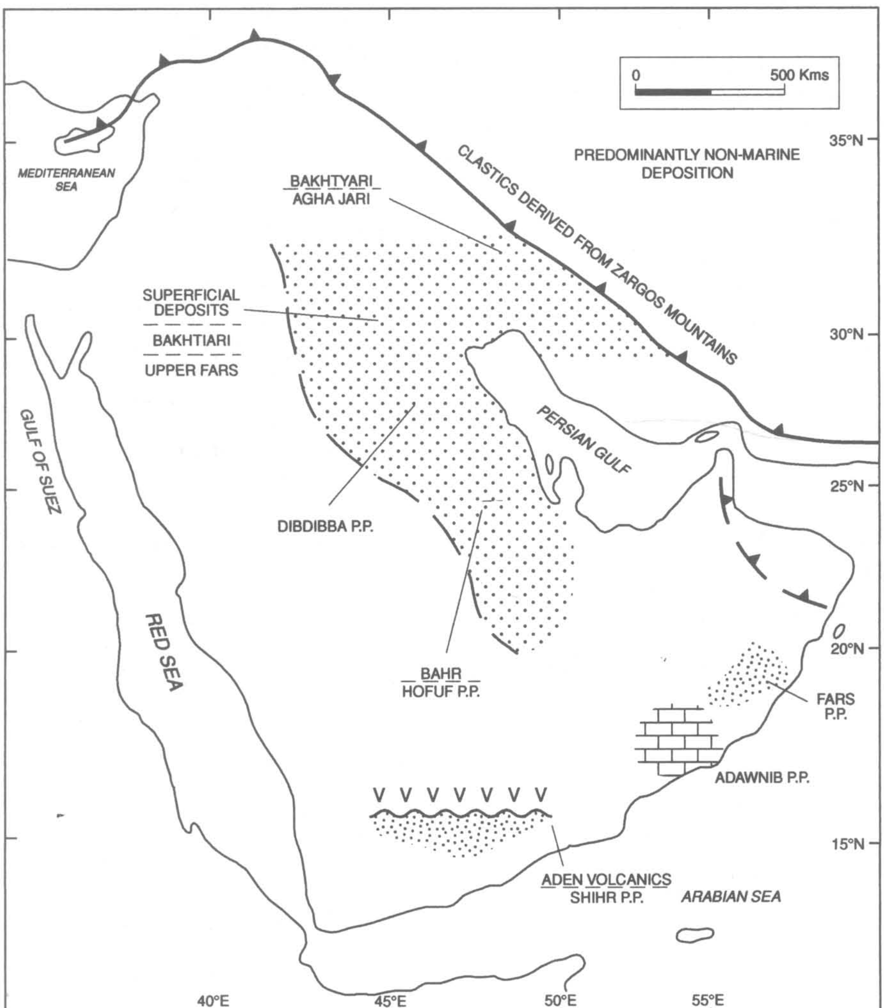

Figure 13.17 Late Miocene–Holocene (Sequences APC3d–APC4) palaeogeography and facies distribution. (For legend refer to Figure 13.10.) See also Dunnington (1958), Ponikarov (1967), Buday (1980), Murris (1980, 1981), Whybrow (1984), Beydoun (1991), Bott *et al.* (1992) and Hughes and Beydoun (1992).

13.14 SUMMARY OF PETROLEUM SOURCE, RESERVOIR AND CAPROCK DEVELOPMENT

13.14.1 Source

Although the principal sources of the Middle East petroleum accumulations are Jurassic to Cretaceous, the Palaeocene to Early Oligocene Pabdeh Formation (Megasequences APC1 and APC2) is locally source-prone.

13.14.2 Reservoir

Proven reservoirs are developed in Palaeocene to Eocene carbonates of the Umm Er Radhuma, Dammam, Jahrum and Habshiya Formations (Megasequence APC1), in Oligocene carbonates of the Kirkuk Group (APC2), and in Oligocene–Miocene carbonates and clastics of the Asmari Formation and its correlatives (APC2 and APC3). Potential reservoirs are developed in Eocene carbonates of the Sinjar and Avanah Formations of Iraq (APC1), and in the Miocene carbonates of the Euphrates Formation of northern Iraq and eastern Syria (APC3).

13.14.3 Caprock

Evaporitic caprocks are developed in the Rus and Dammam Formations (Megasequence APC1) and in the Dhiban, Gachsaran and Lower Fars Formations and Kalhur Member of the Asmari Formation (APC3). Fine clastic caprocks are developed in the Middle Fars and Mishan Formations (APC3).

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