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Carbonate Deposition in Accretionary Prism Settings: Early Miocene Coral Limestones and Corals of the Makran Mountain Range in Southern Iran

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KEYWORDS: ACCRETIONARY PRISM - PLATE CONVERGENCE - LIMESTONES - REEFS - CORALS - BENTHONIC FORAMINIFERA - PALAEOGEOGRAPHY - PALAEOBIOGEOGRAPHY - EVOLUTIONARY PALAEOECOLOGY - RECENT CORAL ASSEMBLAGES - SOUTHERN IRAN - MIOCENE

CONTENTS

SUMMARY

The regional mapping of the Makran mountain range on behalf of the Geological Survey of Iran represents a unique coverage: the entire area of the mountain range was compiled in a unified programme. During this mapping, Miocene limestones containing rich coral and foraminiferal faunas were recorded over a strike length of several hundred kilometres, as minor developments within thick neritic clastic sequences which in turn overlie great thicknesses of Eocene-Miocene flysch. These limestones include rigid bioconstructional frameworks, loosely compacted coralline assemblages and foraminiferal calcarenites: they include *in situ* reefal deposits and material redeposited quite close to their original site of deposition. Most are Burdigalian, as shown by the benthonic foraminifera, but some are Aquitanian. The geotectonic setting was an accretionary prism in a zone of plate convergence. The limestones and enclosing clastic sediments comprise an intensely folded, reverse-faulted and locally dislocated sequence, the duplex structure being the result of a major Late Miocene-Pliocene episode of regional deformation. This concentration of the intense tectonic deformation in a late major episode requires a different model for this zone of plate convergence to the model widely applied to such zones. The possible controls on limestone deposition are discussed - tectonic uplift and shallowing of the sea, climatic warming and eustatic factors. Depositional features of reefal formations in the late Jurassic of the Caucasus, the Pliocene-Recent of Halmahera, and the early Miocene of SE France are discussed in comparison with the Makran model.

The previously unknown corals from the limestones comprise more than 40 genera and 90 species and represent the largest recorded Miocene coral collection between the Mediterranean and Indonesia. A faunal list is provided and their significance is discussed, especially with respect to the apparent absence of higher energy assemblages. The respective influence of local ecological conditions, regional palaeogeographical setting, and late Cainozoic global change are assessed as causes of this pattern, and the latter favoured. The

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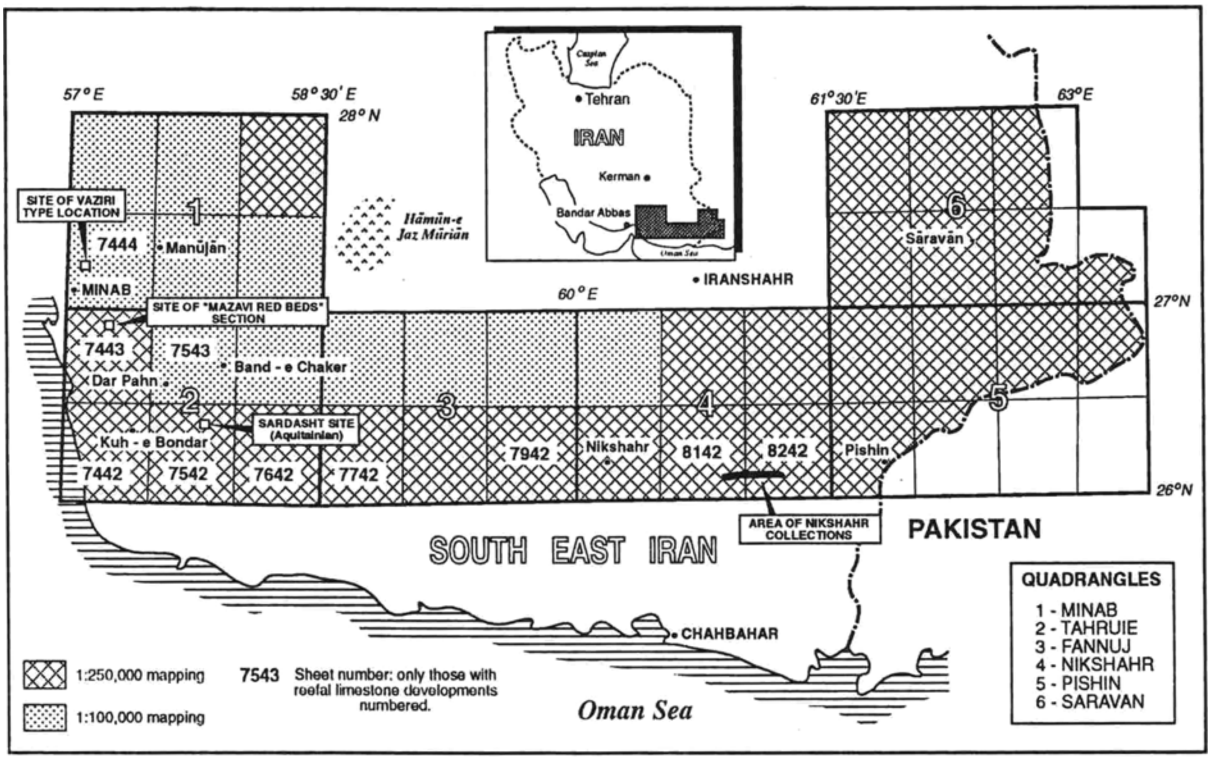

Fig. 1. Map of the project area showing the six (1.5° x 1°) Quadrangles (large numbers: see legend) mapped in whole or in part, and their component sheets (small four-figure numbers). The entire mapped area is c.650 km across. Place-names marked include all localities or areas mentioned in the text as having Lower Miocene limestone developments. The numbers allocated to these localities are as follows: Vaziri (Locality 1); Band-e Chaker (2); Mazavi (3); Sardasht (4); area of Nikshahr collections (Lashgar Rud: 5); Dar Pahn (6); south of Kuh-e Bondar (7). Limestones at all these localities are Burdigalian unless shown otherwise; see also Figure 3.

essential poritid-faviid character of most global coral communities remained relatively static for much of the Cainozoic notwithstanding background taxonomic turnover. Coral assemblages typical of higher energy, especially those dominated by *Acropora*, then appeared late in the Cainozoic alongside the older assemblages. However, a global increase in wave energy around this time is probably too naïve an explanation and causes arising from intensification of glacio-eustasy should be considered instead.

Associated algae, foraminifera and molluscs are briefly discussed. The Makran fossils have especial palaeobiogeographical and palaeogeographical interest as they come from localities close to the areas of Miocene uplift which finally severed the Middle Eastern seaways of Tethys. Together with several previously recorded faunas elsewhere in Iran, their original location lay within an arm of the Miocene Arabian Sea, named here 'The Proto-Persian Gulf', at a palaeolatitude of about 25°N. The corals and foraminifera show an almost entirely Indo-Pacific affinity which began to emerge even before the final Zagros closure, indicative of strong biogeographical discontinuity with the early Miocene Mediterranean region.

1 INTRODUCTION

1.1 Background and scope

This account relates to a programme of regional mapping carried out from 1976 to 1978 over a land area of the Makran Mountain Range in Southern Iran c.650 km across using helicopter-borne traverse parties (McCall & Simonian 1986). About thirty geologists were involved in this contract, carried out by Paragon-Contech (an Australian-Iranian joint venture) on behalf of the Geological Survey of Iran. Of the three present authors, only G.J.H. McCall was actually engaged in this field mapping programme, and was fully involved throughout. B.R. Rosen and J.G. Darrell worked entirely on the samples collected, principally on the corals, and were not part of the field team.

The Miocene of the Makran Mountain Range was found to include limestones, some of which have features in common with reefs (e.g. bioconstructional frameworks) as well as rich coral faunas. Up until now, the only information about these limestones has been in the original Paragon-Contech maps and mapping reports (see below) and no synthesis or discussion of them has previously been presented. Even though our information is very incomplete, we

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Fig. 2. The geotectonic zones recognized in the Makran (details in Table 1).
(A) - sketch map; same scale as Figure 1 (see caption).
(B), (C) - sketch sections along lines shown in (A), showing the structural relations of Zone 7 which includes the limestones discussed in this paper. 'Vaziri Unit' - see text section 1.4.

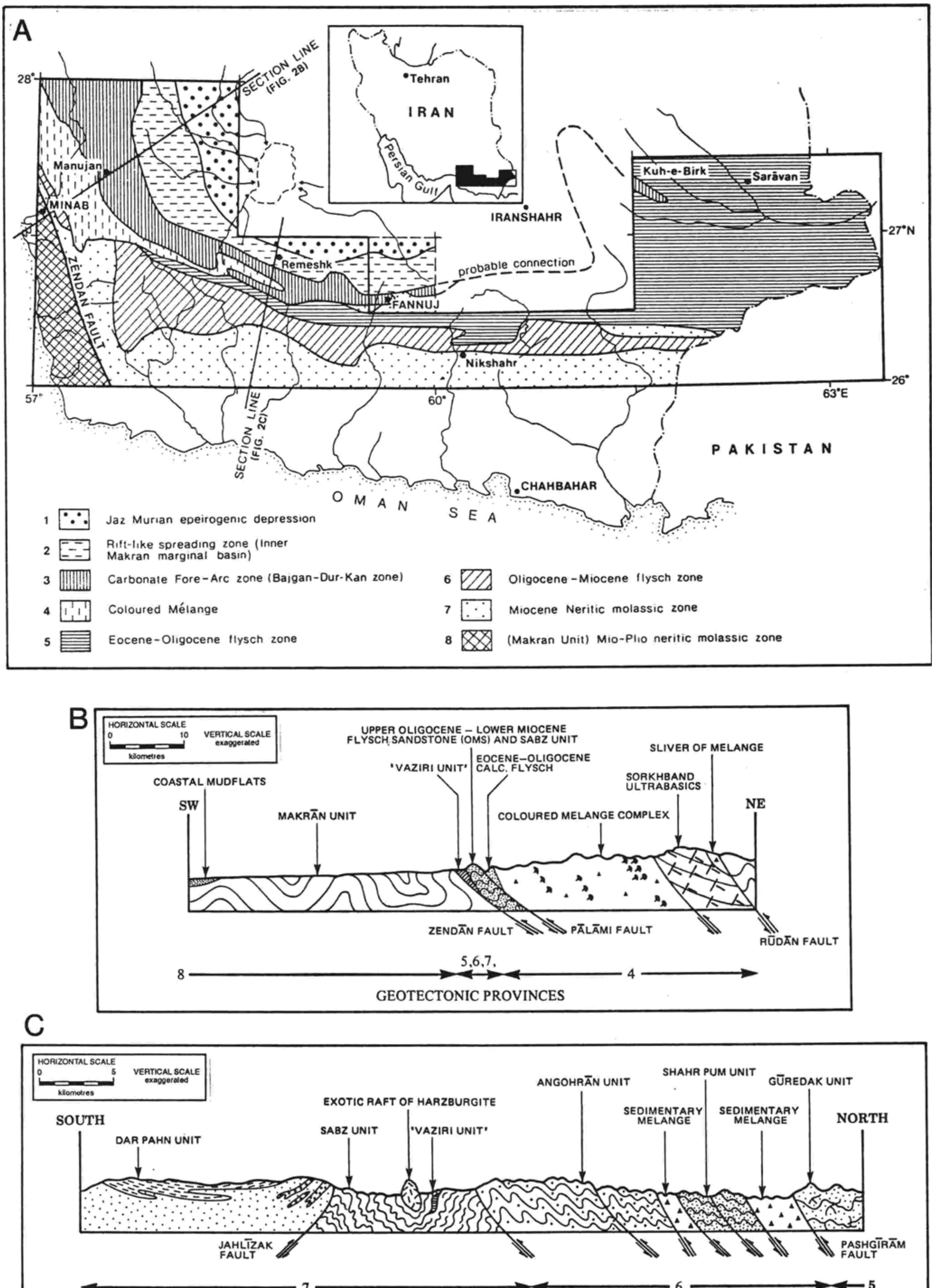

A
28°
57°
60°
63°E
27°N
26°
SECTION LINE (FIG. 2B)
SECTION LINE (FIG. 2C)
Tehran
IRAN
Persian Gulf
Manujan
MINAB
ZENDAN FAULT
Remeshk
FANNUJ
probable connection
IRANSHAHR
Kuh-e-Birk
Sarāvan
Nikshahr
PAKISTAN
CHAHBAHAR
OMAN SEA
1 Jaz Murian epeirogenic depression
2 Rift-like spreading zone (Inner Makran marginal basin)
3 Carbonate Fore-Arc zone (Bajgan-Dur-Kan zone)
4 Coloured Mélange
5 Eocene-Oligocene flysch zone
6 Oligocene-Miocene flysch zone
7 Miocene Neritic molassic zone
8 (Makran Unit) Mio-Plio neritic molassic zone
B
HORIZONTAL SCALE 0 10 kilometres
VERTICAL SCALE exaggerated
SW
NE
COASTAL MUDFLATS
MAKRĀN UNIT
'VAZIRI UNIT'
UPPER OLIGOCENE – LOWER MIOCENE FLYSCH SANDSTONE (OMS) AND SABZ UNIT
EOCENE–OLIGOCENE CALC. FLYSCH
COLOURED MELANGE COMPLEX
SORKHBAND ULTRABASICS
SLIVER OF MELANGE
ZENDĀN FAULT
PĀLAMI FAULT
RŪDĀN FAULT
8
5,6,7,
4
GEOTECTONIC PROVINCES
C
HORIZONTAL SCALE 0 5 kilometres
VERTICAL SCALE exaggerated
SOUTH
NORTH
DAR PAHN UNIT
SABZ UNIT
EXOTIC RAFT OF HARZBURGITE
'VAZIRI UNIT'
ANGOHRĀN UNIT
SEDIMENTARY MELANGE
SHAHR PUM UNIT
SEDIMENTARY MELANGE
GŪREDAK UNIT
JAHLĪZAK FAULT
PASHGĪRĀM FAULT
7
6
5
GEOTECTONIC PROVINCES

Table 1. The eight geotectonic zones recognized in the Makran (McCall & Kidd 1982, McCall 1985e) (see also Figures 2A-C). Zone 7 (in bold) includes the limestones discussed in this paper.

Notes:

Zone 1 is bounded by the unconformable overlap of the superficial deposits of the Jaz Murian Depression on the older rocks. Zones 6 and 7 are separated by facies transitions, but the remainder of the boundaries are major reverse faults. Continental deposits (fanglomerates) etc. of Late Miocene, Pliocene and Quaternary age have a limited development in Zones 5, 6 and 7. There is no evidence for major discordance within Zones 5 to 8.

1.	Jaz Murian Depression	Recent epeirogenic depression; bedrock entirely obscured by Quaternary aeolian, fluvial and playa lake deposits.
2.	Spreading Zone	Narrow, deep rift-like marine basin, initiated in Jurassic or earlier; site of ophiolitic eruptivity and pelagic sedimentation up to Palaeocene.
3.	Carbonate Fore-arc Zone	Continental crust including Palaeozoic metamorphic rocks overlain by shelf sediments of Carboniferous to Palaeocene age; separated from the Lut Block (the ancient microcontinental core) in the Jurassic by the rift-like Spreading Zone 2..
4.	Trench Zone	Zone of subduction and tectonic (ophiolitic) mélange formation ("Coloured Mélange"); the pelagic sediments include micrites and radiolarites as old as Jurassic (possibly Triassic), but the principal component is Upper Cretaceous Globotruncana Limestone; turbidites are common and a Palaeocene globigerinid ooze is the youngest component recognised.
5.	Eocene-Oligocene Flysch Zone	Dominated by monotonous flysch sequences.
6.	Oligocene-Miocene Flysch Zone	Dominated by monotonous flysch sequences.
7.	**Miocene Neritic Sediment Zone**	**Dominated by siliciclastic stratigraphic units including some 'flysch-like' turbidites. These sequences show rapid variations of facies (unlike the flysch sensu stricto of Zones 5 and 6) and include coral-algal limestones and associated foraminiferal calcarenites.**
8.	Miocene-Pliocene Neritic-Continental Sediment Coastal Zone	

believe a summary and partial interpretation will be of interest.

The following constraints apply to the present account and especially bear on the limestone descriptions and interpretation: (1) the field observations, sample collections and initial interpretations that form the basis of the present account are drawn from work done by different members of the Paragon-Contech team at different times; (2) their goal was regional mapping with an economic objective; (3) the limestones were not mapped in detail nor singled out for special study; (4) field parties did not usually include a reef specialist; (5) no detailed record was made of lateral changes in the limestones along strike; and (6) limestone depositional surfaces were often eroded or obscured. These last two factors in particular make it difficult to provide three-dimensional details and interpretation of the limestones. It has not been possible to mount further research programmes that would normally have followed the regional mapping, and which could resolve such omissions. It is hoped that such a follow-up programme will be encouraged by our account.

The aims and objectives of this paper are:

(1) to summarise the lithology of the limestones and give their stratigraphical, structural and geotectonic context.

(2) to provide a preliminary interpretation of some of the limestones drawing attention to reefal features.

(3) to summarise the palaeontology of the limestones, concentrating on the corals and the age-diagnostic foraminifera.

(4) to discuss the regional and global significance of the coral fauna.

1.2 Previous work

The Makran has been comparatively neglected by geologists compared with the Zagros, Oman and Alborz mountain ranges. What work has been previously carried out was mainly of a reconnaissance nature and hydrocarbon-related (Harrison et al. 1935-6, Harrison & Falcon 1936, Huber 1952, Stöcklin 1952, AGIP/SIRIP 1962). A full list of previous work is given by McCall (1985e, pp. 44-46).

Publications based on the Paragon-Contech regional study of 1976-8 include five quadrangle maps on a scale of 1:250,000 and accompanying reports (McCall 1985a-d, McCall & Eftekhar Nezhad 1993), together with nine maps on a scale of 1:100,000 with explanatory notes (McCall & Peterson, 1980a-e, 1981a-d). A further quadrangle, Saravan, was mapped on a scale of 1:250,000 by Paragon-Contech (southern half) and Intercon (northern half) and the report and map will shortly be published (McCall &

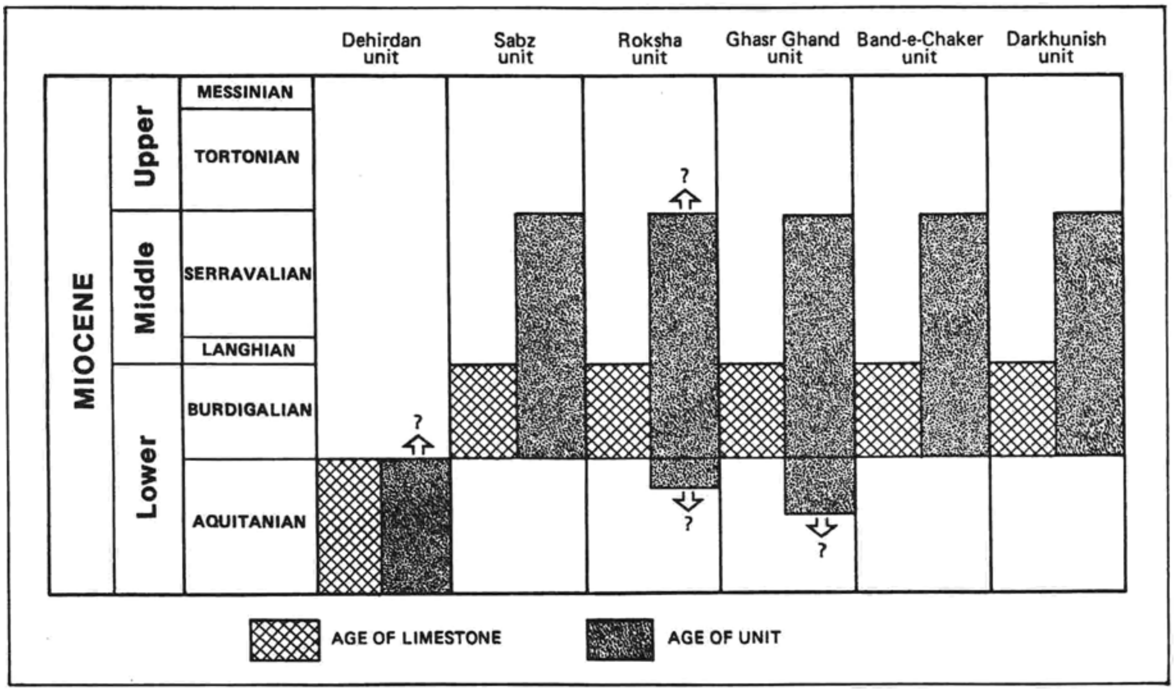


Fig. 3. Diagram showing the age limits of the Miocene limestones discussed here, and the six informally designated Miocene stratigraphic units within which they occur (see also Table 2). Stratigraphic positions of the limestones at the main localities are: Vaziri (Locality 1) and south of Kuh-e Bondar (Locality 7) in Sabz Unit; Band-e Chaker (Locality 2) in Band-e Chaker Unit; Mazavi (Locality 3) and Dar Pahn (Locality 6) in Darkhunish Unit; Sardasht (Locality 4) in Dehirdan Unit; Lashgar Rud (Locality 5) in Ghasr Ghand Unit.

Eftekhar Nezhad 1993, in the press) The six component quadrangles and their component sheets are shown in Figure 1. An account of the background to the entire project was also published (McCall 1985e). The plate tectonics of the region were placed in their wider context by McCall & Kidd (1982), and McCall (1983) gave an account of the mélange development. McCall (1993, in the press) has recently commented further on the broader geotectonic assembly of southeastern Iran. Crimes & McCall (1994, in the press) have also compiled an account of the remarkably well preserved and varied trace fossils contained in the Eocene-Miocene clastic sequences of the Makran.

1.3 Localities

The location of the study region is shown in Figure 1. Exposure throughout most of the region is excellent, especially of the limestones. The present paper gives generalized information about the Miocene limestones and their palaeontology in the area covered by the Minab, Tahruie, Fannuj and Nikshahr quadrangles (not the Pishin or Saravan quadrangles, where Miocene coral limestones are not represented). Reference is also made to seven particular localities or areas, shown within their respective Quadrangles in Figure 1, and summarised in the list below. {The stratigraphical details mentioned in this list are explained further in the next section (and see Figure 3)}.

1. Vaziri: the 'type locality' (but see Section 1.4) just west of Vaziri village at data point 2084 (McCall 1985a), lat.27°19'00"N, long.57°07'00"W. Seven separate outcrops along a major fault over 12 km. Only the main, northwesternmost one, was studied and sampled in detail; c. 1.5 x 1.5 km in area. These outcrops are mostly fault-bounded but the southeasternmost one, though faulted, is within the Sabz Unit and was probably deposited as a 'member' within it. These limestones have been dated as Burdigalian.

2. Band-e Chaker: area consists of a synclinorium c. 30 km long with more than fifty separate limestone outcrops on both flanks and round the closure to the northwest; it includes site of Measured Section 31 (McCall 1985b). One narrow continuous outcrop was mapped as 4 km long but most are much smaller. The limestones are low down in the Band-e Chaker Unit near the contact with the Dehirdan Unit and have been dated as Burdigalian.

3. Mazavi: site of Measured Section 44 (McCall 1985b), approx. 26°48'N, 57°16'E. Numerous very small lenses and beds of limestone within a vertical section of c. 2000 m mapped as the 'Vaziri Unit' and occurring within the Darkhunish Unit; measured section is near the lower contact of this unit with the Dehirdan Unit. These limestones have been dated as Burdigalian.

4. Sardasht: one main locality, site of Measured Section 100 (McCall 1985b; and Table 3, Figures 5a, 5b, Plate 17/3-5), lat.26°28'20"N. long.57°54'35"E (bottom of section) and lat.26°28'25"N. long.57°54'20"E (top of section), c. 200 m thick; also numerous small outcrops nearby. All outcrops are within Dehirdan Unit. Measured section includes six limestones, the uppermost two dated as Aquitanian.

5. Lashgar Rud, Nikshahr: area of Measured Section 66 (McCall & Eftekhar Nezhad 1993, in the press); and Table 4, Figures 6-9, lat.26°00'52"N. long.61°00'30"E. for bottom of section and lat.26°00'45"N. long.61°00'27" for top of section. There are fourteen outcrops in all, over an east-west strike-length of 23 km. There is one continuous band mapped for 6-7 km but most outcrops are less continuous including the section described here, which is the thickest at 190 m, but this fades out abruptly, laterally. All outcrops are within the Ghasr Ghand unit. These limestones have been dated as Burdigalian.

6. Dar Pahn: major fossil locality (Plate 17/1), approx 26°32'N, 57°35'E (McCall 1985b). Two outcrops; largest 2 km long and c. 200 m thick, low in Darkhunish Unit near contact with Dehirdan Unit. These limestones have been dated as Burdigalian.

7. South of Kuh-e Bondar: major fossil locality, faulted into Sabz unit (Plate 18/2), approx. 26°20'N, 57°17'E (McCall 1985b). These limestones have been dated as Burdigalian.

Table 2. List of informally named stratigraphic units of Miocene and younger age in the mapped area of the Makran. Units within the Early to Middle Miocene are largely contemporaneous (see text and Figure 3).
A-limestones - indicates sequences that also include coral-algal and foraminiferal limestones of Aquitanian age (previously referred to as 'Vaziri Unit': see text section 1-4)
B-limestones - same, of Burdigalian age (previously referred to collectively as 'Vaziri Unit')

	QUATERNARY	
		Superficial deposits.
	PLIOCENE	
		Fluvial deposits.
	MIDDLE TO LATE MIOCENE TO EARLY PLIOCENE	
PALAMI, TAHTUN, MAKRAN, DAR PHAN and JAGHIN UNITS		Fluvial, estuarine, littoral, lagoonal and deltaic deposits.
	EARLY TO MIDDLE MIOCENE	
DARKHUNISH UNIT	Shale, minor siltstone and sandstone; very minor gypsiferous beds; **B-limestones**.	Marine; some turbidites low in sequence; mainly neritic.
BAND-E CHAKER UNIT	Sandstone, siltstone, shale, pebble beds, coaly sapropelic horizons; **B-limestones.**	*(as above)*
ROKSHA UNIT	Sandstone, siltstone, shale, shell beds, evaporites, massive marine conglomerates; **B-limestones.**	*(as above)*
SAHAN TANG UNIT	Sandstone, gypsiferous mudstone	Marine, ?mainly evaporitic.
GHASR GHAND UNIT	Thin sandstone and gypsiferous mudstone; **B-limestones**.	Marine, mainly evaporitic; turbidites low in sequence.
JARUT UNIT	Sandstone, siltstone, shale, carbonaceous shale	Marine, deltaic and estuarine with mangrove swamps; turbidites low in sequence.
SABZ UNIT	Gypsiferous mudstone, thin sandstone, minor conglomerate; **B-limestones.**	Marine, evaporitic; turbidites low in sequence.
SHAHR-PUM UNIT	Monotonous sandstone/shale alternations with typical primary sedimentary structure of turbidites.	Marine, deep water; proximal flysch.
AB-E SHAHR UNIT	Thinly bedded non-rhythmic sandstone and shale.	Marine; shallow water; non-rhythmic proximal flysch.
HICHAN UNIT	Thinly bedded sandstone and shale sequence with turbidite characteristics.	*(as above)*
PISHIN UNIT	*(as above)*	Marine, deep water; turbidites (true flysch).
	LOWER MIOCENE (AQUITANIAN)	
DEHIRDAN UNIT	Thinly bedded shale and sandstone, with carbonate but no gypsum; **A-limestones.**	Marine; true flysch passing up into neritic facies.

These localities are widely separated geographically, and there are many smaller and sporadic outcrops of Miocene limestones elsewhere along the L-shaped zone in which they occur. This zone runs southwards from the Minab quadrangle to the south of the Tahruie quadrangle, and then eastwards through the Fannuj quadrangle and most of the Nikshahr quadrangle, in all, a linear distance of nearly 640 km.

1.4 Stratigraphy

The regional stratigraphy is complicated because the Makran comprises a 'fore-arc' complex (McCall & Kidd 1982), dominated by 'Schuppen' (a 'duplex' structure). Eight geotectonic Zones have been defined (McCall & Kidd 1982; McCall 1985e) (Table 1, Figures 2A-C), and numbered outwards towards the coast. Each zone generally consists of progressively younger rocks towards the coast, the Miocene limestones being entirely contained within Zone 7. The stratigraphy is described in full elsewhere (McCall 1985e): only the Neogene components which are developed in Zones 6, 7 and 8 are summarised in Table 2.

The nature of the structure - parcelled up into 'packets' by numerous low angle faults - makes correlation of similar but geographically separated sequences difficult, despite numerous foraminiferal determinations establishing their age (e.g. Tables 3, 4 and text Section 4.1). For this reason, a large number of informal unit names had to be erected, though many of the units are broadly time-equivalent. There is also evidence of diachroneity. The similar coral-algal-foraminiferal limestones found throughout the Miocene of the mapped area (McCall 1985e, pp. 237-244), occur within six such informally-named sedimentary units (Sabz, Band-e Chaker, Roksha, Ghasr Ghand, Darkhunish, Dehirdan), all of which are wholly, or in part, of Early Miocene age (Figure 3).

The single name 'Vaziri Unit' was initially allocated to all these limestones but this was perhaps premature because it was later found more satisfactory to classify them as intervals within these larger units. They also proved to be of two ages, Aquitanian and Burdigalian. Moreover, the choice of the name 'Vaziri' is unsatisfactory, because the locality of that name (Locality 1) is not suitable for a type section. It was initially chosen because Miocene limestone was first discovered there {during the mapping of the Minab Quadrangle (McCall 1985a)}, but the thick limestone section at Vaziri is entirely fault-bounded (see above), and its upper and lower stratigraphical boundaries are not preserved. Thus while 'Vaziri Unit' has been previously used as a collective name for the Miocene limestones discussed here, it should now be formally replaced with separately named limestone members of the above sedimentary units. Such stratigraphical revision however must await formalisation by the Geological Survey of Iran. In this paper we refer to them as Burdigalian (or Aquitanian) limestones of a particular unit, though the name 'Vaziri Unit' is sometimes used (in inverted commas) when the original mapping work has been directly incorporated (Figures 2B, 2C, 6, 8).

Dating was based on larger benthonic foraminifera throughout, but only on selected limestone outcrops. Initially this was done by field laboratory examination, but later, samples were also sent elsewhere for definitive dating (see text Section 4.1). Rocks including limestones of Aquitanian age definitely occur within the Dehirdan Unit (e.g. Sardasht, Locality 4; see Table 3 and text Section 4.1), and may also occur within at least two of the other six units listed above (see Figure 3). However, apart from Sardasht, the limestones at all other localities (1-3, 5-7) were dated as Burdigalian. Further stratigraphical details for the section at Sardasht (Locality 4) are given in Table 3, Figures 5a and 5b, and Plate 17/3-5. Details for Lashgar Rud (Locality 5) are given in Table 4 and Figures 6-9.

1.5 Structure and geotectonic setting

The Makran was a region of considerable tectonic instability during deposition of Miocene rocks, and the thick Miocene turbiditic (flysch-like) to neritic sequences that enclose the limestones are characterised by rapid changes of facies, in contrast to the monotonous older (Eocene to early Miocene) true flysch sequences of the Makran. Tectonic instability is related to the presence of an active convergent plate boundary in the region. Further details of the geotectonics of the Makran are summarized below because few (if any) previous accounts exist of carbonate deposition in an identical setting to that of the Miocene limestones of the Makran.

The geotectonic locus of deposition of the limestones and associated siliciclastic rocks is the Makran accretionary prism which lies along the convergent plate margin between the Gulf of Oman on the Arabian Plate and the Iranian part of the Eurasian Plate (Jacob & Quittmeyer 1979: see their Figure 1). Continuation of this convergence northwestwards is represented by the Zagros closure. To the south, in the Gulf of Oman and parallel to the southern coastline of the Makran, the subduction zone is still active (McCall & Kidd 1982: their Figure 4, White 1982, McCall 1993 in the press). The convergent plate system terminates at the east edge of the Makran against the major transform fault system that marks the western boundary of the Indian Plate {Owen Fracture Zone, Murray Ridge and Chaman Fault, etc. (Jacob & Quittmeyer 1979)}.

The Iranian part of the Makran to the west of the Pishin and Saravan Quadrangles is made up of (1) pre-Cretaceous and Cretaceous to Lower Palaeocene rocks, inland; (2) an accretionary prism of Eocene to early Pliocene age nearer the coast and built out southwards from a foreland of these older rocks, and strongly folded in the post-early Pliocene; and (3) the present southward-advancing prism of sediments accreted since this latter folding of the older part of the prism. The geotectonic zones of the Iranian Makran have been mentioned above (text Section 1.4) and the tectonics are summarized in Table 1, Figures 2 and 4. The present-day prism front is 100-150 km south of the coast. The volcanic arc related to this prism is the Bazman-Taftan arc, 400-600 km inland (Jacob & Quittmeyer 1979). The broad geographical separation between the arc and the prism front may indicate a gently dipping subduction zone that only steepens beneath the arc itself. The oldest (pre-late Palaeocene) rock assemblage relates to the earliest subduction phase and is dominated by the ophiolitic Coloured Mélange (McCall 1983). The next phase is represented by the Eocene to Lower Pliocene assemblage which is sediment-dominated, the only mélange present consisting of dislocated sedimentary rocks with scattered exotics derived from the older formations and 'squeezed up like pips' (McCall 1983). There is no sign of an associated volcanic arc in the Makran ranges that was contemporaneous with these Eocene to Lower Pliocene sediments, and, if one existed, it must have been far inland like the present Bazman-Taftan arc. It is believed to be represented by the zone of Eocene calc-alkaline eruptives north of the Jaz Murian Depression: McCall (1993 in the press).

That the Makran accretionary prism does not conform to the widely accepted models for accretionary terranes (Farhoudi & Karig 1977; Karig 1982) has previously been noted by Platt et al. (1985), and also independently by one of us (G.J.H.McCall during the Makran project (McCall 1993 in the press). Platt et al., discussing the eastward continuation of the Makran in Pakistan, 'emphasize the role of deformation and accretion in the immediate area of the prism front, with only limited deformation within the body of the prism.' They found no evidence for structural or

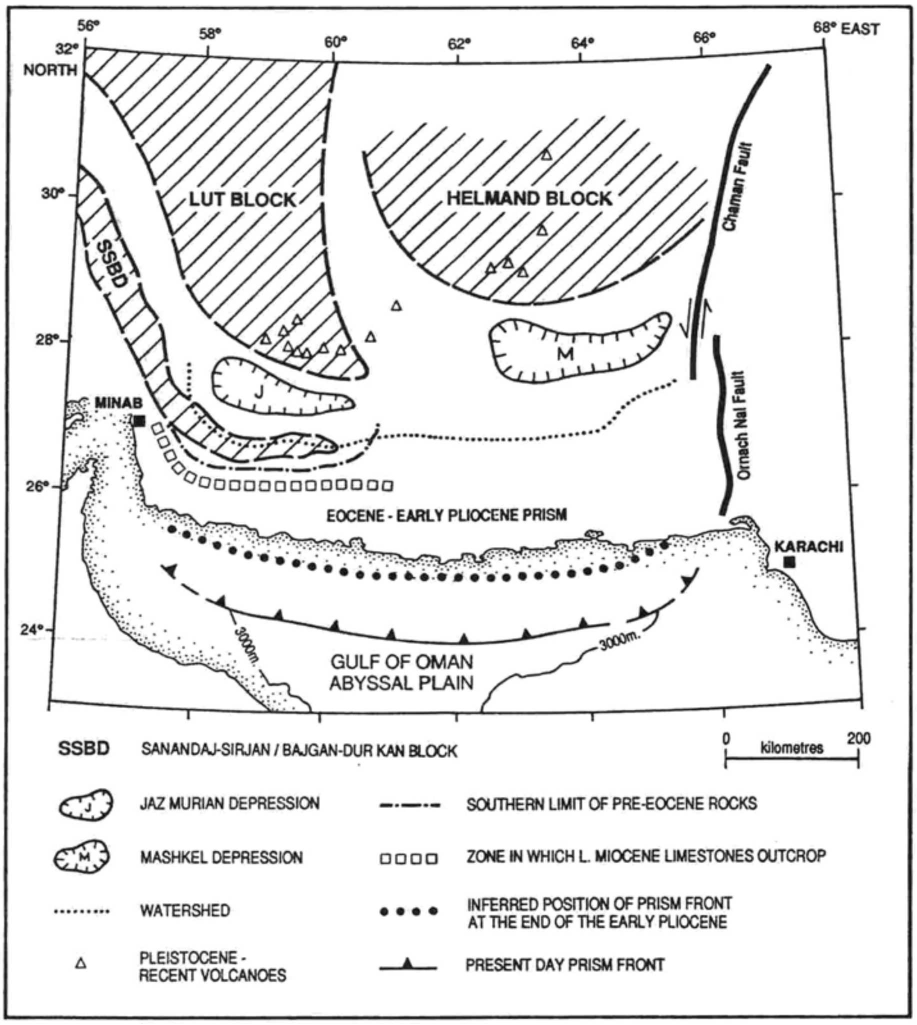


Fig. 4. Structural relationships of the Tertiary accretionary prism of Makran.

Fig. 4A. Diagram illustrating the relationship of the Eocene-early Pliocene accretionary prism of the Makran to the older components in southeast Iran and southwest Pakistan. The Lut, Helmand and Sanandaj-Sirjan/Bajgan-Dur Kan (SSBD) blocks are older microcontinental nucleii capped by platform sedimentary sequences (McCall & Kidd 1982). The position of the zone of Lower Miocene limestones, the inferred position of the Eocene-early Pliocene prism front at the time of gross folding at the end of the early Pliocene, and the site of the present active prism front 100-150 km offshore (White 1982) are shown together with the position of the present volcanic arc. Diagram developed from a figure by Platt et al.1985)

stratigraphic discordance between the flysch (abyssal plain turbidites) and the shallower water (slope and shelf) sequences above them, such as Moore & Karig (1980) described for Nias in the Sunda fore-arc (but see also see also Harbury & Kallagher 1991). The concordant pattern found in Pakistan also exists in the Iranian Makran where Lower-Middle Miocene 'flysch-like to neritic' sequences of considerable thickness containing turbidites, as well as shallow water sediments like the coral-algal limestones discussed here, are followed by wholly shallow water Upper Miocene to Lower Pliocene sequences (Table 2). The fold style is the same throughout the whole sequence from largely deep water Eocene, Oligocene and earliest Miocene sediments (Zones 5 and 6 of Table 1) to the broadly shallowing-upwards sequence represented by the later Miocene and Pliocene rocks (Zones 7 and 8): and there is no evidence at all of more than a single major episode of folding. This indicates that these sequences have all been folded together by the same very late (post-early Pliocene) event. Synclines are dominant and anticlines subordinate and appressed, which is the reverse of the Zagros style. The more open fold style observed in the youngest shallow water sequences is attributable to the influence of thick incompetent sandstone and conglomerate beds.

Quite small-scale deformations involving flexure and uplift were noted by White (1982) at the present-day prism front. Such deformations may influence the style of the gross folding. However, there appears to be no escaping the conclusion arrived at quite independently by Platt et al. (1985) for the Pakistan Makran, that in the Iranian Makran, gross folding and prism front deformation were widely separated in time, the gross folding having occurred as a single post-early Pliocene paroxysmal event after the prism front had been advancing for millions of years. The Makran has a history of plate convergence going back at least to the Cretaceous or before, there having been an earlier deformation after the early Palaeocene. Prism accretion has continued quietly since the Pliocene deformation (White 1982), apparently in much the same way as before.

The Miocene limestones occur within the strongly folded sequences. Though they themselves display little evidence of folding, they can be traced around large scale folds, for example in the Band-e Chaker Synclinorium (Locality 2) and the Bashiraz Anticline nearby (Dar Pahn: Locality 6; McCall 1985b). The folding is associated with quite steep reverse faults that dip inwards from the arcuate regional strike towards the present continental interior (Figure 2). They probably flatten out and unite at some depth to produce listric patterns. The folds may be open or tight and have abrupt hinge zones and gentle to steep limbs. Chevron and

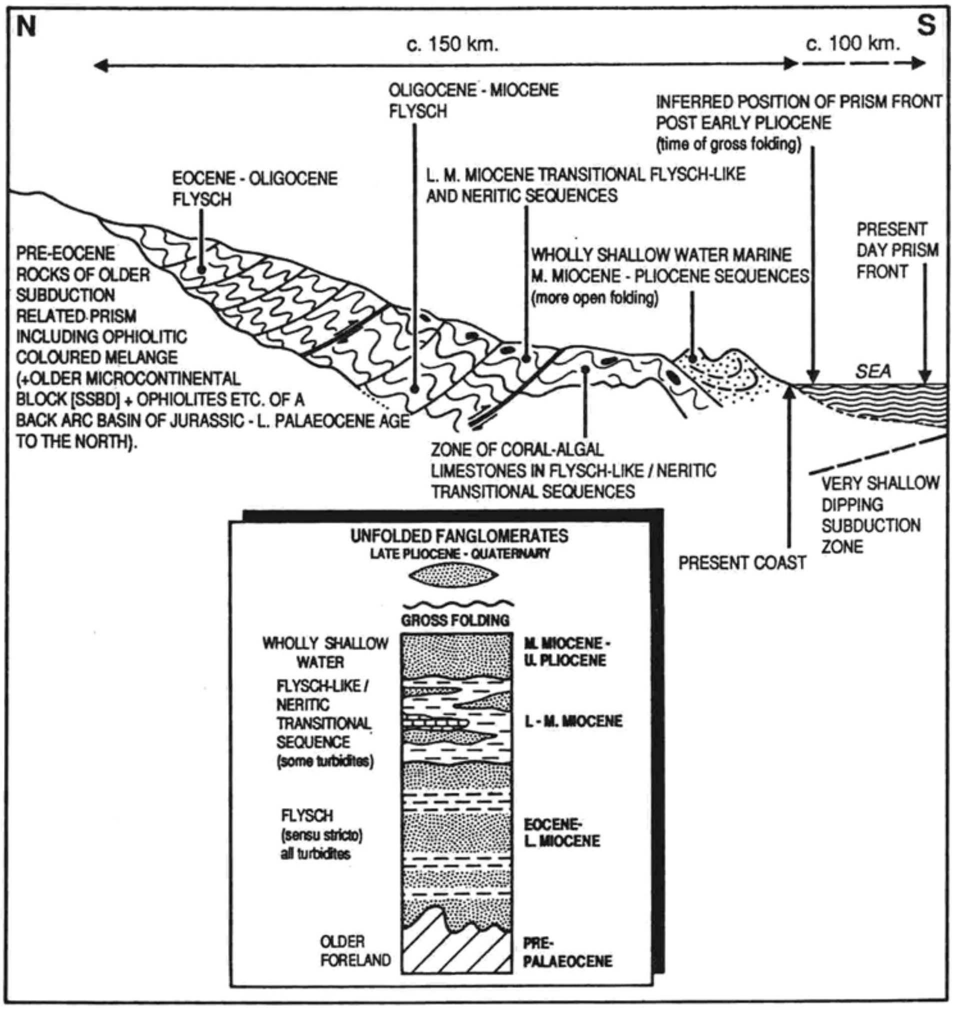


Fig. 4B. Cartoon section showing the present relationships of the Eocene-early Pliocene accretionary prism of the Iranian Makran after gross folding (post-early Pliocene). Dips of faults are exaggerated.
Inset shows:
(1) the lack of evidence of discordance prior to this gross folding in the immensely thick Eocene-Lower Miocene flysch (sensu stricto) sequences;
(2) the transitional Lower-Middle Miocene flysch-like to neritic sequences that contain the limestones described here; and
(3) the wholly shallow water Middle Miocene-Lower Pliocene sequences above. Continental fanglomerates (unfolded or only weakly folded) succeeded the gross folding, shed from the abruptly uplifted emergent landmass.

box-shaped styles are common. The Miocene limestones occur as integral parts of the 'flysch-like to neritic' sequences (Table 2, Figure 3). Though often faulted, they are generally conformable with the deeper water facies in these sequences. They do not occur either as unconformable terraces resting on deformed deeper water clastics, nor in unconformable basins within deeper water sequences.

2 LITHOFACIES

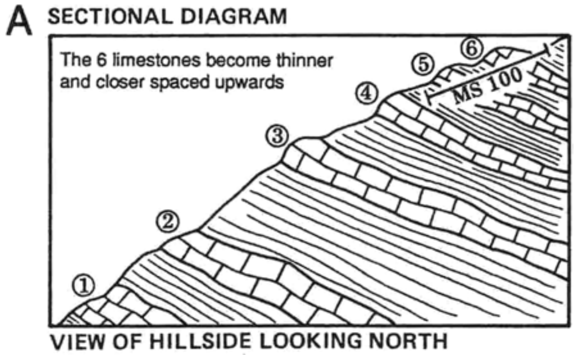
2.1 Lithologies

2.1.1 Limestones

As far as possible, we have used Dunham's (1962) limestone terminology here (see also Embry & Klovan, 1971) but different petrologists in the Paragon-Contech team adopted different terminologies in their original reports and it is difficult to translate them routinely into Dunham's scheme without risk of misinterpretation. In places, we have therefore preferred to retain *verbatim* their original use of Grabau's terms, such as 'calcarenite' and 'calcirudite' (see Wilson, 1975), and of Folk's (1959) terms. For example, the descriptions in Tables 3 and 4 include non-Dunham terms from the original report. Similarly 'reef talus' is retained in some of the figures and tables after the original reports, though this term is interpretative and may not be correct here. It generally corresponds to bioclastic limestones of various grain sizes including 'coral breccias'.

Throughout the region, limestones seem to occur in one of three geometrical forms:
1) extensive sheets each of more or less uniform thickness, ranging in thickness from about 5 m to about 50 m.
2) large, laterally extensive or abruptly tapering lenses which the mapping suggests may be up to 150 m thick, but are typically 30-50 m thick. These are rarely continuous for more than a few hundred metres along strike.
3) small lenses, about 1 m thick and only a few metres in diameter.

Mapped units of limestone commonly consist of individual beds of differing lithologies, which vary from thick beds (up to 5 m) of very coarse grained limestone, with frameworks made up largely of coralline and algal material, to finer-grained, thinly and well-bedded limestones (calcarenites) with minor corals and algae, but dominated by entire or broken foraminiferal tests. The corals and algae in these finer beds may be dispersed through them, or form a thin layer at the base of the bed. Some of the finer limestones show evidence of erosion of nearby penecontemporaneous limestones together with other sedimentary and igneous material (see text Section 4.1). Other finer limestones are conglomeratic with small 'pebbles' consisting of poorly



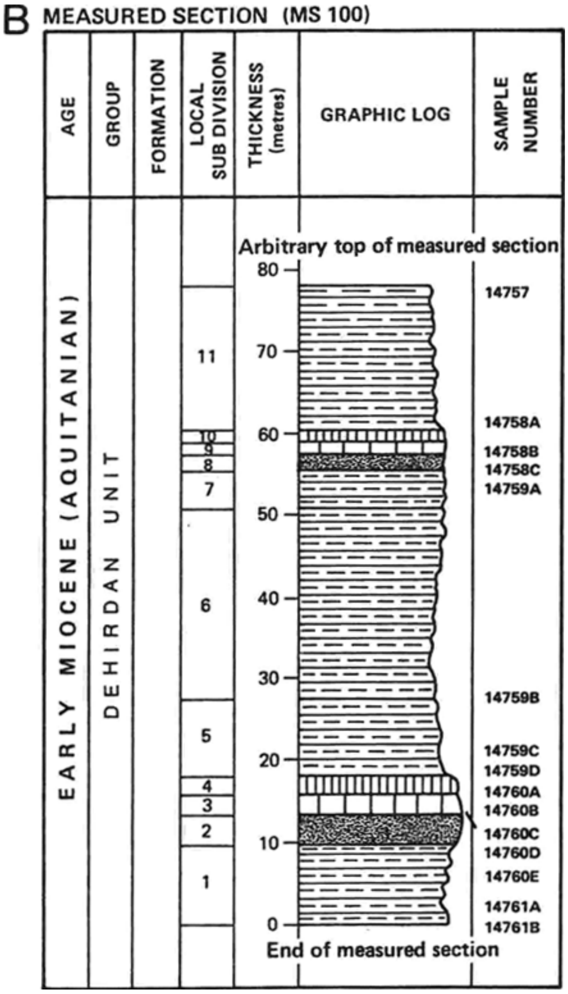


Fig. 5. The Aquitanian sequence at Sardasht (Locality 4). (A) Sketch of sequence shown in Plate 17/3 (which is photographed from the opposite direction), with position of Measured Section 100. (B) Details of Measured Section 100 (see also Table 3). Foraminifera identified in some of the numbered samples are mentioned in the text Section 4.1.

sorted coral, algal, mulluscan and foraminiferal fragments. These are conspicuous at Band-e Chaker (Locality 2).

The coarser limestones consist in part of framework lithologies which can be assigned to one of the two types of framework distinguished by Geister's (1983) German terms, *starr* (= rigid; see his Figure 24) and *locker* (= loose; see his Figure 25). These were based on modern unlithified reef sediments of the Caribbean. His 'rigid frameworks' correspond to bindstones and framestones and this follows standard usage. He translated his other term *(locker)* as 'non-rigid' which could be taken to imply that the organisms concerned were flexible when alive, like marine grasses and some octocorals, and hence generating confusion with 'bafflestones'. However, following discussion between one of us (B.R. Rosen) and Geister (pers. comm.) 'non-rigid frameworks' can now be more accurately re-translated as 'loose frameworks'. They consist of coral material that has grown on unconsolidated substrate. In some cases the corals have been broken and transported from elsewhere, and have sometimes also regenerated. In both cases the coral material has also trapped further sediment. This kind of accumulation is therefore intermediate between truly clastic deposits (rudstones and wackestones) and entirely biogenic (*in situ*) deposits (framestones and bafflestones). 'Loose frameworks' was found a useful term here because it was not always

Plate 17 Photographs of some outcrops of some Miocene limestones in the Iranian Makran.

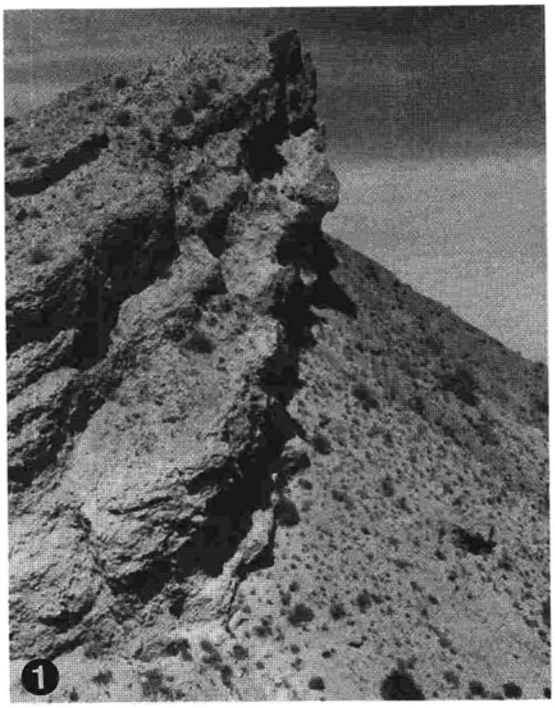
Fig. 1. Burdigalian coral limestone outcrop in the Darkhunish Unit west of Dar Pahn (Locality 6). The limestone is massive with a coral-algal breccia zone at its base but corals are in situ above, together with algae, gastropods and bivalves. The outcrop appears to part of a patch-reef, having no great lateral extent in plan. Thickness of limestone visible in this view is c.10 m.

Fig. 2. Upfaulted block within the Sabz Unit of Burdigalian coral-algal framework limestone south of Kuh-e Bondar (Locality 7); view looking south. Both upper and lower contacts of the limestone are visibly faulted and the limestone beds dip steeply to the west. Limestone thickness here is about 50 m.

Fig. 3. General view of the six coral-algal limestone intervals at Sardasht (Locality 4) within finely bedded shales and sandstones of the Dehirdan Unit (compare Figure 5A which is 'viewed' from the opposite direction). The uppermost two limestones are Aquitanian (Measured Section 100; Table 3 and Figure 5B). Total thickness of section in this view is c.320 m.

Fig. 4. Close-up view of the fifth from lowest of the six limestone intervals at Sardasht (Locality 4) shown in Plate 17/3. The lower part is coral-algal breccia; above is massive foraminiferal limestone, overlain in turn by bedded calcarenite. Thickness of whole limestone interval here is about 8 m, and age is Aquitanian (Measured Section 100; Table 3 and Figure 5a, 5b).

Fig. 5. Close-up of the same Aquitanian limestone interval at Sardasht(Locality 4) as Plate 17/4, showing the abrupt contact with the interbedded thin sandstones and shales of the Dehirdan Unit.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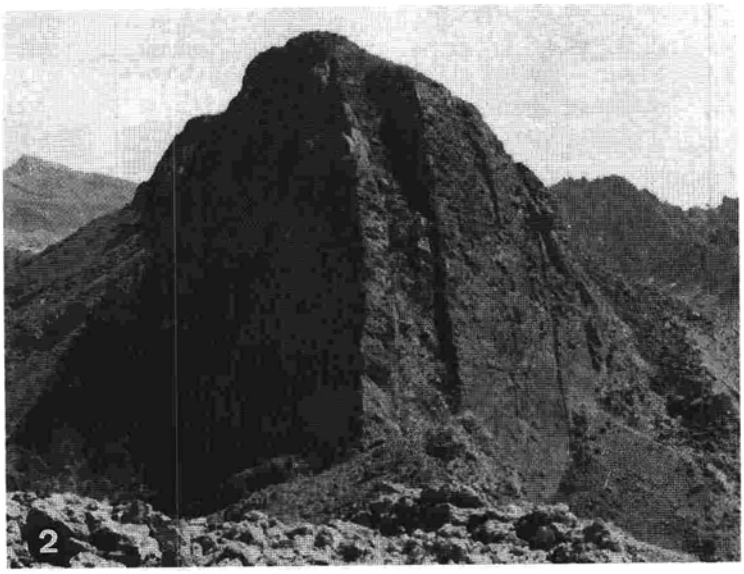
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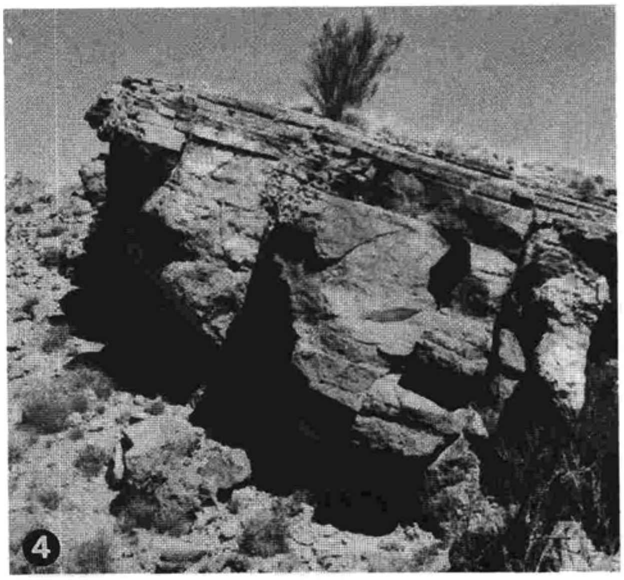
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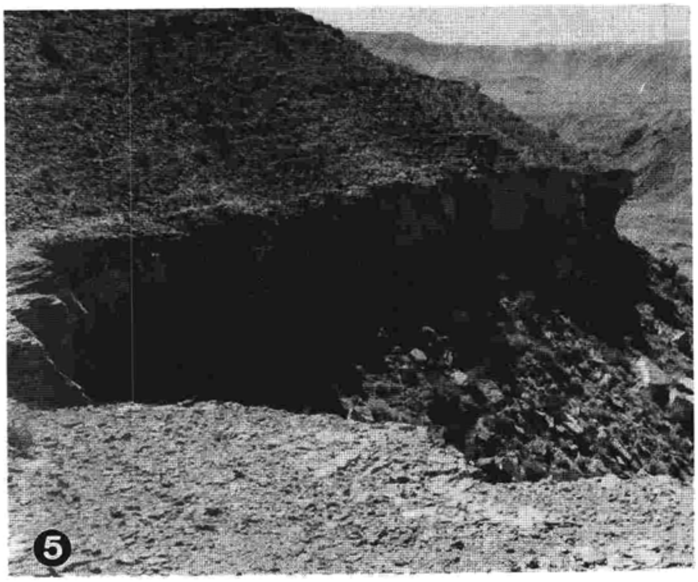
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possible to assign Makran limestones retrospectively to one of these two latter lithological terms, there being much intergradation between them.

The coarser limestones are poorly bedded, and characteristically form massive outcrops with an anastomosing, near horizontal, laminar but undulating structure that appears to be stylolitic in origin and related to compaction. This passes sinuously around resistant masses such as large coral heads. Rigid frameworks show both primary and secondary components, in SCOFFIN's (1987) sense, i.e. secondary framework consists of organisms, like calcareous coralline algae, that have filled, encrusted and bound the primary framework of larger in situ organisms. Corals and algae, either separately or together, contribute to both primary and secondary framework, though algae are most conspicuous in the role of secondary framework. The loose frameworks consist of coral and algal masses up to 0.5 m in diameter, but locally these masses may be in situ indicating transition between rigid and loose frameworks. Rigid frameworks are particular well developed at Dar Pahn (Locality 6, Plate 17/1), though generally, loose frameworks appear to be more common in the Makran than rigid frameworks.

At Mazavi (Locality 3), limestone lenses within the 'Mazavi Red Beds' (HUBER 1952) consist of grain-supported limestone that includes foraminiferal tests and some micrite, with subordinate coral, algal and shell fragments.

The corals that occur in many of the limestones are mainly colonial, generally massive, rounded, nodular or encrusting with some laminar forms, but solitary corals (notably *Parascolymia*; Plate 18/2) may be prominent, and

Plate 18 Selection of corals from the Early Miocene coral formations of the Makran. All are from limestones which are almost certainly of Burdigalian age, though not all the relevant outcrops were actually dated. The corals are important contributors to the limestones or are otherwise of intrinsic interest. The coral names follow those in the original map reports and in Table 5, but additional remarks are given here in the light of our more recent studies. Names that now require revision are given in inverted commas. Taxonomic comments apply strictly to the specimens illustrated, not necessarily to any other corals bearing the same name, either within the Makran collection, or of other authors. Specimen numbers, prefixed 'R', are those of the Department of Palaeontology, The Natural History Museum, London.

Figs. 1., 5., 6. '*Trochoseris persica* (KÜHN, 1933)'. Original identification of this specimen requires revision as subsequent examination of Kühn's type shows it to be different. Makran specimen is a (new?) mussid or faviid. Sheet 7443 Tahruie, 26°43'N 57°21'E, Data point 14010/1, R53720. Figure 1: weathered surface of secondary calice; note dentate septa. x1.4. Figure 5: weathered calicinal surface; note circumoral colony development. x 0.7. Figure 6: weathered underside (with cut surface) showing epithecal 'shreds'. x 0.7

Fig. 2. *Parascolymia vitiensis* (BRUEGGEMANN, 1877), the most common of the large cylindrical solitary corals in the Makran. Transverse polished section across half a calice; note typical mussid differences in thickness of septal orders. Widely accepted generic name for this genus is now *Scolymia*, by subjective synonymy. Sheet 7444 Minab, 27°19'N 57°07'E, Vaziri (Locality 1, dated as Burdigalian), Data point 2084/1, R50897. x 1.6

Fig. 3. *Porites* cf. *pusilla* FELIX, 1884, an important contributor to Makran limestones. Transverse thin section; skeletal structure is seen as pale coloured detail; septal formation is best seen at centre left, where an almost complete 'trident' is developed; walls consist of two to three synapticular rings; characters very close to those of *P.* cf. *lutea* (Plate 18/4). Sheet 7443 Tahruie, 26°49'N 57°20'E, Data point 14004/2, R53727. x 10

Fig. 4. *Porites* cf.*lutea* (MILNE EDWARDS & HAIME, 1851), an important contributor to Makran limestones. Side view of weathered colony showing four growth phases; calicinal details (not shown) are very similar to those of *P.* cf. *pusilla* (Plate 18/3). Sheet 7443 Tahruie, 26°39'N 57°20'E, Data point 14008/9, R53721. x 0.25

Figs. 7., 9. *Leptoseris delicatissima* KÜHN, 1933. Genus may indicate deeper waters of photic zone. Sheet 7543 Tahruie, 26°42'N 57°55'E, Data point 14255A/9, R53722. Figure 7: polished transverse section of peripheral calices; note synapticula-like structures, lower right; x 2.2. {A central calice is preserved in another specimen (not shown)}. Figure 9: detail showing pennular ornamentation of septa. x 5

Fig. 8. *Acanthastrea hillae* WELLS, 1955. Weathered calicinal surface; mussid teeth on septa but worn; this form has fewer septa than Recent and Pleistocene forms. Sheet 7543 Tahruie, 26°39'N 57°58'E, Data point 4177C/2, R53723. x 1.5

Fig. 10. *Echinophyllia costata* (DUNCAN, 1864), a pectiniid that may indicate deeper waters of photic zone. Transverse polished section of peripheral calices; note typical absence of columellae. Sheet 7543 Tahruie, 26°42'N 57°55'E, Data point 14255C, R53724. x 1.2

Fig. 11. *Hydnophora* cf. *rudis* DUNCAN, 1864. The genus is a common faviid in Makran limestones. Transverse polished section; smaller monticules and finer septa than the type. Sheet 7443 Tahruie, 26°47-50'N 57°18-20'E, Data point 13533D, R53725. x 3

Fig. 12. '*Favia laxa* (KLUNZINGER, 1879)'; a common faviid in Makran limestones. Revised identification necessary because *F. laxa* (Recent) has more septa and more widely spaced calices. Transverse polished section; note well-developed pali, and intratentacular division at lower left. Sheet 7543 Tahruie, 26°34'N 57°56'E, Data point 3965/1, R53726. x 3


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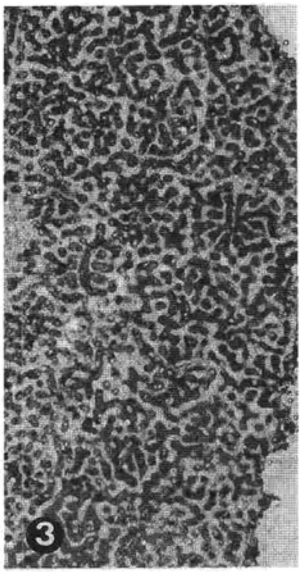
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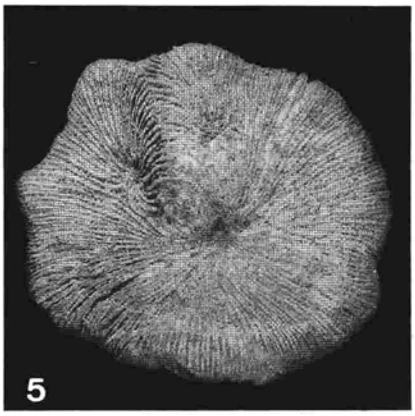
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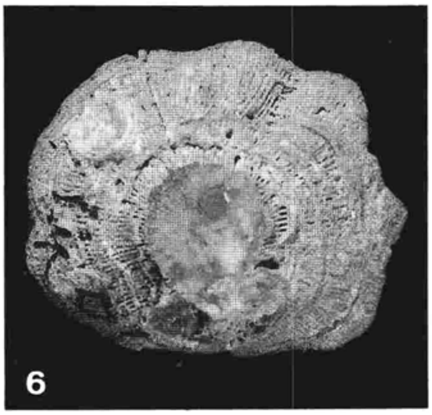
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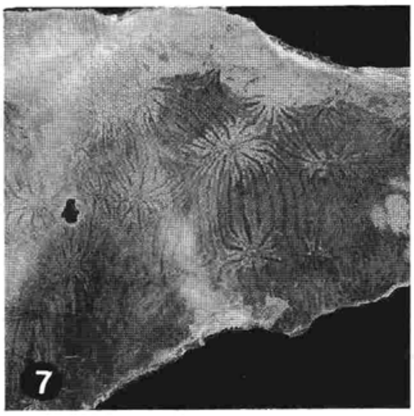
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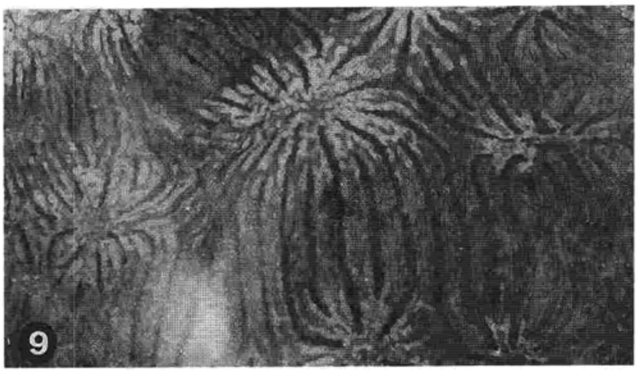
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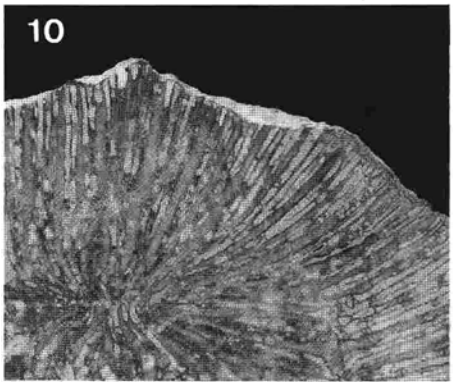
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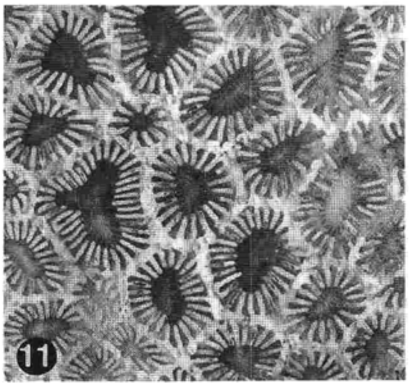
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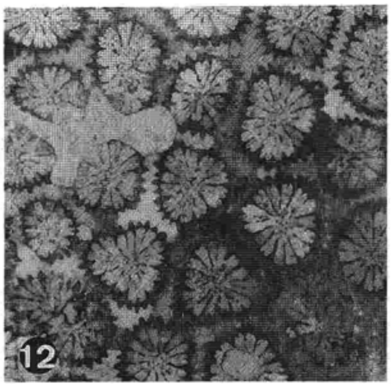
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Table 3. Measured Section 100 through the upper part of Aquitanian sequence at Sardasht within the Dehirdan Unit (Locality 4) (after Paragon-Contech field geologists). Numbers in left column correspond to the subdivisions defined on the measured section. Only the uppermost two of the six limestone developments were measured and sampled, the top and bottom of the section being arbitrarily defined (see also Figures 5a, 5b: Plate 17/ 3-5). Further foraminiferan records are given in text Section 4.1.

11.	16 m	Sequence of siltstone-shale beds, grey-green, soft, blocky to fissile, forming 5 cm thick intervals between sandstone beds, brown weathering, grey, medium grained; sandstone/shale ratio 1:4. The sandstone is a quartzose arenite, plane-laminated at the base and ripple cross-laminated at the top. Bioturbation is evident in the form of burrows.
10.	1 m	Grey, well-bedded clastic limestone, calcarenite with angular carbonate grains; other grains 5% very dirty, ferruginous. This interval contains *Lepidocyclina (E.), Lepidocyclina (N.), Gypsina, Nodosaria*; also planktonics, including *Globigerinoides* (*G. trilobus*), *Globigerina, Globoquadrina* (*G. venezuelana*), miliolids and coral-algal debris.
9.	2 m	Coarse, grey, massive, foraminiferal limestone with a line of coral and algal cobble-sized clasts at its base, above a well-defined bedding plane joint. This interval contains *Amphistegina, Carpentaria, Lepidocyclina (N.)* cf. *sumatrensis, Miogypsina, Spiroclypeus* cf. *margaritatus, ?Heterostegina, ?Operculina*; planktonic foraminifera including *Globigerina*, miliolids, rotalids. Also contains corals, echinoid spines, calcareous algae.
8.	3 m	Coral-algal rubble breccia, with clasts averaging 2-5 cm diameter and up to 50 cm diameter, poorly sorted with clast size decreasing upwards - bioclastic calcirudite. Bryozoans but no molluscs.
7.	3 m	Sandstone, brown weathering, alternating with shale (1:3 ratio): sandstone beds are plane-laminated at the base and ripple cross-laminated at the top. Sandstone with an anomalously high dip is in direct contact with the limestone above, across a minor fault (?).
6.	26 m	Sandstone and shale alternations (1:4 ratio). Sandstone is medium-grained, brown weathering, even-textured, quartzose arenite; the shale is grey-green, silty and blocky to fissile.
5.	8 m	Well-bedded, well-jointed, brown-weathering, grey sandstone, in beds 5-40cm thick with irregular load-casted basal surfaces; plane lamination at the base of the beds and ripple cross-lamination at the top; bioturbation, trace fossil *Helminthoida* on a sandstone sole. Just above the contact with the limestone below, the beds are arenites 3-10 cm thick, containing 5-10% feldspar, appreciable quartz and ferromagnesian grains. Shale content increases just above this contact.
4.	2 m	Grey, well-bedded, cross-laminated and convolute-bedded calcarenite passing up into slightly muddy, nodular, grey, carbonaceous calcarenite.
3.	2 m	Massive, coarse foraminiferal limestone with a thin layer of cobble-sized coral and algal clasts at the base, separated from Bed 2 by a well-developed bedding-plane joint. This interval contains *Gypsina globula, Lepidocyclina (E.)* cf. *dilatata, Lepidocyclina (N.)* sp., *Miogypsina* cf. *gunteri, Spiroclypeus* cf. *margaritatus* and *Operculina*, together with a few planktonic foraminifera and coral-algal debris.
2.	4 m	Layer of coral-algal breccia, cobble to boulder grade, matrix-supported, poorly-sorted, bioclastic calcirudite. The size of the clasts decreases upwards. Bryozoans present but no molluscs. Sandstone lens within the limestone. Basic igneous rock clasts.
1.	10 m	Brown-weathering, grey, well-jointed, well-bedded sandstone and silty shale, interbedded (1:3 ratio). The uppermost sandstone beds are in normal contact with the breccia of Bed 2.

locally may even dominate. Large coral heads may be preserved apparently *in situ* (a relatively small example is shown in Plate 18/4), but more commonly, corals occur along with other organisms as fragments, forming a breccia that appears to have been derived contemporaneously from active or passive breakage of original growths. Such breccias are characteristic of the coarse Burdigalian limestones. The Aquitanian breccias at Sardasht (Locality 4; Table 3, Figures 5a,5b; Plate 17/3-5) consist of fragments of similar composition that have almost certainly been transported and redeposited much further from their original growth sites and into deeper water (see below).

Coralline algae occur both as the main binding (i.e. secondary framework) organism and also, less commonly, as contributors to primary frameworks. Molluscs contribute little to frameworks and are generally subordinate in abundance to corals and algae, though at one outcrop of Burdigalian limestone at Lashgar Rud (Locality 5) they are the most common group of organisms. Only a few genera are represented, mostly gastropods.

2.1.2 Other lithologies associated with the limestones

Most, but not all rocks associated with the limestones are siliciclastics, but there are also gypsum-bearing strata. Siliciclastic sequences occur above and below the limestone units and are much thicker than the limestone sequences. The six stratigraphic units (Table 2, Figure 3) range from an estimated 1000 m to more than twice that thickness. They consist of sandstones and shales, locally with conglomerates. Parallel lamination, ripple marks, graded bedding and flute casts are recorded, together with bioturbation and plant débris. The sedimentary structures include many that are characteristic of turbidites. The trace fossil *Helminthoida* was found immediately above one of the Aquitanian limestones at Sardasht (Locality 4; details in Table 3). This is generally regarded as a deep water form and suggests that as there was no evidence for a break in deposition between limestones and clastics, the coral and algal fragments in the limestones were transported from shallower water.

The clastic sediments of the Dehirdan unit which en-

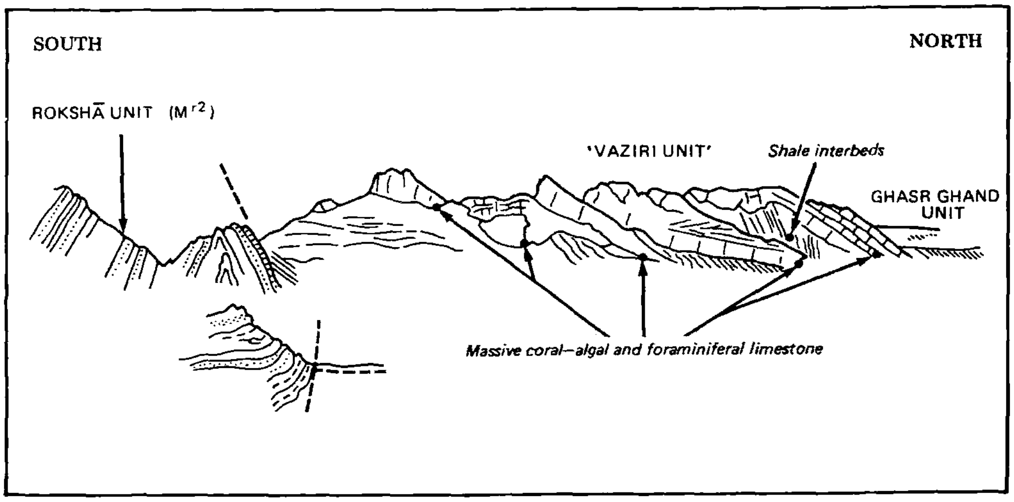

Fig. 6. Sketch of the Lashgar Rud area (Locality 5) showing the easternmost outcrops of Miocene limestones in the study area (drawn in the field by A. Gansser). 'Vaziri Unit' - see text section 1.4. Breadth of view is c.5 km.

closes these same Aquitanian limestones are calcareous and carbonate-bearing, as are also those in the Band-e Chaker unit, but of the other units which enclose Burdigalian limestones, the Sabz unit and Ghasr Ghand unit are gypsiferous, while the Roksha unit and Darkhunish unit are also locally so (Table 2). Red beds are rare amongst the siliciclastic sediments, but those of the 'Mazavi Red Bed' section (HUBER 1952), at Mazavi (Locality 3), are reddened, due apparently to an increment of reddened oxidised detritus derived from the Coloured Mélange complex to the northeast (MCCALL 1985b). This material has not undergone reduction after deposition.

2.2 Distribution of facies

2.2.1 Facies patterns within the limestones

Limestone may occur as essentially single lithological units (Plate 17/1), but more commonly they consist of complex sequences of various lithologies. This may take the form of a vertical transition between well-bedded foraminiferal calcarenites and coarse coral-algal limestones (including breccias), or boundaries between such lithological types may be sharp. There may be an upward passage from calcarenite into coarse coral-algal limestone, or *vice versa*, and there may be repetitions of such changes within a single section of continuous limestones. Also, coral-dominated beds may alternate with algal-dominated beds. The intimate association between rigid and loose frameworks, and the frequent transition between them has been mentioned already, but no further details can be given here of this particular pattern, or of the three-dimensional relationships between frameworks and other facies. Two localities, Sardasht (Locality 4) and Lashgar Rud (Locality 5) provide contrasting facies details as follows:-

At Sardasht (Locality 4), six Aquitanian limestones occur within a section 200 m thick in the Dehirdan unit, consisting largely of thinly bedded shales and sandstones (Table 3; Figures 5a,5b; Plate 17/3-5). Each of the limestones is between 6 m and 10 m thick and displays a regular fining-upward sequence (e.g. Plate 17/4) which may be generalized as follows:

5. Transition from 4. below into nodular, very fine-grained, slightly muddy calcarenite (in which carbonaceous material was reported by one of the team petrologists); thickness 1 m or less.
4. Calcarenite (finer than 2 below), 2 m thick, containing many small foraminiferal fragments and displaying fine internal lamination, cross-bedding and convolute lamination. This grades upwards into 5. above.
3. Sharp contact

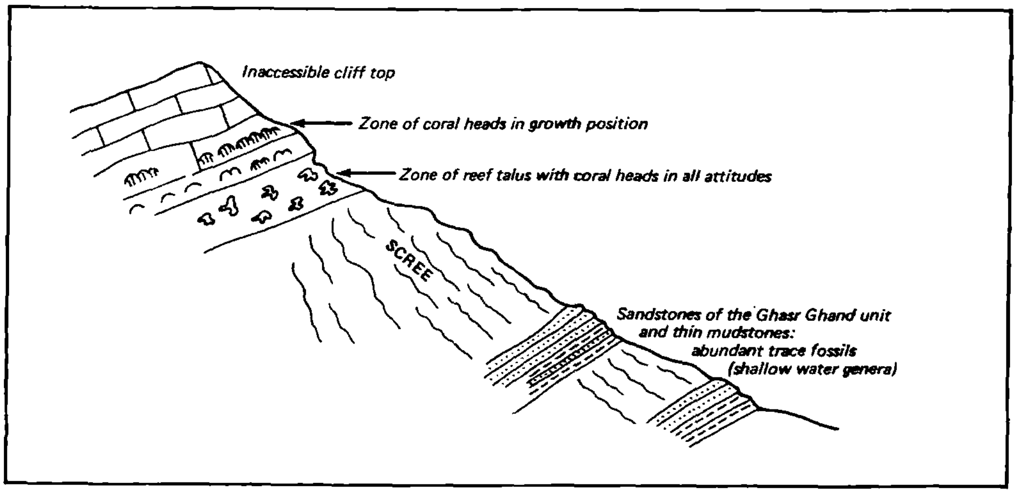

Fig. 7. Schematic sketch of sequence at Lashgar Rud (Locality 5) close to the site of Measured Section 66 (details in Table 4 and Figure 8). Total thickness of limestones above the scree is c. 200 m.

Table 4. Measured Section 66 through the Burdigalian limestones within the Ghasr Ghand Unit in the valley of Lashgar Rud, a tributary of the Sarbaz River (Locality 5; see also Figures 6-9) (after Paragon-Contech field geologists). Numbers in left column correspond to the subdivisions defined on the measured section. Further foraminiferan records are given in text Section 4.1.

		(SECTION TERMINATED AT THE TOP OF THE RIDGE: THE TOP OF THE LIMESTONE WAS NOT REACHED)
8.	26.0 m	Coral boundstone, abundant coral heads (30% of the surface area). Pebbly to moderately well-bedded, 5% cavities with cement fills. Corals and algal 'oncolites'. Microscopic examination shows it to be a coral-algal boundstone with green algae, filamentous algae, echinoid spines, corals, *Sporadotrema* and homotremid foraminifera (indeterminate).
7.	24.5 m	Algal boundstone, algal and coral fragments. Approximately 3% cavities with cement fills. Microscopic examination shows it to be a sparry iron-stained algal boundstone biomicrudite with algal fragments (*Lithophyllum, Lithothamnium*), ?corals, echinoid spines, benthonic foraminifera (*Lepidocyclina* sp.).
6.	43.5 m	Algal boundstone interbedded with bioclastic (biomicrite) limestone in bands 10-20 cm thick. Bedding is not everywhere evident. Microscopic examination of a specimen from the top of the interval shows it to be a partly recrystallized algal biomicrite boundstone with benthonic foraminifera (planar uvulinidae, miliolidae, homotremidae), algae and echinoid spines. Microscopic examination of a specimen from immediately below shows it to be a biomicrite wackestone with sparse planktonic foraminifera, homotremidae fragments, algal fragments and echinoid spines. A specimen from just below the middle of the interval is a coral boundstone with micrite in the interstices, and another from the base of the interval is a medium-grained sparry biomicrite packstone containing *Miogypsina, Pyrgo*, elphidiidae, algal fragments, echinoid fragments and spines.
5.	16.5 m	Limestone, massive, bioclastic, weathering with a coarse honeycomb structure and onion skin pattern, grading upwards generally to coarser rubbly limestone. Abundant iron staining near the top of the interval and a large gastropod present near the base.
4.	39.3 m	Limestone, grey, masive, bioclastic with bryozoan fragments in the middle of the interval, and coral fragments near the base. Microscopic examination of a specimen from the top of the interval shows it to be a biomicrite wackestone containing *Lepidocyclina, Miogypsina*, common *Cibicidides, ?Dyocibicidides*, planorbulinidae, textularidae, algal fragments and shell material. A specimen from the middle of the interval is a sparry algal biomicrite wackestone with *Miogypsina*, sparse rotalids, abundant algal fragments (*Lithophyllum, ?Corallina*) and echinoid spines. A specimen from the base of the interval is a sparry foraminiferal biomicrudite with *Miogypsina thecideaeformis, ?Miolepidocyclina*, coarse algal fragments (*Lithophyllum*), encrusting algae and echinoid spines.
3.	2.2 m	Limestone, grey, bioclastic with coral fragments. Microscopic examination shows it to be foraminiferal biosparite wackestone containing abundant *Miogypsina thecideaeformis, ?Miolepidocyclina*, sparse algal fragments, small gastropods, shell fragments and echinoid spines.
	20.0 m	(INTERVAL OF NON-EXPOSURE)
2.	1.5 m	Mudstone, weathered and calcite-veined.
1.	8.5 m	Alternation of sandstone beds (individually c. 50 cm thick), calcareous, greenish-grey, with ripple cross-lamination, bioturbation (trace fossils, *Thalassinoides*, groove casts on basal surfaces, interbedded mudstones.
		(SEQUENCE CONTINUES DOWN)

2. Massive calcarenitic limestone 2 m thick, composed of foraminiferal tests, but with a layer of cobble-sized coral and algal clasts at its base.
1. Basal breccia (calcirudite or rudstone) up to 4 m thick consisting of coarse cobble- to boulder-grade coral-algal material and including clasts of basic lava; sharp basal contact. The character of this breccia is consistent with transport but its mechanically immature nature suggests that the clasts have not moved far from the site of growth of the contained organisms.

The absence of rigid frameworks at Sardasht above contrasts with the very thick section of Burdigalian limestone examined in some detail in the valley of the Lashgar Rud (Locality 5; Table 4, Figures 6-9). The limestones occur in a continuous sequence over 150 m thick, dominated by coarse limestone largely composed of coral-algal débris, though rigid frameworks of algal and coral boundstone were also recorded higher in the section by the field geologist. The base of the limestone sequence is composed of a thin foraminiferal wackestone layer; a coarse, massive bioclastic limestone above is succeeded by massive limestones with corals and algae in growth position. Corals appear in increasing numbers upwards, and in places account for 30% of the rock. However, there are layers in the limestone dominated by coralline algal growths, described in the field as oncolites (but possibly rhodolites). The coarse limestones contain few foraminifera, but there are beds of flaggy, richly foraminiferal calcarenite. Because of inaccessibility, a further 40 m or so of limestone at the top of this section were not examined, but in nearby exposures, the limestone sequence is also capped by such beds. The facies relationships are summarized schematically and provisionally interpreted in Figure 9.

2.2.2 Relationship of limestones to other associated lithologies

The multiple repetition of limestone beds seen within thin sandstones and shales at Sardasht, above, is unusual. In the mapping of the Dar Pahn 1:100,000 sheet (McCall & Peterson 1981a), there is however indication of at least a two-fold repetition of Burdigalian limestone in the Band-e

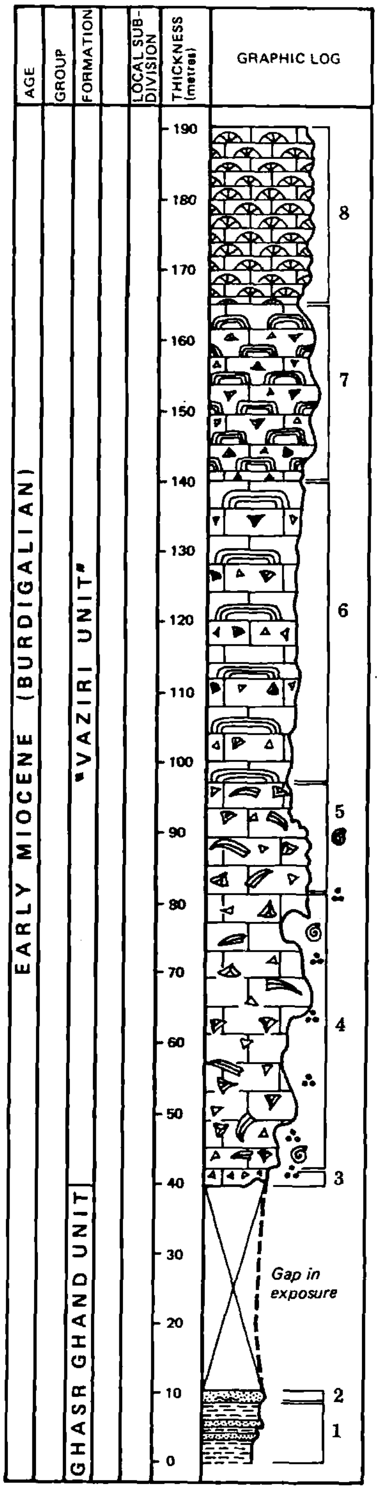

Fig. 8. Diagrammatic representation (drawn by I. Deighton) of Measured Section 66 at Lashgar Rud (Locality 5); further details in Table 4. Ornamentation as in Figure 9. 'Vaziri Unit' - see text section 1.4.

Chaker fold structure (Locality 2) which is not structural. In the exposures at Mazavi (Locality 3), numerous metre-thick limestone lenses are repeated up a section hundreds of metres thick within rather calcareous clastic sediments. In general limestones occur in normal stratigraphic relationship with the siliciclastic beds, but the fault-bounded relationship of thick coarse limestone to the surrounding rocks at the 'type locality', Vaziri (Locality 1), was sometimes found elsewhere, such as at various localities within sheet 7442 of the Tahruie quadrangle (e.g. south of Kuh-e Bondar, Locality 7; Plate 17/2).

At several localities within the Tahruie and Fannuj quadrangles, the Burdigalian limestones rest conformably on silty shales and sandstones, with a sharp contact, but elsewhere in these quadrangles, there is no sharp boundary and an intermediate passage facies consisting of partly siliciclastic foraminiferal calcarenite rests on the sandstones. This calcarenite is overlain by a coarse limestone with coral heads apparently *in situ*, and above this is a muddy foraminiferal limestone which grades up into shale and sandstone. It is also quite common for coarse coral-algal limestone to rest directly, with sharp contact, on poorly-sorted sandstone that also includes lenses of pebbly conglomerate. A section has also been recorded in the Tahruie Quadrangle where a conglomerate composed of pebbles of quartz, white crystalline limestone and serpentinised ultrabasic rock rests directly on coarse coral-algal limestone, reflecting the close stratigraphical relationship of the Burdigalian limestones in the Tahruie quadrangle with the remarkable Harzburgite conglomerate of probable early Miocene age (McCall 1985b, pp. 137-146).

Thus, in the Fannuj and Tahruie quadrangles, the upper and lower contacts of limestone units with the enclosing siliciclastic sediments are mostly conformable and usually sharp, but there may be some transition between them where finer-grained limestone beds occur in lowermost and uppermost beds of the limestone units. The siliciclastic sediments above and below the limestone units may be shales, sandstones, or, less commonly, conglomerates.

3 INTERPRETATION AND DISCUSSION OF THE LIMESTONES AND ASSOCIATED SEDIMENTS

3.1 Limestone facies

3.1.1 Approach to reefal interpretation

The nature of many of the Makran limestones with their abundant corals and algae, and frequent occurrence of framework lithologies, suggests that some of these limestones include truly reefal structures. The term 'reef', however denotes a wide variety of Recent and ancient structures (e.g. Wilson 1975, Scholle et al., 1983, Geological society of London 1989) and we are not able to specify the type of reefs present, or to interpret them fully. However, we comment below on the extent to which the five main criteria used for identifying reefs, based on modern tropical coral-algal reefs (e.g. Rosen 1990), apply to the Makran limestones: (1) raised relief above surrounding sea-floor, (2) occurrence of rigid frameworks, (3) evidence for deposition within wave-base or photic zone, (4) wave resistance and (5) tropical occurrence.

3.1.2 Contemporaneous relief

Elevation above surrounding sea-floor is difficult to establish for the Makran formations because of current lack of positive evidence. However, it seems reasonable to infer

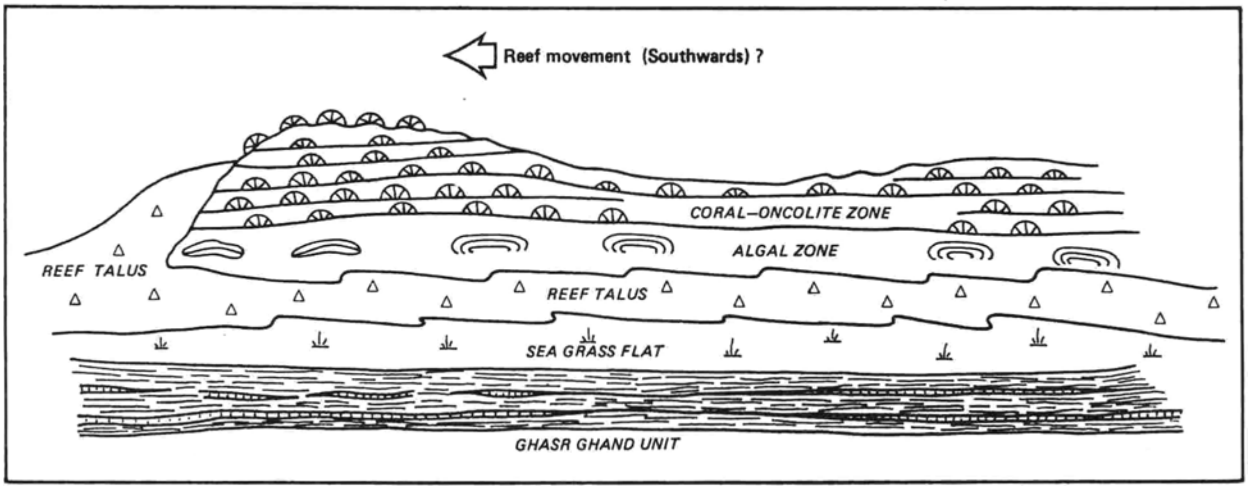

Fig. 9. Diagram by I. Deighton showing his interpretation of limestone facies relationships in the Lashgar Rud area (Locality 5) with progradation of reefal deposits including frameworks over a sea grass flat (thicknesses are exaggerated). The interpretation is broadly based on details shown in Table 4 and Figure 8.

that the thick (100 m) coral-algal limestone sequence at Vaziri (Locality 1), and the even thicker (150 m) sequence at Lashgar Rud (Locality 5; Figures 6-9), represent eminences that stood up above the surrounding sea floor, firstly because of their gross lenticular form in relation to adjacent beds, and secondly because their greater thickness appears to be due to continuous deposition. No evidence for major intraformational breaks was recorded in the field. Contemporaneous mud and sand fringed these patches of limestone, in lower-lying surrounding areas of the sea floor. The limestone lenses at Mazavi (Locality 3) appear to be entirely depositional features, not elevated by bioconstructional processes.

Many authors have stressed that much of the supposed relief of present-day reefs is antecedent, and this criterion must therefore be used with caution for fossil reefs. Fortunately, even today, there are also substantial structures being built by corals and other reef-builders without any apparent antecedent relief, e.g. some of those described by WAINWRIGHT (1965) in the southern Red Sea, by BRAITHWAITE (1971) and ROSEN (1971) in the Seychelles, and by SHEPPARD & SALM (1988), SHEPPARD et al. (1992) and GLYNN (1993) in the Gulf of Oman. Wainwright and Glynn regard such features as reefs so long as the organisms are clearly growing densely enough to build framework, and these are a better model for the some of the present Miocene features than antecedent-structure reefs. (In contrast Sheppard and co-authors argue that true reefs should also have recognizable reef flats, though in practice, this usually also implies antecedent relief - see Glynn's remarks on this).

3.1.3 Rigid frameworks

As already indicated, rigid frameworks are abundant in the limestones, though they are absent in the Aquitanian section at Sardasht (Locality 4) and in the small limestone lenses at Mazavi (Locality 3). They occur typically within the more extensive developments of Burdigalian limestones (e.g. Lashgar Rud, Locality 5, and at Dar Pahn, Locality 6, Plate 17/1). They are the main basis for inferring the existence of reefs in the Makran limestones.

3.1.4 Depth of deposition

Many of the corals that occur within the Miocene limestones (Table 5) belong to extant genera that are zooxanthellate today, suggesting that they were similarly symbiotic during the Miocene. If so, they would have dwelt at depths less than c. 120m, or a good deal less, but within the photic zone and above the compensation depth (HALLOCK & SCHLAGER 1986). This alone does not indicate that they were actually building reefs (SCHUHMACHER & ZIBROWIUS 1985, COATES & JACKSON 1987). Density of potential reef builders also matters (see under framework). Photic zone deposition is also supported by the abundance of coralline algae, the maximum depth of which is 250 m today (DODD & STANTON 1990) and by larger benthonic foraminifera, the latter suggesting depths less than c. 30 m. The foraminifera in the lower limestones in the Lashgar Rud section (Locality 5) indicate the presence of sea-grass beds (text Section 4.1; Table 4, Figures 8, 9) which in turn point to well-lit conditions and shallow water.

Of course, for facies in which the corals and algae are not in situ, these general depth constraints may not apply, though transport of coral-algal material does not appear to have been far, except for organisms in the Mazavi lenses (Locality 3), and at Sardasht (Locality 4). In these cases, independent evidence points to limestone deposition in water deeper than that in which zooxanthellate corals occur (see above), perhaps by turbidity currents or subaqueous flows.

An interesting feature of the Makran coral fauna is that it is dominated by corals like poritids (e.g. Plate 18/3, 4) and faviids (e.g. Plate 18/11, 12). On today's evidence, these suggest either slightly deeper water, though still within the photic zone (say about 5-20 m), or conditions that were

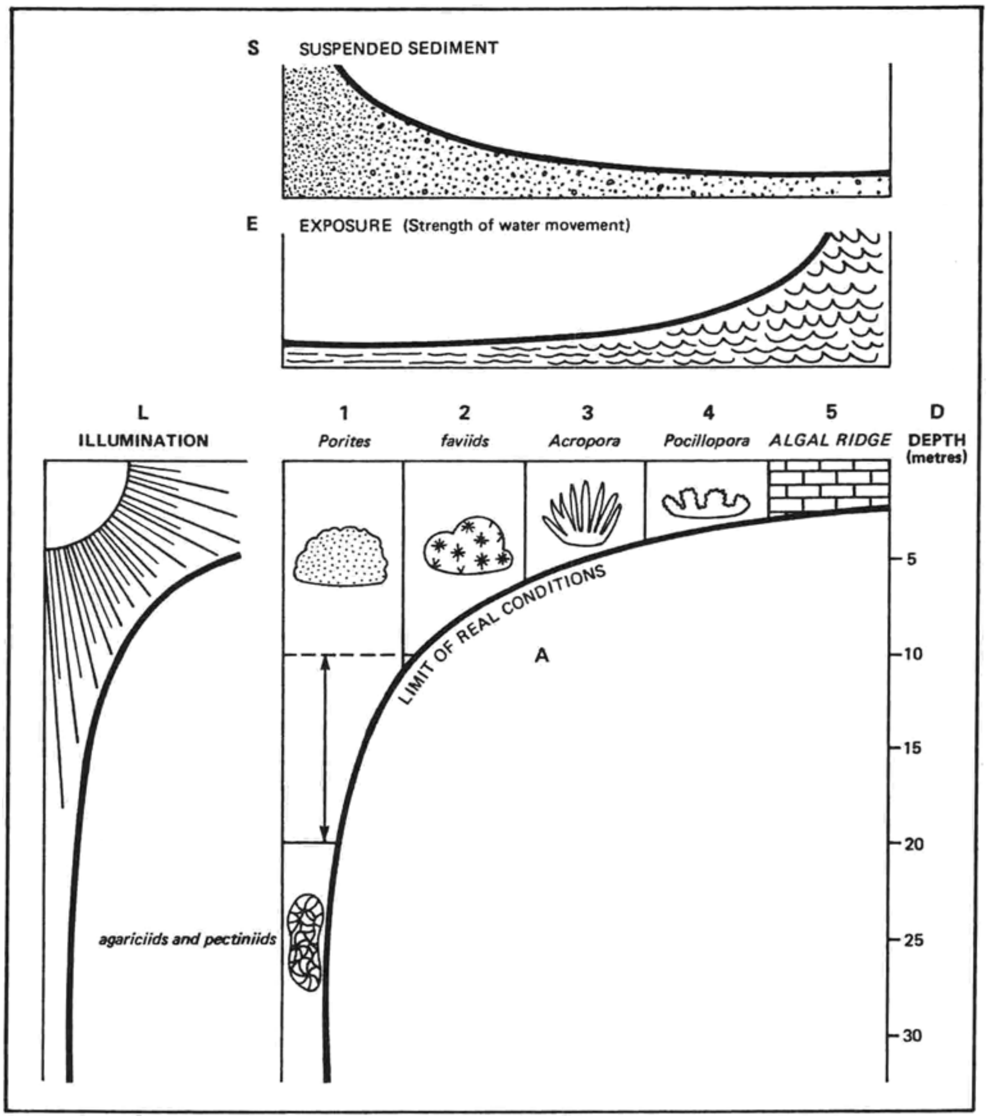

Fig. 10. Conjectured controlling gradients of ecological assemblages of living Indopacific zooxanthellate corals (after ROSEN 1981). In the main central plot (A), coral assemblages, denoted by index names of dominant taxa, are shown in relation to two principal parameters, depth (D) and energy of water movement (E). Since these are not independent of each other there is a limit of real conditions as shown. Depth correlates with illumination (L) and illumination is really the main vertical variable. However, the precise depths at which assemblages controlled by illumination occur, vary with local and regional conditions: in poorly-lit areas they will encroach upwards on energy-controlled assemblages. This is indicated by the double-headed arrow symbol. On the horizontal axis, the amount of suspended sediment (S) correlates negatively with energy (E), and these two factors together behave as two counteracting gradients of adverse conditions. The coral fauna of the Miocene limestones in the Makran corresponds most closely to the assemblages labelled '*Porites*', 'faviids' and 'agariciids and pectiniids', though not necessarily as distinct assemblages.

otherwise calmer, or more turbid (Figure 10; see also DONE 1983). Hence *in situ* coral facies of the Makran Miocene may have lain some way below the immediate water surface. This is possibly also supported by the occurrence of *Leptoseris* (Plate 18/7, 9) and pectiniids (e.g. Plate 18/10), corals which are today typical of deeper water reef facies down to 100-130 m (Figure 10), though still within the photic zone. This is further discussed in Section 4.2.

3.1.5 Wave resistance

Although rigid frameworks are compatible with wave action, they may be difficult to distinguish from coral structures built up in calmer and deeper water. The close relationship between rigid and loose frameworks, and also between framework with breccias in many of the Makran limestones, suggests that the latter might have been contemporaneously derived from *in situ* coral and algal growths, perhaps through relatively infrequent destructive wave action (?storms). Alternatively, frameworks might have been subjected to wave action (or other kinds of erosion?) during a post-depositional fall in relative sea-level (e.g. due to tectonic movements - see text Section 3.3). Wave resistance (and also elevated relief) is often inferred from the presence of ecological zonation, but the evidence for this in the Makran limestones is limited and requires confirmation (see above and text Section 4.2). In general therefore, evidence that frameworks grew in conditions of strong wave action is equivocal.

3.1.6 Tropical occurrence

The widespread occurrence of apparently zooxanthellate corals in the Makran fauna (see above) suggests warm, tropical to sub-tropical waters. Miocene palaeomagnetic reconstructions for the Makran, however, indicate a palaeolatitude of 25°N (Table 8). This is just outside the tropics (23° 30' N and S), though not beyond the latitudinal limits of many modern zooxanthellate corals and reefs. The distribution of reef corals is more fully discussed in section 4.2.3. For discussion of the limits of modern coral-algal reefs, see FULTHORPE & SCHLANGER, 1989 {especially their Figure 4, from SCHLANGER & KONISHI (1979)}. Reefs occur at a similar latitude in the Gulf of Oman today (SHEPPARD & SALM 1988, SHEPPARD et al., 1992, GLYNN 1993) as already discussed above. Moreover, the reef belt was latitudinally wider than today during the early Miocene (RÖGL & STEININGER 1984, FULTHORPE & SCHLANGER 1989; ADAMS et al., 1990), hence the Makran was not as marginal with respect to the reef belt as its palaeolatitude might suggest (Table 8, and see text Section 4.2).

3.1.7 Conclusions

(1) The limited evidence suggests that the Miocene limestones of the Makran, particularly those of Burdigalian age at Vaziri (Locality 1), Band-e Chaker (2), Lashgar Rud (5), Dar Pahn (6), and Kuh-e Bondar (7), include shallow-water (photic zone), tropical-type reefal constructions consisting of rigid coral-algal frameworks together with foraminifera and molluscs. They appear to have been patch-like developments that were discontinuous and intermittent in space and time.

(2) The *in situ* coral facies are dominated by taxa that represent slightly deeper (say about 5-20 m or more), or otherwise calmer or more turbid environments. The reef structures as a whole may therefore have occurred at depths a little below the sea surface itelf.

(3) The exact morphology and facies patterns of these reefs are not yet clear. However, the frequent passage of rigid into loose frameworks, and the greater general abundance of loose frameworks and breccias, suggests that many original reef structures are no longer preserved intact, if at all. The Aquitanian limestones at Sardasht (Locality 4) and the Mazavi lenses (Locality 3) represent an extreme of this pattern, as *in situ* reefal facies are absent. These limestones indicate destruction and transport of reefal and other shallow water carbonate material some distance into deeper water.

(4) The reef structures were developed locally within more extensive areas of finer-grained, grain-supported limestones of a non-reefal character, including foraminiferal calcarenites, some of which represent sea-grass beds. Some of the clasts in these finer-grained limestones appear to be reworked reefal (framework?) material.

(5) The limestones as a whole represent shoal-like areas within an otherwise neritic environment dominated by clastics, but also associated in some areas with evaporites.

3.2 Other lithologies associated with the limestones

The siliciclastic sequences that enclose the limestones are dominantly of neritic facies, but they also include some turbidites, generally in the lower part. The presence of the turbidites does suggest that some of these sequences represent, at least in part, a deeper environment than many of the limestones. The mapping details (MCCALL 1985a-d) indicate that although some of turbidites resemble flysch, they are not strictly flysch in DZULYNSKI & WALTON'S (1965) sense, hence MCCALL (1985e) referred to them as 'of flysch-type'. As indicated in Table 2, the shallowest water environments of some of the stratigraphic units that include the limestones also consist of evaporites and deltaics. Thus the sequences with limestones are collectively transitional between neritic and flysch, and are here interpreted as 'flysch-like to neritic'. MCCALL (1985e) interpreted them as having been deposited on the shelf and upper slope. Very thick and monotonous flysch sequences (*sensu stricto*) do occur in the Eocene-Oligocene and Oligocene-Miocene of the Makran below the present sequences but they do not contain the kinds of coral-algal limestones discussed here, only allodapic limestone lenses.

3.3 Possible controls on limestone and reef development

Limestone deposition of reefal or reef-derived origin recurred six times in the Aquitanian and at least twice (or more, if one accepts the evidence of the Mazavi lens repetitions) in the Burdigalian. Limestone conditions contrast sharply with more extensive 'flysch-like to neritic' deposits in which the limestones occur. In the Makran, well-developed and relatively widespread limestones with framework facies are restricted to the Early Miocene. This differs from both the older (Eocene-Oligocene, Oligocene-earliest Miocene) and younger (post-Burdigalian Miocene to Pliocene) sequences. While these do contain some shelf limestones with sparse corals and algae {e.g. the Eocene Bard-e Marz limestone of the Minab Quadrangle (MCCALL 1985a), and the lower part of the Eocene Zaboli unit in the Saravan quadrangle (MCCALL & EFTEKHAR NEZHAD 1993 in the press}, these do not appear to be reefal. It is of course possible that reefal limestones existed intermittently throughout much of the Tertiary and Quaternary of the region, but are not seen or preserved in the exposed sequences. Several different factors might explain (1) the relative concentration of reefal environments in the Early Miocene, and (2) their relatively frequent repetition during this time: tectonics, eustasy, climate and salinity, together with indirect sedimentation factors arising from any of these. It is difficult on present evidence to separate them clearly.

Taking the concentration of reefal conditions in the early Miocene first, this could be related either to the stage of 'forearc' development reached in the Early Miocene, or to global climatic conditions, or both. In favour of the first, uplift occurred continuously throughout the region during the Cainozoic. Shallow water conditions became more widespread in the Early Miocene, with true flysch (abyssal) passing up into flysch-like slope deposits and finally into neritic, shallower conditions including those of most of the limestones. Deepening of the sea then occurred after the Burdigalian limestones of the Makran were deposited, and prior to later continued uplift, for the overlying sediments include much deeper-water facies. In favour of climatic control, the palaeolatitudinal range of reefs during the Early Miocene was wider than today, and reefs and limestones were globally well developed, apparently in response to a phase of global warming (references cited above). As the palaeolatitude of Makran at that time (25°N; Table 8) would otherwise have been marginal to unfavourable for modern reef development, a short-lived warm phase like this would have been critical. Concentrated development of reefs and associated limestones during the early Miocene appears to be a global phenomenon and corresponds to a first order cycle of climatic/eustatic origin in the Mediterranean region (Mateu Esteban pers. comm.).

Turning to the problem of relatively rapid fluctuations in sedimentary conditions within this main early Miocene interval, the most immediately obvious causal factor is the general tectonic instability that prevailed throughout the Makran from the Miocene onwards. Frequent changes in sedimentation occur throughout the immensely thick sequences of Miocene to Pliocene age. Tectonic instability would have affected depth of water, both locally and regionally (episodic uplift and subsidence within the overall uplift trend), as well as rate of siliciclastic sediment supply. Limestones would be favoured in shallow-water areas especially when siliciclastic input was also much reduced or absent. In extreme conditions of shallowing, salinity control would also become important, giving rise to evaporitic deposits, as in the Ghasr Ghand and Sabz units. Eustatic factors might also have been important, but are difficult to identify and to distinguish from possible tectonic influence, on present knowledge of the region. Long term eustatic change (e.g. as plotted by Haq et al. 1988) was too gradual to account for the observed repetition of limestones, though it might have influenced their early Miocene concentration (see above). Moreover the four 'short term' Aquitanian-Burdigalian transgressive cycles of these authors are too few to explain the observed repetition on their own. Glacio-eustatic changes are of much higher frequency, typically 10^4 - 10^5 years (Matthews 1984), but presuppose the contemporaneous existence of extensive ice sheets. Mattews (1984) has argued for an Antarctic ice sheet throughout most of the Tertiary (in contrast with the conventional view that continental ice sheets were absent prior to the Middle Miocene) but the global warm phase implied by the wider reef belt during the early Miocene (above), suggests that the total amount of global ice could not have been very extensive. Hence glacio-eustatic influence is questionable for the Makran limestones.

3.4 Depositional model and possible analogues outside Iran

3.4.1 Models of carbonate deposition in accretionary prism settings

Depositional conditions of the Makran limestones, in which extensive carbonate platforms and shelves are absent, were clearly very different from those on passive margins and oceanic platforms, where many Recent coral reefs occur. The occurrence of conditions favourable to coral-algal limestone deposition was clearly ephemeral within a fluctuating environment dominated by siliciclastics and evidently influenced by tectonic instability, which persisted from the Miocene to the present day. These conditions were, at least in part, controlled by the accretionary prism setting of the Makran limestones.

However, there appear to be few detailed accounts or depositional models of reefs and associated carbonates in accretionary prism settings. Fulthorpe & Schlanger (1989) reviewed tectonic settings for reefs and associated carbonates mainly for the early Miocene of Southeast Asia. For convergent plate boundaries they suggested that there were basically four tectonic settings on the overriding plate (their Figures 14 and 15), of which their model 'D' applies to accretionary prisms. However, they noted only that accretionary prisms provide a 'potential setting for reef development' and did not cite any definite examples either from the Tertiary or elsewhere in the geological column. Their accretionary prism model envisages that limestones are deposited unconformably on the uppermost surfaces (i.e. at the sea-floor) of contemporaneously upthrusted prism slices that mostly originated in abyssal or trench environments. Limestones can be deposited once these surfaces are uplifted into the photic zone, e.g. as fringing reefs around uplifted areas or patch reefs on local highs. This would result in reefs and associated carbonates forming as 'terraced limestone caps', which would probably be faulted and rest unconformably on rocks of deeper water origin. This model does not apply to the Makran however where the limestones are an integral and conformable part of 'flysch-like to neritic' sequences within the prism itself.

A widely quoted example of an accretionary prism that includes reef limestones is that of the Sunda fore-arc of Nias, northern Sumatra (Moore & Karig 1980). More recent studies by Harbury & Kallagher (1991) have revised Moore and Karig's interpretation. Neogene limestones, including reefs, are exposed on the islands of Nias and Simeulue. Although terraced limestone caps in the sense of Fulthorpe and Schlanger (above) occur in the Quaternary of these islands, the Miocene limestones are different, having developed on a shallow shelf corresponding to the area of an outer-arc ridge formed by the most elevated slices of the accretionary prism. The limestones occur conformably within shallowing-upward sequences (e.g. Nias Beds) but these sequences themselves lie unconformably on rocks of much deeper water origin. Although not yet fully understood, the shallowing-upwards sequences represent a slope-to-shelf environment, perhaps developed initially in slope basins, but, with continued uplift and infill, their deposits spread out more generally as an unconformable mantle over the uppermost (shallowest) slices of the prism. This later stage includes limestones. The Sunda fore-arc therefore provides an alternative model for reef limestone deposition in accretionary prism settings to the Fulthorpe and Schlanger model. Moreover, its shallowing-upwards sequences appear to be broadly similar to the above 'flysch-like to neritic' sequences that include the Miocene limestones of the Makran.

In other respects, however, the Makran is different from the Nias model. As already mentioned (text Section 1.5), the study by Platt et al. (1985) of the eastward continuation of the Makran accretionary prism in southwest Pakistan, shows that Miocene to early Pliocene slope and shelf sequences have been deposited concordantly (not unconformably) on undisturbed abyssal-plain sequences. The same kind of structure has been independently recognized in the Iranian Makran, where there is concordance between true flysch of the older Tertiaries and the 'flysch-like to neritic sequences' of the Miocene (Geotectonic Zones 5 to 8; see text Section 1.4, Table 1 and Figure 2). The Pakistan Makran differs only in that concordance applies to the whole prism structure, not just a part of it, as in Iran. Platt et al. relate concordant development to the very low angle of subduction and associated thrusting in the Makran, and invoked underplating and uplift to explain the observed rapid shoaling. Whether their explanation is correct or not, we suggest that the Makran thus provides a third model for reef and limestone deposition in an accretionary prism setting. Here, the limestones occur as an integral part of the accretionary prism, not in unconformable sequences upon it. However, both the Nias model and the Pakistan model envisage that reefs and carbonates were deposited (probably intermittently) on a shelf formed on the shallowest part of an accretionary prism, in the case of Nias, on a fore-arc ridge. It is possible that an analogous ridge existed in the Iranian Makran too, giving rise to relatively localized sites for carbonate deposition. Thus although Read's (1982) models for carbonate platforms are in passive margin settings, and therefore have a fundamentally different underlying structure and dynamics, the facies patterns of the Miocene limestones and associated lithologies in the Makran most closely resemble his intermittently developed rimmed shelf model.

3.4.2 Some regional comparisons

Elsewhere, among Recent and ancient reefs, Hall (pers. comm.) has suggested that the tectonically unstable setting in the Makran of the Miocene reefs in a fore-arc situation above a subduction zone may resemble that of the late Pliocene-Recent coral reefs of Halmahera (Hall et al. 1988). In this area there was an inhibition of reef growth by terrigenous sedimentation, leading to discontinuous strip-like fringing-reef developments. The laterally discontinuous nature of the Burdigalian limestones of the Makran {particularly obvious in the mapping of the Nikshahr and Tahruie quadrangles (McCall & Eftekar Nezhad 1993, McCall 1985b) } might have been similarly controlled by local variations in clastic sediment supply, though most appear to have been deposited not in a fringing situation but rather well offshore. Some evidence for this is seen in the palaeogeographic reconstructions by McCall (1985b: see his Figures 48-51) which suggest that in the Tahruie quadrangle, the Burdigalian sequences which contain the limestones were mainly deposited in a shoaling zone separated from the coast by a deeper basin of flysch deposition.

Cainozoic analogues from the Caribbean have also been suggested (J. Geister pers. comm). There, tectonically unstable conditions similar to those of the Makran have existed in a region of plate interaction. In the Dominican Republic, coral carpets occur in a thick Neogene turbidite section near Fonde Negro and the coral beds contain 'typical reef corals, living or tumbled ... intercalated in turbiditic rocks' (J. Geister pers. comm., citing Mascle et al. 1980, close to Stop 3). Geister's description of 'tumbled corals' is reminiscent of the breccias of the Aquitanian limestones at Sardasht (Locality 4), and also the thin lenses of Burdigalian limestone in the Mazavi section (Locality 3). In the case of the Middle Miocene occurrences of Anguilla (Budd et al. 1989), influxes of sand interrupted reef growth, and calcarenites are interbedded with reefal limestones as in the Makran.

Another possible ancient analogue is the 'flyschoid reef subformation' of the Jurassic Malm in the Greater Caucasus (Bendukidze 1977). This is characterised by well-developed rhythmic bedding of terrigenous material, the abundance of which is held to have prevented continuous growth of reefs, so that limestones occurred as alternations, and never developed as proper reefs. This is reminiscent of the Aquitanian limestone repetitions at Sardasht (Locality 4).

The small Early Miocene (Aquitanian) fringing reefs of the Nerthe section near Marseille in the south of France (Monleau et al. 1989) also display alternations of reefs and siliciclastic sediments. These siliciclastics however are continental sediments, whereas in the Makran continental sediments do not appear until the late Middle Miocene to early Pliocene, i.e. after the present limestone phases. Another difference is that there are abundant branching corals, especially *Porites*, in the Nerthe limestones, whereas in the Makran, such corals are rare.

4 PALAEONTOLOGY

4.1 Foraminifera

Thirty six limestone samples and eighty eight random thin sections were examined by Dr. C.G. Adams at The Natural History Museum, London (Adams in McCall , 1985b,e, and in McCall & Eftekar Nezhad 1993). This section of the paper represents a summary of his reports updated by some subsequent re-examination (Adams, pers. comm.). His conclusions accord with the results of the study of the larger collections held in Tehran, described by I. Deighton and C.W. Mallett (in McCall 1985e), some of whose results are incorporated in Tables 3 and 4. These determinations are based on representative specimens of the Paragon-Contech fossil collections from the Makran, deposited in the Department of Palaeontology of The Natural History Museum in London, and in the Geological Survey of Iran, Tehran. Some of the wider palaeobiogeographical implications of the Makran foraminifera were discussed by

Table 5. Determinations of Miocene corals of the Makran in relation to neighbouring areas in Iran and western Pakistan. All corals are scleractinians unless indicated otherwise.

EXPLANATION OF SYMBOLS USED IN EACH COLUMN OF THE TABLE

Notes

1 - see respective caption for Pl. 18figures for additional remarks on this species
2 - probably a new species
3 - *Heliopora* is an octocoral
4 - perhaps an *Actinacis*, though this genus is usually regarded as extinct by end of Oligocene
5 - Veron & Pichon (1980) have subsequently referred the living representatives of this species to *S.* cf. *recta* (Dana, 1846), and Veron (1986) later dropped the 'cf.'

New or previous species records

* - new species record for the region
Letter symbols indicate authors of previous species records:
A1 - Abich (1859) for ?Burdigalian, Urmia, N. Iran
A2 - Abich (1882) for ?Burdigalian, Urmia, N. Iran
D - Duncan (1880) for Burdigalian-Langhian, Western Pakistan
G - Gregory (1899) for ? Burdigalian, Urmia, N. Iran
K - Kühn (1933), Sierp et al. (1969) for Burdigalian, Saidabad (= Sirjan), Central Iran
Blanks are left in this column where no species name is given.

Age of species record in Makran (this study)

A - Aquitanian
B - Burdigalian
EM^{SU} - Early Miocene of the Sabz Unit

Previously known stratigraphical range of the species

All abbreviations are based on the first syllable of the epoch or period, but note:
E - Early
M - Middle
Late (in full, to avoid confusion with 'Lower')
Pal - Palaeocene
Parentheses are used for forms whose species or genus is uncertain

Environment and symbiotic status

(NR) - species extinct, uncertain or not known, belonging to extant genus which is not reef-dwelling
R - extant reef-dwelling (including constructional) species
(R) - species extinct, uncertain or not known, belonging to extant reef-dwelling (including constructional) genus
?(R) - as (R) but genus uncertain
(AZ) - species extinct, uncertain or not known, belonging to extant genus usually regarded as azooxanthellate
Z - extant species usually regarded as zooxanthellate
(Z) - species extinct, uncertain or not known, belonging to extant genus usually regarded as zooxanthellate
?(Z) - as (Z) but genus uncertain
Z-like - extinct species whose genus has colony form known only in zooxanthellate forms
Terminology mostly after Schuhmacher & Zibrowius (1985). Note that all taxa without any symbol are closely related to extant zooxanthellate genera.

Species	Notes	New or previous species record	Age in Makran	Stratigraphical ranges	Environment and symbiotic status
Acanthastrea echinata (Dana, 1846)		*	B	Moc-Rec	ZR
Acanthastrea cf. *echinata* (Dana, 1846)		*	B	(Mioc-Rec)	(ZR)
Acanthastrea hillae Wells 1955	1 (Pl. 18/8)	*	B	Rec	ZR
Acanthastrea cf. *polygonalis*, Felix, 1921 *non* Martin 1880		*	B	(Mio)	(ZR)
Acropora duncani (Reuss, 1867)		*	A	Mio-Plio	(ZR)
Acropora sp.		-	B	-	(ZR)
Alveopora daedalea (Forskål, 1775)		*	B	Mio-Rec	ZR
Alveopora cf. *deningeri* Gerth 1910 (cf. Gerth 1925)		*	B	(Mio-Plio)	(ZR)
Anisocoenia cf. *Favia junghuhni* (Reuss, 1866)		*	B	(Mio)	
Anisocoenia variabilis Gerth, 1923		K	B	Mio	
Anisocoenia sp.		-	B	-	
Astreopora cf. *hemisphaerica* Duncan, 1880		D	B	(M.Mio)	(ZR)
Astreopora [Polysolenia] hochstetteri (Reuss, 1866)		*	B	Mio-Plio	(ZR)
Astreopora [Polysolenia] cf. *solida* (Umbgrove, 1924)		*	B	(Plio-Pleist)	(ZR)
Astrocoenia gerthi Kühn, 1933		K	B	E.Mio	
Caulastraea [Rhabdophyllia] retiformans (Kühn, 1933)		K	B	E.Mio	(ZR)
Coenocyathus cf. *anthophyllites* Milne Edwards & Haime, 1848		*	B	(Mio-Rec)	(AZ, NR)
Cyathoseris crassilamellata (Gerth, 1923)		*	B	Mio	Z-like
Cyathoseris [Agaricia] cf. *danae* (Duncan, 1880)		D	B	(M.Mio)	Z-like
Cyathoseris cf. *lophiophora* (Felix, 1921)		*	B	(Mio)	Z-like
Cyathoseris "*parvistella*, Gerth, 1925"		*	B	Mio	Z-like

Table 5 continued

Species	Notes	New or previous species record	Age in Makran	Stratigraphical ranges	Environment and symbiotic status
Cyphastrea niasensis Gerth 1925		*	B	Mio	(ZR)
Cyphastrea cf. *serailia* (Forskål, 1775)		*	B	(Mio-Rec)	(ZR)
Cyphastrea [Solenastrea] turonensis (Michelin, 1847)		?A2,G	B	Mio	(ZR)
Cyphastrea sp.		-	B	-	(ZR)
Dichocoenia sp.	2	-	B	(Late Cret-Rec genus)	(ZR)
Echinophyllia aspera (Ellis & Solander, 1786)		*	B	Mio-Rec	ZR
Echinophyllia [Mycedium] costata (Duncan 1864)	1 (Pl. 18/10)	*	B	'Tertiary'	(ZR)
Favia amicorum (Milne Edwards & Haime, 1850)		*	B	Rec	ZR
Favia laxa (Klunzinger, 1879)	1 (Pl. 18/12)	*	A-B	Mio-Rec	ZR
Favia pallida (Dana, 1846)		*	B	Mio-Rec	ZR
Favia preamplior (Gregory, 1925)		*	B	Mio	(ZR)
Favia [Heliastrea] sindiana (Duncan, 1880)		D	A	M.-Mio	(ZR)
Favites crassisepta (Gregory, 1900)		*	B	E.Mio	(ZR)
Favites [Prionastrea] fungiformis (Duncan, 1880)		D	B	M.Mio	(ZR)
Favites [Prionastrea] rhomboidea (Kühn, 1933)		K	B	E.Mio	(ZR)
Fungophyllia aspera Gerth, 1923		*	B	E.Mio	
Galaxea fascicularis Linnaeus, 1767		*	B	Mio-Rec	ZR
Galaxea haligena Felix, 1913		*	B	Mio-Plio	(ZR)
Goniopora [Porites] cf. *gajensis* (Duncan, 1880)		D,K	B	(E-M.Mio)	(ZR)
Goniopora [Porites] incrassata (Reuss, 1866)		*	B	Mio	(ZR)
Heliopora coerulea (Pallas, 1766)	3	*	B	Cret-Rec	ZR
Hydnophora [Monticulastraea] insignis (Duncan, 1880)		D	A-B	Mio	(ZR)
Hydnophora [Monticulastraea] regularis (Kühn, 1933)		K	A-B	E.Mio	(ZR)
Hydnophora cf. *rudis* (Duncan, 1864)	1 (Pl. 18/11)	D	B	(Pal-?M.Mio)	(ZR)
Hydnophora [Monticulastraea] solidior (Duncan, 1880)		D,K	B	Mio	(ZR)
Indosmilia rembangensis Gerth, 1933		*	B	E-M.Mio	
Leptomussa variabilis d'Achiardi, 1867		*	B	Eoc-Olig	
Leptoseris delicatissima Kühn, 1933	1 (Pl. 18/7, 9)	K	B	E.Mio	(ZR)
Leptoseris densicostata Gerth, 1923		*	B	Mio	(ZR)
Leptoseris cf. *floriformis* Gerth, 1923		K	B	(Mio)	(ZR)
"Lithophyllia" spinosa Gerth, 1921		*	B	Mio	
Lobophyllia cf. *corymbosa* (Forskål, 1775)		*	B	(Mio-Rec)	(ZR)
Montastraea [Heliastrea] irregularis (Martin 1880)		*	B	Late Mio	(ZR)
Montastraea [Orbicella] transiens (Felix, 1921)		*	B	Mio	(ZR)
Montastraea sp.		-	A	-	(ZR)
Montipora cf. *"Alveopora" micropora* Felix, 1921		*	B	(Mio)	(ZR)
Montipora sp.		-	B	-	(ZR)
Oulophyllia [Hydnophyllia] malayica (Gerth, 1933)		*	B	Mio	(ZR)
Oulophyllia sp.		-	B	-	(ZR)
Pachyseris affinis Duncan, 1880		D	A	Mio	(ZR)
Parascolymia [Circophyllia] farquharsoni (Latham, 1929)		*	B	Olig	(ZR)
Parascolymia vitiensis (Brueggemann, 1877)	1 (Pl. 18/2)	*	B	Mio-Rec	ZR
Pattalophyllia verbeeki (Gerth, 1921)		*	B	Mio	
Pavona folium Martin 1880		*	LM^{SU}	Mio	(ZR)
Pavona [Comoseris] javana (Gerth 1921)		*	LM^{SU}	Mio	(ZR)
Platygyra daedalea (Ellis & Solander, 1786)		*	B	Plio-Rec	ZR
Plesiastrea decipiens Duncan, 1880		D	?B	M.Mio	(ZR)
Plesiastrea fungiformis Kühn, 1933		K	A-B	E.Mio	(ZR)
Plesiastrea grayi Kühn, 1933		K	B	E.Mio	(ZR)
Plesiastrea cf. *grayi* Kühn, 1933		-	B	(E.Mio)	(ZR)
Porites (Porites) cf. *lutea* Milne Edwards & Haime, 1851	1 (Pl. 18/4)	*	B	(?Mio, Plio-Rec)	(ZR)
Porites (Porites) multilamellata Gregory, 1925		*	B	Mio	(ZR)
Porites (Porites) pusilla Felix, 1884		*	B	Mio	(ZR)
Porites (Porites) cf. *pusilla* Felix, 1884	1 (Pl. 18/3)	-	B	(Mio)	(ZR)
Porites (Porites) sp.		-	B	-	(ZR)
Porites (Synaraea) amplectans (Felix, 1921)		*	B	Mio	(ZR)
Porites (Synaraea) delicatissima (Kühn, 1933)?	4	K	A	E.Mio	?(ZR)

Table 5 continued

Species	Notes	New or previous species record	Age in Makran	Stratigraphical ranges	Environment and symbiotic status
Porites (Synaraea) cf. *delicatissima* (Kohn, 1933)?	4	-	B	(E.Mio)	?(ZR)
Porites (Synaraea) sp.		-	B	-	(ZR)
Porites (Synaraea) [Thamnaraea] polymorpha (Abich, 1859)		A1, G	B	Mio	(ZR)
Progyrosmilia [Coelocoenia] cf. *vacua* (Gerth, 1923)		*	A	(Mio)	
Scalariogyra escharoides Gerth, 1923		*	B	Mio	Z-like
Seriatopora sp.		-	B	-	(ZR)
Stylophora africana Latham, 1929		*	B	Mio	(ZR)
Stylophora cyclopleura Felix, 1921		*	B	Mio	(ZR)
Stylophora cf. *gemmans* Gerth, 1923		*	B	(E.Mio)	(ZR)
Stylophora pistillata (Esper, 1797)		*	B	Mio-Rec	ZR
Symphyllia nobilis (Dana, 1846)	5	*	B	Plio-Rec	ZR
Symphyllia sp.		-	B	-	(ZR)
Trochoseris [Palaeoseris] persica (Kohn 1933)	1 (Pl. 18/1, 5, 6)	K	B	E.Mio	
"Trochosmilia" progoensis Gerth, 1933		*	B	Mio	

Adams et al. (1983), and are mentioned below (text Section 5). It must be emphasized that the finer-grained limestones rather than coarse rudstones (biorudites) were submitted for foraminiferal examination and some selectivity is recognized. Adams noted that although of two distinct ages (Aquitanian and Burdigalian), the limestones examined are essentially of the same character. They are partly conglomeratic and include smaller clasts of older carbonates and igneous material. All samples contained tests of larger foraminifera together with coral, echinoid, bryozoan and mollusc shell débris, and skeletal remains of calcareous algae. He interpreted the limestones as shallow-water and 'detrital' in origin. Although in part conglomeratic, neither the Aquitanian nor Burdigalian limestones show evidence of significant reworking or mixing of faunas. The clasts of older limestones cannot be dated, and there is no evidence that they are significantly older than their matrix. They may reflect erosion of nearby limestones, but other sedimentary and igneous material in the conglomerates must have originated elsewhere.

Three of the samples came from the limestones at Sardasht (Locality 4) within the Dehirdan Unit, the enclosing clastic sediments containing planktonic and benthonic foraminifera compatible with an Aquitanian age. Thin sections described by Adams include 14760C from Bed 3 (Table 3 and Figure 5B), 14758B from Bed 9, and 14758A from Bed 10, and all were determined as Aquitanian, 'probably early'. It should therefore be noted that the four unsampled limestones at Sardasht (Figure 5A) lower than those from which the foregoing samples were collected, must be earlier Aquitanian or even Oligocene (Chattian). The samples yielded rich assemblages of larger foraminifera including: *Amphiste-*

Table 6. Regional and stratigraphic distribution of Miocene coral species from Iran and neighbouring West Pakistan.

Locality	Miocene Age	Number of Species	References
W. Pakistan	Burdigalian-Langhian	55	Duncan 1880
Urmia, N. Iran	?Burdigalian	23	Abich 1859, 1882 Gregory 1899 Felix 1910 Dietrich 1918
Saidabad (= Sirjan), Central Iran	Burdigalian	40	Kühn 1933 (Sjerp et al. 1969)[3]
Makran, S. Iran	Burdigalian Aquitanian	82 (+2)[1] 10[2] 90 (92)[1]	Rosen & Darrell *in* McCall 1985e; and this paper

[1] The figures of 82 and 90 are for species from the Lower Miocene limestones alone. The additional two species are of *Pavona* and come from the clastic beds in the Miocene Sabz Unit. The total for Lower Miocene of the Makran is 92.

[2] Two of these species are also represented in the Burdigalian limestones, thus the total number of species for the reefal limestones is 90.

[3] Sjerp et al.'s fauna is from the Chahar Gonbad copper mine of the Saidabad (=Sirjan) district, whose corals were studied by Kühn (1933), but some of Sjerp et al.'s corals may be older (Oligocene), and hence their list is not included in the total shown here.

gina sp., *Borelis* sp., *Lepidocyclina* sp., *Lepidocyclina (Nephrolepidina)* cf. *sumatrensis* (Brady), *L.(N.)* sp. indet., *Miogypsina* cf. *gunteri* (Cole), *Miogypsinoides* cf. *dehaarti* van de Vlerk, *Spiroclypeus* cf. *margaritatus* Schlumberger. The identifications in this list are stratigraphically consistent with, but not identical to those provisionally provided by I. Deighton and C.W. Mallett from field laboratory examination of samples from the same beds at Sardasht (Table 3). Assemblages of this type can be found from Europe to South East Asia and the Western Pacific in strata of early Miocene (Aquitanian) age (Eames et al. 1962, Adams 1970).

All the other samples submitted to Adams contain a younger Miocene fauna. Thin sections of limestones examined include: 2084 from Vaziri (Locality 1); 9527A from Bed 3 at Lashgar Rud (Locality 5; Table 4); and 9528E, 9529, B, E1 and F1 from an outcrop nearby. The fauna is less diverse than that of the Aquitanian limestones above, and is dominated by the genus *Miogypsina*. The species all belong to the *globulina-mediterranea* end of the lineage and so are not older than Burdigalian (Drooger 1963, De Mulder 1975). This is confirmed by the presence of *Austrotrillina howchini* (Schlumberger), the end member of the lineage which is typical of Burdigalian and slightly younger strata (Adams 1968, 1970); and also of *Borelis melo* (Fichtel & Moll), a species appearing in the Burdigalian but ranging up into the late Miocene. Rare individuals of *Archaias* and *Lepidocyclina (Nephrolepidina)* were also recorded, together with encrusting foraminifera, other miliolids and rare indeterminate globigerinids. While it is theoretically possible for a fauna of this kind to be found in the earliest Middle Miocene (Planktonic Zone N9), the absence of any typical Middle Miocene taxa in these samples makes this highly unlikely.

As most of the genera and all the species present in these Miocene limestones are now extinct, it is impossible to be precise about the depth of water in which they were deposited. By analogy with living larger foraminifera, they inhabited shallow water, probably less than c.30 m depth. The paucity of pelagic foraminifera, except in one sample, is a further indication of shallow water deposition.

Deighton (in McCall & Eftekhar Nezhad 1993) interpreted the foraminiferal assemblages low in the Lashgar Rud section (Locality 5; Table 4 and Figures 7, 8) as typical of sea grass beds, and indicative of depths of less than 50 m. He inferred that reefal limestones higher in the section had prograded over stabilized reef talus and sea grass flats (Figure 9) (though sea grass beds actually occur on the surface platforms of modern reefs as well in shallow inter-reef environments).

4.2 Corals

4.2.1 Summary of composition and diversity

Preliminary determinations of the corals are given in Table 5. Taxonomic notes and illustrations of these can be found in the reports by Rosen & Darrell, and by Rosen (in McCall 1985 a,b,c,e, and McCall & Eftekhar Nezhad 1993). Some of the more common or otherwise interesting corals are illustrated in Plate 18, with taxonomic remarks. Most of the Makran corals are preserved in fine matrix, bearing clasts of coral and shell material. Some corals show good weathered-out detail of the external morphology (Plate 18), but internal structure is often diagenetically altered to varying degrees even within single specimens.

The taxonomy of Tertiary corals from Asia and the Indopacific margins is almost entirely based on works that are sixty years old or more, and coral taxonomy has advanced considerably since that time. As these older works are often difficult to interpret without direct comparison with specimens concerned, recourse to recent monographs of living Indopacific corals was sometimes found necessary. The difference in geological time between the early Miocene and the present being c.16-24 Ma, this was felt to offer a reasonable working approximation for making initial identifications. {At the time of our taxonomic study, the only data available on coral species durations were those reviewed by Stanley (1979), who suggested a working figure of 20 Ma. Since then however, data by Johnson et al. (in the press) suggest that in the Caribbean at least, this figure is an overestimate}. A full taxonomic revision of Miocene Tethyan corals is also needed, in the light of advances in Recent coral taxonomy but this was not possible here. The present identifications must therefore be regarded as preliminary, e.g. see caption remarks on some of the corals illustrated in Plate 18. The primary purpose of this paper is to provide a general discussion of the significance of the coral fauna. This largely revises the discussion sections in the above Paragon-Contech reports, now a decade old.

Previous knowledge of Miocene corals from this part of Asia is moderately good, considering the age of the relevant literature (see references cited in Tables 5 and 6). The Makran collection includes 41 genera of which 40 are from the Miocene limestones discussed here (previously referred to as the 'Vaziri Unit') and one is from clastic sediments of the Sabz Unit. Of a total of 137 species previously recorded from this part of Asia, 23 occur in the Makran collections, but a further 69 species are new records, bringing the Makran total to 92 species (90 from the Miocene limestones - see above). This represents a significant addition to the knowledge of Tertiary corals in this region.

The present coral collections appear to be reasonably comprehensive. Even though the field parties involved in the present Makran survey included no macrofossil specialists, coral collecting was evidently careful and effective. The number of taxa present in each of the five scleractinian coral suborders in our Makran list is proportional to those for the global Miocene as whole, as extracted from Wells' (1956) compilation of scleractinian genera. The Makran collection now appears to be the largest published coral collection of Miocene age between the western Mediterranean and Indonesia.

The numbers of individual genera collected from the different areas (denoted by the numerical codes of the 1:100,000 geological sheets; see Figure 1) and the two relevant stratigraphical divisions (Aquitanian and Burdigalian) are shown in Table 7. This field log of sampling gives a preliminary indication of variations in abundance and taxonomic diversity within the region, though it was not always possible to make equally good collections at every locality. The table is not a palaeontological survey and is

Table 7. Numbers of individual specimens of early Miocene coral genera collected from different districts (corresponding to geological sheets) within the Makran study area. Sheets and their respective Quadrangles are shown in Figure 1. Aquitanian corals (first column) are all from Sardasht (Locality 4).
* *Pavona* was recovered from the siliciclastic rocks of the Sabz Unit and not from limestone.

	age --------------->	AQUI-TANIAN	BURDIGALIAN									
	Quadrangle ------->	Tahruie	Minab	Tahruie					Fannuj		Nikshahr	
	Sheet -------------->	7542	7444	7442	7443	7542	7543	7642	7742	7942	8142	8242
OCTOCORALLIA COENOTHECALIA HELIOPORIDAE	*Heliopora*	-	-	-	-	1	-	-	-	-	-	-
ZOANTHARIA SCLERACTINIA												
ASTROCOENIDAE	*Astrocoenia*	-	2	1	-	1	-	-	-	-	-	-
POCILLOPORIDAE	*Stylophora*	-	1	-	-	-	3	-	-	-	-	2
	Seriatopora	-	-	-	-	-	-	-	-	-	-	1
ACROPORIDAE	*Acropora*	1	-	-	-	-	-	-	-	-	-	1
	Astreopora	-	-	-	1	-	-	-	-	-	-	4
	Montipora	-	-	-	-	-	4	-	-	-	-	-
AGARICIIDAE	*Trochoseris*	-	-	1	-	-	2	-	-	-	-	-
	Cyathoseris	-	1	-	2	1	1	-	-	-	-	-
	Leptoseris	-	-	-	-	-	3	-	1?	-	-	1
	Pachyseris	1	-	-	-	-	-	-	-	-	-	-
	agariciid sp.	-	-	-	-	-	1	-	-	-	-	-
	Pavona *	-	2	-	-	-	-	-	-	-	-	-
PORITIDAE	*Goniopora*	-	1	-	-	-	-	-	-	-	-	1
	Porites	2	-	1	1	1	12	1	-	-	-	4
	Alveopora	-	-	-	-	-	2	-	-	-	-	-
FAVIIDAE	*Indosmilia*	-	-	-	-	1	2	-	-	-	-	-
	Caulastraea	-	-	-	-	1	1	-	-	-	-	-
	Plesiastrea	1	11	-	-	-	4	-	-	-	-	11
	Favia	2	2	12	5	3	3	-	3	2	2	12
	Favites	-	1	-	-	-	-	-	-	-	-	1
	Oulophyllia	-	-	-	-	-	2	-	-	-	-	1
	Anisocoenia	-	-	-	1	-	-	-	-	-	-	3
	Platygyra	-	-	-	1	-	-	-	-	-	-	-
	Hydnophora	3	9	-	2	-	3	-	-	-	1	7
	Montastraea	1	-	2	8	3	1	-	-	-	-	10
	Cyphastrea	-	-	-	1	1	2	-	-	-	-	1
	Pattalophyllia	-	-	-	1	-	-	-	-	-	-	1
OCULINIDAE	*Galaxea*	-	-	-	-	-	1	-	-	-	-	3
MEANDRINIDAE	*Dichocoenia*	-	-	-	-	-	-	-	-	-	-	1
	Scalariogyra	-	-	-	-	1	-	-	-	-	-	-
MUSSIDAE	*Trochosmilia*	-	-	-	-	-	-	-	-	-	-	1
	"Lithophyllia"	-	-	-	-	-	2	-	-	-	-	-
	Parascolymia	-	13	-	1	2	9	-	-	-	-	5
	Acanthastrea	-	2	1	3	-	8	-	1	-	-	2
	Leptomussa	-	-	-	-	-	1	-	-	-	-	-
	Lobophyllia	-	-	-	-	-	1	-	-	-	-	-
	Symphyllia	-	-	-	-	-	1	-	-	-	-	-
PECTINIIDAE	*Fungophyllia*	-	-	-	-	-	1	-	1	-	-	-
	Echinophyllia	-	1	-	-	1	4	-	-	-	-	-
CARYOPHYLLIIDAE	*Coenocyathus*	-	-	-	-	-	-	-	1	-	-	-
	Progyrosmilia	1	-	-	-	-	-	-	-	-	-	-

probably selective and incomplete. Taken at face value, the data suggest that the coral faunas appear to become richer in time, with the Aquitanian represented by only eight genera, whereas the two or three adjacent Burdigalian limestone exposures at Lashgar Rud (Locality 5, within Sheet 8242, Nikshahr quadrangle) yielded 20 genera. However, the Aquitanian is represented by only one locality (4: Sardasht), and the corals here have been transported post mortem from elsewhere (as already discussed). The numerous Burdigalian exposures of Tahruie (Sheet 7543) yielded no fewer than 25 genera, and a single extensive outcrop at Vaziri (Locality 1) yielded 11 genera.

Most of the Makran coral genera and many of the species (Table 5), as identified here, are extant forms. However, the apparent number of extant species may prove misleadingly high when the fauna is eventually revised, because the use of some extant species names arose from taxonomic difficulties (see above). Members of two particular families dominate the Makran fauna both taxonomically and in abundance (Table 7): the Poritidae (notably *Porites* itself; Plate 18/3, 4) and the Faviidae {notably *Favia* (Plate 18/12), *Plesiastrea*, *Montastraea* and *Hydnophora* (Plate 18/11)}. Moreover, most of the remaining corals belong to close relatives of the Faviidae, i.e. to families within the same suborder (*Faviina*; Plate 18/2, 8, 10), especially colonial mussids like *Acanthastrea* (Plate 18/8) and the large cylindrical solitary mussid *Parascolymia* (Plate 18/2). Other similarly large solitary taxa also occur. Large solitaries were especially common in the Band-e Chaker area (Locality 2). In addition to the foregoing coral groups, members of the Agariciidae (e.g. *Leptoseris*; Plate 18/7, 9) are also relatively common.

While many of the common genera of the Makran and neighbouring regions (e.g. *Favia*, *Montastraea* and *Porites*) also occur in the early Miocene of the Mediterranean, the Makran fauna also contains numerous elements known only from eastern Tethys and the Indopacific margins at that time {e.g. *Anisocoenia*, *Echinophyllia* (Plate 18/10), *Fungophyllia*, *Indosmilia*, *Montipora*, *Oulophyllia*, *Pachyseris*, *Pattalo-*

phyllia, Progyrosmilia, Scalariogyra, Seriatopora and *Symphyllia*). At species level there appears to be virtually no faunal overlap at all with the Mediterranean, though confirmation of this is required through the necessary taxonomic revision. In Table 5, the only clear example of a species known previously from the Mediterranean Miocene is *Cyphastrea turonensis*.

4.2.2 Palaeoecological significance

As mentioned already, most of the corals that occur within the Miocene limestones of the Makran are forms whose living counterparts or congeners are symbiotic with algae (i.e. zooxanthellate), and reef-associated (Table 5, final column). Moreover, of the very few Makran genera that are extinct, some like *Cyathoseris* have colonial morphologies which are unique to living zooxanthellates, and by analogy, were presumably also symbiotic. The predominance of apparently zooxanthellate corals implies that most of the Makran coral fauna dwelt within photic zone depths. Most modern zooxanthellate species actually occur in depths less than c.50 m, but they may occur down to c. 130 m (Rosen 1977, Fricke & Meischner 1985, Fricke & Schuhmacher 1983). Zooxanthellate corals from greater depths than this are known only from dredging and may have been transported into deeper water.

If the Makran coral fauna is compared with modern temperature patterns of generic richness of zooxanthellate corals in the Indopacific (Rosen 1984: see his Figure 11.3), it would indicate a mean minimum sea surface palaeotemperature of at least 18°C. However, it may not be valid to make direct extrapolations of palaeotemperatures in this way because the diversity of the global pool of corals (like that of other organisms) appears to have fluctuated through geological time. The global total at any single time obviously places an absolute numerical limit on what can be realized in any one region at that time (Rosen 1977, Perrin et al. in the press). In the early Miocene, coral global diversity was lower than today but the reef belt was wider (see below).

Further implications for water depth, illumination and energy of water movement are provided by the particular composition of the Makran coral faunas. As already mentioned, the abundance of poritids and faviids (e.g. Plate 18/3-4, 11-12) suggests slightly deeper (5-20 m or more), or otherwise calmer or more turbid conditions, by analogy with ecological assemblages of corals on modern reefs (Figure 10; and see also Rosen 1975, 1981, Geister 1977, Done 1983, Graus & Macintyre 1989). Agariciids like *Leptoseris* are also a common, if less conspicuous constituent of this kind of environment, and they occur in the deepest, least well illuminated parts of modern reefs (Figure 10), where they may be important down to c. 130 m (Fricke & Schuhmacher 1983). In parts of the Indopacific, these particular agariciids are accompanied in the deeper reef environment by pectiniids (Wells 1954, Barnes et al.1971, Faure 1977, Kühlmann 1983). In the Caribbean, *Scolymia* {Recent forms of which are now regarded as a senior synonym of *Parascolymia* (Veron & Pichon 1980) } also occurs in deeper water down to c.80m (Goreau & Wells 1967, Kühlmann 1983). It is interesting therefore that *Parascolymia* (Plate 18/2), *Leptoseris* (Plate 18/7,9), and the pectiniid genera *Echinophyllia* (Plate 18/10) and *Fungophyllia* occur in the Makran faunas. They were recorded most abundantly from localities within Sheet 7543 of the Tahruie Quadrangle (Figure 1 and Table 7). This sheet includes Dar Pahn (Locality 6) and the Band-e Chaker area (Locality 2). The occurrence of these corals suggests that at least two distinct palaeoecological suites may be present in some places, with dominant poritids and faviids representing shallower depths (but not necessarily exclusive to them), and the *Leptoseris-Parascolymia*-pectiniid fauna representing deeper environments. The two suites can be expected to occur in different parts of a reef slope if there is good in situ preservation of reefs and corals, or otherwise they might occur as distinct depth facies at different places. This should be investigated by future studies in the region.

In contrast, it is notable that none of the modern coral assemblages associated with rougher and/or shallower water today is present in the Makran collections, notably *Acropora*-assemblages (and see also the other higher energy assemblages in Figure 10). Although *Acropora* occurs in the Makran, there is no evidence so far of it occurring in extensive stands such as those that exist today on modern reefs of both the Caribbean and the Indopacific. Four possible explanations for the absence of higher energy coral assemblages in the Makran are:

1) preservational: the appropriate palaeoenvironments were not preserved
2) sampling: the appropriate palaeoenvironments were either not visited or were not sampled (or both)
3) regional palaeoenvironmental: the range of palaeoenvironmental conditions for coral facies in the Makran did not favour higher energy assemblages, i.e. Makran coral facies reflect a true pattern of restriction to calmer, deeper or more turbid conditions by extrapolation from their modern counterparts.
4) global: that the kinds of higher energy coral assemblages found today on reefs did not exist in the early Miocene.

It is not possible to eliminate either (1) or (2). However, proximity of clastics to the coral limestones (which often occur within clastic sequences) suggests that high run-off, hence high regional turbidity and nutrient flux, might also have been important and hence lends support to (3). High nutrient levels can inhibit *Acropora* (Acevedo et al. 1989). Palaeogeographically (see below) the Makran coral localities lay within a relatively narrow 'proto-Persian Gulf', and close to a tectonically active shoreline. Relative to modern oceanic reefs and atolls, conditions in a such a gulf would have been sheltered and subjected to high sedimentation rates and run-off. The Makran coral pattern also seems to occur elsewhere in Iran, since the faunas of Kühn (1933) and Sjerp et al. (1969) from the Saidabad (= Sirjan) and Chahar Gonbad area are very similar in composition and setting to the Makran fauna. Perhaps similar palaeoenvironmental conditions prevailed at these localities too, since these Miocene coral localities occur in the same 'proto-Persian

Table 8. Comparison of generic diversity of zooxanthellate corals of the Makran in the Early Miocene with diversity of living zooxanthellate corals in the same region (Gulf of Oman), together with three other regions and their respective latitudes / palaeolatitudes. For this comparison, all the taxa in Table 5 except those marked AZ are taken to be zooxanthellate (see notes for that table). The data are consistent with a wider belt of tropical climate in the Early Miocene than today. (Note that independently of other factors, the 'area effect' should lead to larger areas like the western Mediterranean and Indonesia having more taxa than smaller areas like the Makran or Northland.)

		WESTERN MEDITERR-ANEAN	MAKRAN (early Miocene)/ GULF OF OMAN (Recent)	INDONESIA	NORTHLAND NORTH ISLAND NEW ZEALAND
RECENT	Number of zooxanthellate genera	**0**[1]	**34**[2]	**70+**[1]	**2**[3]
	latitude	30°-45°N	23°-26°N	5°-10°N	35°N
EARLY MIOCENE	Number of zoo-xanthellate-like genera	**44**[4]	**40**[5]	**c.50**[6]	**17**[7]
	palaeolatitude	30°-50°N [8]	c.25°N [8]	5°N-5°S [9]	c.42°S [9]

[1] Rosen (1984, 1988); Veron (1985)

[2] Sheppard & Salm (1988) for Gulf of Oman (i.e. Musandam and Capital Area of Oman). Number of zooxanthellate species is 62. No published data for Makran coast.

[3] Veron (1985); but these 2 genera are known only from the most northern point (North Cape).

[4] Rosen (1988) after Chevalier (1962) and S.H. Frost (pers. comm.).

[5] This paper: 38 genera in Burdigalian with 3 further genera from Aquitanian only = total of 41 from early Miocene, but one of these is probably non-zooxanthellate, leaving 40 in all. Similarly, number of probably zooxanthellate species is 91.

[6] Rosen (unpublished compilation from numerous sources, with partly revised names and stratigraphy).

[7] Hayward (1977, p.109).

[8] Adams (1981, fig. 14.6A) for Aquitanian to early Burdigalian.

[9] Adams et al. (1990, fig.7) after Sclater et al. (1985) for 16 Ma (i.e. approx. latest Burdigalian or earliest Langhian).

Gulf, and close to its tectonically active shoreline. Many of the living coral assemblages of the geographically similar settings of the modern Red Sea and Gulf regions are also dominated by poritids and faviids (Sheppard et al. 1992) though apart from the Gulf of Oman, neither region is tectonically active in the same way as the Makran was in the Miocene. The main problem with these regional arguments, however, is that they are based on direct extrapolation from the ecology of living coral assemblages. It is therefore still necessary to consider the alternative possibility that global factors (4, above) were important (additionally, or instead) and these are therefore considered in a later section (4.2.4).

4.2.3 Ecological palaeobiogeography: diversity patterns

By comparison with the local diversities of many modern reef regions, Makran coral diversity is not especially high. The total of 41 genera (38 in the Burdigalian) is slightly more than half that found in the richest coral regions today {e.g. 70 genera or more in Indo-West Pacific regions like the Great Barrier Reef, Indonesia, etc. (Table 8)}. However, the total number of genera so far recorded for the global early Miocene (90) is also rather lower than the Recent global total (111) (Rosen 1988). On the other hand, further collecting by a specialist would probably add to the Makran total.

The Makran total should also be seen in its contemporaneous context. The Miocene sequences of the Makran were laid down on the northern margin of the Miocene Gulf of Oman where the palaeolatitude was c. 25°N (Adams 1981). For modern corals, this more or less corresponds to the latitudinal limits of most zooxanthellate coral communities {Veron (1993); and see fig. 11.4 in Rosen (1984)}. Coral areas like those of Bermuda (32.5°N) (Thomas & Logan 1992) and Honshu (35°N) (Veron 1992) represent extreme latitudinal outposts. The region of highest coral diversity in the early Miocene was equatorial (Indonesia) and this corresponds to the present day pattern where the Indo-West Pacific region is also the richest (Table 8). Modern coral diversity generally decreases from this region with increasing latitude, so the diversity of the Makran coral fauna is probably due, at least in part, to a similar latitudinal gradient in the Miocene, presumably reflecting similar kinds of climatic factors as those that influence coral distribution today (Rosen 1984).

However, the latitudinal limit of reefs and zooxanthellate corals was wider during the Lower Miocene than today (see Section 3.1.6), and cross-latitude taxonomic diversity gradients of warm-water organisms might therefore have also been less steep at this time. This is supported by the data in Table 8 which shows that the generic diversity in the northern Arabian Sea (i.e. Gulf of Oman) today, is now less than it was in the corresponding region (Makran) during the Burdigalian. The same is true of species numbers. This is notwithstanding similarity of latitude, probable incompleteness of fossil collecting, as well as global incompleteness of the fossil record. Moreover, for Indonesia, the pattern is the reverse, with a higher modern total.

4.2.4 Evolutionary palaeoecology

The possibility that global factors may explain some of main features of the Makran coral assemblages has already been mentioned, and is now discussed further. If regional palaeoenvironmental factors were the only reason for the dominance of poritids and faviids in the Makran, one might expect to find coral faunas comparable with modern higher energy assemblages in other Early Miocene regions elsewhere. A preliminary review however, reveals nothing really like them. For instance, our own field and specimen observations of Early to Mid-Miocene coral formations at La Nerthe (southeastern France), Guam, southern Papua New Guinea, and the Hurghada area of the Gulf of Suez region of Egypt {see also JAMES et al. (1988), PURSER et al. (in the press)} have no large *Acropora* and *Pocillopora* assemblages like modern ones. Where *Acropora* does occur (e.g. La Nerthe), it does so in isolated colonies or at most, modest thickets a few metres across. The same is apparently true of Cyprus (FOLLOWS 1992). For the Caribbean, although FROST (1977a) states that *Acropora* is 'abundant' in Neogene formations, it is clearly not of sufficient ecological abundance for him to cite it as a conspicuous member of the main ecological assemblages of corals (FROST 1977a, b). This is borne out, for example, by the particular details of the Anguilla Miocene (BUDD et al., 1989).

Although this is obviously not a comprehensive survey, there does appear to be a world-wide dearth of *Acropora*-dominated assemblages in the early Miocene, and also of the other higher energy reef facies comparable with modern ones (Fig. 10). As with the Makran, and the Iranian Miocene coral localities generally, this could still be due entirely to observational or preservational gaps, especially as few if any preserved early Miocene reefs, whose coral faunas have been studied, are associated with higher energy kinds of settings like open oceanic platforms.

An alternative hypothesis however, is that the apparent global absence of *Acropora* assemblages is a real pattern, indicating a major global change in coral ecology some time between the end of the early Miocene and the present. This would not be surprising, given the time lapse between then and now (ca.15Ma), but it is interesting that the assemblages that are associated with higher energy today, have emerged ***as additions*** to, not replacements of, the older poritid and faviid assemblages. Major extinctions or turnovers of the global coral fauna do not appear to have occurred - at least, not to such a marked taxonomic degree that it affected the gross ecological patterns. Perhaps Miocene reefs did not aggrade to the sea-surface as they do today, though this would more likely be a consequence of ecological conditions in the Miocene rather than a cause of *Acropora*'s absence. GEISTER (1984) has drawn attention to fundamental differences between Quaternary (including modern) reefs and pre-Quaternary reefs, using this to warn against making simple uniformitarian comparisons. The Miocene pattern, though only tentative here, supports Geister's contention. Clearly, a more thorough investigation of the changing patterns in coral ecology through the Neogene to present is needed. This should also include studies of the coralline algae, especially the kinds that construct algal ridges, these being associated with highest wave energy conditions on reefs (Figure 10; see also BOSENCE 1983, PERRIN et al., 1994 in the press).

What might have explained such an ecological change in major reef assemblages? Two possibilities to consider are that these changes have taken place (1) even though global conditions have remained much the same since the early Miocene, or (2) as a direct response to global change. If the global spectrum of environmental factors has remained broadly similar from the Miocene to the present, and higher energy conditions did exist in potential coral areas, what corals (or other organisms), if any, filled this range of conditions? FROST (1977b) suggests that *Stylophora* assemblages occupied these environments, and the same may be true for the early Miocene at Abu Sha'ar in the Gulf of Suez region of Egypt (personal communication: Noel James; personal observation: B.R.R.). Otherwise, perhaps the hydrodynamic range of poritids and faviids was greater in the early Miocene, and these corals used to occur in both low and high energy conditions. If so, they might have become confined to lower energy environments when the modern higher energy corals like *Acropora* began to radiate taxonomically and ecologically (in the late Miocene?), though this is not to imply a literally competitive explanation.

Acropora appears to be far more diverse today than during the Miocene, so another possibility is that while high energy conditions may have existed during the Early Miocene, corals were generally absent from such environments. This ecological vacuum was then later filled as a result of the taxonomic radiation of *Acropora* and other taxa now found in higher energy conditions (Fig. 10). This model would further imply that these ecological changes in coral faunas resulted from evolutionary events in *Acropora* which took place despite the relevant environmental conditions remaining relatively constant.

On the other hand, global conditions have obviously not remained the same since the early Miocene, and it would be reasonable to look for global environmental causes in the emergence of present day ecological patterns of corals. The reef belt was wider in the early Miocene than now (see above) and there has been onset, or at least greater intensification, of glaciation. The emergence of *Acropora* assemblages could represent a combined evolutionary and ecological response to such changes. It is unlikely however that *Acropora* assemblages resulted from global increase in wave energy, or from global decrease in turbidity, sedimentation or nutrients, even in combination. Such physical factors would not have changed in such a simple, gross, global manner as to affect most reefs, uniformly, everywhere. More conceivably, temperature conditions (i.e. global cooling, which is well documented for the later Cainozoic) might have acted in this way, but it is difficult to see how this would have caused present day coral assemblage patterns: *Acropora* today seems to be less tolerant of low temperatures than *Porites* (VERON & MINCHIN, 1992) though the real differences seem to be between particular species of these genera, rather than the genera themselves. *A. hyacinthus* for example is less tolerant of cold than other forms of *Acropora*. Far more likely, is that all these various physical factors have acted in combination, perhaps driven by overall climatic change. GEISTER (1984) has suggested that the onset of major glaciation, with its frequent, large-scale and abrupt sea-level changes, was critical to major reef changes in the late Cainozoic.

There are also broader evolutionary implications. Poritids and their relatives the actinacids, together with faviids and their immediate relatives, actually dominate most reef coral facies throughout much of the Tertiary until the late Cainozoic (a review of this is not possible here), when *Acropora* assemblages joined them. Yet *Acropora* appeared in the Eocene (WELLS, 1956). It is as if the essential character of coral communities remained static for most of the Cainozoic notwithstanding background taxonomic turnover (and perhaps even some macroevolutionary changes and extinctions during this time). Hence background evolution, in zooxanthellate corals at least, proceeds without necessarily any obvious concomitant ecological evolution. Moreover, when noticeable ecological change does eventually take place, it does not necessarily coincide with macroevolutionary events. In the case of the Indopacific, where *Acropora* is one of the most speciose and abundant corals on modern reefs {more than 150 species (Veron, pers. comm.)}, its ecological emergence seems to be broadly related to a substantial diversification of the genus, but this is not so in the Atlantic region where the total number of Neogene-Recent species is only 5 (JOHNSON et al., in the press). Hence whatever global factors might have driven the ecological changes, they did not necessarily drive diversification.

Finally, a distinct ecological phenomenon of the early Miocene of Makran should be mentioned, that of the relative abundance and diversity of large cylindrical solitary corals (e.g. *Parascolymia*; Plate 18/2). This is typical of other regions at this time, too, and has no obvious parallel on modern reefs. Indeed such corals are a common feature of the fossil coral record in general. Excluding the abundant solitary fungiids of the present Indopacific (which are large but discoidal), large cylindrical solitaries, though present on and around modern reefs, now appear to be relatively insignificant when compared with the earlier Cainozoic. The only living genera of this kind are the mussids *Scolymia* and *cynariina* (see LOGAN 1988, VERON & PICHON 1980). As already mentioned, in the Atlantic region at least, *Scolymia* is more common in deeper and more shaded reefal habitats. There may therefore also be global and evolutionary factors behind the late Cainozoic decline of large cylidrical solitary corals.

In conclusion, the Makran fauna suggests calmer, deeper or more turbid conditions when compared directly with present day coral assemblages, but this simple uniformitarian interpretation becomes questionable when the Makran corals are seen in a more global and longer-term context. The relatively recent emergence of *Acropora*-dominated and other higher energy reefs assemblages supports Geister's caution against bland extrapolation of Recent coral ecology to pre-Quaternary reefs and corals and the need for an independent means of interpreting pre-Quaternary reefs such as that developed by PERRIN et al. (in the press). This will make it possible to assess whether *Acropora*-dominated assemblages (etc.) displaced the older poritid and faviid assemblages from higher energy environments, or whether they developed in apposition to them in previously unoccupied environments. This change must also have altered the whole ecological, sedimentological and structural nature of coral reefs. *Acropora* is apparently critical, for example, to the capacity of Caribbean reefs to keep up or catch up with rising sea levels (NEUMANN & MACINTYRE, 1985).

4.3 Other fossils

The calcareous algae, have been examined and identified by Dr. G.F. Elliott at The Natural History Museum in London as *Lithophyllum*, *Lithothamnium* and ?*Corallina*. However, there has been a major revision of the systematics of these first two algae (inter alia) since Elliott did this work {see BRAGA et al. (1993) for a discussion and key to Cainozoic fossil forms}, but revision of the original Makran material is not possible here. The geological section in Table 4 gives examples of the lithologies in which these algae were found.

The gastropods and bivalves were described by Mr. C.P. Nuttall at The Natural History Museum in London. Gastropods are mainly *Conus* and *Oliva*, and the bivalves are pectinids (*Chlamys*, *Spondylus*) and *Ostrea*. The molluscan fauna is fully marine and would have lived in very shallow, sheltered, possibly intertidal water. All the mollusc genera are extant and live in association with tropical reefs. While the oysters and *Spondylus waylandi* indicate hard substrates (e.g. reef limestones), *Oliva* indicates the presence of a soft substrate (e.g. inter-reef or lagoonal sediments).

There was also a single shark's tooth found in the younger limestones at Vaziri (Locality 1).

5 HISTORICAL PALAEOBIOGEOGRAPHY AND PALAEOGEOGRAPHY

5.1 Global context of Makran faunas

As is well known, much of the modern tropical benthos occurs in two faunal realms, the Atlantic (including the Caribbean) and the Indopacific. For the corals, the realms share some genera, but no species (ROSEN 1988). The widely accepted geological cause of this pattern, particularly as it applies to corals, is as follows. During much of the Palaeogene and before, these oceanic regions were connected by tropical or subtropical seaways (including Tethys) and, in theory at least, their coral faunas were in biogeographical continuity throughout these regions. This pattern was broken up during the later Tertiary by the development of two cross-latitude barriers that extended from the tropics into latitudes unfavourable to zooxanthellate corals resulting in the modern two-realm pattern. These barriers were: (1) an eastern Pacific marine barrier that is believed to have existed in the Miocene and earlier but which was later superseded in the Pliocene by an American land barrier resulting from the uplift of the Isthmus of Panamà (Newell 1971, Rosen & SmiTh 1988, Budd 1989); and (2) an African-Asian land barrier that severed Tethys, resulting from emergence of land in what is now the Middle East during late Oligocene to Miocene {reviewed briefly by Rosen (1984, 1988) and by Rosen & Smith(1988)}.

Of particular importance in the Middle East was 'uplift of that part of the old sea floor that lay across the Middle East' (Adams et al. 1983), in relation to the folding and uplift of the Zagros in the Iranian region. The early Miocene and near-Zagros setting of the Makran corals (and associated faunas) therefore gives them a special palaeobiogeographical interest with respect to the various hypotheses about the location and timing of Middle East emergence.

With the relevant geological history apparently well-established, faunal history is generally assimilated into it or simply regarded as not incompatible with it. Rigorous testing of faunal patterns against geological history has been relatively rare. However, various groups of organisms have recently been studied with a view to establishing for the Middle East region (1) an independently derived date for the biogeographical divergence of marine faunas and complementary convergence of terrestrial faunas; and (2) a palaeogeographical history of the barrier based on facies evidence (i.e. faunas and floras in conjunction with sedimentological evidence). The value of both approaches is that it can supplement geotectonic history of events like the Zagros closure, by providing further constraints on palaeogeographical history. Geotectonic studies identify areas of oceanic and continental crust and their histories, but on their own they cannot directly reconstruct history of land and sea areas. On the other hand, while biogeogeographical patterns are often assumed to be able to assist with this, there is as yet no rigorous basis for using the timing of biogeographical events like divergence for deriving geotectonic and sedimentary history (Rosen 1992). Even on the simplest considerations, such biogeographical changes should lag behind geological events, though by unknown amounts.

5.2 Historical patterns of some Middle East faunas

Divergence of coral faunas and other marine groups is generally regarded as Miocene (e.g. Wells 1956), though coral authors differ on the precise timing of this within the Miocene. Adams et al. (1983: see their Figs. 5-7), Whybrow(1984) and Robba (1986) have all found that biogeographical divergence of marine faunas in the Middle East region occurred in the Burdigalian, becoming complete in the mid-Burdigalian. Adams et al. found that the divergence actually commenced somewhat earlier (Aquitanian). These authors based their conclusions mainly on larger benthonic foraminifera, molluscs and echinoids. Complementary convergence of terrestrial groups like mammals (Adams et al. 1983, Whybrow 1984) is consistent with the marine faunal history.

Rosen & Smith (1988) included the present Makran coral faunas in their biogeographical analysis of early Miocene reef corals and echinoids, and their patterns do not conflict with the conclusions of previous authors. They found that the faunas of the Makran and neighbouring western Pakistan, as well as those from further to the northwest in Iran {i.e. Saidabad (= Sirjan) (Kühn 1933) and Chahar Gonbad (29°34'N, 56°1'E) in the same area (Sjerp et al. 1969)}, were all more closely related in composition (i.e. not necessarily phylogenetically) to each other and to the contemporaneous faunas of western Pakistan and Indonesia, than they were to Mediterranean faunas. However, like Adams et al. (1983), Rosen and Smith also found that marine faunal differentiation commenced earlier than the Burdigalian, even though Middle Eastern Tethyan seaways were supposed to have been open at such times. This appears to be the consequence of earlier barriers, probably caused by intermittent conditions like evaporite deposition that were hostile to most of the marine benthos (see also Adams et al. 1983, Rögl & Steininger 1983, 1984).

5.3 Combined evidence from facies and faunas

Kühn (1933) is the only previous author who seems to have attempted a reasonably detailed relevant discussion of Middle East Miocene palaeogeography based on corals in particular, though he combined the faunal patterns with facies evidence. He argued that land had emerged by the Early Miocene (Burdigalian), more or less across the Zagros orogenic axis in what is now western central Iran, just north of Saidabad (= Sirjan), this being the district from which his coral fauna came. His fauna belongs to the same biogeographical assemblage as that later recorded by Sjerp et al. (1969) from Chahar Gonbad. Kühn observed that the nearest contemporaneous Mediterranean-type coral fauna known to him occurred about 700 km away to the northwest in the Upper Asmari Limestones of Asmari itself, and that between the two faunal regions, there was an area of apparent non-deposition. He therefore envisaged that the Saidabad coral limestone was laid down at the northern head of a narrow arm of the sea extending northwest from the Indian Ocean rather as the Persian Gulf does today (and referred to here as the 'proto-Persian Gulf'). His conclusions anticipate those of later authors mentioned above, though his paper has been largely overlooked.

Rögl & Steininger's (1983, 1984) reconstructions of barrier and seaway history, based on evidence from faunas and facies, also correspond broadly with those of Kühn and of Adams et al. for the Early Miocene. However, Rögl and Steininger also argued that the Middle East Tethyan seaways were not finally closed by fully terrestrial environments until the Late Miocene. In the Burdigalian, they show an apparently open seaway through Iran but this was occupied by evaporites and shoals. These presumably acted as barriers to most marine organisms whilst also being shallow enough to permit faunal exchanges between Asian and African mammals. Adams et al. rule out any fully marine Tethyan reconnection after the Burdigalian.

The palaeobiogeographical analysis of ADAMS et al. (1983) included foraminiferal faunas provided by one of us (G.J.H. McCall) that were collected from the Miocene limestones ('Vaziri Unit') discussed here, and they stated that Makran was 'amongst the two most northerly foraminiferal assemblages with an Indopacific aspect' within the whole region at that geological time (Aquitanian-Burdigalian) {see Foraminifera section above, and ADAMS et al. (1983: Locality 67 in their Figure 7)}. Their other northerly assemblage is in the basal Guri Limestone of the Mishan Formation {(Locality 65 in their Figure 7; after JAMES & WYND (1965)}. Presumably their locality 65 is the type section of the Guri Limestone 'just east of the salt plug on Kuh-e Gach', 29 km southeast of Lar {JAMES & WYND (1965): locality 16C1 on their Figure 2 and see also their pp. 2237-8) }. The Guri Limestone includes substantial reef developments but its corals do not appear to have been studied. The faunas from Kuh-e Gach and the Makran both occupied the 'proto-Persian Gulf', whereas the Qum Basin and the area of deposition of the Urmia Series in northwest Iran (which also contain coral faunas; see Table 6) were connected to the Mediterranean at this time.

ADAMS et al. (1983) were apparently unaware of the above Saidabad [= Sirjan] or nearby Chahar Gonbad faunas in their study. The limestones here are 'Oligocene-Early Miocene, but unequivocally Early Miocene at Kühn's original location, east of Sirjan', according to SJERP et al. (1969). They are therefore slightly older (at least in part) than the Makran corals and foraminifera discussed here. The Saidabad (= Sirjan) localities are today c.180 km north of the nearest occurrence of the Guri Limestone on Kuh-e Baz (c. 27°46'N, 52°58'E) {JAMES & WYND (1965): their Figure 7, the section shown in which is located in their Figure 1}, and about 240 km north-northeast of the Guri type locality on Kuh-e Gach. The Saidabad (= Sirjan) area would have to be placed 'inland' on the Early Miocene palaeogeographical reconstructions of ADAMS et al., implying that the northern margin of the 'proto-Persian Gulf' lay rather further north than they have indicated in their Figure 7. However, as the Saidabad area corals are slightly older than the Guri Limestone (i.e. on Kuh-e Gach), the most reasonable explanation is that the corals were probably deposited in the same gulf, but the sea subsequently had regressed southwestwards from the Saidabad (= Sirjan) area by the time of deposition of the Guri Limestones. (It continued to regress throughout the Cainozoic from the Eocene onwards, as the zone of tectonic covergence shifted southwards, and older shoreline areas were progressively uplifted.) However, the wide separation of the geographical positions at the present time of the Saidabad (= Sirjan) area and Kuh-e Baz suggests that there was probably a northward embayment in the 'proto-Persian Gulf' around Saidabad (= Sirjan), or else there is a palaeogeographical complication that is not yet understood.

It should also be mentioned that as the Guri Limestone continues along strike much further northwest from the type locality (JAMES & WYND 1965: see their Figure 3), but without additional faunal and sedimentological details, it is not safe to extend the 'proto-Persian Gulf' beyond this latter point {see also discussion by ADAMS et al. (1983: p. 289) about possible northwestward continuations of this Gulf}. It is clear that the present suggested limits of the gulf are those for which the evidence to date is reliable, but a more definitive palaeogeography requires further work in Iran.

5.4 Summary of palaeogeographical events

(1) Initial shoaling and uplift had commenced by Aquitanian times to the northwest of the Saidabad (= Sirjan) area, and disrupted Middle East seaways in this area. A narrow arm of the Indian Ocean (the 'proto-Persian Gulf') extended at least as far northwest as Saidabad. The Aquitanian coral limestones of the Makran were deposited in this gulf, but those found so far consist only of transported reefal material.

(2) By Burdigalian times, the northern shoreline of the 'proto-Persian Gulf' had regressed southwards from Saidabad (etc.), and lay close to the Kuh-e Baz area of the Guri Limestone, and to the Makran limestone area. The Burdigalian coral and reef formations of the Makran were laid down at different locations close to the tectonically active northeastern shore of this Gulf.

(3) The exact northwestern limit of the 'proto-Persian Gulf' in Burdigalian times still needs to be established, the most westerly point definitely established being the type locality of the Guri Limestone on Kuh-e Gach near Lar.

(4) The 'proto-Persian Gulf' was the northwesternmost limit of the Indopacific marine realm in this region at this time, and this is reflected by the faunal composition of numerous groups of organisms in the Middle East region, including the Makran corals and foraminifera.

(5) For the corals, like the foraminifera, it seems that marine faunal divergence between the Mediterranean and Indopacific commenced before final emergence of land, probably in response in unfavourable marine or semi-marine conditions developed in the connecting seaways during geotectonic closure of Zagros, i.e. not as a later response to the final, full emergence of land in the region.

6 CONCLUSIONS

The Miocene limestones of the Makran are of Aquitanian to Burdigalian age, as indicated by their age-diagnostic foraminifera, and were laid down within a concordant sequence in an accretionary prism related to the subduction of ocean floor of the Arabian plate northwards beneath the Iranian foreland of the Eurasian plate. The limestones are excellently exposed in numerous scattered outcrops throughout a region ca. 650 km across. They occur at various stratigraphical horizons within predominantly slope-to-shelf sequences of siliciclastics and, in some places, evaporites. These sequences represent flysch-like to neritic conditions. The Aquitanian limestones are relatively fine-grained and though they contain shallow water fossils, were deposited in deeper water (? as turbidites or by subaqueous flows), possibly on the slope. The Burdigalian limestones are much more widespread and consist largely of foraminifera-rich calcarenites, and of coarse limestones (rudstones, framestones and boundstones) rich in zooxanthellate corals and coralline algae indicating deposition within the photic zone and mostly probably less than c.100m. Facies intermediate between rudstones and framestones {cf. the 'loose frameworks' of Geister (1983)} are especially common, together with the calcarenites. The Burdigalian carbonate environment is interpreted as an intermittently developed and discontinous carbonate shelf with patch reefs and marine grass beds, perhaps localized on a 'fore-arc ridge', but the reefs mostly appear to have been locally and penecontemporaneously disturbed, eroded and reworked to varying degrees, prior to preservation. This, and the stratigraphic repetition of the limestones, probably reflects the prevailing tectonic instablility of the region, though the marked development of limestones in the Burdigalian in general is consistent with a global phase of warmer climatic conditions and a latitudinally wider reef belt. The concordant prism structure is indicated by conformable relationships between the shallow water deposits like the limestones, and their associated slope-to-shelf siliciclastics, as well as older abyssal deposits of true flysch (Eocene to earliest Miocene). This differs from the two previously published models of limestone deposition in accretionary prism settings where limestones and associated shelf deposits occur unconformably on deeper water clastics. The Makran is put forward here as a third (concordant) model.

The Makran coral collection (41 genera, 92 species) is the largest studied early Miocene collection between the Mediterranean and Indonesia, and is dominated by genera of poritid and faviid affinities. On modern reefs this fauna would represent conditions of slightly lower energy of water movement (or otherwise more turbid or calmer conditions) than is found at or near the surface of most exposed windward reefs. Pectiniids and agariciids also occur in the Makran, perhaps as a separate ecological assemblage, suggesting the additional presence of 'deep reef' conditions. However, direct uniformitarian comparison with modern reefs may be misleading because coral assemblages of Miocene (and many older Tertiary) reefs worldwide appear to be dominated by poritid and faviid corals. Although more comprehensive supporting data are needed, a tentative pattern of reef community evolution is that it remained static for much of the Cainozoic, notwithstanding background faunal turnover. A fundamental ecological change then appears to have affected reefs in the late Cainozoic, perhaps coincident with onset of more frequent and more pronounced glacio-eustasy. Coral assemblages found in higher energy conditions of modern reefs emerged at this time in both the Atlantic and Indopacific, notably *Acropora* assemblages. Whatever caused this change, it also appears to have coincided with a major species radiation in the genus, but caution is needed in connecting this directly to the ecological changes, since the species radiation was entirely Indopacific.

The Makran corals have special palaeobiogeographical interest because they represent a newly studied fauna located close to the areas of Miocene uplift that finally severed the Middle Eastern seaways of Tethys. They show an almost entirely Indopacific affinity, which, as with the benthonic foraminifera, began to emerge even before the final Zagros closure. The corals, reefs and associated marine faunas and floras were laid down in quite a high palaeolatitude (c. 25°N) in a northwesterly embayment of the Indian Ocean termed here the 'proto-Persian Gulf'. This included the Guri Limestone reefs to the west of the Makran and the slightly older coral limestones of the Sirjan area to the northwest. The exact northwesterly limits of the Indopacific beyond these areas during the early Miocene are still open to further investigation.

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