PETROLOGY AND DIAGENESIS OF THE LIMESTONES OF THE QOM FORMATION (OLIGO-MIOCENE), QOM REGION, CENTRAL IRAN

BY

TOURAN SOLTANZADEH IRANPANAH

B. Sc., M. Sc.

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ABSTRACT

The Qom Formation of north central Iran is Late Oligocene to Early Miocene in age. It is formed of alternations of limestones and marls with some intercalations of sandstones, shales and gypsum. It has been divided into nine members designated by the letters 'a' to 'f' in ascending order. The 'a', 'c_1', part of 'c_2', 'c_3' and 'f' Members comprise limestones. The formation is strongly folded, locally overturned and is exposed in a series of northwest to southeast trending rugged ridges and mountains. The petrology of the limestones has been studied in the vicinity of the city of Qom.

Petrographic study has shown that the limestones are mainly bioclastic and include skeletal packstones, with some wackestones, and a minor proportion of oolitic grainstones and platy limestones. The skeletal components of all the various limestone members are mainly fragments of the calcareous coralline algae, Lithothamnion and Lithophyllum, bryozoans, tests of foraminifera, mostly the larger benthonic varieties, together with echinoids, corals, pelecypods, gastropods, ostracods and calcareous green algae. This faunal and floral assemblage suggests that the Qom limestones were deposited in a warm shallow sea. Within this general environment, some subenvironments can be identified, ranging from intertidal, through shallow subtidal, to offshore shelf.

Rapid lateral and vertical changes of facies are characteristic. At one locality, the marls of the 'c_1' Member are replaced by limestones which form a distinct reef-like mound. The limestones interfinger laterally with the marls, especially towards the east, and gradually disappear. At the top of the succession in another locality, the limestones of the 'f' Member form a 'reef-like' body which interfingers with and changes to marls towards the east. There are also smaller irregular masses of the 'f' limestone, without obvious bedding, which sit on the top of the marls. Petrographic study of these various types of 'reef-like' mounds and masses revealed no

essential differences between them and the normal bedded limestones. Nowhere in any of the 'reefs' is there an obvious framework. They are all composed of skeletal debris and are comparable with some facies zones of the Tertiary reef complexes of Iraq (Henson, 1950), Louisiana (Forman and Schlanger, 1957) and Guam (Schlanger, 1964).

The limestones also carry sand and silt size terrigenous detritus in varying proportions; it appears to have been derived from nearby older Tertiary volcanic and continental outcrops.

Two generations of sparry calcite cement have been identified. Carbonate 'mud' matrices are usually highly recrystallized, and many of the skeletal grains have also been affected. The lowest and highest limestone members are partly dolomitised, and the dolomite has mainly replaced the matrix and ooliths, but to a lesser extent also the skeletal grains. In some samples there is evidence of late replacement of dolomite by calcite. Other diagenetic modifications include silicification, which has affected some skeletal fragments and also the matrix in certain samples. Celestite ($SrSO_4$) was encountered as a cement in a few thin sections. Common fracturing of skeletal grains and pressure welding were due to early compaction; stylolites and calcite-healed fractures appear to be late features.

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ABSTRACT

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CHAPTER 1

GENERAL INTRODUCTION

1.1 Purpose and Scope

This thesis is concerned with the petrology of the Oligocene-Miocene limestones of the Qom Formation in the Qom region of Iran. The research was undertaken in an attempt to extend understanding of the depositional environments of the limestones and to determine the nature, distribution, and sequence of the diagenetic processes. Marls are present in the succession, but these latter were not studied in detail in this project. Thus the descriptions of the marls, especially with regard to the fossil content, are based partly on field observations and partly on the paleontological and stratigraphical studies of former workers.

1.2 Area of Study

The area of study is centered on the city of Qom in north central Iran, approximately 148 kilometres south south-west of Tehran (Fig. 1). It covers an area of about 220 square kilometres in the central part of the Qom Basin.

1.3 History of the Qom Basin and Areal Distribution of the Qom Formation

The first indications of the initiation of the Qom Basin appeared in the Late Cretaceous, when epeirogenic movements that gradually raised the Alborz in the north and the Zagros in the southwest, outlined a roughly northwest-southeast basin in central Iran.

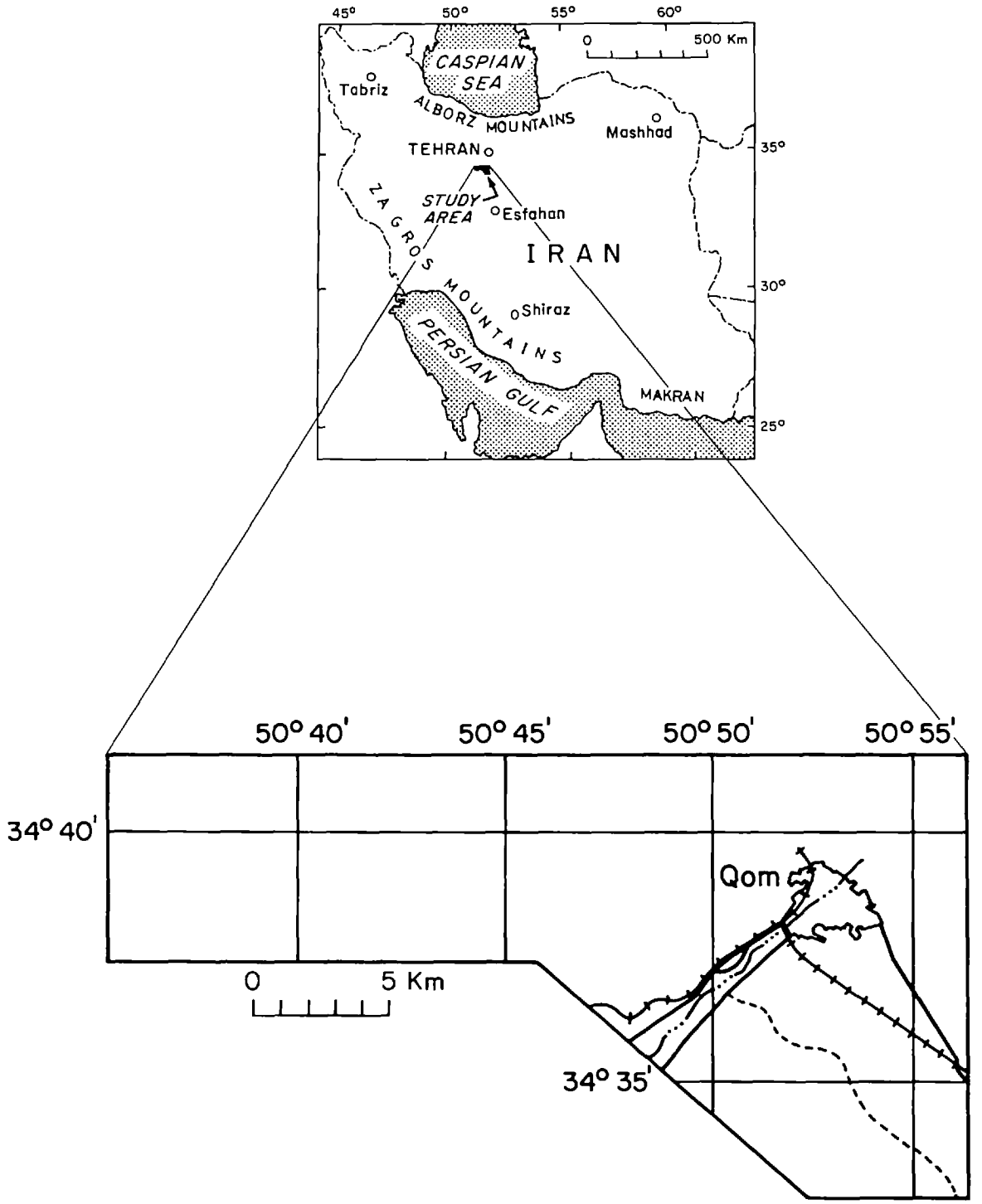


Figure 1. Location of the study area.

During the Eocene period extensive volcanic activity occurred and most of the Eocene rocks in Central Iran are volcanics with some sedimentary intercalations. The latter were deposited in shallow seas. Towards the close of the Eocene, marine sedimentation ceased and volcanic activity declined.

In the Early Oligocene following an episode of local folding, marine sedimentation recommenced across a pre-Oligocene land surface, the depressions on which were filled with red fine-grained clastics of the Lower Red Formation.

Towards the end of the Lower Oligocene, there were local orogenic movements and the sea invaded the Central Basin of Iran from the southwest; this led to deposition of the Qom Formation.

The Qom Formation covers a large part of central Iran. In the north it reaches close to Tehran, it extends westward to longitude 49° and continues into northwest Iran. Eastward it reaches close to eastern limit of the Great Salt Desert and southward it reaches the Esfahan-Saidabad depression (Gansser, 1955; Mostofi et al., 1957).

The areal distribution of the Qom Formation does not necessarily imply deposition in a single large basin. Lateral and vertical facies variations suggest that a number of smaller interconnected basins existed during Oligocene-Miocene times (Gansser, 1955). The Qom Basin was a larger and deeper basin than the others, and it received the thickest deposits. The regional distribution of the formation is shown on the isopach map (Fig. 2).

1.4 Regional Geologic Setting

The rocks exposed in the area of study range in age from Middle Oligocene to Recent, but the Qom Formation itself is Late Oligocene

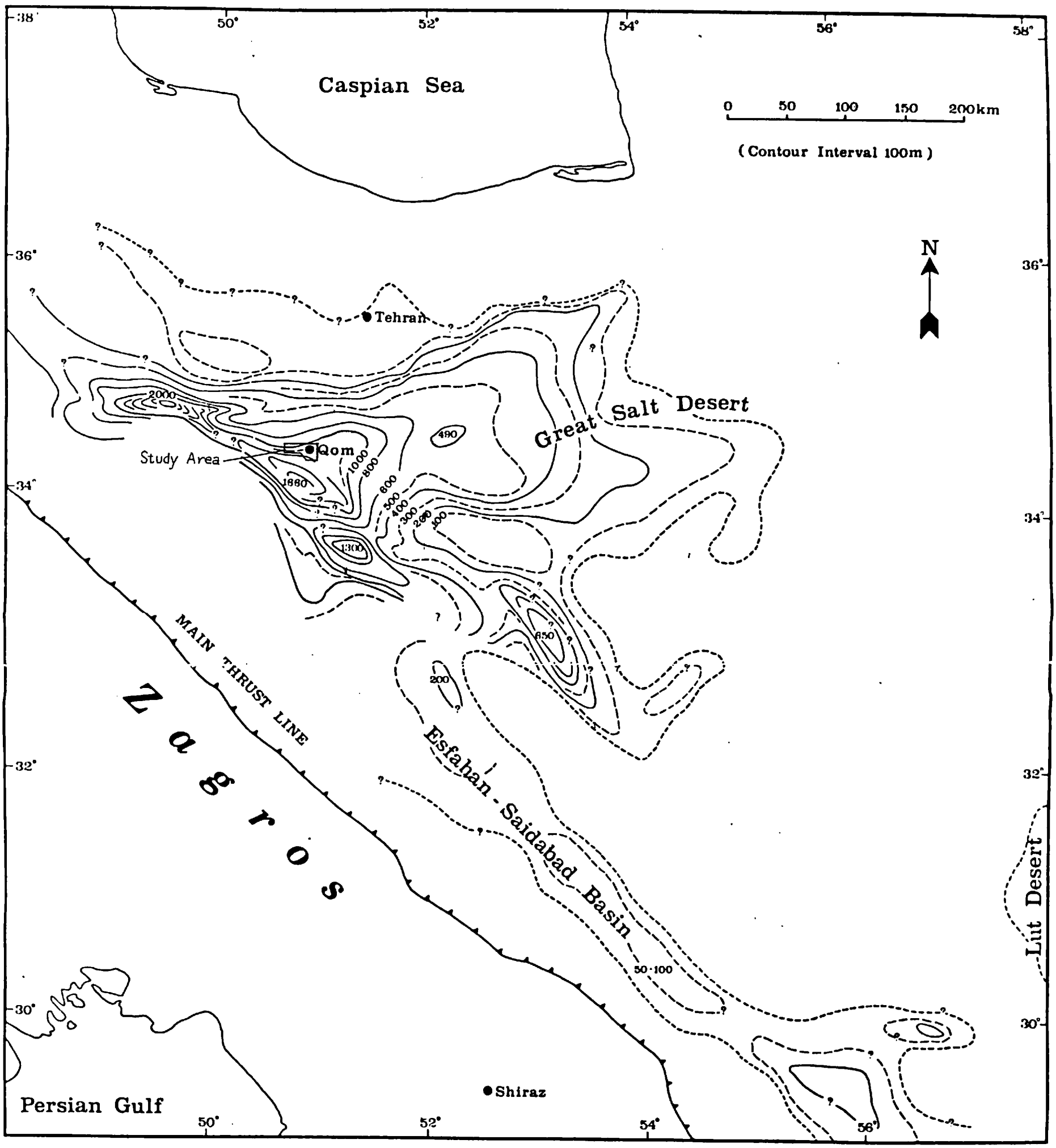


Figure 2 ISOPACH MAP OF THE QOM FORMATION

-TAKEN FROM GANSSER 1955-

to Early Miocene. It is formed of alternations of marls and limestones with intercalations of sandstone, shale and gypsum. It is strongly folded, locally overturned, and stands as a system of northwest to southeast trending rugged ridges and mountains. It overlies the Lower Red Formation of Middle Oligocene age and is overlain by the Upper Red Formation of Middle and Late Miocene age.

The Qom Formation along with the underlying Lower Red Formation and overlying Upper Red Formation were folded, after deposition of the latter, by the Miocene-Pliocene phase of the Late Alpine Orogeny. All the sediments older than Pleistocene were folded again during the Pliocene to Recent phase.

The major structures of the area are large plunging anticlines and synclines some of which are overturned, and there are major faults. In general, the principal folds have east-west trends in the northwestern parts of the area, but in the southeast the trend of the folds changes to west-northwest. The faults show two trends, some are longitudinal and run parallel to the folds, others are transverse, i. e. perpendicular to the strike of the beds (geological map of the area, enclosure 1).

1.5 Previous Work

From the early 1900's geologists have collected and studied fossils from Central Iran, including the Qom region, and commented on the geology. The reader is referred to De Morgan (1905) for details of the very early work. A notable general work was that of De Boeck et al. (1929).

Furon and Marie (1939) described the microfauna, mainly foraminifera, which they collected from the marls, and assigned an Aquitanian age to them.

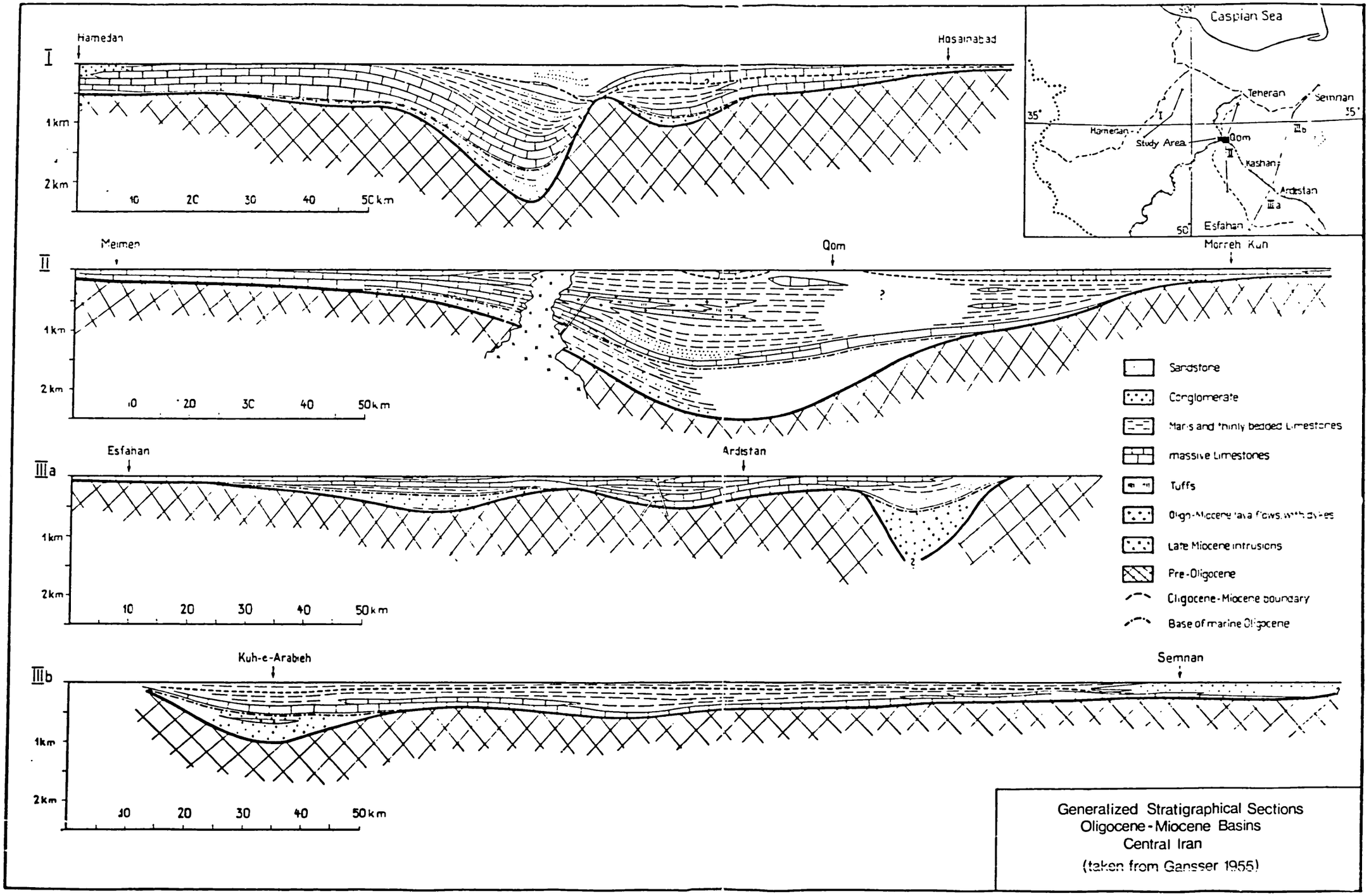
Furon (1941) presented a comprehensive study of the geology of the Iranian plateau which also covered the Qom region.

In the search for oil, the geology of various parts of Central Iran was studied by geologists of the former Iran Oil Company during the years 1950-1955 and subsequently by the National Iranian Oil Company. The regional sedimentary framework of the basins of Central Iran was first established by Gansser (1955, p. 279). He applied the name "Oligo-Miocene Marine Formation" to the deposits, and recognized six stratigraphical subdivisions. The subdivisions from base to top were:

1. A constant basal limestone: Middle-Upper Oligocene.
2. A sandy marl section: Middle-Upper Oligocene.
3. A middle marl-limestone section: Upper Oligocene.
4. A constant gypsum/anhydrite band.
5. A green marl section: Upper Oligocene to Lower Miocene.
6. A top limestone: Lower Miocene.

Three generalized stratigraphical sections, compiled by Huber, through the basins of Central Iran which show the changes of thickness and facies of the formation, also appeared in Gansser's paper (Fig. 3).

In connection with the former investigation Furrer and Soder (1955) carried out a detailed study of the paleontology and stratigraphy of the formation in the Qom region, and on the basis of large and small foraminifera made age determination and correlated the various outcrops. These authors gave six stratigraphical measured sections of the formation in a mountain range south of Qom. The stratigraphic sections show subdivisions of the formation, but no formal names were attached to the individual units. Instead, the authors designated the subdivisions by the letters 'a' to 'f' in ascending order. They also correlated the formation with the Asmari Limestone of



Generalized Stratigraphical Sections
Oligocene-Miocene Basins
Central Iran
(taken from Gansser 1955)

Figure 3

southwest Iran on the basis of the foraminifera.

Mostofi and Frei (1957), in a paper dealing with the ''Main sedimentary basins of Iran and their oil possibilities'', gave the geographical extent and thicknesses of the formation in various parts of the complex of basins in Central Iran and identified possible reservoir and source rocks. They also gave a brief account of the tectonics of the basins.

Furon and Balavoine (1959) identified bryozoans of Aquitanian age in the formation in the Qom region.

The name 'Qom Formation' was first used in a publication by Abai e et al. (1963). They did this because the former name 'The Oligo-Miocene Marine Formation' was not related to a type locality, and the sediments were not marine throughout. These authors also applied the term ' member' to the subdivisions of the formation. They divided it into nine members on the basis of the dominant lithologic characters found in the Alborz and Sarajeh oil and gas fields which lie within the Qom Basin. They kept the same scheme of identifying the members by the letters 'a' to 'e', but subdivided the 'c' Member into four distinct lithologic units and identified them as Members c_1, c_2, c_3 and c_4 in ascending order. They considered that the 'f' subdivision of former authors was a facies variation of the 'e' Member. Further, the evaporite unit of the base of the Upper Red Formation was considered as the topmost member of the Qom Formation.

Bozorgnia (1966) studied the stratigraphy of the Qom Formation in various parts of the central basins of Iran and designed a diagram showing some typical sections. He studied the principal foraminifera of each member and distinguished the subdivisions by their lithologies and to some extent by their microfaunal content.

He also gave an intercontinental correlation chart of the foraminifera. Detailed identification of the foraminifera used in the age determination of the stratigraphic subdivisions of the Qom Formation can be found in his report.

Vatan during his tenure of office in the Technical Faculty of the University of Tehran chose the Qom region as the site of a geologic field training camp, and prepared a geologic guide book of the Qom region for his students (1966 unpublished).

Nowgole-Sadat (1972) did his M.Sc. research on the stratigraphy and tectonics of the Qom region and mapped the area in a scale of 1/50000 (unpublished). He recommended some changes in the definitions of the members in order to make them more easily mappable.

Nabavi (1976) pointed out that the Qom Formation is best exposed in the Do-Chah and Do-Baradar areas. He further mentioned that the various subdivisions of the Qom Formation in Qom region are not applicable in all parts of the central basins in Iran. He suggested the name Qom Formation should be replaced by one of the above geographical names. However, the term Qom Formation has appeared in the Stratigraphic Lexicon of Iran (Stoecklin, 1971) and is widely accepted by Iranian geologists and for these reasons it is used in this thesis.

Although considerable effort has been directed toward the study of the stratigraphy and paleontology of the Qom Formation in the Qom Basin and elsewhere in Iran, no detailed petrographic work had been attempted before this present study.

In the past the limestones of the Qom Formation were described in general terms, as shallow marine. The lithofacies studies presented

in this thesis confirmed this generalization, but have allowed many subenvironments to be identified. These range from supratidal through intertidal and shallow subtidal environments to offshore shelf probably not deeper than 100 metres. The inferences made about the environments of deposition are strengthened by comparison of the Qom limestones with modern areas of carbonate deposition, especially the Great Bahama Bank and the Persian Gulf. Furthermore, in the course of the petrographic studies it was noticed that there are close resemblances between the limestones of the Qom Formation and those of the Tertiary reef complexes of Iraq which were described and illustrated by Henson (1950). Schlanger and Forman (1957) compared the limestones of the Louisiana and Guam with those of Iraq and found close textural similarities. Schlanger (1964), in his petrographic studies of the limestones of Guam, drew attention to similarities between those limestones and those of the reef complexes of Iraq and came to the conclusion that "Lower Tertiary limestones throughout much of the world show similar microfacies attributes". The present study supports his suggestion.

1.6 Regional Stratigraphy

The ages of the rocks exposed in the area of study range from Middle Oligocene to Recent. Table 1 summarizes the ages and lithologies of the various formations exposed in the Qom area.

Lower Red Formation

The Lower Red Formation comprises red and greenish shales; siltstones, claystones, very fine grained reddish brown sandstones, and gypsiferous marls with abundant layers and lenses of gypsum. The maximum thickness of the Lower Red Formation is approximately 1000 metres (Furrer and Soder op. cit.) and the whole of it is believed to have been deposited in a lagoonal and sub-

TABLE I

Stratigraphic chart of the study area

Formation	Lithology	Age
Unnamed	terraces, alluvium and alluvial fans	Pleistocene to Recent
Equivalent to Bakhtiari Formation	poorly indurated polymictic congromerates	Pliocene
Upper Red Formation	conglomerates, calcareous sandstones, siltstones, gypsiferous marls, and evaporites	Middle-Late Miocene
Qom Formation	alternations of marls and limestones with intercalations of sandstones, shales and gypsum	Late Oligocene Early Miocene
Lower Red Formation	shales, siltstones, claystones, fine grained sandstones, gypsiferous marls, evaporates	Middle Oligocene

continental environment. In the sandstones and siltstones, sedimentary structures such as ripple marks, rill marks and salt-casts are abundantly present. No fossils other than a few ostracods and broken pelecypod valves have been reported.

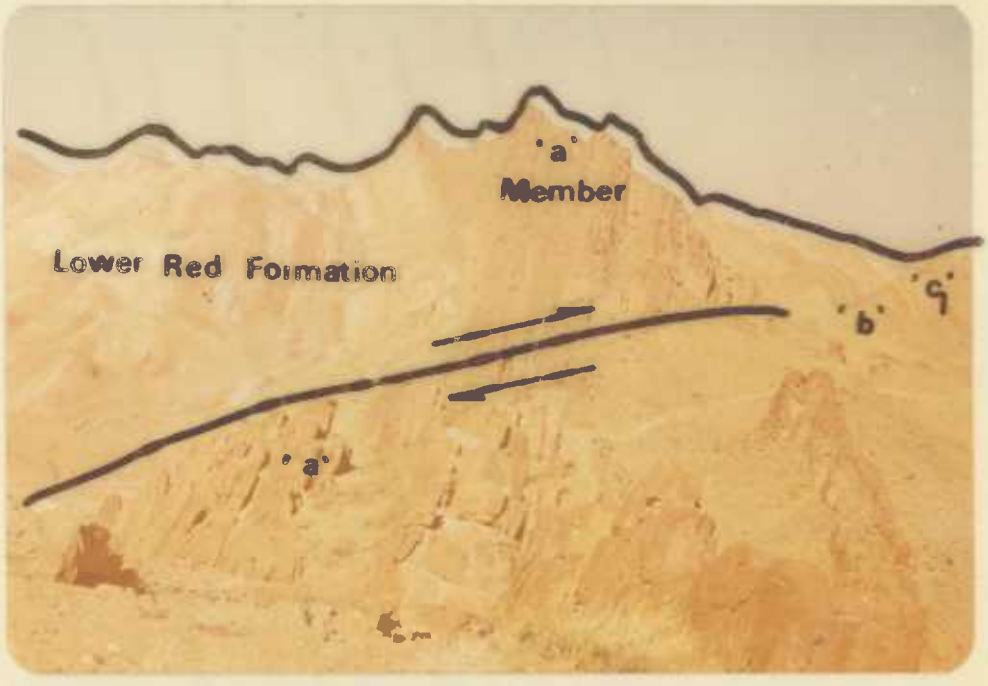
An Early Oligocene age was inferred by Furrer and Soder (op. cit.) on the basis of the stratigraphic position of the formation between the Upper Eocene volcanics and the basal beds of the Qom Formation. The latter were dated in Central Iran as Middle and Late Oligocene on the basis of the assemblage of foraminifera (Furrer and Soder 1955, Bozorgnia 1966). However, Abaie et al. (op. cit.) assigned an Early-Middle Oligocene age to the formation in the Qom Basin.

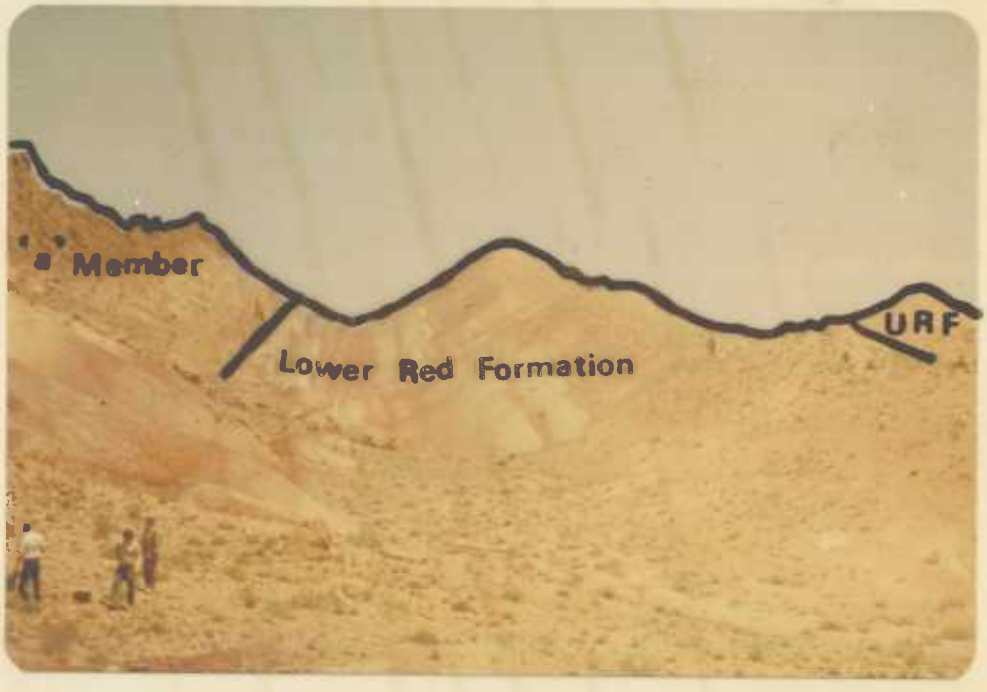
The formation crops out in the Mil-Dochah mountains in the northwestern part of the study area, where it is in contact with the Upper Red Formation along a high angle reverse fault (Fig. 4). In the central part of the area it is exposed along the axis of Zangar anticline and southern flank of Idaghchi syncline. To the south it crops out on the northern flank of Do-Baradar syncline, where it is also in contact with the 'e' Member of the Qom Formation along a high angle reverse fault, and in the core of Do-Baradar anticline.

Nowgole-Sadat (op. cit.) and some of the previous authors mentioned that the contact of the basal limestones of the Qom Formation with the top of the Lower Red Formation was conformable. Furthermore, some of the authors noted the presence of basalt on the top of the Lower Red Formation in the southeast of the area of study, and they concluded that this was a sill. The thickness of the basalt decreases towards the northwest and extends about 3.5 kilometres. However, in the course of the present research it has been found that basalt was in fact a lava flow. The reasons for this are: the top is a highly porous pumice, thus indicating that it formed in a subaerial environment. The top of the flow, i.e. the pumice, was

FIGURE 4 a) The contact between the Lower Red Formation on the left and the 'a' Member of the Qom Formation on the right. The 'b' and 'c_1' Members are partly seen on the upper right hand side of the photograph. Limestones of the 'a' Member are displaced by a fault. Do-Chah section, looking west-northwest.

b) The contacts between the 'a' Member of the Qom Formation and the Lower Red Formation, and between the Lower Red Formation and the Upper Red Formation. The latter is brought into contact with the Lower Red Formation along a fault which cuts out the whole thickness of the Qom Formation. Do-Chah section, looking east-southeast.


'a'
Member
Lower Red Formation
'b'
'c'
'a'


'a' Member
URF
Lower Red Formation

locally eroded and, during the Oligocene transgression, fragments of it were incorporated in the basal conglomerate of the 'a' Member (Fig. 5). The base of the 'a' Member of the Qom Formation is characterized by a basal conglomerate which becomes finer grained upward. Thus the sequence from the Lower Red Formation up into the Qom Formation starts with basalt which overlies the Lower Red Formation. The basalt changes upwards into pumice, above which there is a coarse conglomerate with pumice fragments. It finally passes up into the fossiliferous basal limestone member of the Qom Formation (Fig. 6). Thus, contrary to earlier ideas, since the sill is in fact a lava flow, the contact between the Lower Red Formation and the Qom Formation must therefore be unconformable.

Qom Formation

The surface on which the basal parts of the Qom Formation were deposited was of low relief. A few local 'highs' were present but they did not significantly affect the distribution of the sediments.

The Qom Formation is in general formed of alternations of marls and bioclastic limestones, with intercalations of gypsum, shales and sandstones. One member is entirely gypsum. The thickness in the study area ranges from 675 metres to 1182 metres in the four measured sections. Mention has already been made that the formation was divided into nine members by geologists of the National Iranian Oil Company (Abaie et al., 1963; Bozorgnia, 1966) on the basis of lithology. The members were designated by the letters 'a' to 'f' from bottom to top. The descriptions which follow are based in part on published work and in part on the author's own field observations. Stratigraphic subdivisions of the formation and their lithologies are shown in Table 2.

The 'a' Member. The 'a' Member is a thickly-bedded dark brown, bioclastic sandy limestone. The sand content varies vertically and

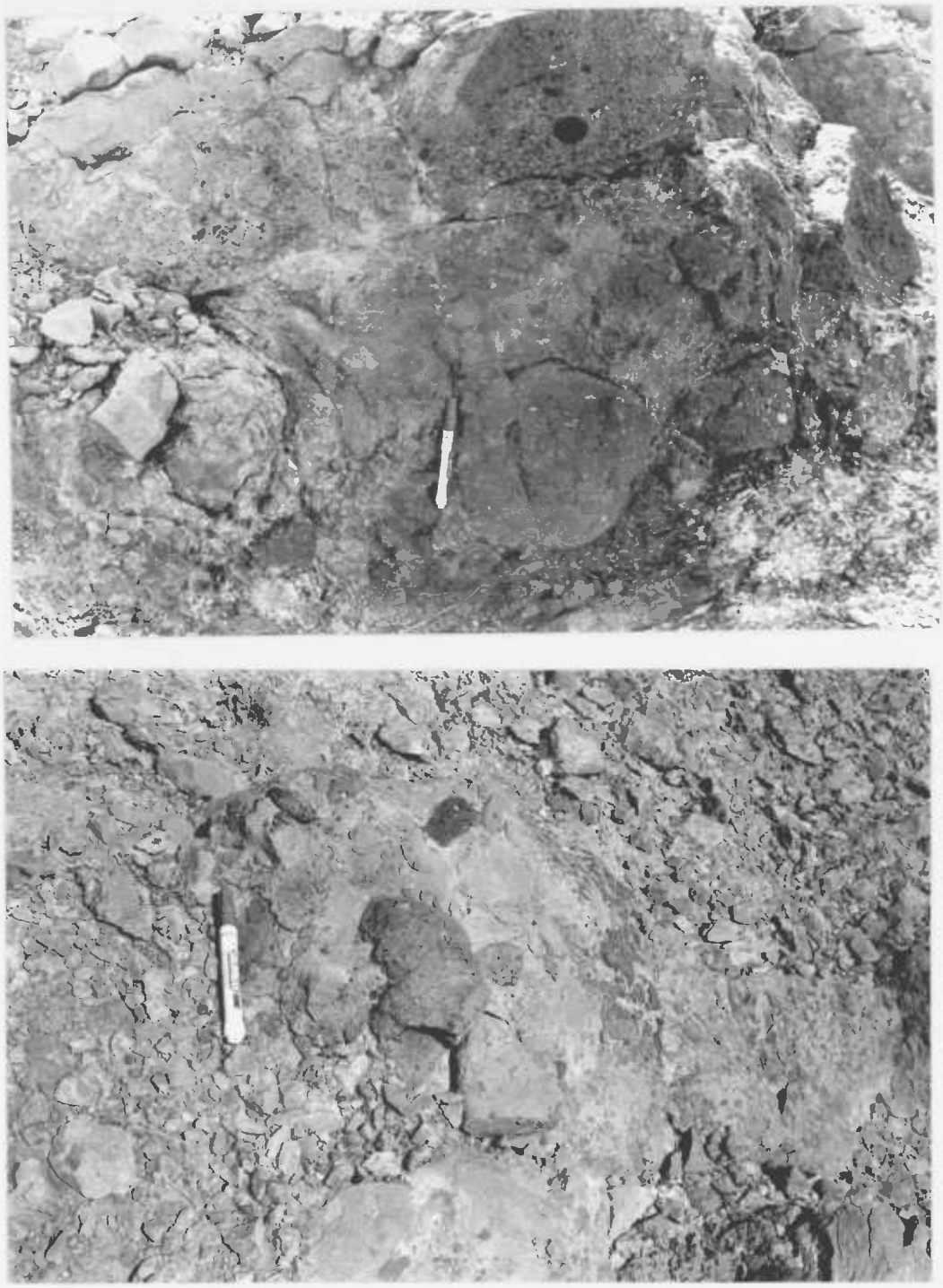


FIGURE 5 The basal conglomerate of the Qom Formation. In the lower photograph fragments of pumice are incorporated in a calcareous conglomerate. In the upper photograph, the conglomerate is fossiliferous; the basal part of the 'a' limestone member is seen at the top left hand corner. Do-Baradar section.

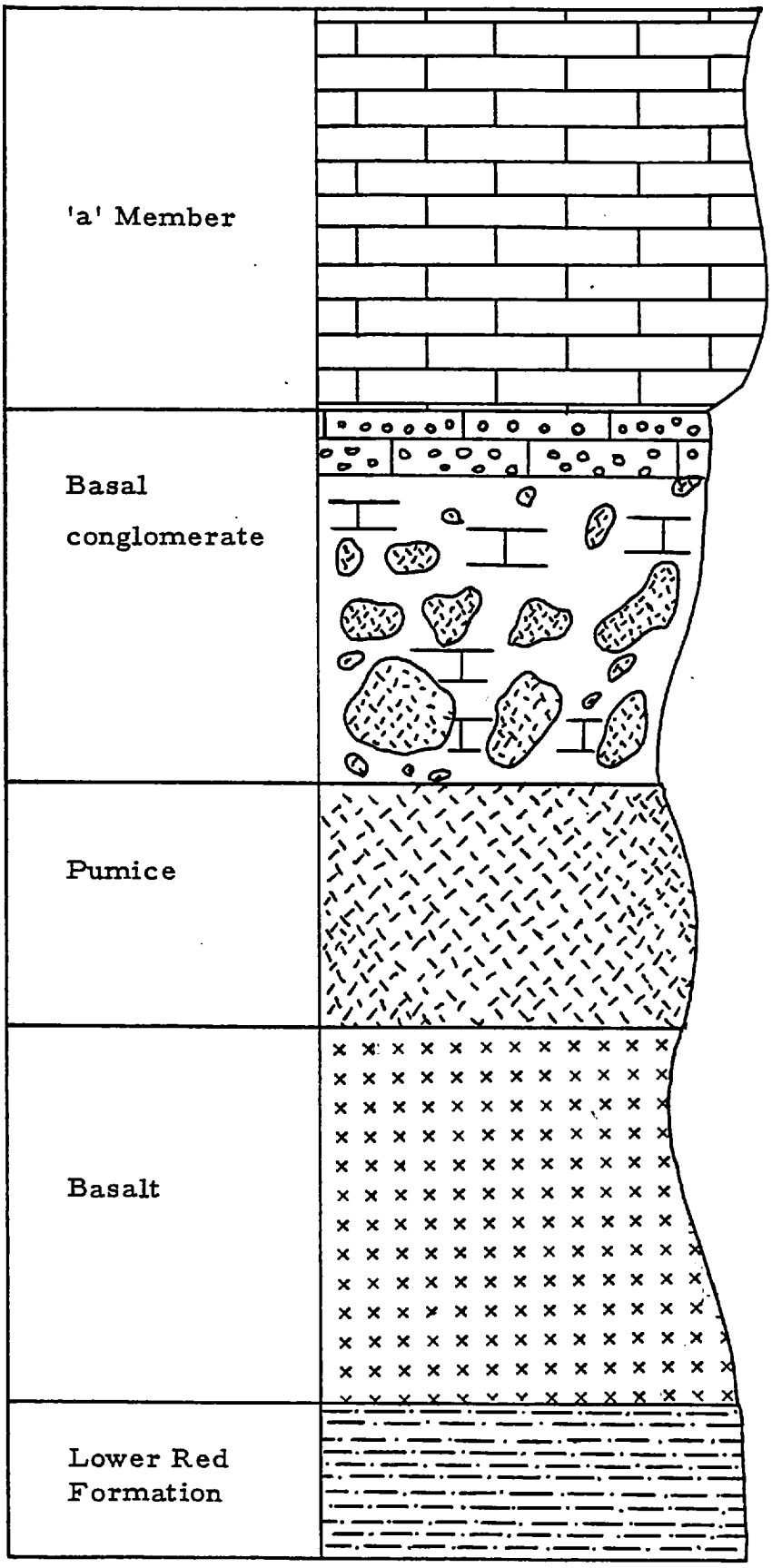
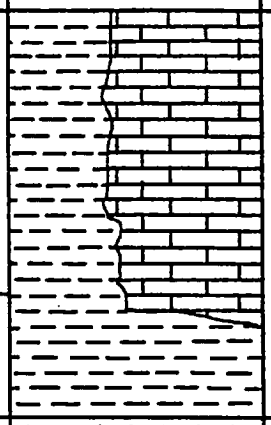
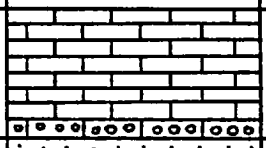
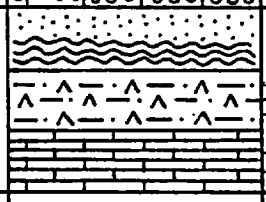
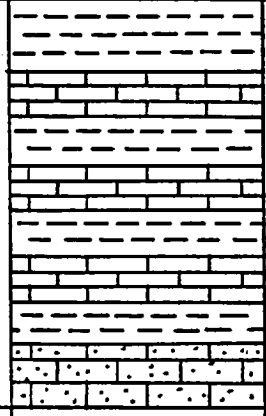
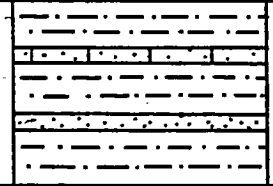
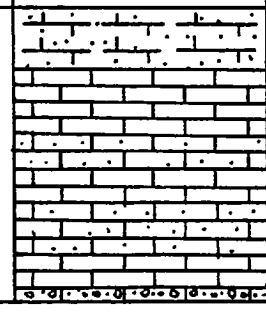


FIGURE 6 Sketch showing the relationship between the base of the 'a' Member and the Lower Red Formation in the measured section at Do-Baradar (not to scale).

TABLE 2

Schematic cross-section and stratigraphic subdivision of the Qom Formation (not to scale)

Age	Member	Lithology	Description
BURDIGALIAN	f		Either marls or marl below and limestones above: limestones discontinuous: local build-ups and limestone masses. Lithologies: algal packstones, foraminiferal algal packstones, bioclastic packstones and wackestones
	e		
AQUITANIAN	d		gypsum
	c_4		marls
	c_3		bryozoan packstones oolitic grainstones and packstones
	c_2		siltstones and sandstones gypsiferous marls and gypsum platy limestones
	c_1		Alternations of foraminiferal-bryozoan packstones, algal-foraminiferal packstones and wackestones and marls. Locally a limestone build-up with similar lithology and some other rock types sandy bioclastic limestone
	b		sandy marls grading to poorly cemented calcarenites with intercalations of sandstones
CHATTIAN	a		calcareous fossiliferous sandstones algal-bryozoan packstones algal-foraminiferal packstones (sandy) oolitic-pelletic-bioclastic packstones locally oolitic grainstones

laterally. In some sections the base is oolitic and it grades up into sandy bioclastic limestones. In other localities the base is sandy limestone or algal limestone. The top is consistently sandy. Glauconite is present as grains and it also fills the internal chambers of some fossils. The oolitic and sandy parts of the member both show cross bedding, but that in the oolitic part is large scale. The thickness of the member varies from 32 to 84 metres and generally decreases from northwest to southeast.

The 'b' Member. The 'b' Member comprises beige to green silty calcarenites, marls and sandy marls with some intercalations of cross bedded argillaceous sandstones and calcareous sandstones which vary laterally and vertically. The thickness varies from 120 metres to 265 metres and is generally thicker towards the southeast. The rocks are all glauconitic, and the glauconite is present either as grains or filling the chambers of foraminifera. Macrofossils are scarce but foraminifera are abundant.

In one area, Kuh-e-Do-Baradar, where the overlying limestone member is a 'reef', the top of the 'b' Member is a polymictic conglomerate some 20 to 25 metres thick. The conglomerate thins laterally and gradually passes into calcareous sandstones and sandy marls.

The 'c_1' Member. The 'c_1' Member varies from 254 to 355metres thick in the four measured sections. It consists of alternations of bioclastic limestones and marls, with marl increasing towards the top. Some of the marls and limestones are sandy. Due to differential erosion of the limestones and marls, the member is easily distinguished in outcrop (Fig. 7).

In Kuh-e-Do-Baradar the entire member is a 'reef': it is a massive limestone about 100 metres thick. It sits on the conglomeratic part

FIGURE 7 Alternations of limestones and marls. 'c_1' Member, Do-Chah section, looking west-northwest.

of the underlying 'b' Member, and around its flanks the limestone interfingers with marls.

The 'c_2' Member. The base of the 'c_2' Member is characterized by a light yellowish gray very thinly bedded microcrystalline limestone. The limestones are occasionally interbedded with very thin layers of light yellowish marls. The limestones are followed by gypsiferous marls or layers of gypsum in most places. Above these there is a succession of interbedded green and red shales and finally fine-grained sandstones. Fine-grained sandstones at the top of this member show ripple marks and rill marks, which are also seen as casts at the base of the overlying member. The thickness of the member varies from 28 to 92 metres.

The 'c_3' Member. An oolitic limestone a few metres thick makes up the base of the 'c_3' Member. The remainder is formed mainly of thick bedded light brown to brownish yellow detrital skeletal limestones with some intercalations of marls and argillaceous limestones. Towards the top the limestones become more marly. The thickness varies from 75 metres in the northwest to 20 metres in the southeast.

The 'c_4' Member. The 'c_4' Member is formed of greenish-gray marls and calcareous shales. Calcareous shales are dominant towards the top. The thickness varies from 35 to 126 metres.

The 'd' Member. The'd' Member is wholly gypsum, some 10 to 21 metres thick. The thickness increases towards the southeast. It is white to gray-white in color. In some areas the gypsum is darker in color and bears narrow stringers of gray clay.

The 'e' Member. The 'e' Member is composed of gray to greenish gray soft marls with some intercalations of marly limestones. Towards the top, in some localities the member is more sandy, but

elsewhere it is calcareous and grades to finely crystalline limestone. The member contains abundant foraminifera, mainly smaller varieties, and some echinoid debris. The thickness varies from 32 metres to 342 metres.

The 'f' Member. The 'f' Member is the top member of the Qom Formation and is a facies variation of the 'e' Member. It consists of yellowish white limestone. In some places the limestone is chalky and microcrystalline at the base, and grades up into a coarser grained organo-detrital limestone. In other areas the transition is not observed, and the member is formed entirely of coarse grained packstones. This member is not uniformly developed throughout the area, but is present as scattered irregular masses (Fig. 8) which pass laterally into and interfinger with marls. The thickness of the member varies from 40 to 300 metres. The areal relation and distribution of the 'e' and 'f' Members are shown in figure 9.

Upper Red Formation

The Upper Red Formation is of Middle-Late Miocene age. It consists of enormous thicknesses of sediments, up to 3,000 metres, which were deposited in a slowly sinking basin in a subcontinental environment. The sediments are generally composed of bedded brownish red calcareous sandstones, conglomerates, red, gray and greenish gypsiferous marls and siltstones, and some gypsum layers.

The Upper Red Formation is similar to the Lower Red Formation in color, but it is lighter in tone and is pinkish red compared with the Lower Red Formation.

The lower part of the formation consists mainly of darker brown bedded sandstones, conglomerates, siltstones and shales. The sediments are mostly gypsiferous. The base in the Do-Chah area

FIGURE 8 Typical occurrence of the limestones of the 'f' Member, as discontinuous and isolated masses. South flank of Do-Baradar syncline, looking south.

NW SE

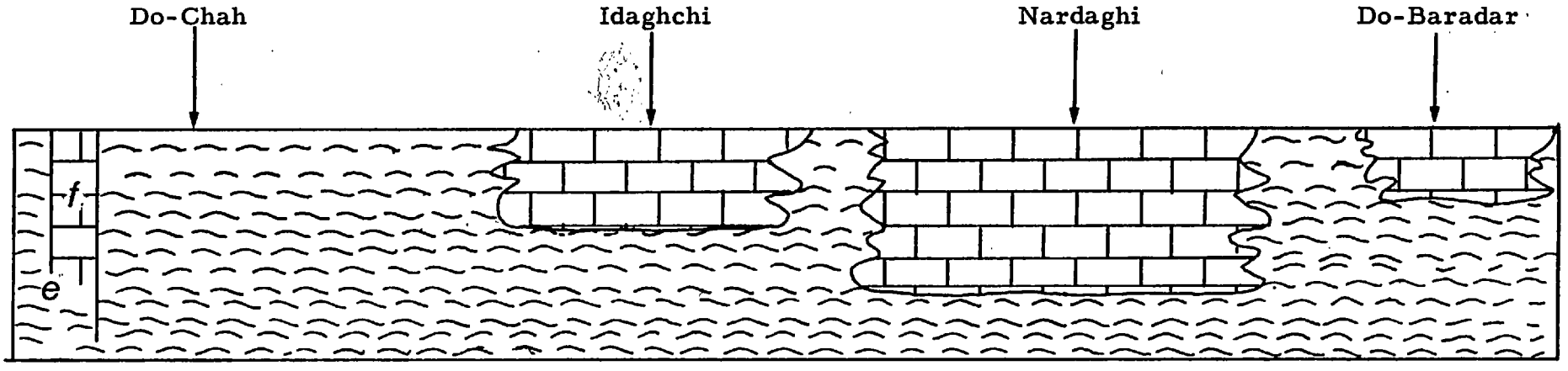


FIGURE 9 A schematic section showing the areal relationships and distribution of the 'e' and 'f' Members (not to scale).

is formed of gypsum which conformably overlies the 'e' Member of the Qom Formation, and was considered by Abaie et al. (op. cit.) to be the top of the Qom Formation. The gypsum is only present in the Do-Chah region and it might record the fact that the Oligocene-Miocene sea regressed earlier in the southern part of the basin, giving rise to lagoonal conditions in the northwest. The presence of mud cracks in some of the siltstones suggests that the sediments were exposed subaerially immediately after deposition. Cross bedding is common in some parts of the sandstones. These deposits are followed by gypsiferous siltstones, claystones, shales and sandstones with some evaporitic layers. The top part is formed mainly of gypsiferous marls and siltstones with some intercalations of poorly indurated sandstones. The sediments are creamy in color.

The base of the formation is believed to be transitional up from the Qom Formation. The formation as a whole is overlain by Pliocene conglomerates, with a strong angular unconformity. The total thickness is about 3000 metres.

The Upper Red Formation crops out in most parts of the study area, south of Do-Chah in the Yazdan Mountain, and in the core of Idaghchi syncline. It is also seen north of Do-Baradar in the Khezr area and as a very small exposure in the core of Do-Baradar syncline.

Pliocene Conglomerates

Pliocene sediments in the study area consist of moderately indurated polymictic conglomerates. They are lithologically comparable with conglomerates of Bakhtiari Formation in southwest Iran. The phenoclasts range in size from boulders down to granules and are set in a matrix of sand, silt and clay. The phenoclasts were derived from both sedimentary and volcanic rocks. The sedimentary rock

fragments came from the Upper Red Formation, the limestones of the Qom Formation and from older rocks down to the Paleozoic. The igneous rock fragments came from Eocene volcanics in the vicinity of the Qom Basin. The contacts with the overlying Pleistocene deposits and the underlying Upper Red Formation are both unconformable. The formation crops out on the south of Do-Chah and north of Zangar. South of Nardaghi the Pliocene conglomerates overlie the 'f' Member of the Qom Formation and the base of Pliocene is composed of about 20 metres of conglomerates (calcilithites), in which the pebbles and cobbles were mainly derived from the limestones of the Qom Formation.

Also in the Late Pliocene there were abundant fissure eruptions of lavas of basaltic and andesitic composition along major faults.

Pleistocene and Recent deposits

Quaternary sediments overlie all the older rocks of the area unconformably. They are mainly gravels, sands and reworked marls. They occur on terraces, and as spreads of alluvium and alluvial fans. The old terraces and alluvium are present at higher elevations. The youngest alluvial sediments are present along ephemeral stream valleys.

CHAPTER 2

INTRODUCTION TO PETROLOGY

2.1 Methods of Study

This present thesis is concerned mainly with the petrology of the limestones of the Qom Formation. Field work was carried out during the springs of 1974, 1975 and 1976. The outcrop of the Qom Formation was examined in several locations and four completely exposed sections located northwest to southeast across the basin were measured, sampled and all sedimentary features described. For each rock unit the following information was recorded: thickness, color, lithology, sedimentary structures, bedding thickness and the kinds of fossils present. Colors were specified by use of the rock color chart of Goddard (1963). All limestone units were sampled. Thick, apparently homogeneous units were sampled at a regular vertical interval of 1.5 to 3 metres. Where there were rapid changes in lithology, samples were collected at closer intervals. At least one sample was taken from units thinner than one metre. In addition, some limestone members were sampled either side of the measured sections where significant lateral variation in lithology was observed. 'Reefs' were sampled separately and, where possible, samples were collected at regular 3 metre vertical intervals. However, because of difficulties of access to the 'reef' core in Kuh-e-Do-Baradar, measurement and sampling was done as close as possible to the core and also around the sides of the 'reef' body. A total of 800 limestone samples was collected, each oriented with respect to bedding. Locations of the measured sections are shown on the geologic map of the area (enclosure 1) Complete logs of the four measured sections were drawn up to show the lithological and thickness variations (enclosure 2). Positions

of thin sections are shown on the sides of columns.

Thin sections, cut normal to bedding, were prepared and were studied petrographically. Data from thin section studies were recorded on a form developed by the writer (Fig. 10).

Mineralogical composition of the rocks was determined mainly from thin sections. X-ray diffraction analysis was used for the confirmation of the mineralogical composition of some limestones and determination of the composition of some of the marls. Thin sections of the samples were treated with alizarine red 's' to distinguish dolomite from calcite, and with potassium ferricyanide to determine whether or not the carbonate minerals were iron-bearing.

General aspects of rock fabric were studied qualitatively. Detailed petrography was based on thin section study of the samples under the polarizing microscope.

2.2 Classification and Terminology of Carbonate Rocks

The nomenclature used in this thesis to describe the limestones is a compromise between the classifications proposed by Folk (1959) and Dunham (1962).

Folk breaks the constituents of limestones into three general categories, termed: allochemical constituents, orthochemical constituents, and terrigenous detritus.

Allochemical constituents (allochems) are defined as aggregates of carbonate materials which were formed by chemical or biochemical precipitation within the basin of deposition, and which have undergone some transportation. Four types of allochems are generally recognized. These are: 1) fossils, 2) ooliths, 3) pellets (rounded

Sample _____ Section _____ Date _____

Rock Name _____

Support _____

	App. %	Size max.	Size ave.	Sorting	Comments
Allochems: Fossils					
Ooliths					
Intraclast					
Pellets					

Grain Contacts _____

Orthochems

Calcite	App. %	Nature of Mosaic
Micrite		
Spar		
Dolomite		
Noncarbonate		

Terrigenous Detritus:	App. %	Comments

Voids: Nature: _____

Replacement Features _____

Recrystallization Features _____

General Remarks: _____

Figure 10. Form for recording petrographic data.

aggregates of microcrystalline calcite devoid of any internal structure which range in size from 0.03 to 0.15 mm), and 4) intraclasts (reworked fragments of penecontemporaneous origin, usually weakly consolidated carbonate sediments which were eroded from adjoining parts of the sea bottom within the general environment of deposition and then redeposited).

The orthochemical constituents (orthochems) are the normal precipitates of calcium carbonate which were formed within the basin of deposition or within the rock itself and which show little or no evidence of transport. Three types of orthochemical constituents are commonly encountered. They are: microcrystalline calcite ooze, sparry calcite cement, and other replacement or recrystallized minerals.

Microcrystalline calcite ooze, or micrite, consists of grains 1 to 4 microns in diameter, which are generally subtranslucent with a faint brownish cast in thin sections. The origin of the micrite is usually not determinable. The tiny particles may have been chemically or biochemically precipitated crystals, or finely comminuted debris from originally larger particles.

Sparry calcite cement consists of the crystals which formed as simple pore-filling cements. They can be distinguished from micrite by their clarity and larger grain size (greater than 10 microns).

The third orthochemical group includes minerals formed by post-depositional replacement or recrystallization. Examples would be replacement dolomite, authigenic quartz, pyrite, and recrystallized calcite.

Terrigenous detritus includes those materials which were derived from the erosion of source lands outside the basin of deposition and

which were transported as solids to the site of deposition: e. g. quartz sand, feldspar grains and clay mineral particles.

In Folk's classification, the rock name is a composite one (see table 3). The first part of the name is an abbreviation of the allochem present: e. g. 'intra-', 'oo-', 'bio-', 'pel-'. The second part of the name indicates the binding agent of the rock: micrite '-mic-', or sparry calcite '-spar-'. The ending of the rock name denotes the average grain size of the allochems. If the average grain size of the allochems is less than 1 mm., the ending is '-ite'. If the average grain size is greater than 1 mm., the ending '-rudite' is used (the writer, however, uses 2 mm. in accordance with the Wentworth scale). Folk has suggested the term 'biolithites' for the rocks made of organic structure in growth position.

Dunham (1962) employed the terms 'mudstone', 'wackestone', 'packstone', and 'grainstone' (table 4) on the basis of the presence or absence of carbonate mud, and the extent to which the grains are mud supported. The term 'grainstone' is used when the rocks are devoid of any intergranular mud. Where the original sediment was bound together during deposition, the term 'boundstone' is used (see table 4).

Dunham (1962) pointed out that the most useful subdivision of micritic rocks is on the basis of abundance of allochems. He used the term 'mud-supported' for rocks in which the allochems are not sufficiently abundant to form a supporting framework but, instead, float in the micrite matrix. The term 'grain-supported' was used for rocks in which the allochems are abundant enough to form a supporting framework.

In some of the rocks examined it is not always easy to determine whether grains are floating in a micrite matrix or whether the micrite is merely filling pores within a framework of grains. The

Table 3 Classification of Carbonate Rocks (from Folk, 1959, p. 14)

Volumetric Allochem Composition				Limestones, Partly Dolomitized Limestones, and Primary Dolomites (see Notes 1 to 6)					Replacement Dolomites[1] (V)		
				>10% Allochems Allochemical Rocks (I and II)		<10% Allochems Microcrystalline Rocks (III)					
				Sparry Calcite Cement > Microcrystalline Ooze Matrix	Microcrystalline Ooze Matrix > Sparry Calcite Cement	1-10% Allochems	<1% Allochems	Undisturbed Bioherm Rocks (IV)	Allochem Ghosts		No Allochem Ghosts
				Sparry Allochemical Rocks (I)	Microcrystalline Alochemical Rocks (II)						
<25% Intraclasts			>25% Intraclasts (i)	Intrasparrudite (Ii:Lr) Intrasparite (Ii:La)	Intramicrudite* (IIi:Lr) Intramicrite* (IIi:La)	Most Abundant Allochem: Intraclasts: Intraclast-bearing Micrite* (IIIi:Lr or La)	Micrite (IIIm:L); if disturbed, Diamicrite (IIImX:L); if primary dolomite, Dolomicrite (IIIm:D)	Biolithite (IV:L)	Evident Allochem: Finely Crystalline Intraclastic Dolomite (Vi:DJ) etc.		Medium Crystalline Dolomite (V:D4)
	<25% Oölites		>25% Oölites (o)	Oösparrudite (Io:Lr) Oösparite (Io:La)	Oömicrudite* (IIo:Lr) Oömicrite* (IIo:La)	Oölites: Oölite-bearing Micrite* (IIIo:Lr or La)				Coarsely Crystalline Oölitic Dolomite (Vo:D3) etc.	Finely Crystalline Dolomite (V:D3)
		Volume Ratio of Fossils to Pellets	>3:1 (b)	Biosparrudite (Ib:Lr) Biosparite (Ib:La)	Biomicrudite (IIb:Lr) Biomicrite (IIb:La)	Fossils: Fossiliferous Micrite (IIIb: Lr, La, or Ll)				Aphanocrystalline Biogenic Dolomite (Vb:Dl) etc.	
			3:1-1:3 (bp)	Biopelsparite (Ibp:La)	Biopelmicrite (IIbp:La)	Pellets: Pelletiferous Micrite (IIIp:La)				Very Finely Crystalline Pellet Dolomite (Vp:D2) etc.	etc.
			<1:3 (p)	Pelsparite (Ip:La)	Pelmicrite (IIp:La)						

NOTES TO TABLE I

* Designates rare rock types.

[1] Names and symbols in the body of the table refer to limestones. If the rock contains more than 10 per cent replacement dolomite, prefix the term "dolomitized" to the rock name, and use DLr or DLa for the symbol (e.g., dolomitized intrasparite, Li:DLa). If the rock contains more than 10 per cent dolomite of uncertain origin, prefix the term "dolomitic" to the rock name, and use dLr or dLa for the symbol (e.g., dolomitic pelsparite, Ip:dLa). If the rock consists of primary (directly deposited) dolomite, prefix the term "primary dolomite" to the rock name, and use Dr or Da for the symbol (e.g., primary dolomite intramicrite, IIi:Da). Instead of "primary dolomite micrite" (IIIm:D) the term "dolomicrite" may be used.

[2] Upper name in each box refers to calcirudites (median allochem size larger than 1.0 mm.); and lower name refers to all rocks with median allochem size smaller than 1.0 mm. Grain size and quantity of ooze matrix, cements or terrigenous grains are ignored.

[3] If the rock contains more than 10 per cent terrigenous material, prefix "sandy," "silty," or "clayey" to the rock name, and "Ts," "Tz," or "Tc" to the symbol depending on which is dominant (e.g., sandy biosparite, TsIb:La, or silty dolomitized pelmicrite, TzIIp:DLa). Glauconite, collophane, chert, pyrite, or other modifiers may also be prefixed.

[4] If the rock contains other allochems in significant quantities that are not mentioned in the main rock name, these should be prefixed as qualifiers preceding the main rock name (e.g., fossiliferous intrasparite, oölitic pelmicrite, pelletiferous oösparite, or intraclastic biomicrudite). This can be shown symbolically as Ii(b), Io(p), IIb(i), respectively.

[5] If the fossils are of rather uniform type or one type is dominant, this fact should be shown in the rock name (e.g., pelecypod biosparrudite, crinoid biomicrite).

[6] If the rock was originally microcrystalline and can be shown to have recrystallized to microspar (5-15 micron, clear calcite) the terms "microsparite," "biomicrosparite," etc. can be used instead of "micrite" or "biomicrite."

[7] Specify crystal size as shown in the examples.

Table 4. Classification of carbonate rocks according to depositional texture (Dunham, 1962, p. 117)

Depositional texture recognizable					Depositional texture not recognizable
Original components not bound together during deposition				Original components were bound together during deposition as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.	crystalline carbonate (Subdivide according to classifications designed to bear on physical texture or diagenesis.)
Contains mud (particles of clay and fine silt size)			Lacks mud and is grain-supported		
Mud-supported		Grain-supported			
Less than 10 percent grains	More than 10 percent grains				
Mudstone	Wackestone	Packstone	Grainstone	Boundstone	

shape of the allochems must be taken into account before establishing the nature of the support. Irregularly shaped fossil fragments which appear in thin section studies to 'float' in a micrite matrix may actually form a supporting framework if they could be seen in 3-dimensions.

It was found that, using Folk's classification, groupings of the rocks were not consistent. Rocks are therefore named after their predominant constituent following the rules of nomenclature proposed by Dunham. The names of the allochems, according to Folk, are used to indicate the predominant allochem types of clastic carbonates. The classification is therefore a compromise one which combines parts of the classifications of both Dunham and Folk.

In this thesis the term 'reef' is used primarily as a field designation and it has not been applied in the petrographic study of the rocks. However, several units recognized in the Qom limestones contain encrusting organisms which actually bound the sediment together. These limestones should be classified as boundstones. It is not intended to imply that these rocks were reefs. They were merely local patches of coralline algae, bryozoans and foraminifera which encrusted one another and thus bound the sediment together.

Chemically precipitated constituents, irrespective of whether they were primary or the products of recrystallization and replacement, are described according to the size scale proposed by Folk (1959, p. 19), shown in table 5.

2.3 Petrology

Terminology of the carbonate constituents follows the classification of Folk (op. cit.). The following classes of components were distinguished:

Table 5. Size scale of orthochems (taken from Folk, 1959)

Aphanocrystalline	under .0039 mm
Very fine crystalline	.0039-.0156 mm
Finely crystalline	.0156-.0625 mm
Medium crystalline	.0625-.25 mm
Coarsely crystalline	.25 -1.00 mm
Very coarsely crystalline	1.00 -4.00 mm
Extremely coarsely crystalline	over 4.00 mm

Allochems

The limestones of the Qom formation are mainly skeletal, and comprise fragments of bryozoans, calcareous red algae, foraminifera, corals, molluscs, echinoids, ostracods and some calcareous green algae.

Non-skeletal carbonate grains, where present, consist mainly of ooliths and pellets. They generally occur as a minor constituent in some of the bioclastic limestones, but oolites locally form beds up to four metres thick. Some intraclasts were identified in a number of thin sections.

Fossils. Bryozoans were one of the main contributors to the limestones of the Qom Formation. They were of branching and encrusting types belonging to the orders Cheilostomata and Cyclostomata. Small colonial fragments, generally less than 3 centimetres long, were collected in the field. However, most fragments range in size from 5 to 10 millimetres and many are smaller sand sized grains.

Under the microscope the bryozoan fragments are readily distinguished by their tubular or sack like chambers. These chambers are usually filled with micrite which has been partially recrystallized to coarser grained mosaic of calcite, or has been replaced by dolomite. Some contain glauconite. The zooecia are defined by a dark line which separates one from another.

The red algae in the Qom Formation are mainly Lithothamnium and Lithophyllum which occur as encrusting and branching forms. They are mostly well preserved, and show well defined cellular structure. In many samples sporangia, now filled with sparry calcite, can be easily identified (Fig. 32). The encrusting varieties occur as nodular crusts (Fig. 32), sometimes surrounding skeletal constituents,

and they also acted as sediment traps which incorporated carbonate mud, silt and sand size skeletal particles as well as quartz and other detrital grains. In the branching forms a large plant skeleton is sometimes preserved intact. Both forms also occur as detrital grains. The size of the fragments varies from sand grade in some well sorted calcarenites to more than 3 centimetres across in calcirudites. The smaller fragments are generally well rounded. High concentrations of rod shaped fragments of Lithophyllum were observed in some thin sections. Some very small grains form the cores of ooliths in the oolitic calcarenites. In some beds the algae are partially dolomitized.

Several genera of benthonic and a few pelagic foraminifera have been found in these limestones. Usually the foraminiferal assemblages of the various lithofacies differ slightly from one another. In some facies they are important constituents while in others they are less common. The most abundant forms are large benthonic types such as Lepidocyclina and its various subgenera which locally reach up to 10 centimetres in diameter (Furon and Balavoine, 1959); Heterostegina, Miogypsina, Miogypsinoides, Amphistegina and Rotalia. Several other benthonic types have also been reported. Small thin walled benthonic foraminifera, such as miliolids and peneroplids, are locally abundant in some limestone members and occur sporadically in others. Planktonic foraminifera are also scattered through many limestone beds but increase in number towards the top of the formation. The chambers of foraminifera are often filled with micrite, sparry calcite or terrigenous detritus; and less commonly by glauconite, dolomite and silica.

Most foraminifera are well preserved and, although some have been fragmented, the broken fragments are angular in most samples. The structure of the foraminifera is not obliterated by micritization, neither do they show much sign of abrasion by transport. However, some abraded tests occur in the limestones of the 'c_1' and 'f' Members.

Corals are abundant, but they are restricted to certain parts of the measured sections. They are generally associated with bryozoans and coralline algae or are embedded in carbonate mud. The recognizable sediment contributions of corals range from a single massive head more than 1 metre in diameter (Fig. 11) to sand size detritus. The wall structure is not usually preserved and is replaced by sparry calcite. Interseptal cavities are filled with micrite and occasionally with detrital grains. Where micrite occurs it is sometimes recrystallized.

Echinoid plates and spines are abundant in most of the limestones. The genera Scutella and Clypeaster have been identified from different members. The plates appear rectangular in thin sections, and range in size up to 2 to 3 centimetres in length. In some of the well sorted calcarenites the echinoid fragments are well rounded. Syntaxial calcite rim cement is characteristically developed around these skeletal grains. In many samples single crystals of the cement extend over large areas and embrace other fossil fragments or detrital grains poikilitically. Some of the fragments show large hollows or buoyancy canals within them. These are sometimes filled with micrite but a geopetal structure is developed in some of the larger cavities. In one case the geopetal filling of the pore comprises carbonate mud, dolomite rhombs and sparry calcite in succession from bottom to top.

Skeletal structures of pelecypods are widespread, and locally they are very abundant. They are mainly shells of the genera Ostrea and Pecten. Some limestone beds are predominantly formed of pelecypod shells. As seen in thin sections, the pelecypods appear superficially to be large broken fragments, but many of them are in fact intact, and the valves extend beyond the field of most thin sections. However, small broken fragments are not uncommon.

FIGURE 11 A field photograph showing large coral heads. Coral heads up to 1 metre in diameter are found locally in the limestones of the Qom Formation. 'c_1' Member, Nardaghi section.

Most gastropods are present as calcite casts of whole shells and as fragments of shells; the casts are in sharp contrast to their surrounding matrix. Many of the thin walled gastropod shells were broken by compaction. The chambers of some shells were filled by ooliths and other carbonate detritus prior to the final deposition in mud matrix. The chambers of other gastropod shells are filled with carbonate mud. In many cases micrite envelopes outline the chambers and surfaces of the shells. Some of the gastropod and pelecypod shells are selectively silicified and, in the case of gastropod shells, silicification has affected the shell walls and also partially filled the chambers.

Segments of green algae are locally found in the limestones of the 'a' and 'c_1' Members. The segments are very similar to genus Halimeda, as described and figured by Milliman (1974, p. 73) and figured by Johnson (1951, p. 178), Horowitz and Potter (1971, p. 215), and Bathurst (1976, p. 62). Fragments are equant to elliptical, range in size from 2 to 5 millimetres and their internal tubes are filled with microcrystalline calcite (Fig. 12). The segments are well preserved.

A few ostracod shells and single valves generally less than 1 millimetre in length were found. Some shells are filled with sparry calcite and others by micrite.

Ooliths. Most of the ooliths have a spherical shape, although some are elongate due to the shape of the core. They are mostly of medium to coarse sand size. The cores may be pelloids, detrital sand grains or fragments of echinoids, calcareous red algae, molluscs or other skeletal fragments. In the 'c_3' Member some of the ooliths have large cores, which have a pelloid appearance. However, in most of the ooliths the cores have been dissolved out or replaced by dolomite. The oolitic coating is formed of one to several layers but most have relatively thin concentric jackets. This type of oolith

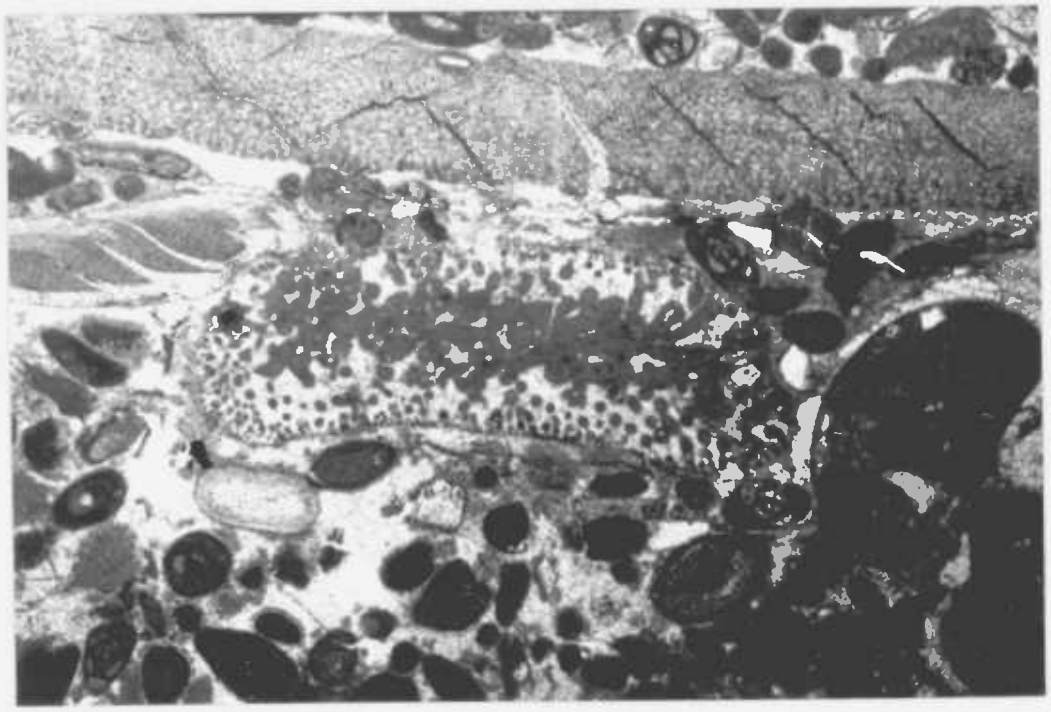


FIGURE 12 Photomicrograph showing a well preserved segment of Halimeda. 'a' Member, Do-Baradar section. (x 30).

was described as 'superficial oolith' by Illing (1954). The term 'superficial oolith' was first introduced by Illing (p. 33-36) to indicate that the oolitization process had only proceeded far enough to coat a thin outer zone of concentric layers around the nucleus. The allowable thickness of a superficial coat varies with different writers. The coating may consist of a single concentric layer (Carozzi, 1957), a thickness less than the radius of the nucleus (Leighton and Pendexler, 1962), or a thickness less than 0.1 mm (Ball, 1967). In describing the ooliths the writer did not take the last definition into consideration. No relation was observed between the thickness of the oolitic coatings and the shape of the cores. In some ooliths the thickest oolitic jackets were found around elongate nuclei, while in others equant cores possessed the thickest coats.

The fabric of the oolitic jackets is concentric and no radial structure can be seen in ordinary light, but some of the ooliths have a good pseudo-uniaxial extinction cross under crossed polars.

Oolitic rocks are porous. The porosity was produced either by dissolution of whole ooliths to leave oomoldic pores, or it was developed as a result of other diagenetic processes which only affected the cores. In some samples the cores of the ooliths are dolomitized. In these, the cores are now occupied by one or few rhombs of dolomite. The dolomites were probably generated after the oolitic jackets had formed. In some, the cores might be completely replaced by dolomite rhombs but in others parts of the former core remain as voids. These voids probably resulted from incomplete replacement of the core by dolomite and subsequent dissolution of the remainder. It seems unlikely that the dolomite of the core was leached to form the pores. In some ooliths individual concentric layers have been selectively dolomitized. In a few instances the dolomite was later dedolomitized leaving calcite pseudomorphs after dolomite rhombs in the cores.

Pellets. Pellets are not a common constituent of the Qom limestones. Where they do occur they are present as rounded or ovoid grains. They are mostly very small, homogeneous cryptocrystalline aggregates of calcium carbonate and are brown in color. The pellets generally show good sorting and are locally concentrated in parts of some thin sections. These small homogeneous pellets were probably faecal in origin.

Pelloids, which are larger in size than the faecal pellets, are found in abundance in some thin sections. They are grayish in color and are less compact and homogeneous. Some are associated with superficial ooliths, and are probably eroded and altered debris of coralline algae. Others, which form a large proportion of some thin sections, are generally similar to the associated micrite and appear to have been formed essentially in place rather than being allochthonous. Some pelloids contain inclusions of more coarsely crystalline spar and others have been almost completely recrystallized to a coarse mosaic of calcite.

Intraclasts. Intraclasts vary from rounded to subrounded and angular and the maximum diameters range from less than 1 millimetre to 4 millimetres. Intraclasts are composed predominantly of micrite and commonly contain small amounts of fossil 'hash' and fine detrital grains (Fig. 13).

Angular to subangular irregular fragments of micrite occur randomly in the carbonate mud matrix. Some of these grains resemble the matrix in composition and texture. Others show textural variation with the surrounding mud matrix.

Terrigenous Detritus

Terrigenous detritus consists of sand, silt and clay. The sand and silt is generally present as scattered grains, and comprises twenty percent or more of some beds; although other samples

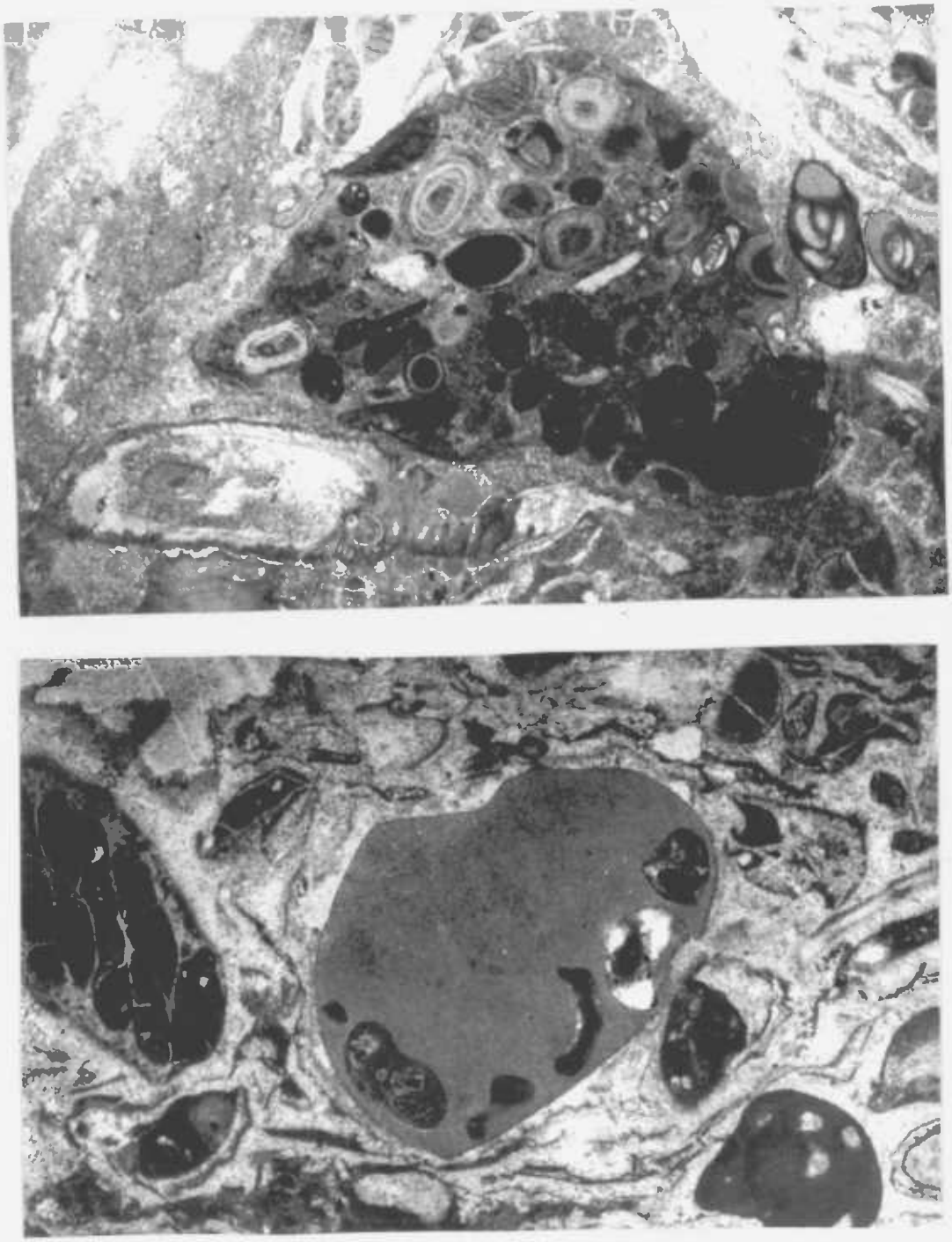


FIGURE 13 Photomicrographs showing intraclasts in the limestones of the 'a' Member. The intraclasts resemble the associated lithology and may have been derived by erosion from underlying or penecontemporaneous deposits. (x 30).

contain less than one percent. The sand and silt size detrital grains are mostly angular to subangular and consist of quartz, zoned feldspars and fragments of volcanic rocks. Illite was the only clay mineral recorded in the samples. The distribution of the detrital material varies from bed to bed and in different parts of the same bed.

The source of the terrigenous detritus was mainly the Eocene volcanics and the Lower Red Formation with its minor igneous intrusions which are exposed both in the southern and northern parts of the basin. It is thought, however, that most of the sand was supplied from the southern part. The sand grains are mostly angular to subangular suggesting no great distance of transport.

Micrite

Although micrite is referred to as an orthochemical component by Folk (1959, op. cit.), it is in fact part of the depositional fabric. Folk states that micrite is considered to have formed by preceipitation in sea water, "settling to the bottom and at times suffering some later drifting by weak currents". Having formed as discrete grains before reaching the sediment - water interface it may be therefore regarded as part of the depositional fabric.

Micrite may be present in such abundance that the other components float in it, i. e. the 'wackestones' of Dunham, or the micrite may partly or wholly fill the interstices between the allochemical grains to give the 'packstones' of Dunham's classification. Micrite forms the bulk of the matrix in all the samples studied. In many samples most of it has been recrystallized into coarse mosaic spar, although some remains as patches within the coarse mosaic. Replacement by dolomite has obliterated the micrite in some rocks.

Sparry calcite

Sparry calcite is a common constituent of the Qom limestones, forming up to 25 percent of some samples. The following modes of occurrence of the sparry calcite are encountered:

Sparry calcite occurs in intergranular pores, and is composed of crystals which nucleated on the surfaces of the depositional grains and grew out into the pore space. The mean grain size of the crystals increases outwards, and the number of crystals decreases with distance from the pore walls. Around echinoid fragments, the single crystals of sparry calcite engulf the host grains and each is developed as syntaxial rim cement in optical continuity with its host.

Sparry calcite also occurs as filling of the chambers of fossils, calcite cast after aragonitic shells, and any voids and cavities other than intergranular pore space. The mosaic of this calcite characteristically resembles that of the intergranular cement. Small irregular patches or islands of the sparry calcite mosaic are sometimes found within the micritic matrix.

Thin veins of clear sparry calcite are found in most of the samples. They transect skeletal grains and all other components. The veins were probably post-lithification in origin and are healed fractures.

Iron oxides

Iron oxides are present in most samples. Generally they occur as small pellets or irregular grains, and are locally abundant. The iron oxides are found both in the matrix and within allochems. Less commonly they encrust skeletal fragments. Iron oxide is also locally concentrated along some stylolites and was probably concentrated there as an insoluble residue. It tends to be most abundant in micritic and clayey laminae. It is apparently an integral part of

most samples, although it does vary in abundance from one rock to another.

Glauconite

The term glauconite is used here as a morphologic term as suggested by Burst (1959b) for small green earthy grains, regardless of their mineralogic composition. It is present throughout the Qom limestones, but is most common in the 'a' and 'c_1' Members.

In thin section the glauconite is found as discrete rounded to irregular grains 0.1 to 0.3 mm in diameter, as faint blobs and as infillings of chambers of foraminifera, zooecia of bryozoans, or pores of echinoid and other skeletal fragments.

Burst suggested that glauconite formed by alteration of layered-lattice silicate minerals and suggested at least three different modes of origin: glauconitization of faecal pellets, cavity infillings and clay agglomerates. Presumably all of the glauconite in the Qom Formation is autochthonous, and it is likely that the grains are glauconitized allochthonous clay aggregates.

Texture

Skeletal grains form from 5 to 85 percent of the various rock types. They occur in grain-supported and mud-supported rocks. Alternating layers of grain-supported and mud-supported textures are common; but the alternation is not uniform or regular.

Grain-supported micritic rocks are more abundant than the other rock types. Sparry rocks, although encountered throughout all of the measured sections, are most abundant in the 'a' and 'c_1' Members. The proportions of the various skeletal components vary considerably, not only in the different members but also vertically and laterally within any one member. Fragments of bryozoans and

calcareous red algae are volumetrically the most abundant fossils.

As seen in thin sections, the skeletal grains range in size from fine sand to more than 3 centimetres in length; however, the true dimensions of many of them cannot be determined in thin section because of the shape factor. Complete unbroken skeletal structures of echinoids (Fig. 14), large fragments of colonial corals (Fig. 11), colonies of bryozoans and calcareous red algae, large tests of foraminifora and whole or disarticulated (but not fragmented) shells of pelecypods are abundant.

The roundness of the grains varies from angular in freshly broken skeletal debris, to well rounded. Grain shapes are highly diverse from equant to elongate and to some extent differ with the nature of the contributing organisms.

Sorting varies from place to place and ranges from fair to good in some grain-supported biomicrites and biosparites. In many grain-supported micritic rocks and mud-supported rocks the sorting of the skeletal grains ranges from fair to very poor.

Orientations of the grains vary in the different rock types. Grain orientation by shape is possible only if grains possess an axis of relative elongation or a plane of flatness. Equant grains can lie either parallel to one another and to bedding or be random. Bladed or rod-shaped fragments can have similar orientations. In most thin sections which display a planar arrangement of grains, the plane was roughly parallel to bedding. Whole fossils laying parallel to bedding were also found (Fig. 15). Mud-supported rocks usually exhibited random orientation of the grains, but vaguely aligned fossil debris was observed in some thin sections. Many framework grains show pressure dissolution contacts.

The distribution of the various grain types with respect to each other

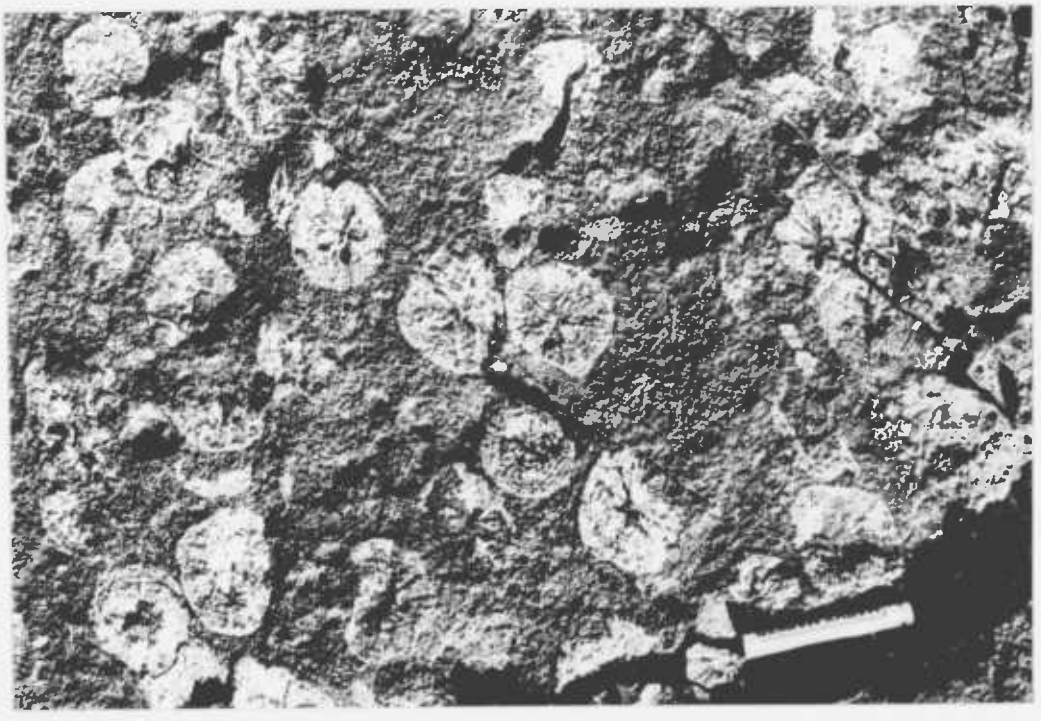


FIGURE 14 Whole tests of echinoids on a bedding surface. 'a' Member, Nardaghi section.

FIGURE 15 Whole tests and debris of echinoids oriented parallel to bedding. 'a' Member, Nardaghi section.

is generally random, although segregation of particular grain types into lenses or layers was observed in some samples.

Limestones can be described petrographically in terms of their constituents and textures. These two factors provide the basis for establishing various facies types. The limestones of the Qom Formation have been divided into facies on the basis of thin section study.

CHAPTER 3

PETROLOGY OF THE LIMESTONES OF THE QOM FORMATION

Refer to enclosure 7 throughout the whole of this chapter

3.1 Petrology of the 'a' Member

The 'a' limestone member is the basal unit of the Qom Formation. It overlies the Lower Red Formation and marks the Upper Oligocene transgression and beginning of carbonate sedimentation over most of Central Iran. The member is cliff-forming, it is commonly well bedded, and yellowish brown to reddish brown in color.

Although lithology varies slightly from location to location, the member is developed throughout the study area. It is thickest in the northwest where it measures 84 metres and from there to the southeast the thickness varies down to 32 metres.

The member as a whole is a bioclastic limestone in which terrigenous detritus is also incorporated. At outcrop thin biostromes are found in which a single type of macrofossil dominates. Such horizons include an oyster bed in the lower part of the member and a few Scutella horizons in the upper part of the member.

Five lithologies were delimited in the course of the present study, and these are thought to have been deposited in slightly different environments. They are: oolitic-pelletic-bioclastic packstones, algal foraminiferal packstones, oolitic grainstones, algal-bryozoan packstones, and calcareous fossiliferous sandstones. Generally, the member begins with oolitic-pelletic limestones which pass up into algal-foraminiferal packstones. These in turn pass up into algal-bryozoan packstones in which the diversity of skeletal fragments suggests derivation from a complex faunal assemblage which included coralline algae, bryozoans, pelecypods, echinoids,

calcareous green algae and ostracods. The top of the member is formed of highly sandy fossiliferous limestones which grade up into calcareous fossiliferous sandstones. These various facies will be described in turn.

Generally, the different facies types follow in sequence from the base to the top of the member, but because of lateral variations the sequence of lithologies is not always the same and the diversities will be mentioned in the descriptions of measured sections from the different areas.

Usually, a bed of oolitic-pelletic-bioclastic packstone occurs at the base of the member, but this is not consistent throughout the area.

Oolitic-pelletic-bioclastic packstones

A rock type which belongs to the algal-foraminiferal packstone facies is the oolitic-pelletic-bioclastic packstone. It is yellowish to reddish brown in outcrop and, where present, always occurs at the base of the 'a' Member. It ranges in thickness from 0 to 2 metres. It is composed of various admixtures of coated grains, fine to medium pelloids and bioclasts. However, in most samples that have been examined ooliths or pelloids predominate (Fig. 16). The ooliths are of medium sand-size and were nucleated around pelloids, skeletal debris or terrigenous sand-grains. They have one to a few oolitic shells. In the basal beds of some of the measured sections, ooliths appear to have been deformed by compaction. The pelloids in these rocks probably formed as a result of micritization of fragments of coralline algae. This is suggested by the fact that where pelloids are associated with algal debris they are usually of the same size as the algal fragments. Bioclastic materials mainly comprise fragments of coralline algae and tests of miliolids. Minor proportions of pelecypod shell debris, bryozoan

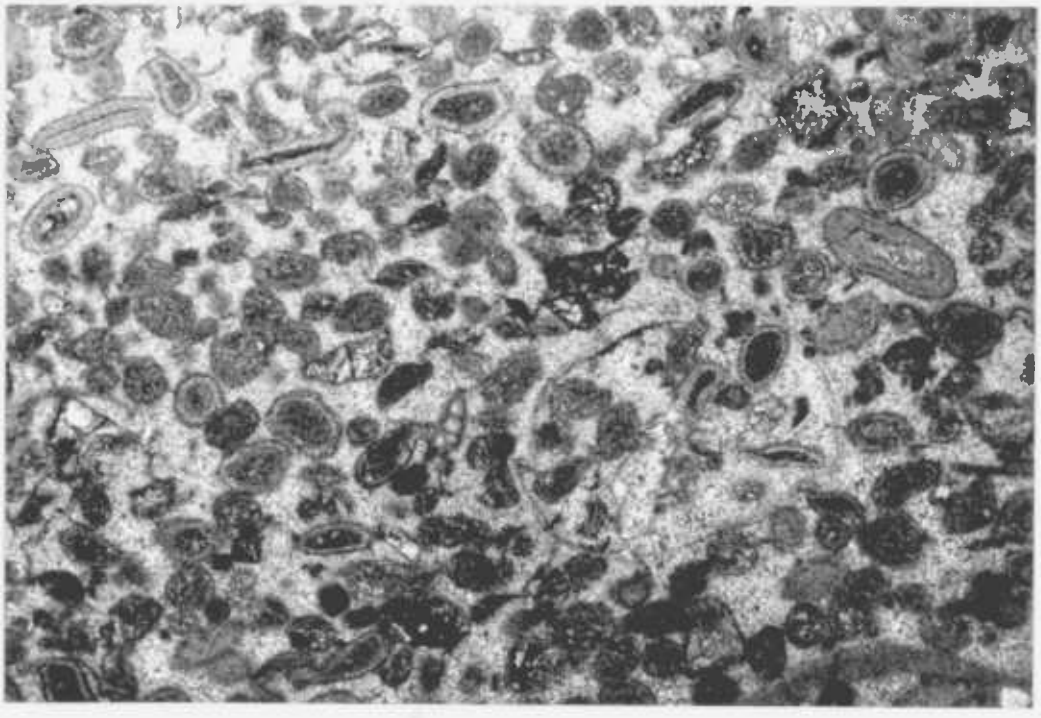


FIGURE 16 Photomicrograph of an oolitic pelletic bioclastic limestone. The rock is composed of ooliths, pelloids and bioclasts but ooliths are predominant. 'a' Member, Do-Baradar section (x.30).

and echinoid fragments and occasional Halimeda segments are present.

A few intraclasts, most of which are usually larger than the other grains, were observed in some thin sections. In terms of composition and texture the intraclasts resemble the associated lithologies (Fig. 13) and appear to have been derived by erosion from underlying or penecontemporaneous deposits.

These various components are set in a matrix of partially recrystallized microcrystalline calcite or sparry calcite. Thin films of ferric oxide coat some of the grains and some ferric oxides occur in the matrix.

Environment of deposition of the oolitic-pelletic-bioclastic packstones

The oolitic-pelletic-bioclastic packstones resemble the sediments that are being deposited in many areas of present day carbonate sedimentation. In the Bahamas similar sediments have been described from the outer lagoonal areas behind the oolitic shoals (Bathurst, 1975). The lagoons are the site of deposition of lime muds and pellets. Ooliths are introduced into the lagoons by flood tides. In the Bahamas, the lagoons are the habitat of most of the deposit feeders, however some skeletal debris is contributed from the surrounding environments.

The oolitic-pelletic-bioclastic packstones contain recrystallized carbonate mud. Tests of miliolids are usually well preserved and the rocks also contain fragments of other fossils. The good preservation of the tests of foraminifera may indicate that they were not introduced but lived in the environment of deposition of the host sediment. The presence of mud matrix may suggest a low energy quiet water environment. Miliolids have been reported from lagoonal and very shallow marine environments by various authors (Henson, 1950; Schlanger, 1964). Thus it is inferred that the oolitic-pelletic-bioclastic packstones were deposited in environments of low turbu-

lence similar to the outer lagoonal environments of the Bahama Banks. An alternative explanation is that oolitic-pelletic-bioclastic packstones formed when oolith shoals shifted to a lagoonal area in response to a transgressing sea.

Oolitic grainstones

Rocks of the oolitic grainstone lithofacies are white in color and have planar cross bedding. The facies is restricted both in vertical and lateral distribution and is only present in the Idaghchi section where it is exposed in a cliff-forming outcrop.

Petrographically, the rocks are composed of medium sand sized ooliths and minor proportions of fossil debris cemented by sparry calcite (Fig. 17). The ooliths do not show much variation in shape and are mostly circular in the thin section. The nuclei of most ooliths have been either dissolved away or replaced by dolomite. Some of the latter have been dedolomitized. In the replaced cores there are some voids between the dolomite rhombs. Such nuclei as remain unaltered include quartz and feldspar grains of fine sand grade and occasionally some bioclastic fragments. The oolitic coatings have also been mostly dolomitized.

Fossils, where present, consist of tests of small foraminifera, mainly miliolids, fragments of coralline algae, and bryozoans, and pelecypod shell debris. The bioclastic fragments are roughly of the same size as the ooliths, so that the rocks are moderately well sorted.

The calcite cement is formed of relatively uniform crystals which become slightly larger away from the substrate. Most of the rocks are highly porous (Fig. 17). This porosity is secondary and was produced by the dissolution of the cores of the ooliths.

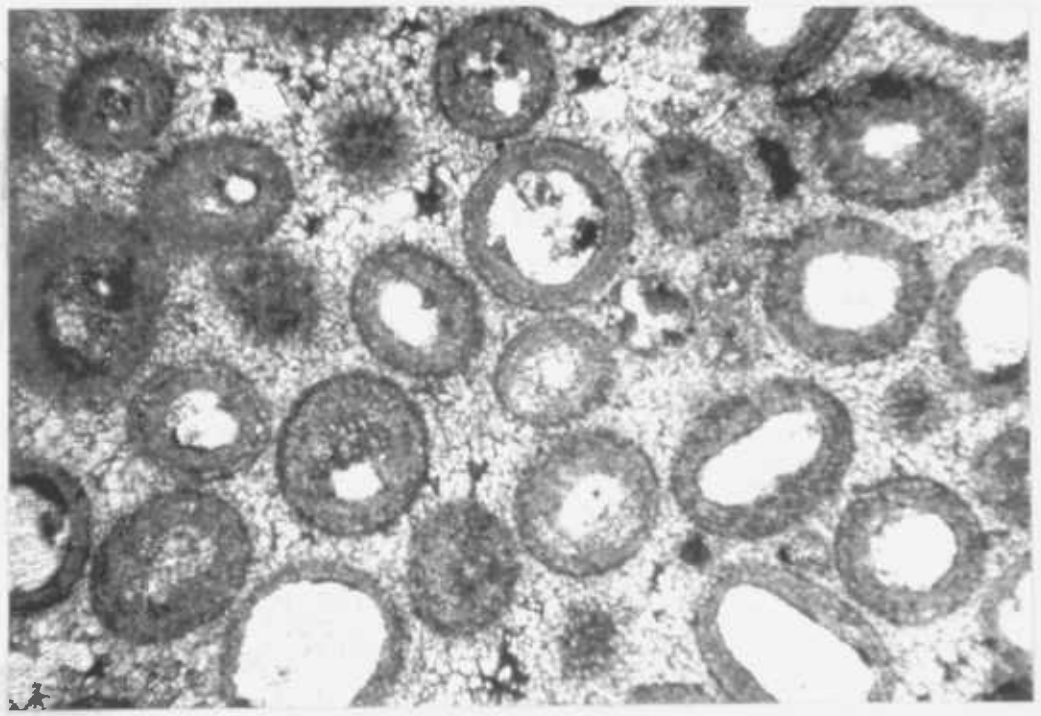


FIGURE 17. Photomicrograph of an oolitic grainstone. Cores of most ooliths havebeen dissolved away to leave voids. 'a' Member, Idaghchi section. (x 64)

Environment of deposition of the oolitic grainstones

Modern areas of oolith formation on the Bahama Bank have been described by Illing (1954), Newell and Rigby (1957), Newell et al. (1960), and Purdy (1961, 1963, 1964) and those along the south-western shore of the Persian Gulf by Sudgen (1963) and Kinsman (1964). These areas are generally characterized by warm, shallow agitated water saturated with respect to calcium carbonate.

On the Bahama Bank ooliths are forming at various places in the shallowest waters along the margins of the bank. The bank passes abruptly around its edges to steep slopes which drop off to depths of a few hundred metres in a short distance. Because of the rapid decrease in water depth as the bank is approached, tidal currents reach their maximum velocities and turbulence at the bank margin. The cold oceanic water coming up onto the bank is warmed, driving off carbon dioxide, causing the water to become supersaturated with respect to calcium carbonate. The grains are in almost constant movement. The location of the oolith shoals are controlled by the uneven surface of the underlying Pleistocene limestone. The shoals develop on topographic highs.

One shoal studied by Newell et al. (1960) is 1-3 kilometres wide, and the upper surface of the shoal is covered by about two to three feet of the water. Here 90 percent of the grains are ooliths with thick oolitic coating. The percentage of ooliths decreases with water depth but sometimes they spread out into a belt up to 60 kilometres wide.

It is presumed that the oolitic grainstones in the Qom Formation record the former presence of oolith shoals similar to those of the Bahama Bank. Environmental conditions were essentially similar, except for the steep slopes to oceanic depth in the Bahamas. The location of the shoal was probably determined by pre-existing

topographic highs on the surface of the Lower Red Formation. Because of their shifting nature, oolith shoals form an unstable substrate and this is unfavourable for the benthonic organism (Purdy, 1964).

The absence of carbonate mud in the oolitic grainstones, the high percentage of the coated grains and the occurrence of cross bedding clearly indicate that these rocks were deposited under conditions of high water turbulence. The occasional presence of a benthonic fauna in some of the oolitic grainstones can possibly be explained by assuming that these fauna lived adjacent to the shoal and were carried on to the shoal by storm waves.

Algal-foraminiferal packstones

The algal-foraminiferal packstones comprise yellowish to reddish brown, thin to thickly bedded bioclastic limestones which are locally cross bedded. The grains are mainly medium sand size bioclasts together with some pelloid types of intraclasts, and some ooliths. Small homogeneous pellets occur sporadically and are locally concentrated in parts of some thin sections. Fine to medium sand-size grains of angular to subangular quartz, zoned feldspar and volcanic rock fragments are scattered through the rocks. Some beds carry abundant terrigenous material.

The bioclastic materials consist mainly of fragments of coralline algae, with abundant tests of foraminifera, mainly miliolids, some peneroplids and rotalids. The tests of small thin-walled miliolids are very well preserved (Fig. 18). Other minor components include fragments of bryozoans, echinoids, pelecypods and gastropods. The bioclasts are abraded and well rounded; they have roughly the same grain size, so that most samples are well sorted.

The distribution of the grains in some of the thin sections shows a

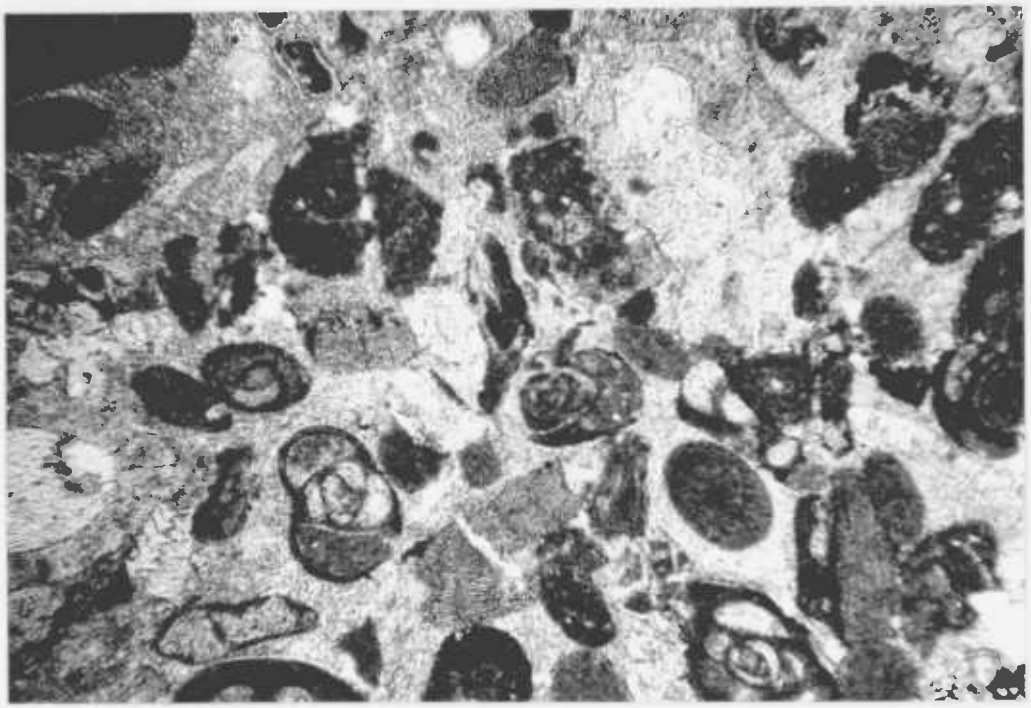


FIGURE 18 a) Photomicrograph of an algal-foraminiferal packstone. Tests of miliolids are well preserved. The original mud matrix has been recrystallized to a coarser mosaic of calcite. Relics of carbonate mud are still present. 'a' Member, Do-Chah section. (x 30).

FIGURE 18 b) Photomicrograph of an algal-foraminiferal packstone from Do-Baradar section. Note that the lithology is identical to that of the above sample. (x 30).

crude form of small scale graded bedding, in that what appears at first sight to be single lamina shows a slight upward decrease in grain size. In one thin section three such laminae were observed.

The original matrix of the rocks appears to have consisted of carbonate mud which 'recrystallized' to form a coarser grained mosaic of calcite crystals (Fig. 18). In many thin sections patches of the original mud matrix are seen to be preserved in the coarser grained recrystallized parts. The tests of foraminifera were also probably filled with microcrystalline calcite which has similarly recrystallized and resembles the intergranular matrix (Fig. 18). Remaining voids are filled with sparry calcite. This facies is locally dolomitized.

Algal-bryozoan packstones

The algal bryozoan packstones are medium to thickly bedded, and are yellowish white to yellowish brown in color. They form the bulk of the 'a' Member throughout the area of study. Sometimes they occur intermixed with the algal-foraminiferal packstones.

Fragments of coralline algae and bryozoans together with pelecypods are the dominant skeletal components of the rocks (Fig. 19); they also contain echinoid and gastropod shell debris. Tests of miliolid, peneroplid and rotalid foraminifera are scattered throughout. Segments of Halimeda are occasionally present, but they are not common.

The kind and abundance of the skeletal debris varies from bed to bed and from locality to locality. Either algae or bryozoans, and in some cases pelecypods, predominate. Occasionally, a layer within a bed may consist predominantly of one fossil type only.

Fossil fragments range in size from sand to granule, and rocks can be described as calcarenites and calcirudites. Large fragments

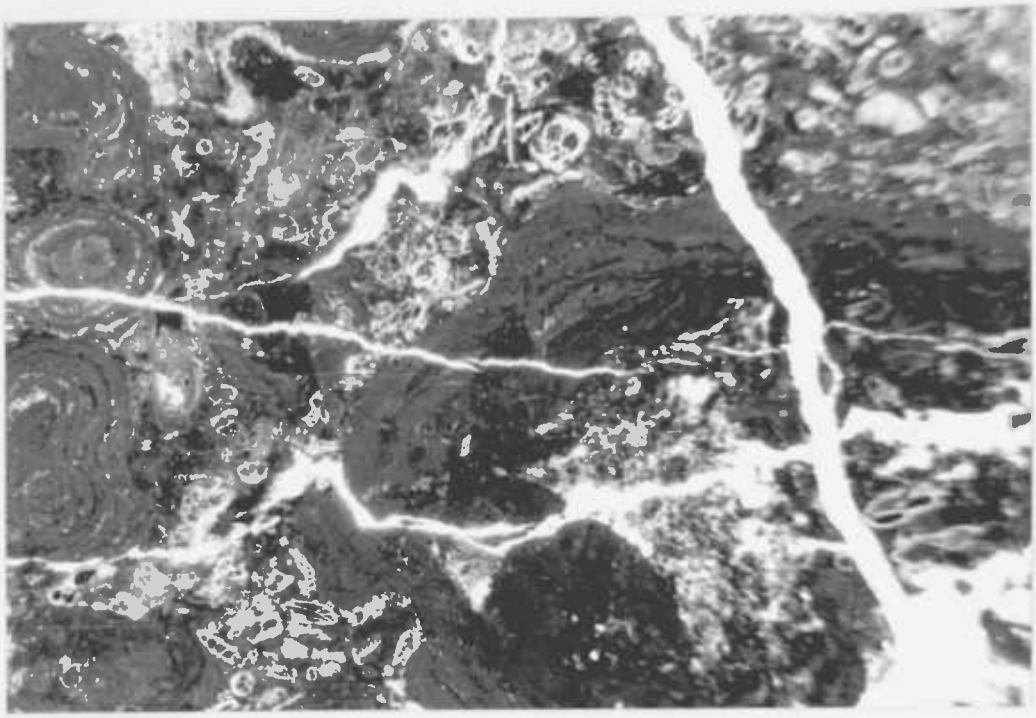


FIGURE 19 a) Photomicrograph of an algal-bryozoan packstone. Algae are present as crusts around detrital materials and also as large continuous laminae. The rock is poorly sorted and constituents are closely packed. Fractures cut through the various components. 'a' Member, Nardaghi section. (x 7).

FIGURE 19 b) Photomicrograph of an algal-bryozoan packstone in which pelecypod shell fragments are also common. 'a' Member, Nardaghi section. (x 7).

of coralline algae coat the skeletal fragments. Terrigenous detritus is also trapped between the algal laminae. In most of the thin sections which have been examined, skeletal fragments are angular to well rounded and of several size grades, so that the rocks are poorly sorted. Some sections show an upward increase and subsequent decrease in grain size, but others show an irregular upward trend. Packing of the grains varies in the samples and in some thin sections the grains are fairly tightly packed.

Intraclasts occur in some thin sections. They are rounded to subangular and elliptical to irregular in shape. They are usually composed of micrite, fossiliferous micrite, or argillaceous micrite. Irregular and subangular intraclasts resemble the matrix. Ooliths are also occasionally found. Small homogeneous pellets probably of faecal origin are locally present in some thin sections.

Terrigenous detritus in coarse grade size consists of feldspar, quartz and volcanic rock fragments. These are fine to medium sand size and show relatively good sorting. Pockets of fine grained terrigenous material occur in some samples. The distribution of terrigenous material is uneven and varies from bed to bed and also within the one bed.

Where a matrix is present, it consists of lithified carbonate mud. Partially recrystallized carbonate mud is present in some samples. Fossil chambers are also sometimes filled with microcrystalline calcite. Sparry calcite cement has been precipitated in those intergranular and intragranular pores not formerly occupied by mud. In several instances, calcite cement has been precipitated as overgrowths on echinoid fragments; examples have been found in which these crystals of calcite grew so large that they surrounded and enclosed several adjacent grains. Micritized grains are fairly common. The aragonitic shells of gastropods are mostly broken

by compaction, but some small ones are preserved unbroken.

Skeletal fragments and matrix are mostly iron stained and many grains are rimmed with iron oxide. The cement is not and remains clear. A green substance, presumably glauconite, fills some of the fossil chambers. The same material occurs also as distinct grains which are subrounded to irregular.

In two of the measured sections this facies has been partially dolomitized. In the dolomitized rocks dolomite rhombs are either scattered as isolated individuals or concentrated in patches. Generally, the rhombs occur in the microcrystalline carbonate matrix, which they appear to have replaced. The mud-filled chambers of fossils were also favourable locations for dolomite replacement. There is also an association between the occurrence of rhombs and the iron stained parts of the rocks. Many rhombs are rimmed with a ferric oxide stain. Some of the dolomite rhombs have been dedolomitized.

Stylolites are developed in the more argillaceous samples. Sub-parallel and intersecting calcite healed fractures are abundant (Fig. 19).

Environments of deposition of the algal-foraminiferal packstones and algal-bryozoan packstones

The algal-foraminiferal packstones and algal-bryozoan packstones were from various lines of evidence deposited in shallow sublittoral environments. The inferences about the environment of deposition are drawn from comparison of these rocks with Recent sediments from the Persian Gulf off the coast of Qatar and off Abu-Dhabi: Bathurst (1975).

Around Qatar the nearshore shelf sediments are rounded calcarenites

composed of bioclastic sands and gravels. Bioclastic fragments are abraded and rounded and the sediments are well sorted The foraminiferal assemblage consists of miliolids and textularids. Further offshore these sediments pass into skeletal calcarenites composed of angular bioclastic fragments which have been broken down mainly by feeding organisms. In both of these environments finer sediments and coarser grains are deposited in depressions and on elevations of the sea floor respectively. The bioclastic calcarenites pass seaward into marly calcarenites and marls.

Off the coast of Abu-Dhabi sediments consist of bioclastic sands. Abrasion of the sand is negligible and grains are angular. Many shells are unbroken and many pelecypod shells remain articulated after death. The distribution of the grains is related to the buttom topography with coarser grains accumulating on topographic highs and finer materials in the depressions.

According to Bathurst the lithofacies and foraminiferal assemblages in these areas are controlled by depth, and in this regard Textularia is a common inner shelf genus and peneroplids are also abundant in the shallowest seas off Qatar. Miliolids have been reported by various writers from lagoonal and the shallowest innershore environments in various parts of the world (Henson, op. cit., Schlanger op. cit.).

Composition and grain characteristics of the algal-foraminiferal packstones are similar to those of the rounded calcarenites off the coast of Qatar. There is also a resemblance between the foraminiferal assemblages. It is therefore suggested that this facies of the Qom limestones was deposited in shallow nearshore environments.

The algal-bryozoan packstones of the Qom limestones are also very similar to the skeletal calcarenites off the coast of Qatar and to the

sediments off the coast of Abu-Dhabi. It is believed that the limestones were deposited in shallow sublittoral environments in waters not deeper than the depths suitable for the prolific growth of the calcareous coralline algae, i. e. 30 metres.

Although algal-foraminiferal packstones and algal-bryozoan packstones are laterally continuous throughout the area of study, nonetheless it is observed that the lateral sequence of lithologies is not consistent, and the two rock types are sometimes intricately intermixed. It is possible that the distribution pattern of these limestones was affected by the nature of the surface which developed on the Lower Red Formation prior to deposition of the 'a' Member. The lateral variation and intermixture of the limestones may be the expression of incipient local elevations and depressions on the pre 'a' surface.

Calcareous fossiliferous sandstones

The top of the 'a' Member is formed of calcareous fossiliferous sandstones. The color of the calcareous sandstones varies from reddish green to green. They are thin to thickly bedded with well defined bedding planes. The contact between the calcareous sandstones and underlying limestones is marked by their differences in color, composition and texture.

The sand content of the rocks varies from fifty to seventy percent and appears to be evenly distributed through any one bed. The sand is fine to very fine grained, and comprises quartz, feldspar and volcanic rock fragments. The quartz and feldspar grains are angular to subangular, but the volcanic rock fragments are rounded. The sand grains are well sorted and evenly distributed in the thin section. The sandstones sometimes contain accessory argillaceous material.

The skeletal components are mostly sand sized fragments of bryozoans, echinoids and pelecypods. Tests of foraminifera and fine grained fragments of coralline algae also occur. The skeletal remains are abraded and rounded and some of the algal fragments are badly worn. In the field the echinoid, Scutella, occurs abundantly, and whole and fragmented tests are arranged in zones parallel to bedding. In one exposure five such zones were seen in approximately 3 feet. In this latter case tests and debris occur in thick bands which alternate with more sandy layers, but the sand also carries scattered fragments and a few intact skeletons. Echinoids probably represent in situ accumulations where these organisms once lived. These various components are cemented by sparry calcite.

There is intensive development of stylolites in these rocks. The stylolites are closely spaced in subparallel array parallel to the bedding. The stylolite seams are filled with fine reddish or gray clay-like material.

Environments of deposition of the calcareous fossiliferous sandstones

Calcareous fossiliferous sandstones have a marine faunal content which is in part similar to that of the limestones. The flat echinoid genus Scutella occurs abundantly in these rocks and some beds are crowded with whole tests and fragments of this creature. Heckel (1972) noted that flat echinoids prefer soft sandy substrates, and the optimum conditions for their development are met today in nearshore shallow waters. The abundance of Scutella and its good preservation indicates that it was an indigenous fauna, and this suggests a near-shore environment for the calcareous-fossiliferous sandstones.

3.2 Petrology of the 'c_1' Member

The 'c_1' Member is the thickest unit of the Qom Formation It is formed of alternations of marls and limestones but the proportions

and thicknesses of the various limestone and marl beds vary considerably over the area. It reaches up to 350 metres in thickness in the Do-chah section, where it also contains the highest proportions of limestone. Although a large part of the member consists of marls, limestones are nevertheless abundant and are impressive topographically. The limestones, with the exception of the Do-Baradar 'reef' which will be dealt with separately, can be broadly divided into three lithofacies which are developed in different parts of the region. These lithofacies are: sandy bioclastic limestones, bryozoan-foraminiferal packstones, and algal-foraminiferal packstones and wackestones each of which will be described in turn.

Sandy bioclastic limestones

The sandy bioclastic limestones are mainly found in the basal parts of the 'c_1' Member in most of the measured sections. The rocks are reddish in color. The red body color of the limestones is due to the iron stained fossil debris and the red color of the fine detrital material. The fossils consist of tests of foraminifera and sand size fragments of bryozoans, coralline algae, echinoids and pelecypods (Fig. 20). Intraclasts of the same grade size are common.

The limestones contain a significant proportion of terrigenous detritus of sand grade. These grains are mainly plagioclase feldspars and volcanic rock fragments. Fine grade detrital material is also incorporated in the matrix. The high content of terrigenous detritus, far more than that found in the other facies, is one of the distinguishing characteristics of this facies. Glauconite grains and infilling by glauconite are another common feature. Microcrystalline carbonate matrix and sparry calcite cement are present in roughly equal proportions. The limestones are usually porous, but the porosity is low and was produced by secondary dissolution.

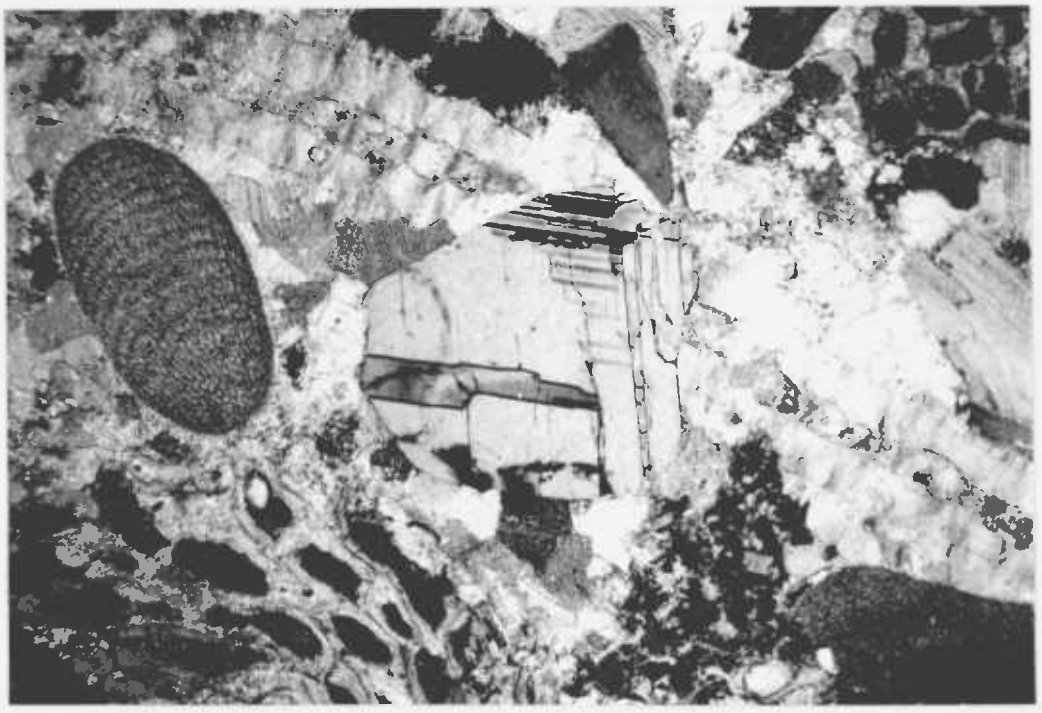


FIGURE 20 Photomicrograph of a sandy bioclastic limestone under crossed polarizers. 'c_1' Member, Do-Baradar section. (x 64).

Bryozoan-foraminiferal packstones

The bryozoan-foraminiferal packstones are buff, gray or yellow, to yellowish brown in color. They are thin to thickly bedded and at outcrop form sharp topographic ledges and walls. In some sections they form the bulk of the 'c_1' Member.

Fragments of bryozoans and unbroken tests of large benthonic foraminifera are the main components (Fig. 21). They are generally present in approximately equal proportions, but in some instances one or the other may predominate. Skeletal fragments of pelecypods, echinoids, encrusting and branching coralline algae are present in less abundance. Tests of small benthonic and planktonic foraminifera are found in minor proportions in many samples but are locally relatively abundant. Segments of Halimeda occur in some samples.

The limestones contain sand sized terrigenous detritus, mainly angular grains of plagioclase feldspar and some quartz and volcanic rock fragments. In many samples, the carbonate grains are coated and pervaded by brown iron oxides. Green to yellowish green grains of the iron silicate mineral glauconite are common both as discrete grains and as an infilling of chambers in some of the skeletal remains. It is sometimes altered to reddish-brown masses of iron oxide, but these are different from the iron oxide stain previously described.

The grain size of the skeletal fragments ranges from fine sand to gravel grade and in some specimens a large fragment of a bryozoan or an alga may comprise the whole of a thin section. Most rocks are coarse grained and poorly sorted and the bioclasts are often angular. Where the proportion of carbonate mud matrix is small, packing of the skeletal material is usually tight and many of the grain contacts are sutured (Fig. 21). In some instances skeletal fragments were broken in places, presumably by compaction. Some of the intragranular as well as intergranular spaces are occupied by the microcrystalline carbonate mud, often with some fine grained terrigenous

FIGURE 21 a) Photomicrograph of a bryozoan-foraminiferal packstone. The rock is composed mainly of fragments of bryozoans and whole tests and fragments of benthonic foraminifera. The packing of the grains is relatively tight. 'c_1' Member, Do-Chah section. (x 7).

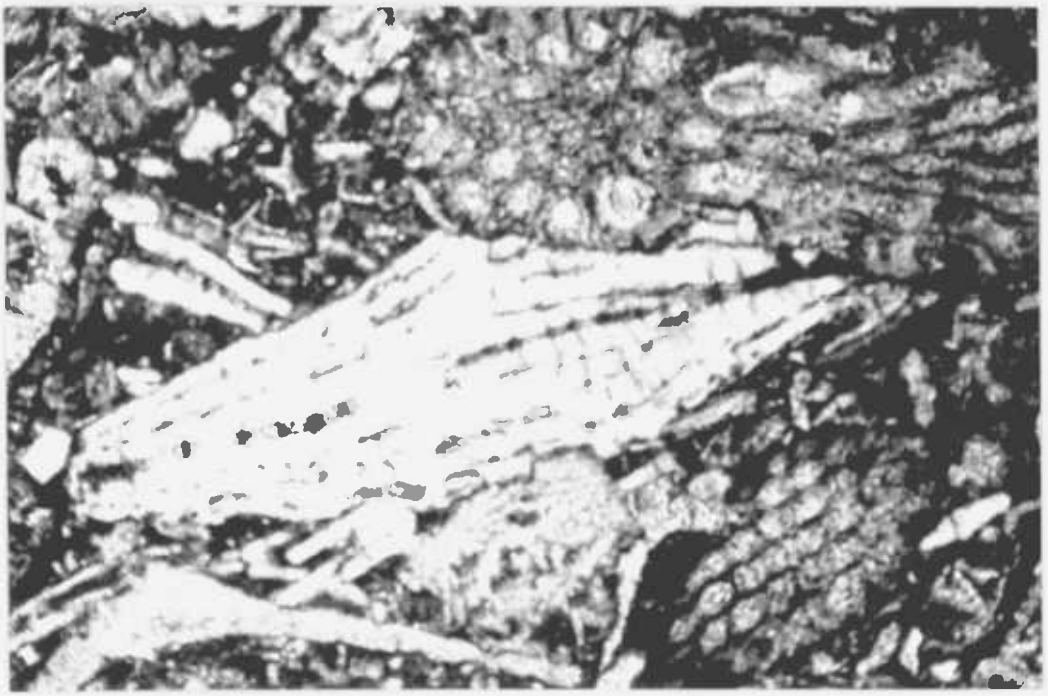


FIGURE 21 b) An enlarged view of the above lithology showing the tight packing and sutured contacts of the grains. (x 45).

detritus. The matrix is often stained by iron oxide, and there are sometimes a few non-stained pellets of uncertain origin. All of the remaining spaces are filled by sparry calcite. Examples are found in which some of the fossil fragments are replaced by silica. The carbonate matrix of the intergranular and intragranular spaces is also locally replaced by silica. The mode of silicification will be dealt with in a later chapter. Subparallel and intersecting fractures filled with sparry calcite are abundant. The fractures cut through skeletal grains, matrix and cement, thus indicating that they occurred after lithification.

Algal-foraminiferal packstones and wackestones

The algal-foraminiferal packstones and wackestones are light gray, yellowish or yellowish brown in color. They are made up of fragments of coralline algae and tests of foraminifera (Fig. 22) in association with large fragments of corals with minor contributions of echinoid, pelecypod and bryozoan debris. Some of the algal fragments are highly abraded and their cellular structure in many cases is only detectable under high magnification. Non-carbonate detritus and carbonate mud are sometimes trapped between the algal laminae. In some thin sections large fragments of coralline algae which have encrusted bryozoan colonies, pelecypod shells, foraminiferal tests or coral heads are occasionally seen. These may be parts of large algal masses which were broken up, transported and redeposited along with other fragments at various distances from their source. Corals occur mainly as large fragments. Their interseptal cavities are filled with very fine grained skeletal detritus or carbonate mud. The walls of the corals appear to have been diagenetically altered to coarser grained calcite.

The rocks are poorly sorted and often contain varying proportions of argillaceous material. Sometimes the distribution of fossil

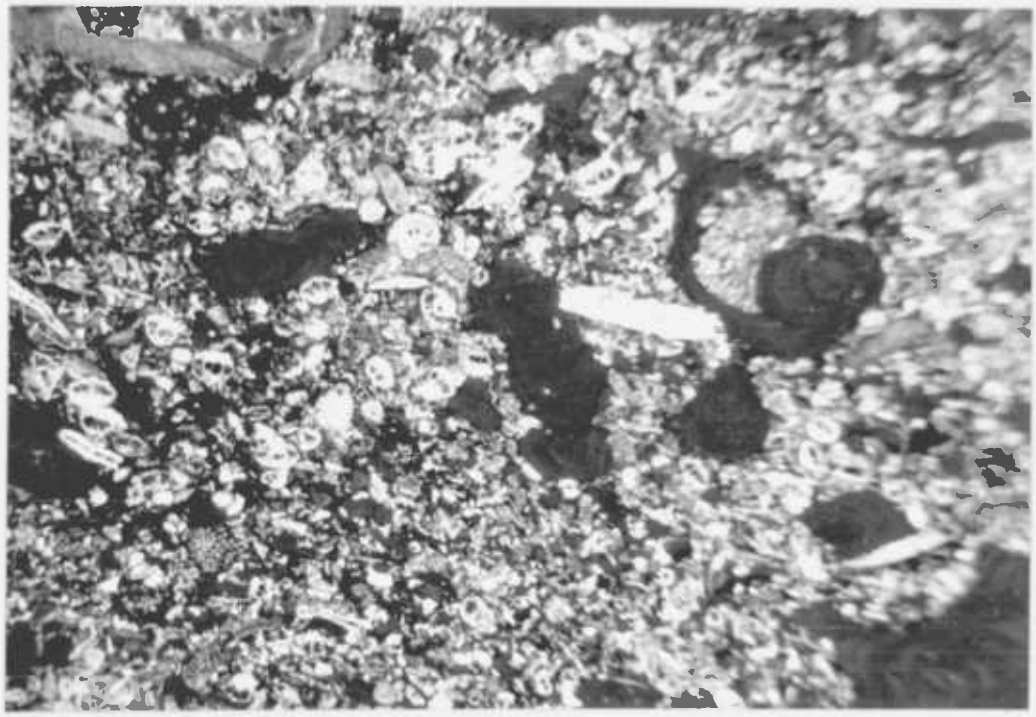


FIGURE 22 a) Photomicrograph of an algal-foraminiferal packstone. The rock is composed of tests of benthonic foraminifera and fragments of coralline algae with minor contributions of other fossil debris and is poorly sorted. 'c_1' Member, Do-Baradar section. (x 7).

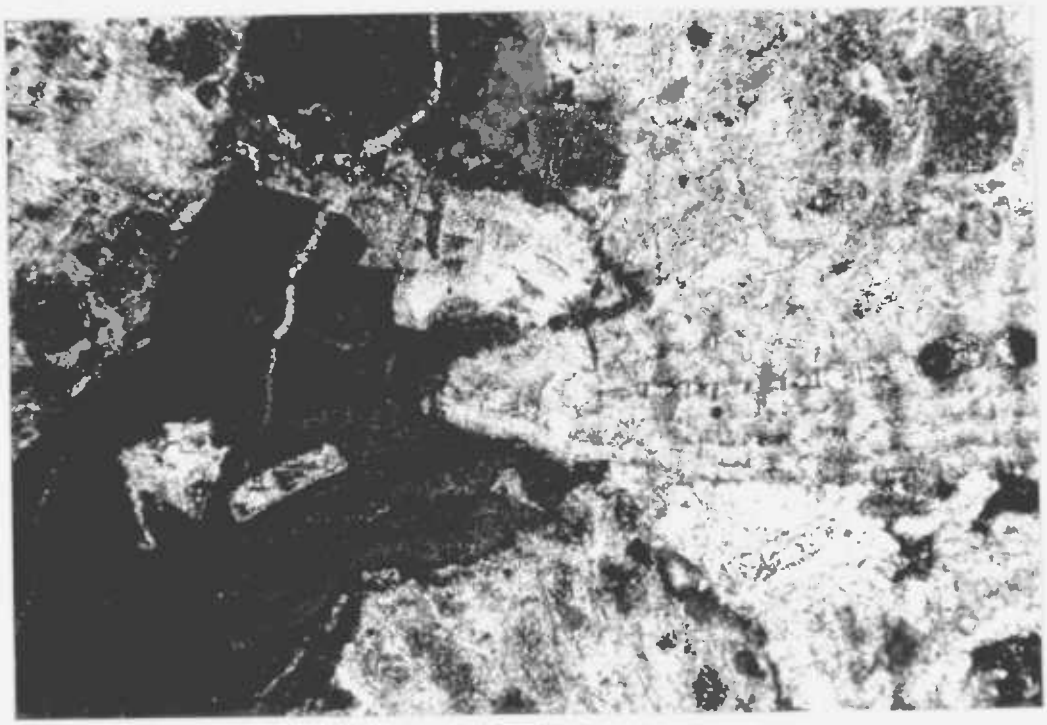


FIGURE 22 b) Photomicrograph of a different texture in the above lithology. 'c_1' Member, Do-Chah section. (x 40).

fragments is patchy even in the one thin section. Locally a few skeletal fragments may float in what is otherwise mud and terrigenous detritus only, while elsewhere the same thin section is dominantly skeletal. Carbonate mud matrix is sometimes recrystallized to a coarser grained mosaic of calcite. Original voids are filled with sparry calcite, but some late dissolution voids are present.

The marls

The marls which alternate with the limestones of the 'c_1' Member are locally developed in thicknesses of up to several metres. In some cases they show distinct bedding, but in others the bedding planes are not distinct. They are yellowish gray in color.

The alternating marls contain a similar fauna to that of the limestones, but they carry a larger content of silty terrigenous material and are poorly indurated. Large benthonic foraminifera such as Lepodocyclina are locally concentrated, sometimes extending through about 1.8 metre vertical thickness. Other large and small benthonic and planktonic foraminifera are also common. Fragments of bryozoans, in various sizes, are the other fossil component. Oyster and coral debris are also present.

3.3 Petrology of the Massive Limestone of Kuh-e-Do-Baradar

As previously mentioned, the 'c_1' Member is formed of alternations of limestones and marls. In most of the Qom area the limestones have very steep dips and in places they stand almost vertically. At one place, Kuh-e-Do-Baradar, the alternations of marls and limestones are not developed and the member becomes entirely massive (Fig. 23) and is more than a hundred metres thick and about 1500 metres across. It stands on end by virtue of the near vertical dip. Laterally towards the west it passes abruptly into marls with only slight interfingering, but towards the east it interfingers with the marls over larger distances (Figs. 24, 25).

FIGURE 23 Kuh-e-Do-Baradar, massive limestone. The beds are nearly vertical. Looking south.

Kuhe-Do-Baradar is about 120 metres above the foreground

FIGURE 24 Interfingering of the massive limestones of the Kuh-e-Do-Baradar with marls to the east of the Do-Baradar mountain. Looking west-northwest.

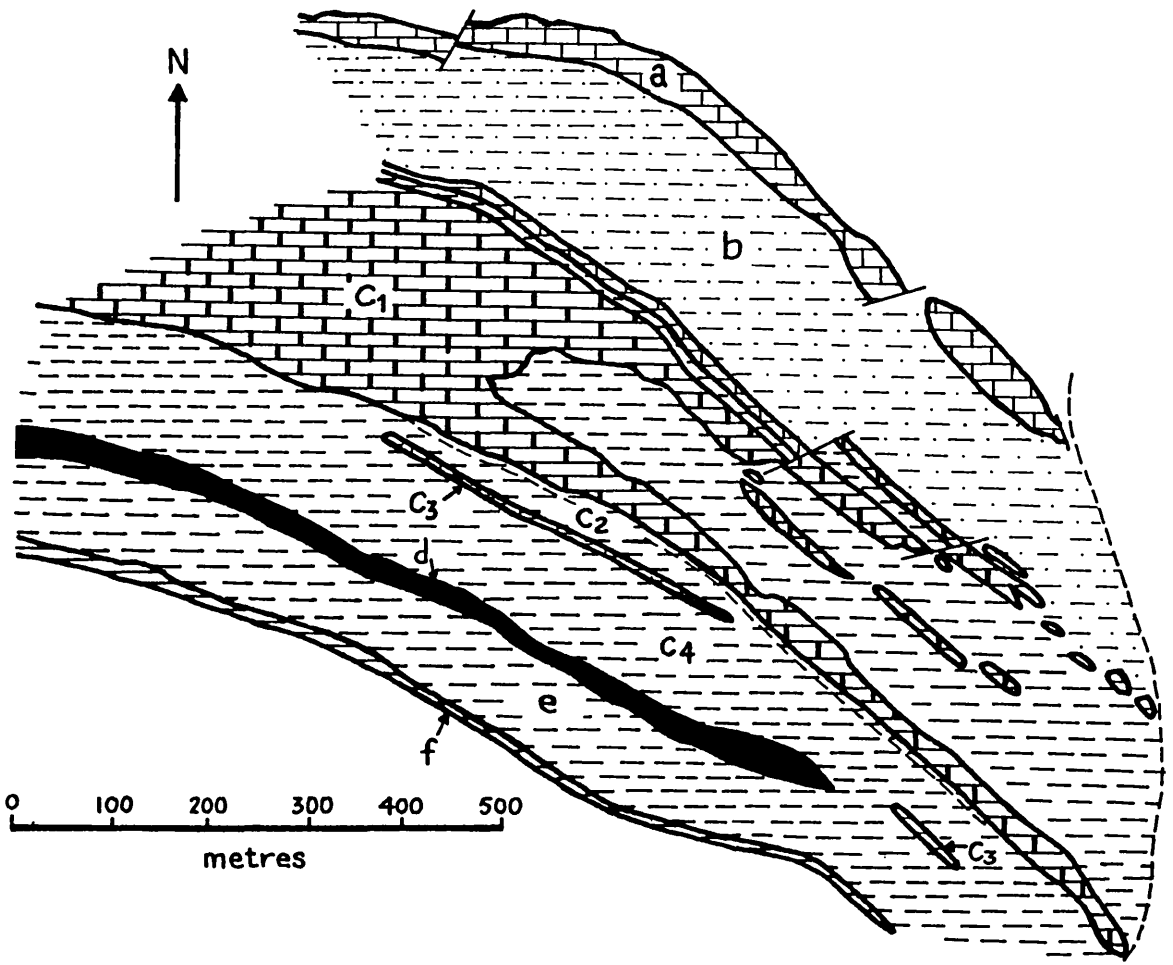


Figure 26 A map view showing the passage and interfingering of the massive limestone of Kuh-e-Do Baradar with marl to the east of Do Baradar

The central part of the build-up appears to be massive but towards the lateral parts bedding becomes distinct. The near vertical dip and the near vertical face prevent close inspection of the individual beds over a large part of the exposure. The east side of the build-up presents a section of the limestone beds approximately parallel to the strike. These beds have slight lateral variation in thickness. The build-up was termed a 'reef' by previous authors (Furrer and Soder 1955; Vatan, 1966), and its general appearance does indeed accord with the suggestion.

The term 'reef', especially when it bears genetic implication, has caused much confusion and disagreement among geologists (Heckel, 1974). For this reason, Heckel suggested the term "build-up" for "positive topographic features in a descriptive sense in order to avoid controversy concerning origin".

Further petrographic study of the Do-Baradar 'Build-up' revealed no essential difference between these rocks and the normal bedded limestones of the 'c_1' Member. There is no obvious framework, and all the rocks comprise skeletal debris. The term 'build-up' has therefore been assigned to the Do-Baradar development in the Qom region. Heckel also suggested a descriptive terminology for the various carbonate build-ups based on their various characteristics. In the view of the present author, distinction of build-ups according to shape is probably a useful scheme; however, because the Do-Baradar build-up is only partially exposed, no attempt has been made to identify it by shape, and the general term 'skeletal build-up' can best be used.

Three sections, as complete as possible through this build-up, were measured and sampled at approximately 3 metre intervals. One section was chosen in what appears to be the center or 'core' of the build-up, and two sections on lateral parts, one on the west side and another on the interfingering east side. The petrography

of these rocks is dealt with in the following pages. It has been found that the details of the composition and texture sometimes vary significantly, both vertically and laterally over short distances, sometimes even within a single hand specimen; but no systematic change in the composition and texture occurs vertically nor from one section to another. A variety of rock types define the limestones of the build-up, any one of which may predominate in a particular part of each section. For purposes of illustration some of the rock types will be discussed.

Algal-foraminiferal-bryozoan packstones

These rocks contain abundant tests of large benthonic foraminifera both whole and fragmented, abundant colonies of bryozoans, nodules of encrusting coralline algae and fragments of branching coralline algae (Fig. 26). Other minor organic constituents include: corals, echinoids, pelecypods, and small benthonic and planktonic foraminifera. Coralline algae have occasionally functioned as binding agents and trapped fine skeletal detritus.

These components range in size from fine sand to gravel and the rocks are poorly sorted. Skeletal debris is present both as rounded and freshly broken angular grains. Carbonate mud matrix is present mostly in the intergranular pores. Intragranular areas are usually filled with sparry calcite but some contain carbonate mud. The distribution and relative abundance of the three more abundant faunal elements, micrite matrix and sparry calcite vary in different thin sections.

Foraminiferal-algal packstones and wackestones

Foraminiferal-algal packstones and wackestones are the common rock types throughout the sections, but there are minor variations in composition and texture. The rocks consist mainly of tests of benthonic foraminifera and fragments of coralline algae (Fig. 27).

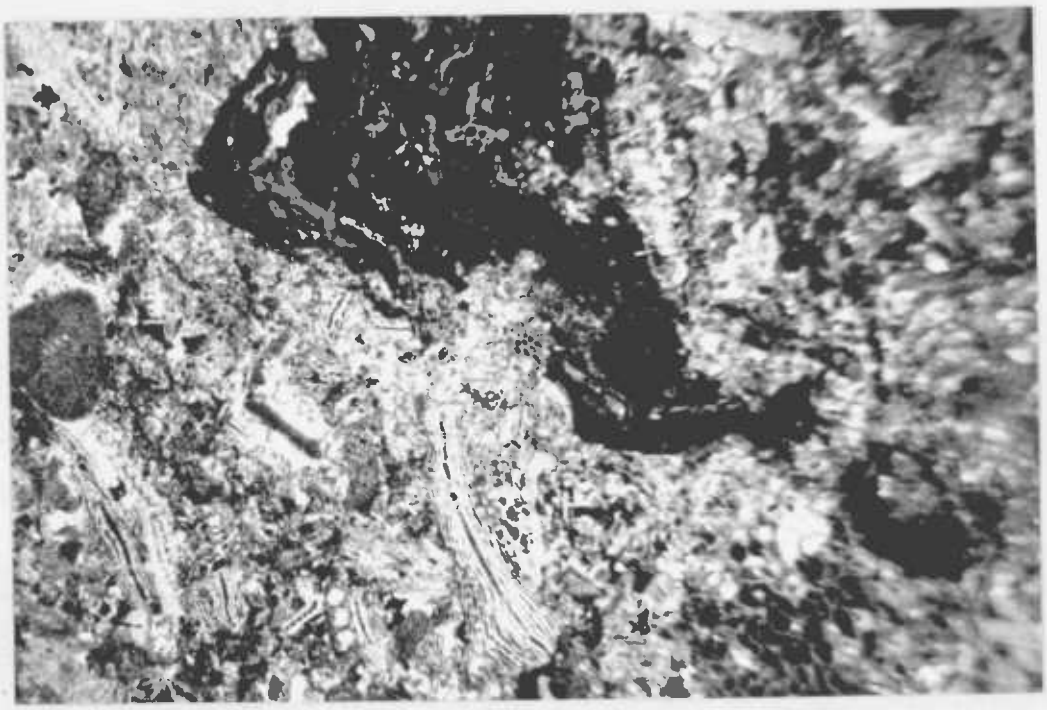


FIGURE 26 Photomicrograph of an algal-foraminiferal-bryozoan packstone. The rock shows variation in composition and texture. 'c_1' Member, Do-Baradar build-up. (x 7).

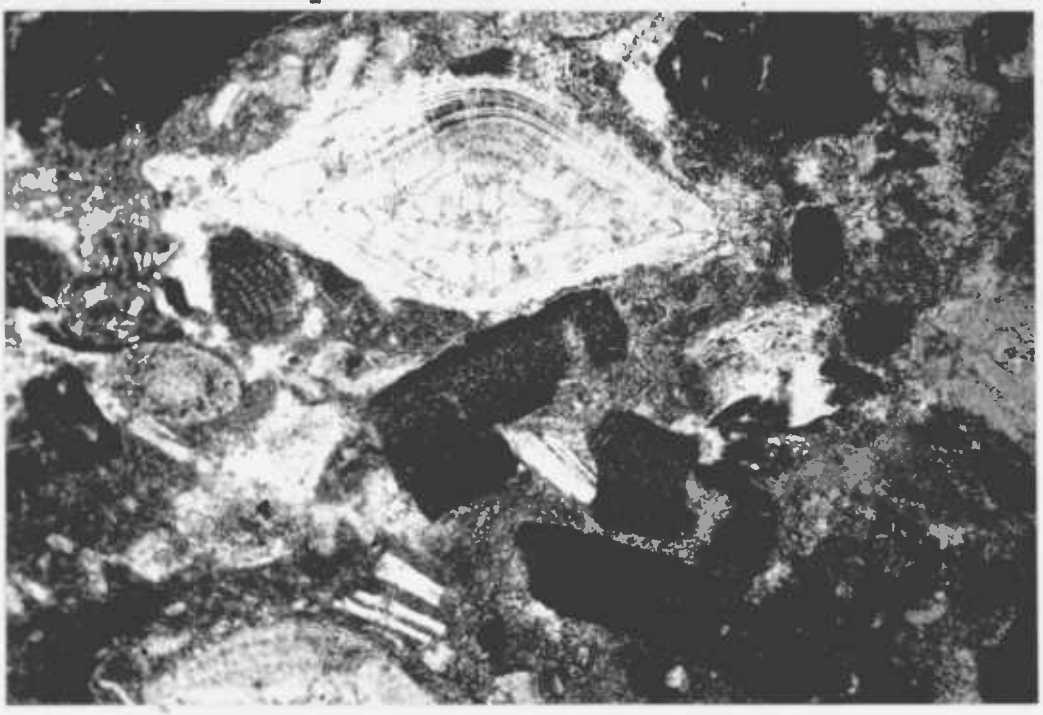


FIGURE 27. Photomicrograph of a foraminiferal-algal packstone. The rock is composed mainly of tests of benethonic foraminifera and fragments of coralline algae set in a carbonate mud matrix. The carbonate mud matrix is partialiy recrystallized. Algal debris is also affected by recrystallization. 'c_1' Member, Do-Baradar build-up (x 30).

Other components which are present in minor amounts include pelecypod shell debris, fragments of corals, bryozoans and echinoids.

The skeletal fragments are of sand grade size to gravel size, and they are poorly to moderately well sorted. In some thin sections the rocks are sparsely fossiliferous, whereas others contain abundant fossils (Fig. 27). In the latter rocks the grains locally have a tight packing, and sutured contacts are observed here and there.

The skeletal components are set in a carbonate mud matrix. The mud matrix is everywhere recrystallized and various stages in the process can be seen. Most commonly the recrystallization has produced a mosaic of clear calcite without any trace of mud.

Algal packstones and wackestones

Algal limestones are the third rock type in the Kuh-e-Do-Baradar 'build-up'. They are composed predominantly of poorly to moderately well sorted fragments of both branching and encrusting coralline algae with minor proportions of other fossil fragments.

A large proportion of mud matrix is usually present, and texturally the rocks range from wackestones to packstones. In the wackestones, skeletal debris appears to float in a micrite matrix but in the packstones the skeletal fragments are sufficiently abundant to form a grain supported framework.

Recrystallization of the carbonate mud matrix is locally intense in the packstones, but in some of the wackestones the effects of recrystallization appear to be much less severe (Fig. 28). In the packstones the grains are mostly algal; they are occasionally all of approximately the same size, and are rounded to subangular. In some

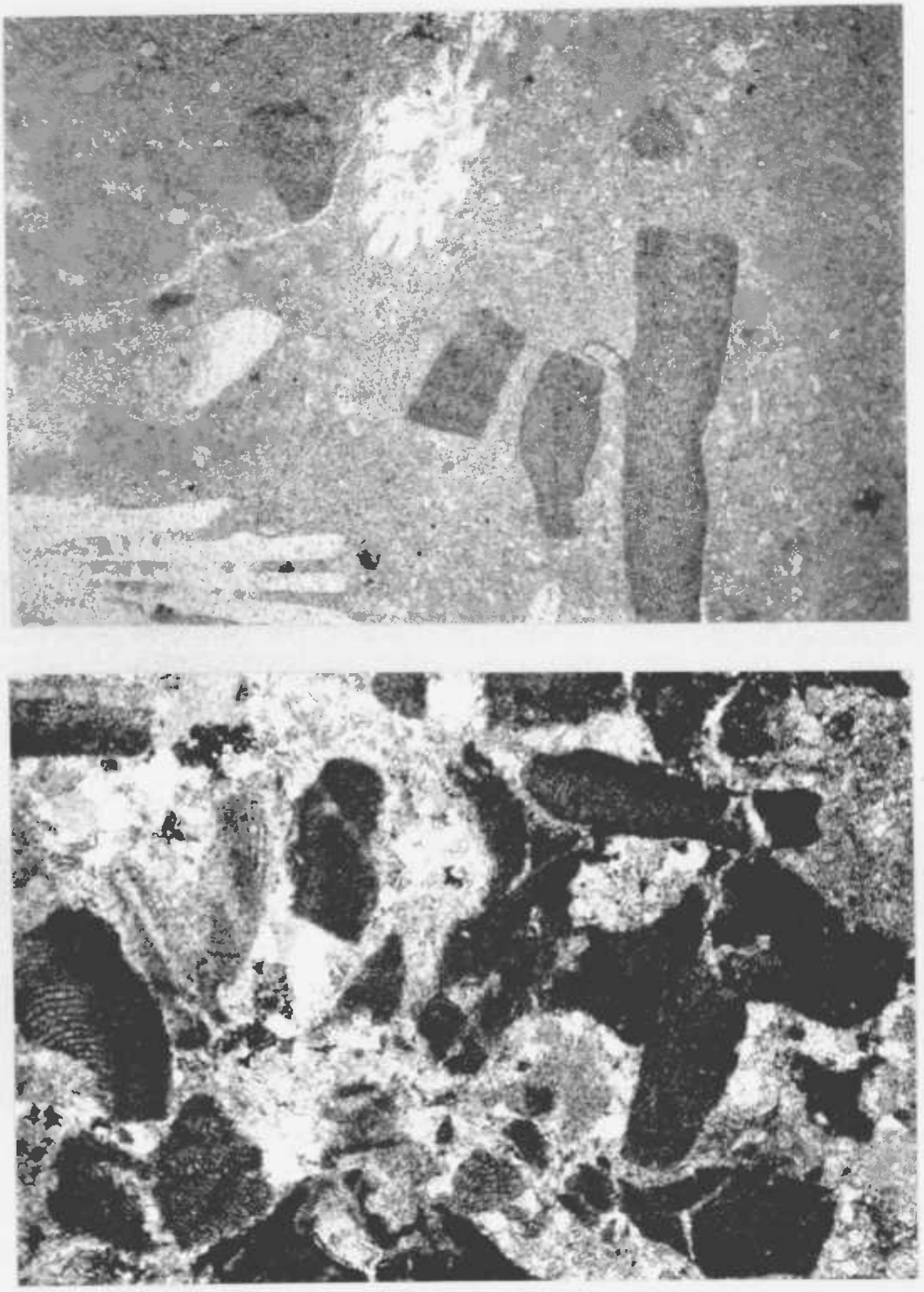


FIGURE 28 a) Photomicrographs of an algal wackestone (above) and an algal packstone (below). The packstone is intensely recrystallized. These two rock types are found mainly towards the top of the build-up and on the sides of it. 'c_1' Member, Kuh-e-Do-Baradar build-up. (x 30).

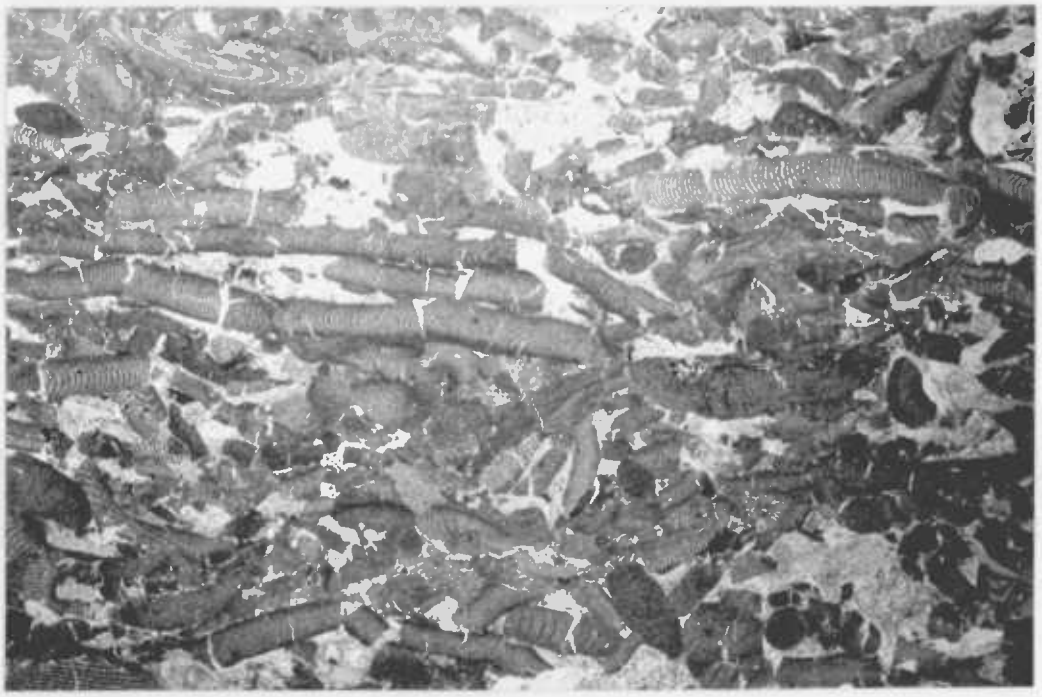


FIGURE 28 b) Photomicrograph of an algal packstone from the central part of the Kuh-e-Do-Baradar. (x 15).

thin sections of the packstones skeletal fragments lie sub-parallel to bedding, but commonly they do not show an obvious orientation.

Other rock types are variations on the themes described above, but they do not show an obvious trend. However, the core of the build-up is composed mainly of algal-bryozoan-foraminiferal packstones and algal-foraminiferal packstones. Algal-foraminiferal wackestones are most abundant in the lower parts of the lateral measured sections, and algal packstones and wackestones increase in frequency towards the top of the west side and form the bulk of the interfingering east side of the build-up. The boundaries between the various carbonate rock types are not always clear cut and some of the rock types of the lateral and central parts cannot be obviously differentiated.

The rocks are porous, but the porosity is secondary and was produced by dissolution.

Terrigenous sand grains are present in all of the various rock types but only rarely do they comprise more than 2 percent of the rock.

Environment of deposition of the 'c_1' Member

The depositional environment of the 'c_1' Member can be inferred from certain of the biological and lithological characteristics of the rocks. It is thought that the limestones were deposited as follows:

After deposition of the 'b' Member influx of clay became reduced. Skeletal carbonate sediments then began to accumulate. Benthonic organisms pioneered the shallow sea bottom and the fauna became progressively more diverse. During this early phase, influx of the sand size terrigenous material was substantial, so that sandy bioclastic packstones were deposited.

At those times when influx of terrigenous detritus was small the sea floor was a broad well illuminated area on which various carbonate secreting organisms grew prolifically. Red algae began to appear in abundance. They encrusted various skeletal materials and at the same time bound and trapped tiny suspended carbonate grains. In situ breakdown of the algal skeletons produced further carbonate sediment. Although algae may have formed wave resistant crusts, they probably did not build a wave resistant structure. Large benthonic foraminifera flourished and their tests contributed significantly to the sediments. Bryozoans encrusted the tests of these large foraminifera. Corals became abundant locally and coral heads grew in size up to 1 metre across. Some organisms such as coralline algae, corals and bryozoans locally functioned as baffles and entrapped some carbonate mud. Agitation of the waters by waves and currents resulted in the fragmentation of the hard parts of bryozoans, corals, pelecypods and echinoids, and continued agitation abraded many of the fragments to some extent, but they were not strongly rounded. These detrital sediments blanketed the sea floor, but locally small bound skeletal structures survived intact.

From the study of the rocks it appears that coralline algae, bryozoans and foraminifera were the main constituents of the rocks and the contribution of corals, echinoids and pelecypods was locally important. Coralline algae require light, moderate water agitation and a firm substrate for their development and they are usually best developed in waters up to 30 metres deep (Heckel, 1972; Milliman, 1974). Bryozoans are suspension feeders and prefer clear water where there is good circulation (Johnson, 1951; Milliman, 1974). A firm substrate is essential for their development (Heckel, 1972). In the Qom limestones this was provided by the tests of foraminifera. Corals are also limited to about the same depths as are coralline algae. Benthonic foraminifera, however, have a wider depth range. The various organisms found in these limestones all

require normal marine salinity (Heckel, 1972). It is therefore suggested that the limestones of the 'c_1' Member were deposited in a shallow water, sublittoral environment with good water circulation, low turbidity, normal marine salinity, and oxygenated bottom sediments.

It is believed that the various facies of the 'c_1' Member were all formed in the same general type of environment. The lateral differences in the abundance of the various elements of the flora and fauna appear to reflect minor differences of environment, and are not of major consequence.

Fluctuations of relative sea level during the deposition of the 'c_1' Member introduced clayey material to the sea from time to time and produced the alternating limestone-marl sequences. The marls contain abundant large benthonic foraminifera and some small benthonic and planktonic genera. The large tests of foraminifera provided a substrate for bryozoans and these fossils are also abundant in the marls (Furon and Balavoine, 1959). While some beds are crowded with tests of large foraminifera, oysters are abundant in others (Vatan, 1966). It is not easy to accurately determine the environment of deposition of the marls. They could equally well have been deposited in deeper or shallower water than the limestones, but the likelihood is that it was shallower and sublittoral.

Environment of deposition of Do-Baradar build-up

Deposition of the alternating limestones and marls continued widespread across the Qom Basin, but in one locality, a carbonate build-up developed. This is called the Do-Baradar (two brothers). It is sited on a shoestring conglomerate at the top of the 'b' Member. This latter probably caused a slight topographic high on the sea bottom which may have been more favourable for the growth of organisms. The various rock types which comprise the build-up

resemble the other facies of the 'c_1' Member although some different rock types are developed. Do-Baradar is essentially a mixed build-up (Heckel, 1974) but in some instances coralline algae become the dominant element. The build-up generally has detrital texture with some scattered bounded structures. It contains abundant recrystallized carbonate mud. The original bedding of the build-up cannot be accurately reconstructed, because distinct core and flanking facies (Nelson et al., 1962) are not developed and the beds do not change much in thickness laterally, except that they ultimately interfinger laterally with marls. The facies of the build-up are comparable with the open shoal-reefs of other Tertiary reef complexes of the Middle East (Henson, op. cit.) and in some aspects the reef-breccia facies of the Louisiana and Guam reef complexes (Forman and Schlanger, op. cit.; Schlanger, op. cit.). In the former shoal reefs developed locally under favourable, clear water conditions, in areas where other types of sediment were predominant. The Do-Baradar build-up might therefore have formed in a local shoaling environment.

3.4 Petrology of the 'c_2' Member

The 'c_2' Member consists of three distinctly different lithologies, which are different in color and are easily recognised at outcrop. Some variations occur within the member in different locations, but generally the three lithologies appear in a sequence from the bottom to the top of the member. The lower part consists of platy limestones. These are succeeded by gypsiferous marls and gypsum, and the upper part is characterized by the occurrence of siltstones and very fine grained sandstones. Rocks of the various units of the 'c_2' Member are softer than the limestones of the overlying member and as a result the member forms a gently sloping valley. However, the platy limestones usually appear as a distinct low ledge. The member is reported to be essentially barren of fossils. Bozorgnia (op. cit.) mentioned the presence of a few ostracods in the 'c_2' Member of the Qom Formation in Central Iran, but there have been none

reported or found in the area of this study.

Platy limestones

These rocks have been called platy limestones by previous authors (Vatan, op. cit). The platy characteristic of the rocks is due to the presence of very thin layers of clay minerals, which allow weathered rocks to split easily along bedding planes. The limestones are yellowish gray in color and up to 8 metres in thickness. Individual beds are laminar and 3 to 5 centimetres thick. The thickness of laminae varies from 3 to 7 millimetres. The laminae are the expressions of slight variations in grain size. They show no other observable sedimentary structures. As a result of the platy bedding and intersecting sets of joints, the rocks split into uniform lozenge-shaped pieces, the fresh surfaces of which have an oily smell.

The platy limestones show some variations and three lithofacies can be recognized. These are: pelletoidal limestones, micrites and recrystallized limestones.

Pelletoidal limestones. The pelletoidal limestones consist of dark uniform pelloids cemented with fine-grained crystalline calcite (Fig. 29). The pelloids are of fine to medium sand grade size, and the majority are ovoid. They are mostly closely packed, although some looser packing is observed in places. The cement is finely crystalline calcite and, where the pelloids are closely packed, the cement appears subtranslucent. In the more sparsely packed parts of the thin section, each pelloid is surrounded by a wide halo of slightly more coarsely crystalline calcite which has a uniform texture throughout the whole of the thin section. Occasionally, examples are found in which larger crystals of calcite have filled the few cavities available to them.

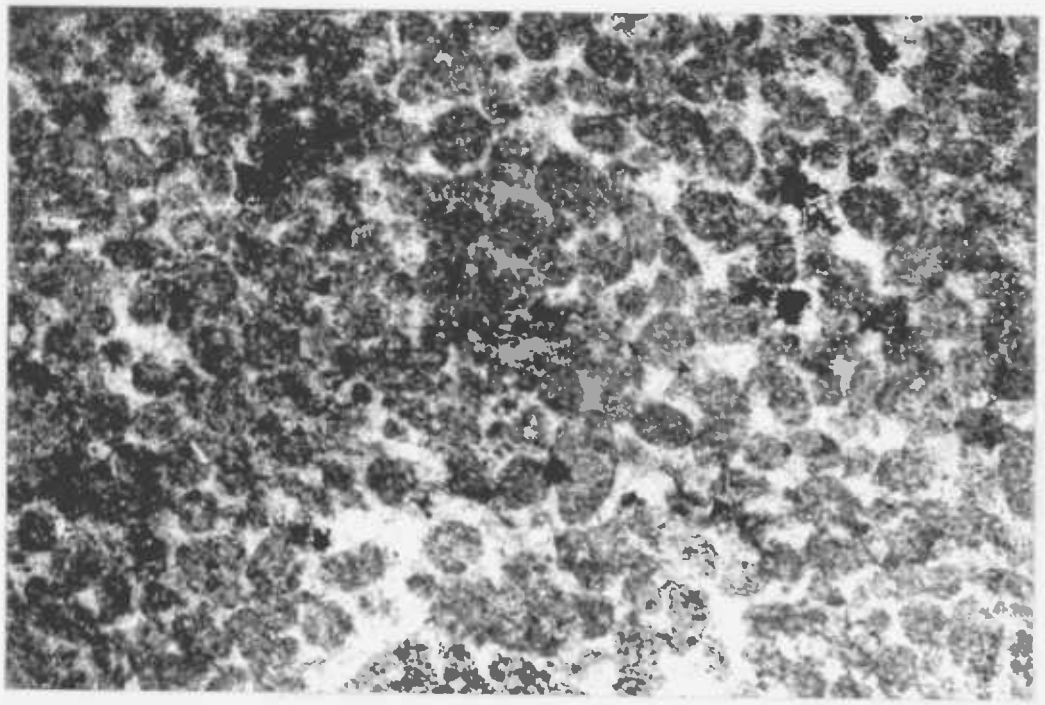


FIGURE 29 a) Photomicrograph of a pelletoidal limestone. 'c_2' Member, Nardaghi section. (x30).

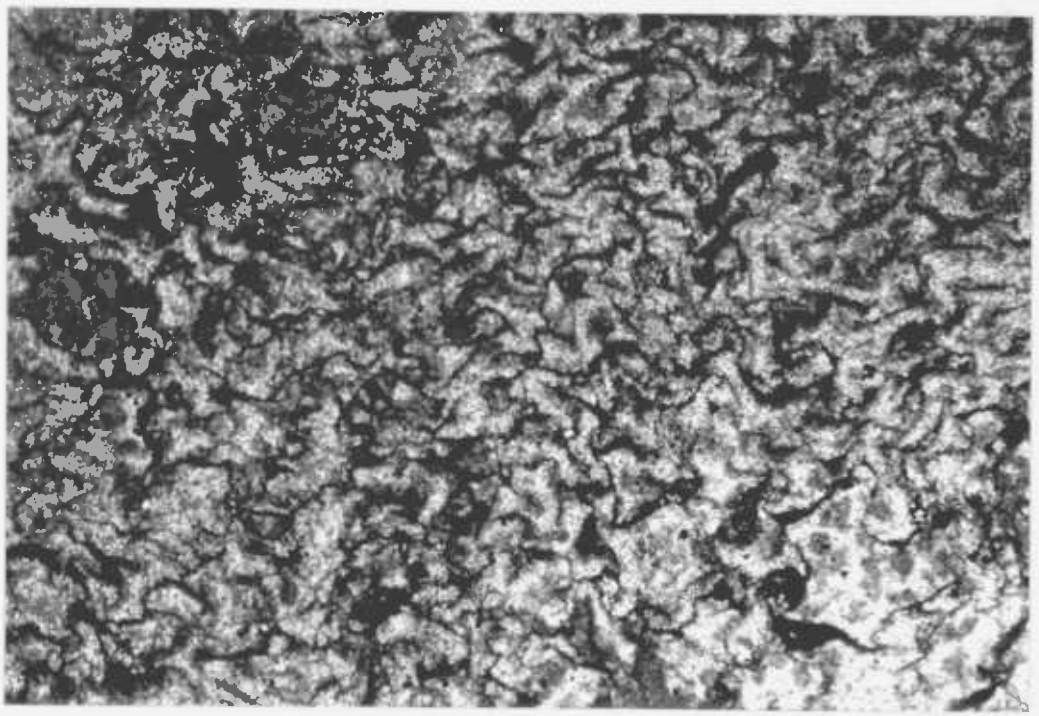


FIGURE 29 b) Photomicrograph of a different texture in the above lithology. Darker areas are iron staining. 'c_2' Member, Nardaghi section. (x30).

Other variations include rocks which are composed of admixtures of tightly packed fine sand size pelloids, silt sized irregular pelloids, and micrite or finely to coarsely crystalline calcite (Fig. 29). The coarser pelloids occur as clotted micrite masses. The boundaries of grains are indistinct, but the individual pellets can be positively identified under higher magnification. Silt sized pelloids are sparsely spaced and some are vaguely defined; they are evenly intermixed with micrite or finely crystalline calcite. Some of the silt sized pelloids have blurred edges. In some of the thin sections, patches of coarser pelloids are absent and the rock comprises fine grained pelloids and finely to coarsely crystalline calcite. The texture of these rocks is identical with the grumeleuse texture described by Cayeux (1935). It is difficult to decide whether the pelloids were inherent depositional grains which were later cemented by calcite, or whether the texture was produced by recrystallization of carbonate mud. The evidence for recrystallization is scanty and no relic patches of micrite can be seen. Another possibility is that the texture was produced by bioturbation of an originally pelletoidal mud.

Small pellets of iron oxide are scattered in almost all of the thin sections of this rock type and are locally concentrated. They are rounded, uniform in shape, and deep reddish brown in color. It is thought that the pellets are formed only of iron oxides. There are other small pellets which are only stained with iron oxides. In this latter type the dark grayish body color of the pellets can be seen at the grain edges. Irregular small concentrations of iron oxides are also abundant.

Recrystallized limestones. These limestones have a crystalline texture. They are composed of calcite crystals of various sizes which are randomly distributed through the thin sections. Although small crystals predominate, coarser ones are not uncommon. Patches of microcrystalline calcite occur in most of the thin sections. These

features suggest that the textures of the limestones were produced by the recrystallization of carbonate mud

Micrites. The micrites are formed of uniformly textured microcrystalline calcite. The rocks are porous. The pore spaces are of very small size and appear uniformly distributed in the thin sections.

Gypsiferous marls

The marls are thinly bedded and light yellow in color. They contain various proportions of clay material and gypsum crystals. In some parts gypsum is developed as bands or beds and is grayish white in color. In some sections it shows layering, but not any other sedimentary structure. Gypsum beds are usually found on top of the platy limestones and are only separated from them by a thin layer of marl. Gypsum is in turn followed by gypsiferous marls and siltstones.

Siltstones and sandstones

The siltstones of the 'c_2' Member are reddish to grayish green in color. They show various structures and textures which are present in different parts of the sections.

Generally, they are thinly bedded and calcareous in the lower parts. Petrographically, they consist of clay minerals and silt size subangular grains of quartz, feldspars, mica and some microcrystalline calcite.

The siltstones of the upper parts show irregular wavy and lenticular bedding (Reineck and Wunderlich, 1968). Petrographically, they are largely formed of terrigenous silt grains, which consist of feldspar, volcanic rock fragments and mica. They also contain some microcrystalline calcite and iron oxide. The texture of these

rocks shows some variation. In some examples silt is evenly intermixed with finer clayey material, whereas in others the silt is segregated and interlayered with the clayey material.

The sandstones are red in color and thin-bedded. They are rippled towards the top. Ripples are symmetrical and sharp crested with average amplitude of 2 centimetres and wave length of about 10-15 centimetres. Petrographically, the sandstones are composed of fine sand sized grains of volcanic rock fragments, quartz and feldspar. They contain various proportions of iron oxides both as grains and as staining.

Environment of deposition of the platy limestones

It is difficult to infer the environment of deposition of the platy limestones accurately. The rocks are devoid of fossils and do not show any sedimentary structures other than thin bedding. Some of the pelloidal limestones are mottled and this is attributed to bioturbation. These characteristics are not indicative of a single particular environment; they could develop under a variety of environmental conditions. Nevertheless, for reasons that will be discussed below, it is thought that these rocks are analogues to the pelleted carbonate muds and carbonate muds that are accumulating at the present time in coastal lagoonal areas along the Persian Gulf (Bathurst, 1975). The stratigraphic position of the platy limestones can be used as an aid in the interpretation of the environment of deposition. The platy limestones occur between the sublittoral marls of the top of the 'c_1' Member, and the overlying gypsiferous marls and gypsum. The gypsiferous marls and gypsum beds are assumed to have been formed in upper intertidal and supratidal environments. The conclusion is that the platy limestones were deposited in lower intertidal lagoonal environments.

3.5 Petrology of the 'c_3' Member

The 'c_3' Member is yellowish in color and, compared with the other limestone members, is rather soft and friable. It comprises thick beds which alternate with a few thin marly layers. It produces a higher topography than the underlying and overlying shaly and marly members. Two distinct facies types can be recognized in this member. They are: oolitic grainstones and packstones at the base, and Bryozoan packstones above. These are persistent throughout the whole area, but they decrease in thickness from northwest towards the southeast. The two facies types indicate different environments of deposition.

Oolitic grainstones and packstones

Oolitic grainstones occur at the base of the 'c_3' Member, where they form a well developed marker bed throughout the area which is 1.4 to 4 metres thick. The lowest part is in fact a pelloidal grainstone in which oolitic coatings are either not developed or are so thin that they can hardly be identified. The origin of pelloids is uncertain, but they could be worn micritized grains of coralline algae. The ooliths are of medium to coarse sand size and vary in shape from rounded to oval or elongate (Fig. 30). The shapes of the ooliths are related to the shapes of their cores. Around a long shell fragment the ooliths are elongate, while around subequant shell debris or pelloids the ooliths are more or less spherical. Most ooliths have been nucleated around pelloid type grains and the nuclei are usually large compared with the overall size of the oolith. The number of oolitic coatings varies greatly. The thickness of the oolitic coatings bears no relation to the shape of the nuclei, and can be as thick around a pelloid as around long bioclastic grains. Some nuclei appear to have 'recrystallized' to a coarse mosaic of calcite; these were probably fragments of aragonitic mollusc shells, now replaced by calcite. At certain levels some of the ooliths have been totally dissolved away to leave moulds, but others are only partially

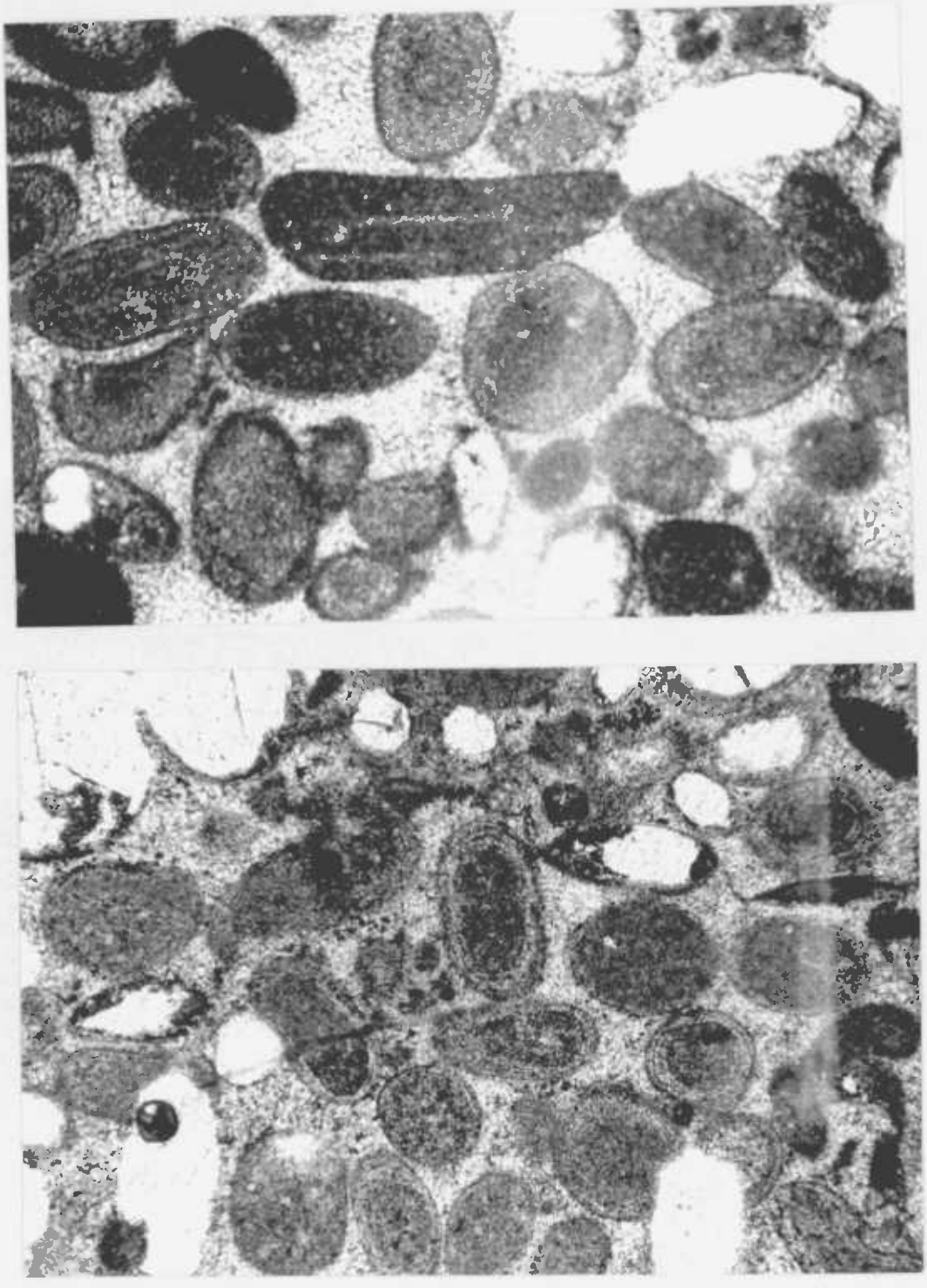


FIGURE 30 Photomicrographs of an oolitic grainstone (above) and an oolitic packstone (below). Part of the nuclei and oolitic jackets of some ooliths have been dissolved away to leave voids. 'c_3' Member, Do-Chah section. (x64).

dissolved. In the latter, dissolution has often removed part of the nucleus and part of the oolitic jacket, but other parts of the same oolith are preserved intact (Fig. 30).

Towards the upper parts of the sections skeletal fragments become important constituents. They include broken gastropod and pelecypod shells, fragments of coralline algae, echinoid plates, bryozoan debris and tests of foraminifera. These various components are cemented by sparry calcite. Lithified carbonate mud matrix is also present, and in some samples it is locally recrystallized.

Environment of deposition of oolitic grainstones and packstones

From what is known of the conditions of formation of modern ooliths, it is evident that the ooliths of the oolitic grainstones were formed in shallow agitated warm waters, supersaturated with calcium carbonate. These conditions are usually met on shoals and where tidal currents and/or breaking waves are active. These areas occupy only restricted parts of present day carbonate sedimentary environments. However, ooliths formed in one place can be transported and spread over large areas and ultimately be incorporated in lagoonal and other subtidal sediments or even blown inland as dunes. Thus it is important in ancient oolitic sediments to try to differentiate oolith 'factories' from accumulations of transported ooliths.

Oolitic grainstones of the 'c_3' Member overlie the supratidal rocks of the 'c_2' Member and probably mark a transgression of the Qom sea. Some of the oolitic grains are superficial and are associated with pelloid type grains. In the upper part of the bed fossil debris becomes an important component. It is assumed that oolitic grains were formed on shoals along the shorelines and carried forward as the sea transgressed over the lagoonal areas.

Bryozoan packstones

Bryozoans fragments, in varying sizes, are the dominant rock-forming constituent of this facies (Fig. 31). Pelecypod shell fragments and tests of foraminifera are other important components. Echinoid and coralline algal debris are minor constituents.

The grains are either tightly packed and cemented by sparry calcite, or are embedded in a dark dense lithified carbonate mud matrix which also occupies many of the zooecia of the bryozoans. In some thin sections the carbonate matrix contains some argillaceous detrital material (Fig. 31). The carbonate mud is sometimes 'recrystallized' to a coarser grained mosaic of clear calcite. This is true both in the case of intergranular and intragranular carbonate mud and the recrystallization is verified by the presence of the relict patches of microcrystalline calcite. The bryozoan packstones occur as calcarenites and calcirudites. The latter are more common, but they are alike apart from the difference in grain size.

Environment of deposition of the bryozoan packstones

The bryozoan packstones were formed in sublittoral environments similar to the other bioclastic bedded limestones in the Qom Formation. The characteristics of the bryozoan packstones accord with the definition of biostrom by Cumings (1932), i. e. they are structureless beds of fossils which consist mainly of sedentary organisms.

3.6 Petrology of the 'f' Member

The 'f' Member is the uppermost limestone member in the Qom region. Some workers (Abaie et al., 1963; Vatan, 1966) have considered the 'f' limestone to be a facies variation of the 'e' marl member. It overlies, and passes laterally into and interfingers with the marls. In certain locations the limestones dominate and in others it is not developed. Where present, it occurs

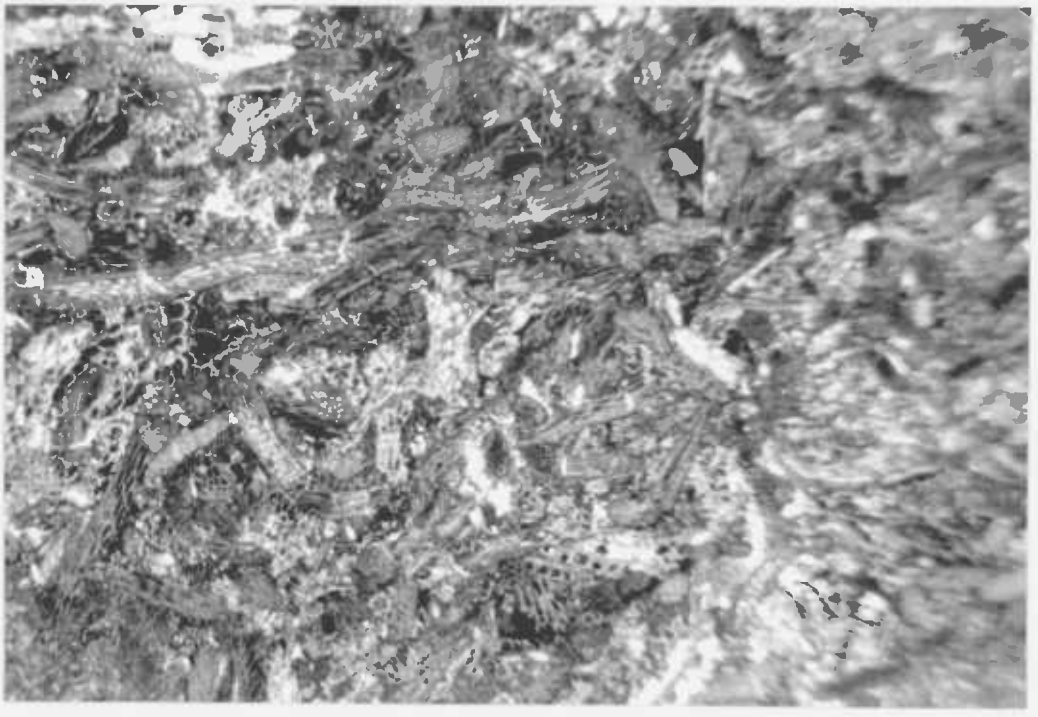


FIGURE 31 a) Photomicrograph of a bryozoan packstone. The rock is crowded with fragments of bryozoans. Most zooecia are filled with carbonate mud. 'c_3' Member, Nardaghi section. (x 7).

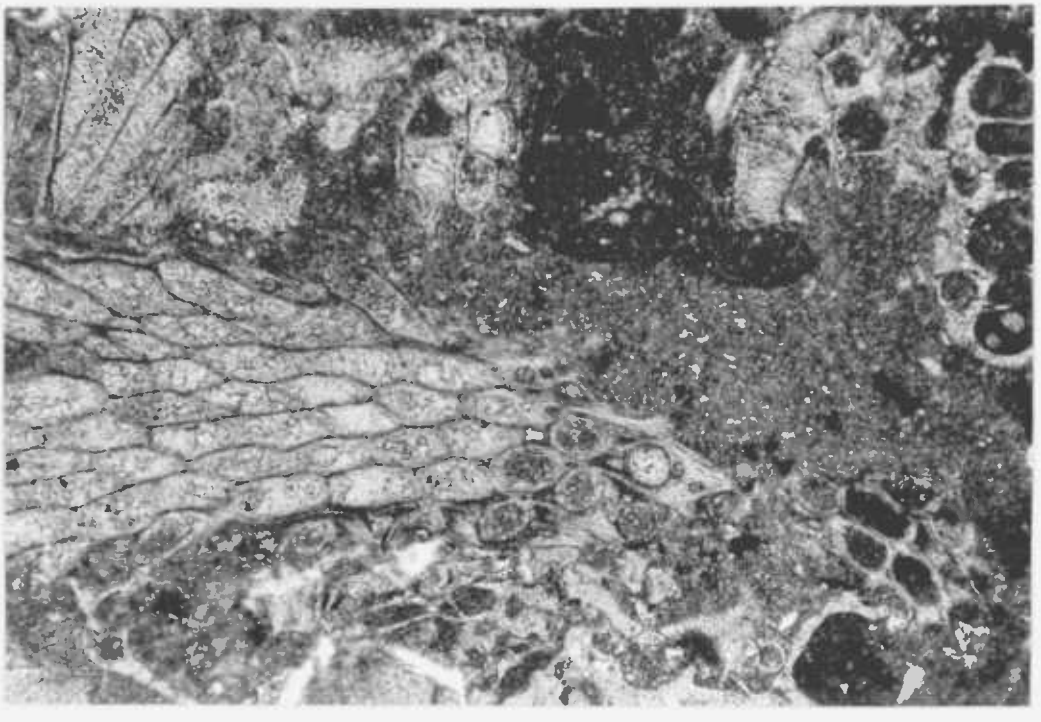


FIGURE 31 b) Photomicrograph of a bryozoan packstone. Where packing of the grains is not tight intergranular spaces are filled with carbonate mud and argillaceous detritus. Carbonate mud in the zooecia of some fragments is recrystallized. 'c_3' Member, Do-Chah section. (x 36).

either as thick beds which continue for long distances, or as isolated masses and irregular bodies. Lithologically, it is a distinct unit and locally reaches considerable thicknesses. In one place, Kuh-e-Nardaghi, it is present as a build-up which passes laterally into marls. This build-up will be described immediately following the petrology of the 'f' Member.

Several rock types have been recognized in the 'f' Member. Some are present in certain sections and are probably facies types. Others, which occur mainly in the build-up, are also present in other sections.

Algal packstones

The main components of the algal packstones are fragments of coralline algae and whole and broken tests of foraminifera, but most examples have been found to be dominantly algal. Corals locally become abundant and large fragments of pelecypod shells, echinoid and bryozoan debris in minor proportions are sometimes present. Gastropods are preserved as calcite casts. A few tests of planktonic foraminifera such as Globigerina are found scattered in the background; in addition, tests of smaller benthonic foraminifera such as miliolids also appear in the thin sections. The algal fragments usually have large continuous laminae but many are badly preserved. On the other hand, locally intact knobbly heads of encrusting coralline algae connected together by laminae are observed in some thin sections. In the knobbly algae the central part does not show the inherent layering and cellular structure and is more pelloid like (Fig. 32). In some of the slides that have been examined algae are present as rounded and ball-like grains. These balls are sometimes closely packed and are badly preserved around their edges. Specimens have been found in which large fragments of corals together with coralline algae comprise the major rock components (Fig. 32). Carbonate mud matrix is present in nearly all samples and is sometimes recrystallized. Any

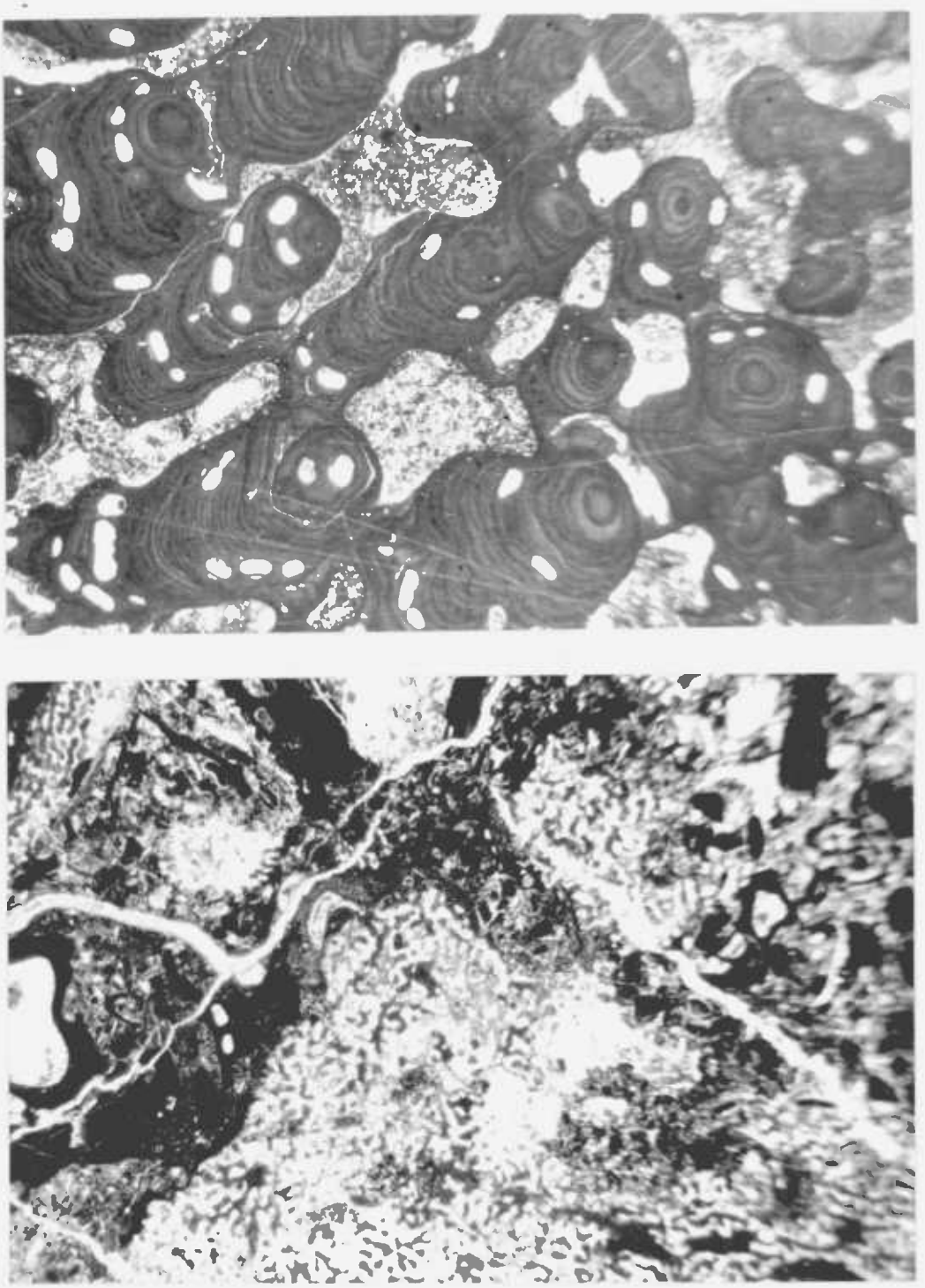


FIGURE 32 Photomicrographs of two examples of algal packstones. In the upper photograph algae are dominant. The lower example contains abundant coral fragments. 'f' Member, Do-Baradar section. (x 7).

remaining voids are now occupied by sparry calcite. Coralline algae in many samples have been affected by dolomitization and rhombs of dolomite are present in some of the laminae and around the margins of the grains. Dolomite rhombs are even more abundant in the matrix. Mollusc shells are sometimes silicified, but ghosts of the original structure of the shells are preserved. Stylolites and calcite healed fractures (Fig. 32) are a common feature of these rocks.

Foraminiferal-Algal Packstones

The foraminiferal-algal packstones comprise white to buff coloured well bedded limestones. They are composed mainly of tests of foraminifera and fragments of coralline algae (Fig. 33), but they sometimes also contain minor proportions of echinoid, pelecypod and bryozoan debris. Tests of the planktonic and small benthonic foraminifera are also present. Variation is observed in the composition and texture of the packstones. In composition they differ from being predominantly foraminiferal to foraminiferal-algal but with other minor skeletal components. In some specimens the bioclastic material is closely packed, whereas in others a large proportion of mud matrix is present. Skeletal debris is mostly of coarse sand grade size. Algal fragments are either angular to subangular or rounded but tests of foraminifera are rather abraded. Where the rocks are dominantly composed of tests of foraminifera or comprise foraminiferal and algal debris, they are moderately well sorted. In these rocks the grains are tightly packed and carbonate mud is either absent or subordinate (Fig. 33). Most and nearly all adjacent bioclasts are in close contact and pressure dissolution seams are developed between them (Fig. 33). Some examples contain fewer bioclasts. In these the grains are loosely packed and are set in a dense carbonate mud. Tests of Globigerina and benthonic small foraminifera together with echinoid spines are found scattered in the matrix. Detrital sand grains, which consist of plagioclase and volcanic rock fragments, occur occasionally. The matrix is sometimes contaminated by the red iron oxide. Any remaining space is

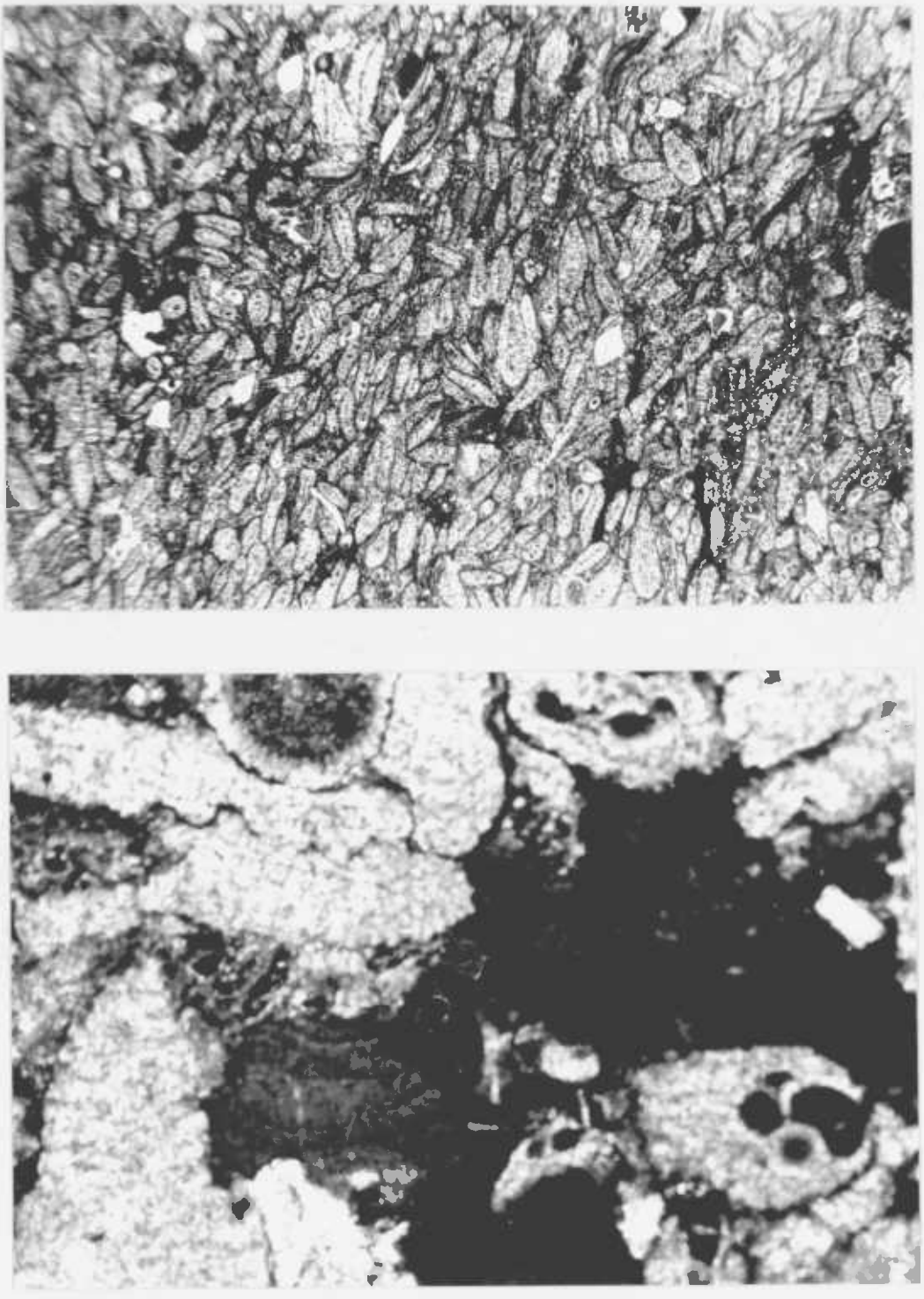


FIGURE 33 Photomicrographs of foraminiferal-algal packstone. In the upper photograph the rock is dominantly formed of tests of foraminifera. The tests are packed and no intergranular porosity is left. (x 7). In the lower photograph algae and other fossil debris are also incorporated in the rock, and these grains are also tightly packed. (x 30). 'f' Member, Idaghchi section.

filled with sparry calcite.

3.7 Petrology of the Kuh-e-Nardaghi Build-up

Kuh-e-Nardaghi is a massive body which extends for about 2000 metres (Fig. 34). Due to tectonic activity the body has assumed a near vertical dip. It has a maximum thickness of about 300 metres and laterally interfingers with and changes to marls towards the east (Fig. 35). The limestones are white to yellowish white in color and are partly chalky and partly dense at outcrop. The limestones of the 'f' Member in general and Kuh-e-Nardaghi in particular have been referred to as 'reefal' by previous workers (Abaie et al., op. cit.; Vatan, op. cit.). As already mentioned, to avoid confusion over origin the limestone is regarded as a mixed build-up by the present writer and further discussions concerning the origin will be made in a later part of this chapter.

Several rock types have been recognized in the Kuh-e-Nardaghi build-up. These rocks are not distinct units within the body but grade into each other and occur as alternating and intergraded units. The division by rock types permits a more systematic study of the build-up.

It is believed that these various rock types belong essentially to one facies, and variations in grain size and fossil content represent minor fluctuations in the environment of deposition. Some of the rock types, which occur in the Kuh-e-Nardaghi build-up, also occur in other sections.

The bioclastic packstone and wackestone lithofacies

The term bioclastic packstone and wackestone lithofacies is used here to embrace several lithologic varieties of the 'f' limestones which are not detectable in the field. Petrographic examination has revealed that tests of larger benthonic foraminifera and frag-

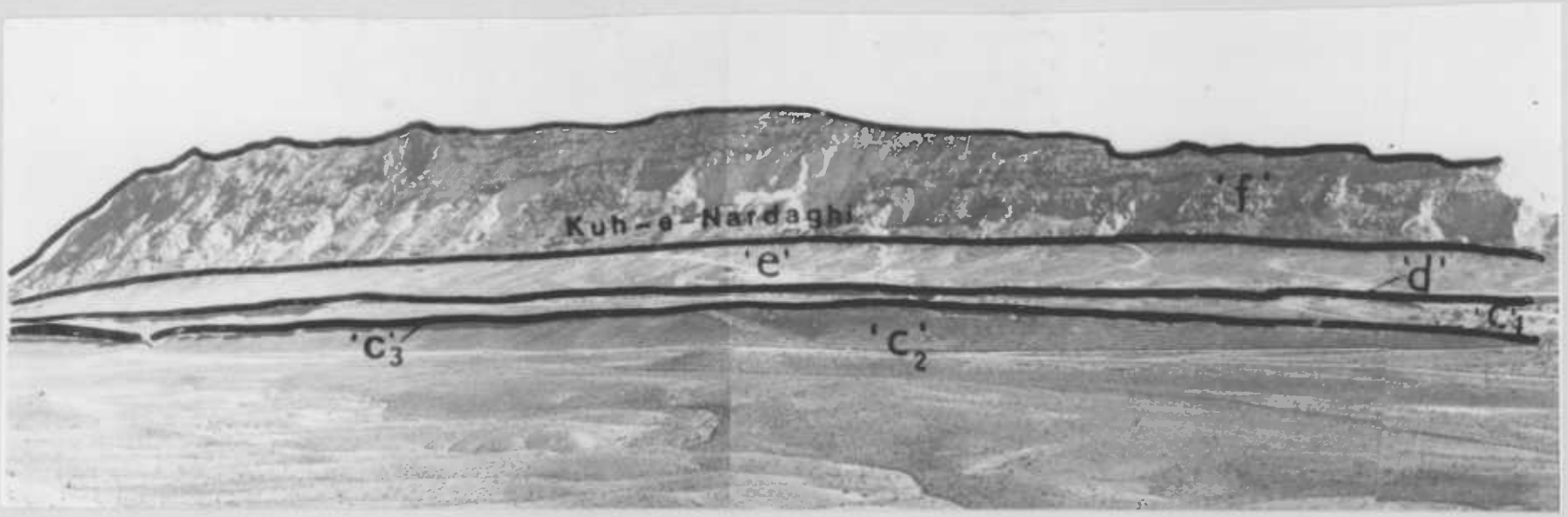


FIGURE 34 A panoramic view of the Kuh-e-Nardaghi. Looking south.
Kuh-e Nardaghi is about 120 metres above the foreground

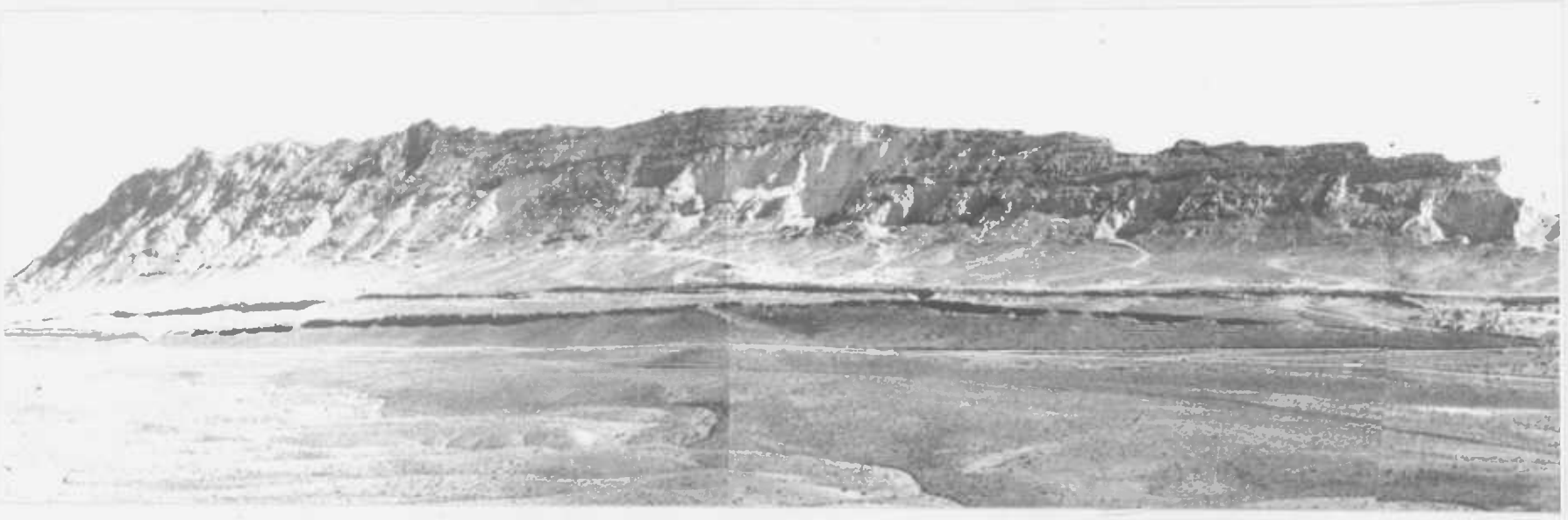


FIGURE 34 A panoramic view of the Kuh-e-Nardaghi. Looking south.

Kuh-e Nardaghi is about 120 metres above the foreground

FIGURE 35 The east end of the Kuh-e-Nardaghi showing the lateral passage of the limestones to marls. Looking west.

ments of coralline algae persistently occur and compose the main part of the rocks. Other bioclasts which are incorporated in the rocks include echinoid plates and spines, pelecypod shells and bryozoans. Corals locally become important components. Tests of small planktonic foraminifera are characteristic and small benthonic types are usually present. The bioclasts show a wide range of grain size, from fine-sand to large gravel size. These grains show different stages of angularity and wear. Some fragments are strikingly angular whereas others are rounded and many are badly preserved. The rocks vary from being poorly to moderately well sorted. The bioclasts are mostly closely packed, but sparse packing is not uncommon. Varying proportions of carbonate mud matrix are present. It is either highly recrystallized with only a few relics of it left, or it is only partially recrystallized. In some packstones and wackestones the original calcareous mud is lithified. Sparry calcite is developed in some skeletal moulds or any spaces which were available to it.

The rock types of this lithofacies include: foraminiferal-algal packstone, fine grained foraminiferal algal packstone, well sorted algal foraminiferal packstone, admixed bioclastic packstones, coral bearing packstone, bioclastic wackestone and fossiliferous mudstone.

Foraminiferal-algal packstones. The foraminiferal-algal packstones are dominantly composed of tests of large benthonic foraminifera with a smaller proportion of algal debris. Tests of foraminifera occur both as whole and broken fragments. Broken tests are angular and constitute a large part of the rock (Fig. 36). Other fossil debris includes minor proportions of echinoids and pelecypods. Fragments of coralline algae are angular to subangular and are mostly small. In some of the samples large foraminiferal tests show a tendency for preferred orientation. Angular broken fragments and algal debris occur in spaces between the whole tests. These grains are usually closely packed and finer grained skeletal debris forms the

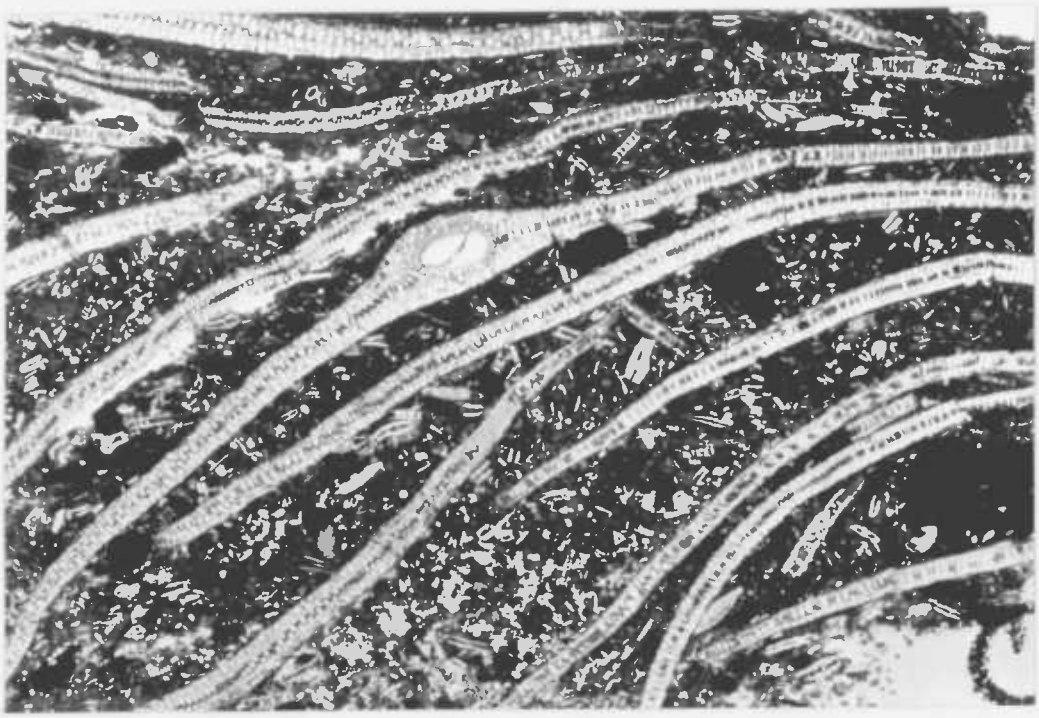


FIGURE 36 Photomicrograph of a foraminiferal packstone. Broken fragments of foraminiferal tests are angular. These fragments together with small algal debris act as matrix. Large tests of foraminifera are roughly aligned. 'f' Member, Nardaghi section. (x 7).

matrix (Fig. 36). In the samples which do not show tight packing, the various components are set in a carbonate mud matrix.

Fine grained foraminiferal algal packstones. The fine grained foraminiferal algal packstones are composed of comminuted fragments of coralline algae and foraminifera. The intergranular areas are occupied by lithified carbonate mud matrix. Occasionally a large fragment of coralline alga or a whole test of a large benthonic foraminifer may be found in a thin section. Echinoid spines and a few tests of planktonic foraminifera are also occasionally present (Fig. 37).

Well sorted algal foraminiferal packstones. The rock comprises medium sand sized fragments of coralline algae and foraminifera in roughly equal proportions. Fragments are angular and are evenly distributed in the partially recrystallized carbonate matrix. Either algal or foraminiferal debris predominates, but in most cases algae are more abundant. Occasionally, an angular plagioclase crystal or a rounded volcanic rock fragment of sand grade size is present.

Admixed bioclastic packstones. Fragments of tests of larger foraminifera, debris of coralline algae, echinoid plates, pelecypod shells, bryozoans, together with whole tests of smaller benthonic and planktonic foraminifera are the components of this rock (Fig. 38). These various bioclasts are poorly sorted and are angular to subrounded and rounded. A carbonate matrix is usually present and this is partly recrystallized. Tests of foraminifera and former void spaces are filled with sparry calcite cement.

Coral bearing packstones. Corals become an important faunal component in some of the bioclastic packstones. Some thin sections are wholly or in large part comprised of coral fragments. Algal debris of sand size is usually associated. There are also thin sections in which pelecypod shell debris and tests of foraminifera are incorpor-

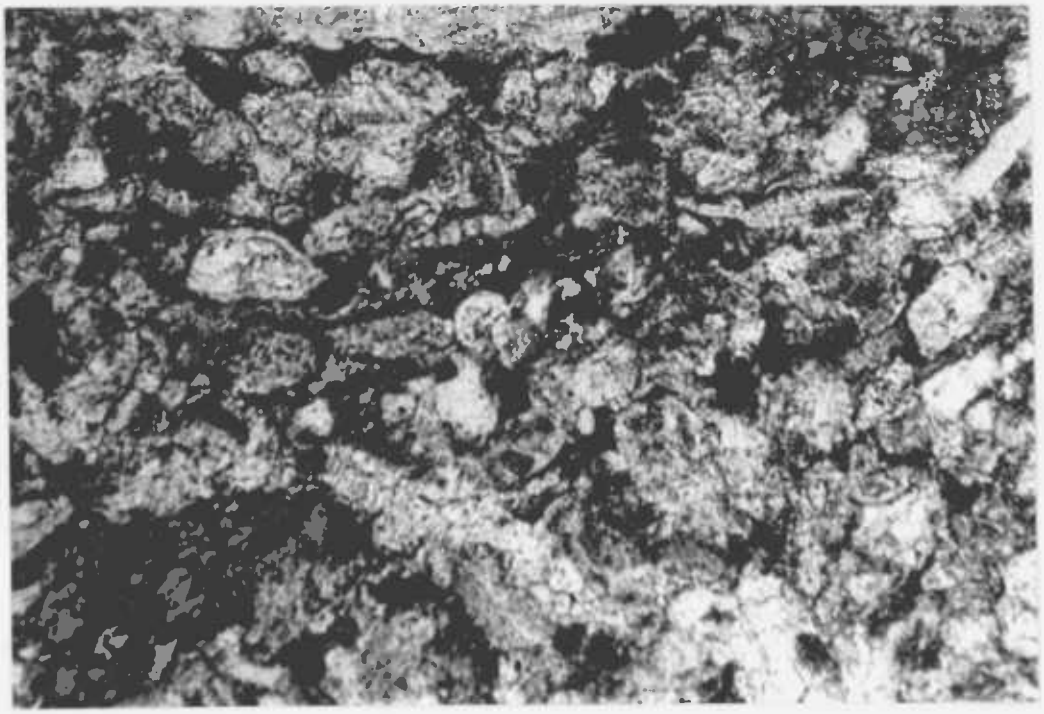


FIGURE 37 Photomicrograph of a fine grained algal-foraminiferal packstone. 'f' Member, Nardaghi section. (x 60).

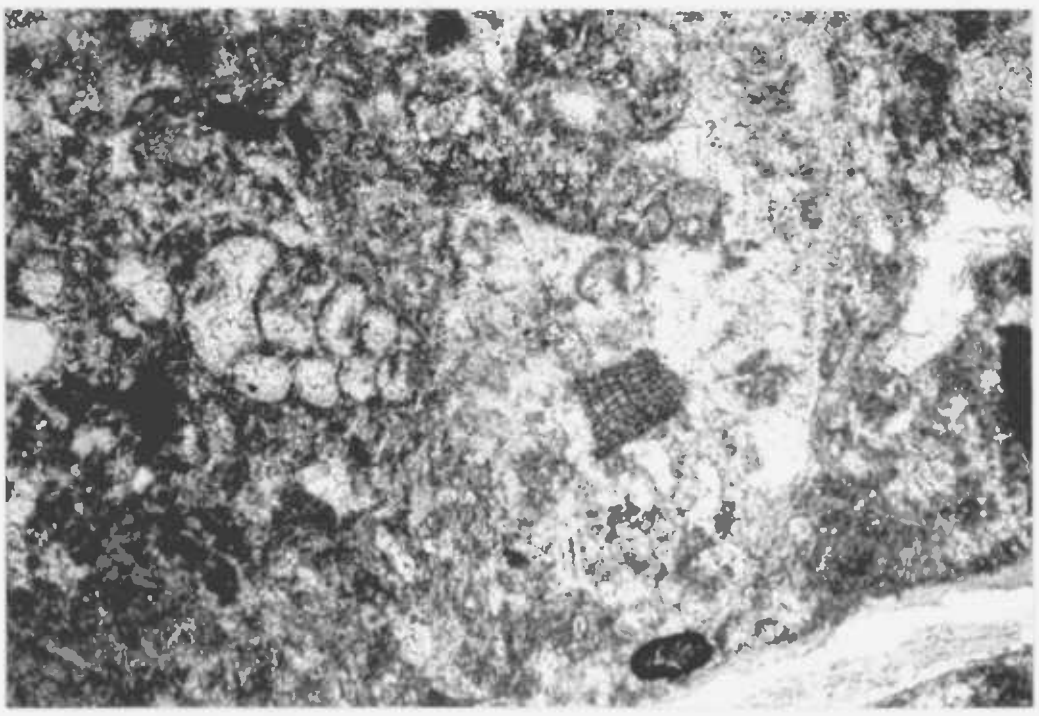


FIGURE 38 Photomicrograph of an admixed bioclastic packstone. 'f' Member, Nardaghi section. (x 30).

ated. These bioclasts are set in a partially recrystallized carbonate mud matrix. The interseptal cavities of corals may be occupied by lithified mud or the mud might have been recrystallized as well.

Fossiliferous mudstone. In the fossiliferous mudstones minute fragments of coralline algae and foraminifera are distributed rather patchily in a dense carbonate mud matrix. Tests of planktonic foraminifera and echinoid spines are also scattered in the background.

A variant on these lithologies are samples in which tests of planktonic and small benthonic foraminifera are set in a dark dense carbonate mud (Fig. 39). Small fragments of larger foraminifera, pelecypod shells and echinoid spines also occur. An occasional gastropod cast and a few angular grains of plagioclase have also been found scattered in the mud.

Foraminiferal mudstone is characterized by the occurrence of only tests of Globigerina in the dark dense mud in which few minute fossil debris and angular plagioclase are also present.
The Globigerina tests are filled either with carbonate mud, or occasionally sparry calcite. Some tests carry silica infillings.

Environment of deposition of the 'f' Member

The environment of deposition of the 'f' Member can satisfactorily be explained by the comparison of the 'f' limetones with facies of the Tertiary reef complexes of the Middle East (Henson, op. cit.), Louisiana (Forman and Schlanger, op. cit.) and Guam (Schlanger, op. cit.). It has already been mentioned that the limestones of the 'f' Member are discontinuous in lateral distribution, they are thick bedded and locally form limestone masses and the Nardaghi build-up. This pattern of distribution may imply that limestones developed only locally under favourable environmental conditions while marls

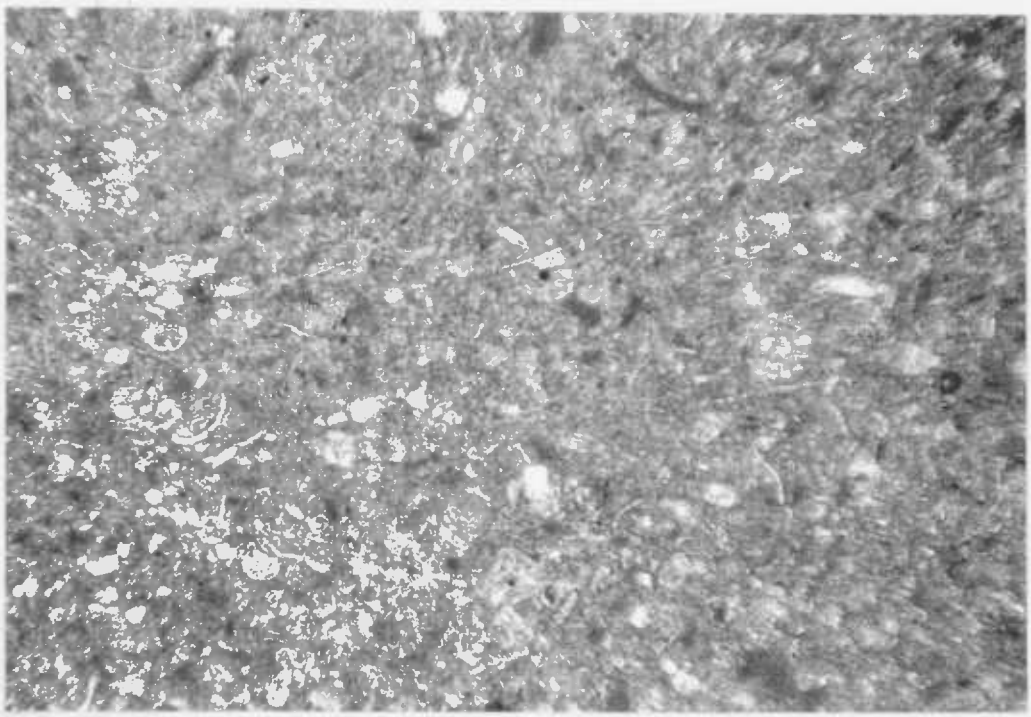


FIGURE 39 Photomicrograph of a fossiliferous mudstone with tests of globigerina, echinoid spines and other minute fossil debris. These are set in a carbonate mud matrix. 'f' Member, Nardaghi section. (x 24).

were deposited in the adjacent areas.

Henson (1950) applied the term 'shoal-reefs' to all formations in which reef growth develops in irregular patches amidst submerged shoals of calcareous debris. Shoal reefs may compose parts, or the whole, of fringing-, barrier- or bank-reefs and they may develop locally and sporadically under suitable, clear-water conditions where other types of sediment predominate.

Henson (op. cit.) noticed that, in the Cretaceous and Tertiary rocks of the Middle East, there are numerous patchy occurrences of algal-foraminiferal limestones, with some corals, and with associated detrital limestones, which do not seem to be connected with true coralline fringing, barrier or bank reefs. He interpreted these as open shoal-reefs or reef-shoals. The rocks forming these shoals are composed mainly of fragments of calcareous coralline algae and foraminifera with echinoids, coral and mollusc debris. Tests of large benthonic foraminifera are predominant and locally there might be a concentration of a particular species. Patch reefs, mainly of algae and bryozoans, may be occasionally present. The various facies of the 'f' Member are very similar to these facies and fit into the description of open shoal-reefs.

The Nardaghi build-up, however, shows some different lithologies and is formed of alternating and intergrading foraminiferal-algal packstone and bioclastic packstones and wackestones. In the foraminiferal-algal packstones large tests of benthonic foraminifera are broken, but broken fragments have angular edges. This might suggest that they were broken at the site of deposition probably due to organic activity. The bioclastic packstones and wackestones are composed of fairly to poorly sorted fine grained skeletal debris, with tests of Globigerina and other fossils set in slightly recrystallized or dense carbonate mud matrices. Some rocks are formed of only tests of Globigerina set in a dense carbonate mud. These lithologies and their relationships are similar to the fore-reef shoal

and fore-reef transitional facies of the reef complexes of the Middle East (Henson, op. cit.) and fore-reef and fore-reef transitional zones of reef complexes of Louisiana (Forman and Schlanger, op. cit.) and Guam (Schlanger, op. cit.).

Fore-reef transitional facies of those complexes also consist of limestones composed of comminuted debris of large benthonic foraminifera, coralline algae, echinoid and tests of globigerinids in a dense carbonate matrix which alternates and intergrades with globigerinid chalks, shales and limestones.

Those limestones have been interpreted as deeper and quieter water sediments by the authors. It is then probable that in spite of its field expression and similarities to a 'reef', the Nardaghi build-up was in fact formed in deeper waters.

CHAPTER 4

DIAGENESIS

The limestones of the Qom Formation have undergone considerable changes from the time of deposition up to the present day. The alternations of beds of limestones with marls and the occasional presence of evaporites are evidence of major fluctuations of relative sea level during deposition. Further, the various facies which are present in the limestones are indications of less radical changes in the depositional environment. The rocks were strongly folded, locally being overturned, by the two phases of the 'Alpine' orogeny as it affected Iran. These events must be expressed to some degree at least in the fabrics of the limestones. Petrographic studies have shown that skeletal fragments, ooliths and the depositional carbonate mud matrix have all been affected by diagenetic changes.

Diagenesis is defined as those changes which take place in sediments after deposition and prior to lithification. However, in practice the establishment of such a 'cut off' is difficult and arbitrary. The diagenetic changes which have affected the Qom Limestones include: precipitation of calcite cement, recrystallization of calcium carbonate muds, dolomitization and dedolomitization, silicification, and local formation of celestite cement.

Physical modifications of the sediments below the sediment/water interface, such as burrowing as well as compaction and pressure dissolution, are also included in diagenesis. Processes which operated on the lithified rocks are discussed following the diagenesis. Included in the latter processes are: formation of microstylolites and development of fractures.

4.1 Borings and Burrows

Borings

Many of the former aragonitic and calcitic skeletal fragments are pervaded by minute borings. These were probably produced by blue-green algae during deposition. The results of this boring are manifested in different ways. Around the former aragonitic shells a dark line, i.e. a micrite envelope, was produced by the alteration of the surface parts of the shells, and these mitrite envelopes outline the present calcite casts. On calcitic grains, the borings appear to have penetrated somewhat deeper and are impregnated by microcrystalline calcite (Fig. 40).

Burrows

Some of the micritic rocks show burrows, generally near vertical or at high angles to the bedding (Fig. 41). They are tubelike, and circular in cross-section up to 2 centimetres wide. They are made apparent by differences in grain size of the matrix, coloration, and/or the amount of fossil material (Fig. 42). Some of the irregular areas of non-fossiliferous micrite-microspar surrounded by grain supported carbonate are probably the traces of burrows. Burrowing is difficult to detect in the sparry rocks, but some of the thin sections show areas of micrite which could have been the infill of burrows.

4.2 Compaction

Although various authors, notably Pray (1960), have stated that little or no compaction takes place in limestones, the Qom limestones have undoubtedly undergone substantial compaction. The evidence can be seen abundantly in nearly all thin sections. It is not only recorded by pressure welded contacts, but in the majority of thin sections there has been in situ post depositional fragmentation of bioclasts. In some cases, detrital feldspar grains are also

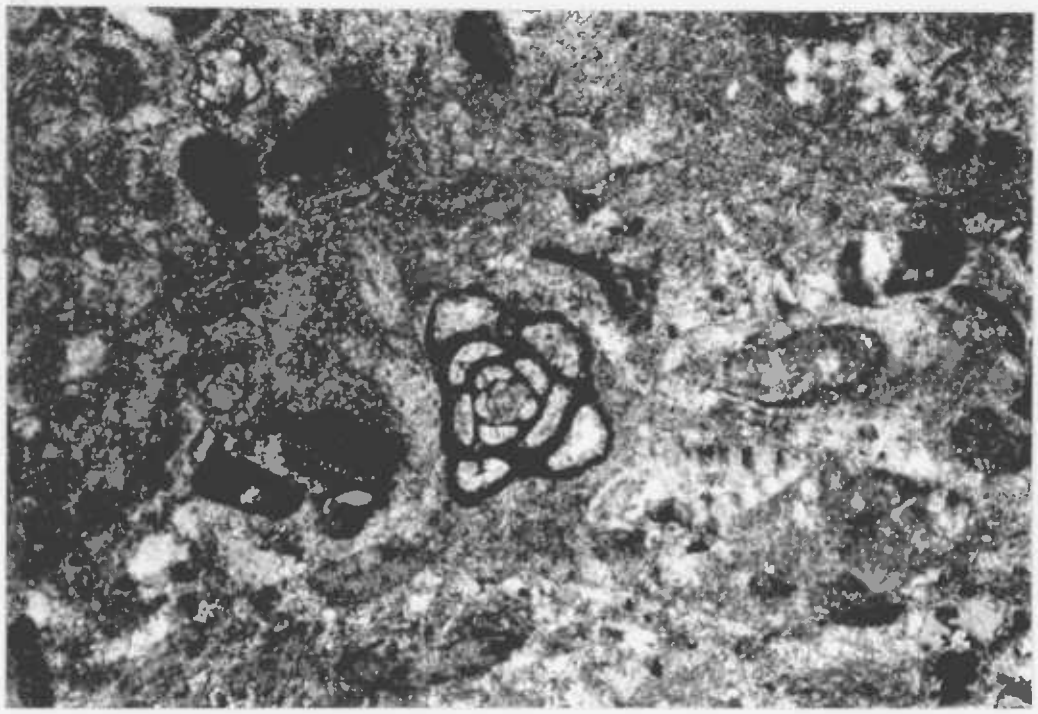


FIGURE 40 Photomicrograph showing a micrite envelope around the test of a foraminifer. 'f' Member, Kuh-e-Nardaghi build-up. (x 30).

FIGURE 41 A tube-like cast of a burrow. It stands nearly normal to the bedding. 'f' Member, Idaghchi section.

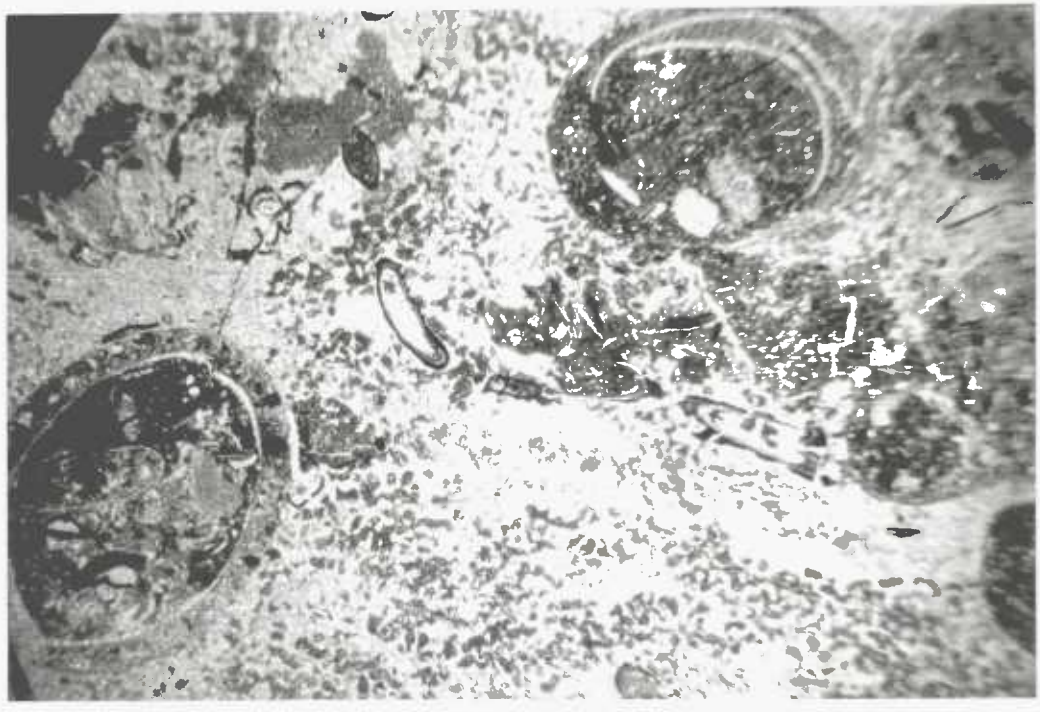


FIGURE 42 Photomicrograph showing the circular cross-sections of burrows now occupied by 'nestlers'. 'f' Member, Kuh-e-Nardaghi section. (x 7).

broken. The effects of compaction on bioclasts are seen in various ways. Some of the former aragonitic gastropod shells are completely smashed and appear as a higgledy-piggledy mass of thin dark lines scattered in the sparry calcite cement. The thin dark lines probably represent the micrite envelopes which surrounded the shells before breakage. The overall outline of former shells can sometimes be reconstructed in the mind's eye by careful examination and matching of the lines. This allows an assessment to be made of the extent of the compaction, which in some instances is as much as 30 percent.

Monocrystalline echinoid fragments are often broken into two parts and the pieces displaced, but not rotated, so that the syntaxial overgrowths on the two parts coalesce and become in effect one crystal (Fig. 43). Rod-shaped fragments of branching coralline algae and other fossil fragments are often broken into several pieces, with or without the separation of broken parts (Fig. 44). Some foraminiferal tests are broken and moved in the plane of breakage with no apparent horizontal displacement (Fig. 45). Many of the fragments of coralline algae show wedge-shaped fractures which do not completely cross the grains. These wedges are now filled with fine-grained sparry calcite (Fig. 44). There is no unequivocal evidence of compaction in the carbonate muds, but the possibility must be considered that the muds originally had considerable amounts of water which was lost during the compaction.

It is believed that the pressure dissolution contacts and in situ fragmentation of the grains were early diagenetic phenomena in the Qom limestones. They took place either prior to, or just after, the formation of the first phase cement. The latter time is the

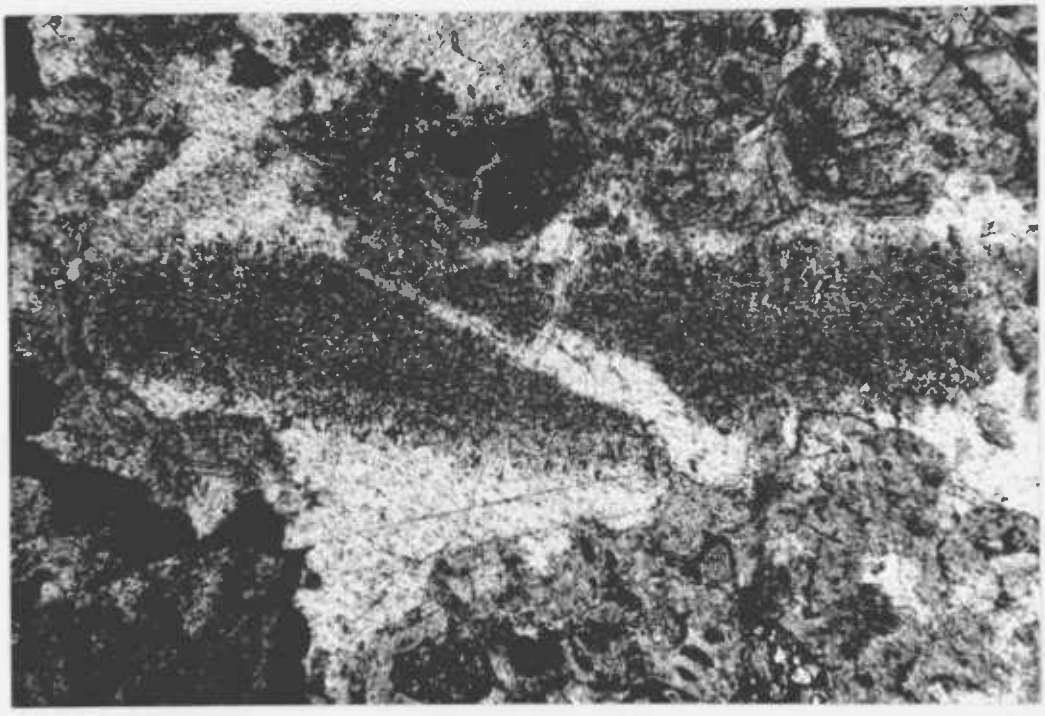


FIGURE 43 Photomicrograph showing the effect of post-depositional compaction on an echinoid fragment. The fragment has been broken and slightly displaced. The syntaxial overgrowths on the two parts have coalesced so that they are in effect almost one crystal. 'c_1' Member, Do-Chah section. (x 64).

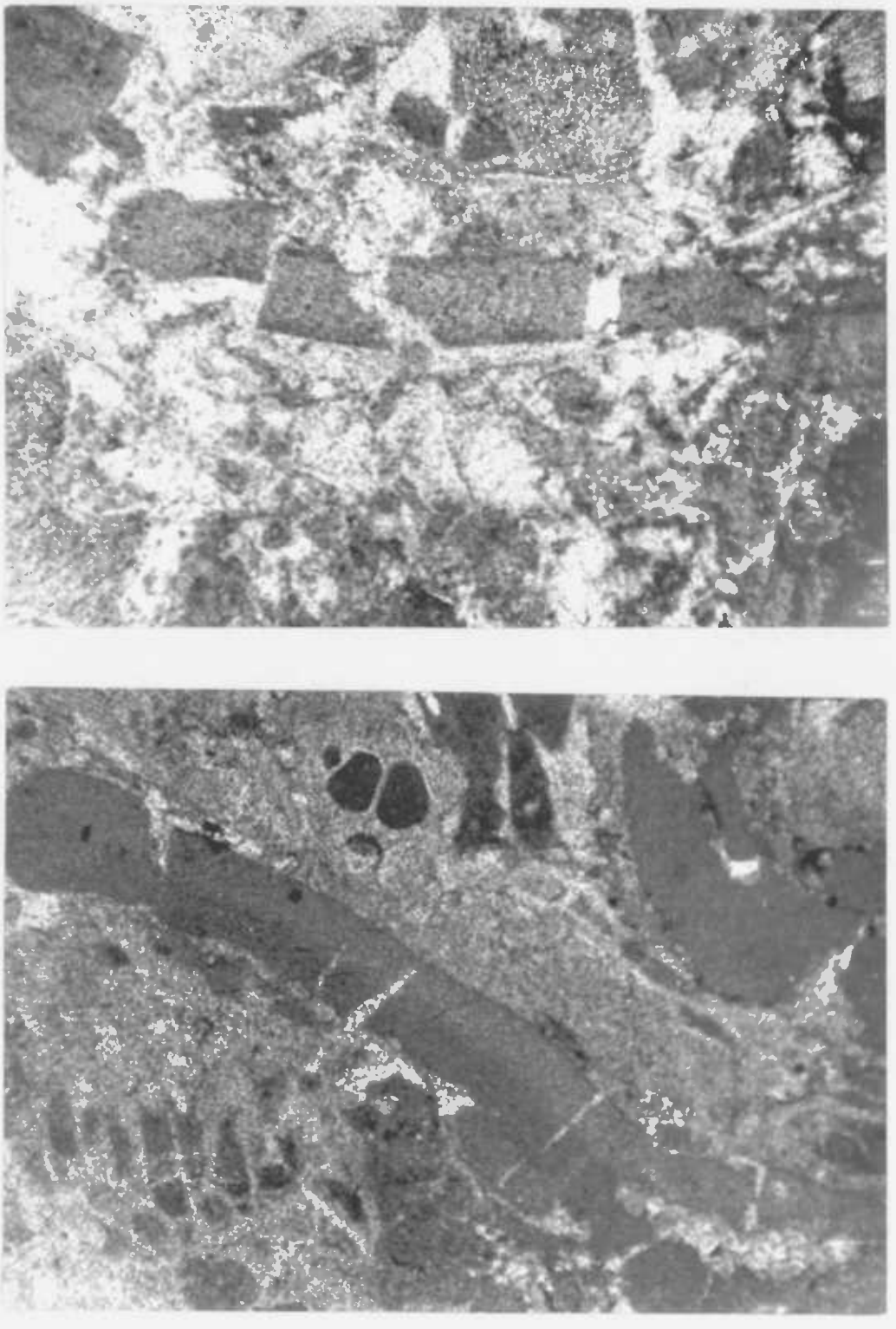


FIGURE 44 Photomicrographs showing effects of compaction.

a) In situ fragmentation of alga lithophyllum. 'c_1' Member, Do-Baradar section. (x 45).

b) Wedge-like fractures developed across a fragment of Lithophyllum and later healed by sparry calcite. 'a' Member, Nardaghi section. (x 45).

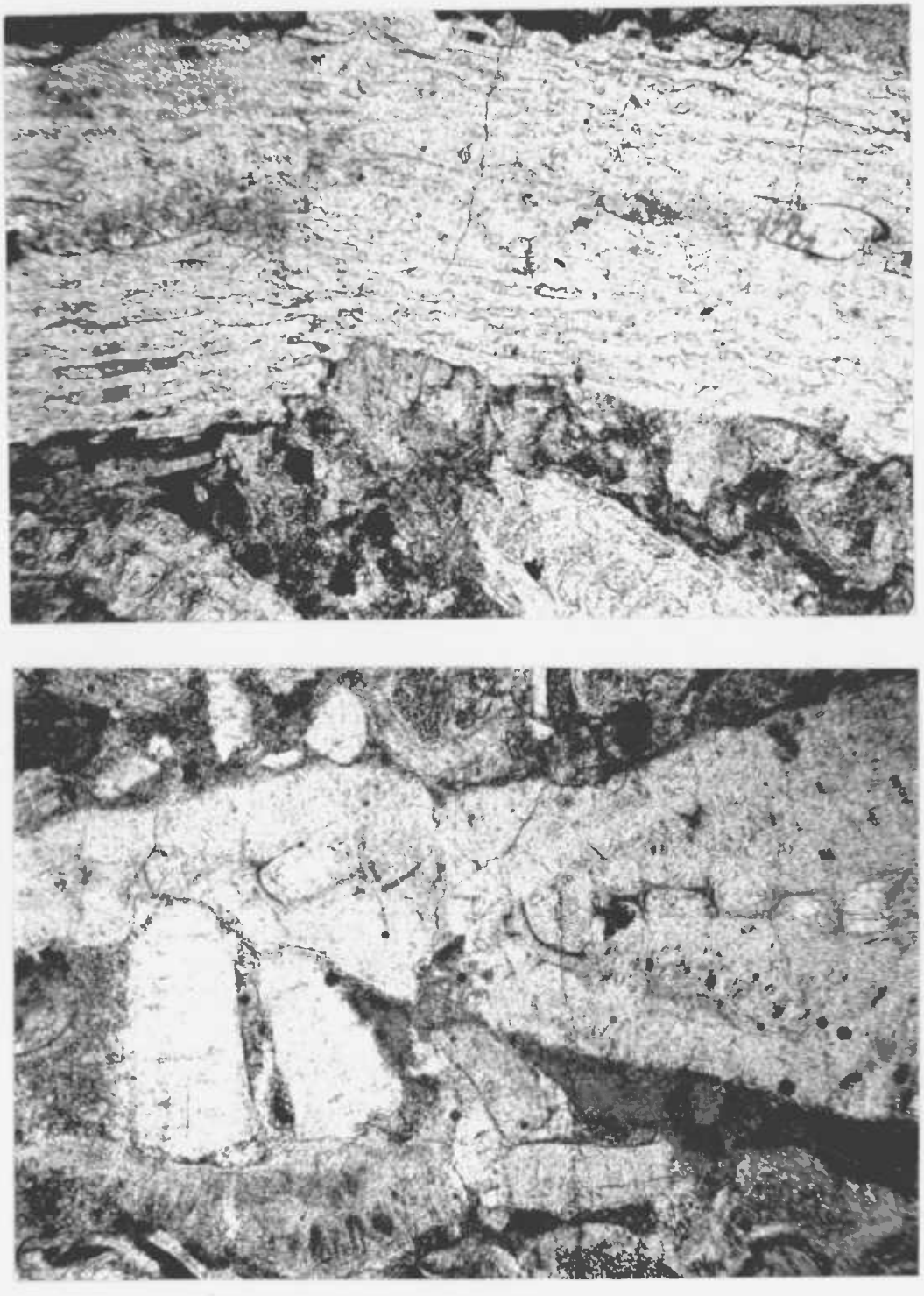


FIGURE 45 Photomicrographs showing the effect of compaction on tests of benthonic foraminifera. The broken fragments were moved in the plane of breakage with no apparent horizontal displacement. 'c_1' Member, Do-Chah section. (x 64).

more reasonable assumption because some broken fossil fragments, which are otherwise rimmed by first phase cement, have no such cement on the broken surfaces. In the case of tightly packed rocks, however, and in the more micritic rocks, compaction probably occurred before the cementation.

4.3 Pressure Dissolution

Pressure welded contacts, i. e. the presence of sutured contacts between adjacent grains, is a very common feature in the Qom limestones. Sutured contacts occur between any two adjacent allochems irrespective of whether they are similar or different in composition and crystal fabrics (Fig. 46). Along any one grain contact one or both allochems may show dissolution effects. In the tightly packed foraminiferal algal limestones the grains have penetrated deeply into one another and the contacts appear as dark relatively thick zigzag lines. In some samples the allochems have become so deeply impressed, one into another, that the porosity was almost completely obliterated (Fig. 47). There seems to have been no relation between the packing density of the grains and the occurrence of pressure dissolution, because sutured contacts are equally as common in tightly packed samples as they are in specimens where some of the grains float in a microcrystalline carbonate matrix or are cemented by sparry calcite. There are also many instances where terrigenous detrital grains have been pushed deep into adjacent allochems.

4.4 Diagenetic Alteration of Skeletal Grains

The skeletal components of the Qom limestones comprise mainly fragments of bryozoans, coralline algae, molluscs, echinoderms, corals and tests of foraminifera. In some of these the crystal fabrics of the calcite are clearly primary and preserve the original architecture of the skeletal structure. These are clearly the remains of organic structures which were calcitic in life. In other

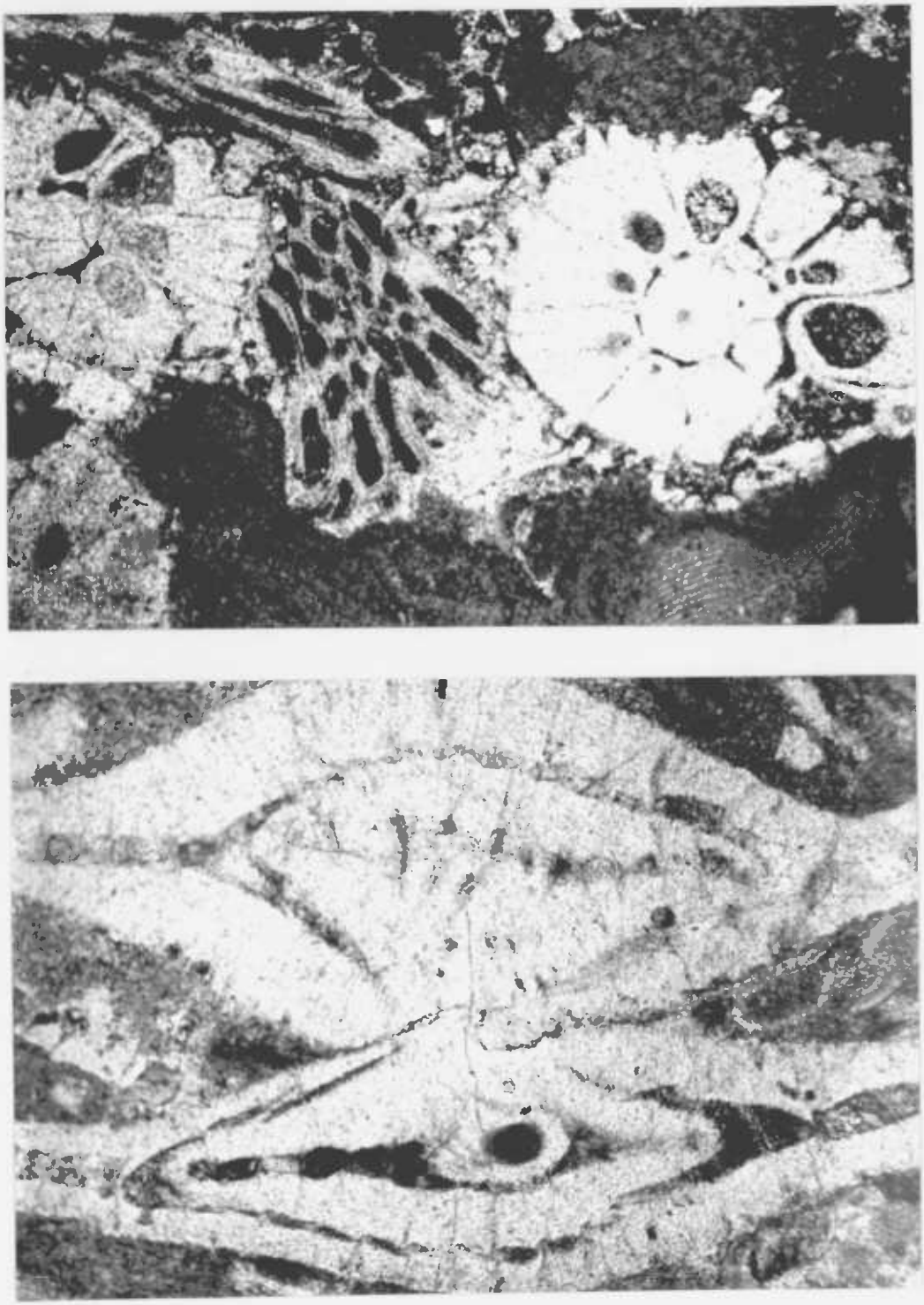


FIGURE 46 a) Photomicrograph showing pressure dissolution contacts between different types of skeletal grains. 'a' Member, Nardaghi section. (x 64).

FIGURE 46 b) Photomicrograph showing pressure dissolution contacts between adjacent tests of the same genera of foraminifera. 'c_1' Member, Do-Chah section. (x 64).

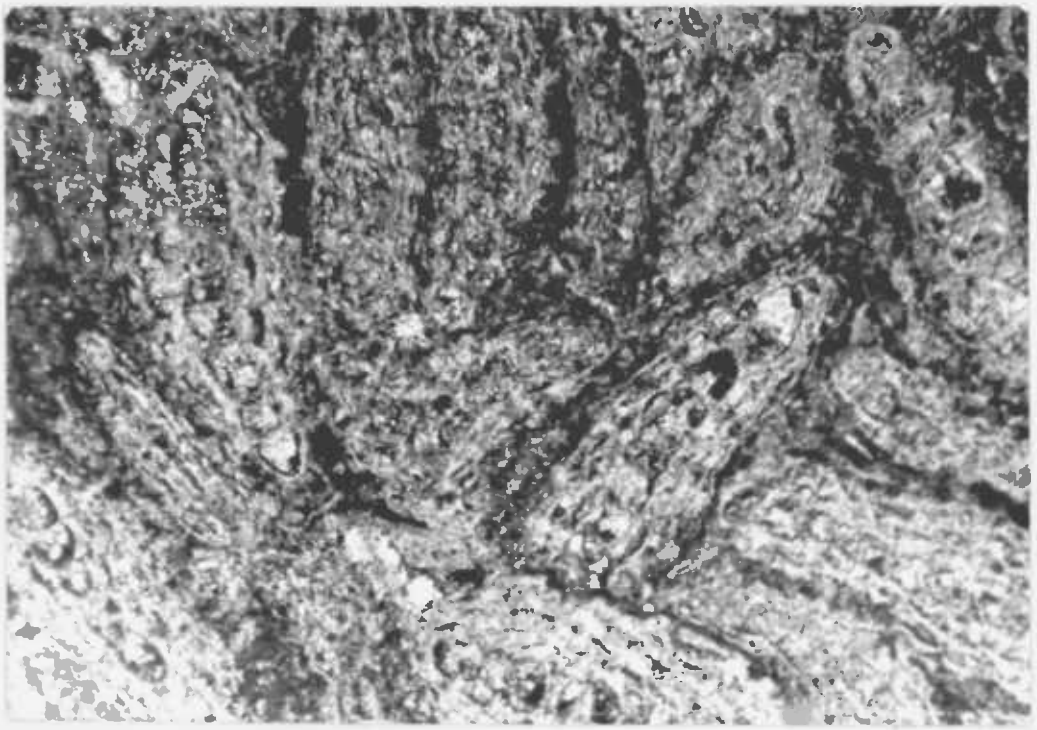


FIGURE 47 Photomicrograph showing the effect of pressure dissolution on tests of foraminifera. Porosity has been completely obliterated. 'f' Member, Idaghchi section. (x 40).

skeletal grains the crystal fabrics of the calcite of the structure are obviously inorganic, and it is reasonable to suppose that these are calcite replacements of former aragonitic skeletal structures. Some of the organic remains have a composite structure which consists in part of calcite which shows purposeful organization and, in part, of calcite which has an inorganic fabric. These were evidently pelecypod valves which in life had a two-layer structure which consisted in part of calcite and in part of aragonite.

A) Primary calcite skeletal structures

(i) Echinoderms. In life each element of the skeletal structure of the echinoderms is a single crystal of calcite, and is preserved as such when fossil. In this respect, they stand apart from all the other groups of calcite-secreting organisms, and are in consequence easily recognized in thin section. In the limestones of the Qom Formation, the echinoderm remains all appear to be fragments of plates and spines of echinoids. In each fragment the optical vibration direction of the calcite, as seen in thin section, is symmetrically related to the morphology: in all instances studied the fast vibration direction, i. e. the c-crystal axis, was found to be normal to the surface of echinoid plates and parallel to the length of spines. The skeletal structures of living echinoids consist of high magnesium calcite with approximately $12\frac{1}{2}$ % $MgCo_3$ in the calcite lattice. X-ray diffraction studies of the Qom limestones have shown that no high magnesian calcite is present. Thus, although the original crystal fabrics appear to have been preserved intact, magnesium has somehow been lost from the crystals in the course of diagenesis.

(ii) Coralline algae. Coralline algae are structurally crustose or branching. The encrusting type consists of tissue built of layers of cells which may be differentiated into a basal part with larger curved cells and an overlying portion formed of smaller more regular cells. The spore cases are embedded within the tissue and, in the genera present in the Qom limestones, they have either

circular or roughly oval outlines in section. In the living organism, high-magnesium calcite is deposited within and between the cell walls. Fossils show the same cellular structure, except that the calcite is low magnesium calcite. The detail of the crystal fabrics of the cell walls is not clear due to the very fine grain size; the walls are defined only by dark outlines. The sporangia are filled with sparry calcite cement in most cases.

(iii) Bryozoa. Bryozoa in the Qom limestones include branching and encrusting varieties. The latter are found mainly on the tests of the foraminifera, Lepidocyclina. In life the calcareous parts of the bryozoa are composed of high-magnesium calcite, but they are low magnesium calcite in the fossils. Each individual consists of a double-walled calcareous elongate tube or a short oval and box-shaped chamber. This overall structure remains intact throughout time. The structure of the wall is not detectable in many samples, but zooecia can be identified by their outlines. In some of the samples studied, the wall comprises very fine-grained granular calcite, which appears to have been produced by 'recrystallization'. Some zooecia are filled with sparry calcite, but others contain carbonate mud.

(iv) Foraminifera. Foraminifera present in the Qom limestones are mainly thick-walled large benthonic varieties, but there are some thin-walled small benthonic, and some planktonic types. They are generally well preserved and have sharp contacts with the surrounding materials. The microstructure of the walls in the thick-walled forms is radial-fibrous. Where seen in thin sections, and under crossed polars, they show a black pseudo-uniaxial cross. With a quartz wedge the crystals are radially fast which implies that the c-crystal axes of the calcite crystals are arranged perpendicular to the walls of the tests.

In the case of small thin-walled foraminifera the wall microstructure

is not distinct, and the walls are so thin that they appear as little more than dark lines of very fine-grained calcite crystals which do not appear to show any preferred optical orientation. This might be due to a porcellaneous wall microstructure (Horowitz and Potter, 1975, p. 106). Chambers of these latter foraminifera are usually filled with sparry calcite, but some contain micrite. Most living foraminifera have high-magnesium calcite tests but, as with the organisms mentioned earlier, those in the Qom limestones are all low magnesium calcite.

(vi) Ostracods. Ostracods are well preserved. Their original composition was high magnesium calcite (Chave, 1954a), but they are now formed only of low magnesium calcite.

B. Former aragonitic skeletal structures

I. Corals. The structures of the living forms are all composed of aragonite. The skeleton consists of an outer wall inside which there is a series of vertical plates with a radial arrangement. These plates may or may not meet at the center. In many of the corals horitzontal plates also occur. The aragonite of the skeleton is dissolved in the course of diagenesis and is replaced by fine to coarse grained mosaics of low magnesium calcite. In consequence, the coral remains do not exhibit the original skeletal structure, and the overall structure of the skeleton can often only be recognized by virtue of the fact that interseptal cavities are filled with carbonate mud or detrital material (Fig. 48).

II. Gastropods. Gastropods in the Qom limestones are present mainly as calcite casts. In some specimens the casts are surrounded by carbonate mud or 'recrystallized' micrite matrix and shell outline is made apparent by the change in crystal size. The original aragonite of the shell was clearly lost by dissolution, and the casts now comprise low magnesium calcite. The dark outer line which

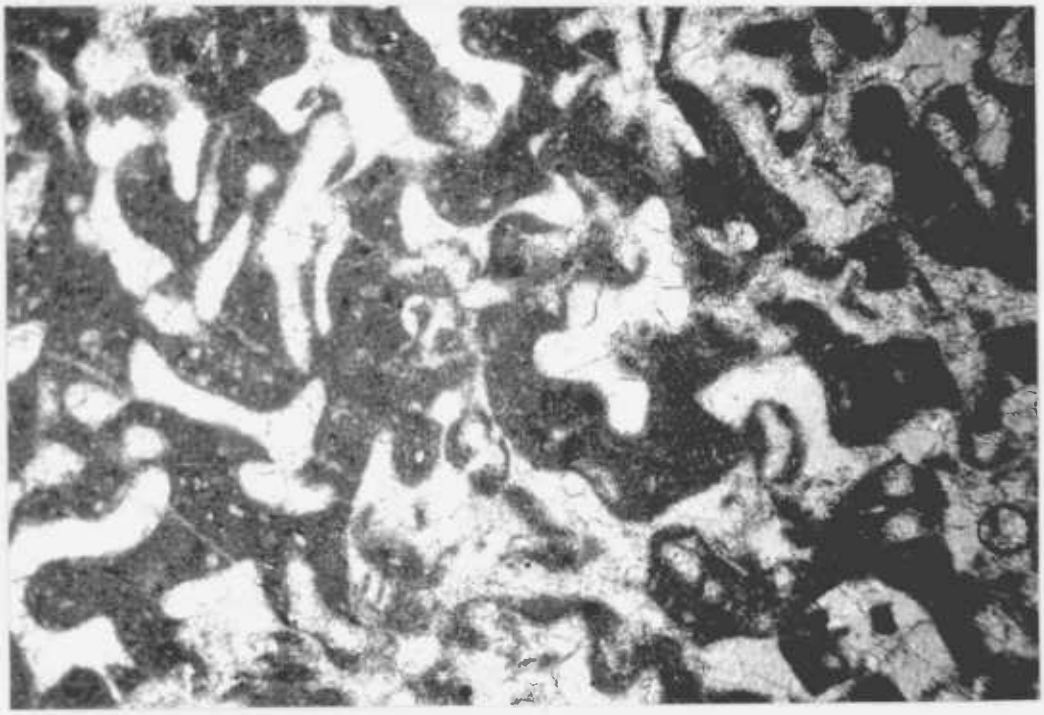


FIGURE 48 Photomicrograph showing the recrystallization of corals. The interseptal spaces are filled with carbonate mud and other detrital materials. The original aragonite of the skeletal structure has been replaced by clear calcite. 'c_1' Member, Kuh-e-Do-Baradar section. (x 45).

marks some of these casts is considered to be a micrite envelope (Bathurst, 1975, p. 333), which is thought to have been produced by the activities of blue-green algae.

III. Green algae. Halimeda is present as elongate or rectangular fragments. It is brownish gray in color and is composed of microcrystalline carbonate. Although the original mineral composition was aragonite, the internal structure which consists of variously arranged tubes is well preserved in low magnesium calcite (Fig. 13).

C. Composite Skeletal Structures

I. Pelecypods. The microstructure of some pelecypod shells is beautifully preserved. They show various prismatic and foliated crystal fabrics (Bathurst, 1975; Horowitz and Potter, 1975).

4.5 Diagenetic Alteration of Nonskeletal Grains

A. Ooliths

Most modern marine ooliths are composed of aragonite. Their internal structure is concentric, usually around some form of nucleus. The arrangement of individual aragonite crystals is tangential. Sorby (1879) and subsequent workers found by studying the present day ooliths that under crossed polars individual ooliths show a symmetrical extinction cross, thus indicating that the constituent crystals are symmetrically arranged. Optically the ooliths are radially slow and from this it is inferred that the c-crystal axes of the aragonite crystals are tangentially oriented. In many limestones, where ooliths have changed to calcite, the calcite crystals have a radial arrangement of c-axes.

In most of the ooliths of the Qom limestones the original concentric structure is retained, but no radial structure is seen. Nevertheless, there have been changes in the crystal fabrics. Shearman et al. (1970) have shown that retention of the original concentric structure in ooliths is related to the distribution of the inherent mucilaginous

organic matter. These authors showed that in Recent ooliths the crystals of aragonite are set in a diffuse matrix of organic mucilage, and that the aragonite layers are separated by concentric layers of mucilage. They argued that during the diagenetic replacement of aragonite by calcite, the calcite crystals grew perpendicular to the surfaces of the layers of concentric mucilage by pushing aside the intervening diffuse mucilage. They therefore believed that the radial fabric of ancient ooliths is a diagenetic feature.

The ooliths of the 'a' limestone Member contain some iron oxide in the concentric shells. Conspicuous reddish brown seams outline the boundaries between the concentric layers of fine grained calcite. In many ooliths of the 'a' Member some layers have been selectively dolomitized, and each individual oolith comprises alternating concentric layers of reddish brown material, dolomite rings, and sometimes calcitic layers. Presumably aragonite was either dissolved or replaced by dolomite in the course of diagenesis and granular calcite of the concentric layers was later deposited as cement.

Ooliths of the 'c_3' Member have no inclusions and delicate, barely noticeable lines of crypto-crystalline calcite separate the concentric layers.

B. Pellets

Individual pellets are dark brown in color and their internal structure is generally homogeneous. The original composition was probably aragonite, which was replaced by calcite.

4.6 Cementation

In this thesis the term 'cement' is used in the sense defined by Bathurst (1975, p. 416) as "all passively precipitated, space-filling carbonate crystals, which grow attached to a free surface".

Primary pore spaces and dissolution voids in the Qom limestones are occupied by sparry calcite cement and two distinct phases of cement can be distinguished in most of them. The first phase cement is apparent as a thin fringe of very tiny calcite crystals around the bioclastic grains and ooliths. The calcite crystals of this rim cement have grown mostly at right angles to the surfaces of the grains. Some crystals have scalenohedral termination but others are delicately fibrous.

Around monocrystalline echinoderm fragments the calcite cement is present as syntaxial overgrowths in which the two phases cannot be distinguished (Fig. 49). Many overgrowths completely enclose the host grains but others are partial and occur only locally; presumably impurities prevented the growth of calcite on these parts on the host. In some samples the partial overgrowths tend to be more abundant either on the tops or the bottoms of the echinoderm fragments (Fig. 49). Overgrowths are usually clear but some carry dusty inclusions. In rare instances overgrowths are marginally replaced by dolomite. The growth of rim cement on echinoderm debris in most samples is extensive and in extreme cases it forms large crystals which poikilitically enclose several of the surrounding grains (Fig. 49). A considerable proportion of cement in many samples, as seen in thin section, is formed of large crystals of calcite. It is likely that these large crystals are in fact overgrowths on echinoderm fragments above or below the plane of the thin section.

Folk (1965) related the morphology of the sparry cement to the substrate upon which cement is built. He noted that overgrowths on echinoderm grains usually extend out much farther than other types of cement and concluded that they formed either earlier or faster than other types. Evamy and Shearman (1965) suggested that overgrowths on echinoderm fragments grow faster than the polycrystalline cement because the latter requires nucleation, whereas the echinoderms provide an existing calcite lattice. Evamy and Shear-

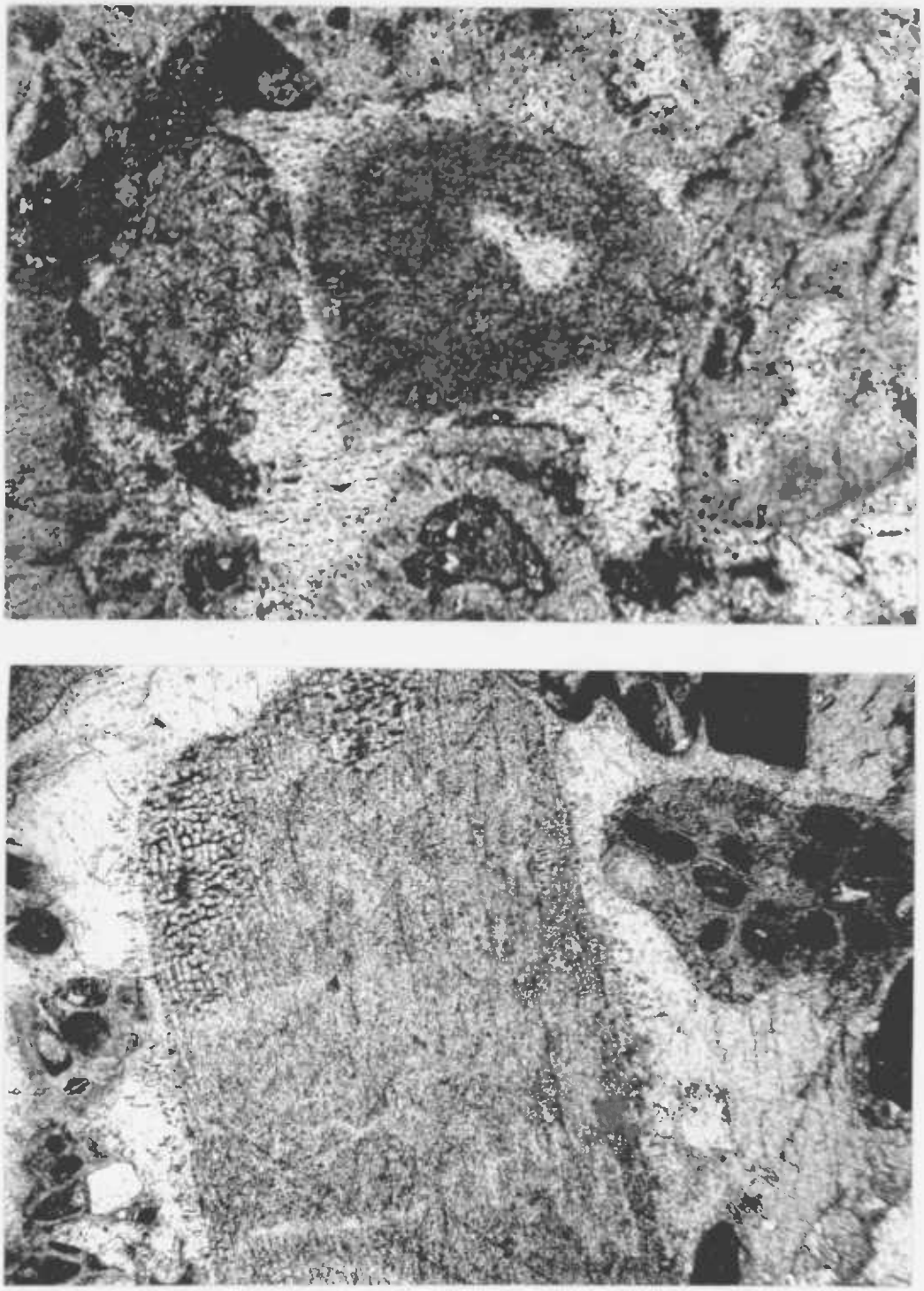


FIGURE 49 a) Photomicrograph showing that overgrowth on echinoid fragment is concentrated on the bottom of echinoid host. It grew far enough to enclose other fossil fragments poikilitically. 'c_1' Member, Do-Chah section. (x 64).

FIGURE 49 b) Photomicrograph showing extensive development of overgrowth on an echinoid fragment to embrace other fossil fragments. 'a' Member, Idaghchi section. (x64).

man were able to resolve the successive stages of the development of syntaxial sparry calcite overgrowth around the echinoderm fragments by staining techniques. They traced the distribution of ferrous iron in the calcite crystals and identified iron-free and variably iron-bearing zones. They found that the calcite of the echinoderm fragments and of the inner parts of overgrowths remains unstained. This was true also in the cases of the other polycrystalline shell fragments. Each of these latter grains was also surrounded by a narrow fringe of small crystals which passed outwards into coarsely crystalline iron-bearing mosaics. They concluded that the inner unstained parts of overgrowths and the narrow inner fringe around polycrystalline grains represented first phase cementation. They came to the same conclusion also by studying the compacted grains where the first phase cement is present only on the outer surface of the ruptured grains. In the Qom limestones no iron was found in the overgrowths and it was not therefore possible to show the successive stages of the syntaxial development of sparry calcite by the staining technique. A time lapse between the two phases of formation of sparry calcite cement can be shown, however, by means of the occurrences of skeletal and nonskeletal grains, which were broken by compaction after the first phase of cementation.

In the rocks with abundant carbonate mud matrix, development of overgrowths is restricted, and overgrowths are only present on one or two sides as small spires (Fig. 50). Evamy and Shearman (op. cit.) found similar occurrences; they proved that the carbonate mud matrix was introduced later and that the overgrowths represent first phase cement and part of the subsequent second phase cement. In the Qom limestones, however, no such evidence exists to prove the late introduction of the carbonate mud. Folk (1962) stated that sparry calcite may form by displacing the surrounding mud matrix or allochems. The relationships of the components in the Qom limestones indicate an early diagenetic origin of the rim cements, and it is probable that overgrowths were formed by pushing the intergranular mud matrix aside mechanically, while the lime mud was still soft.

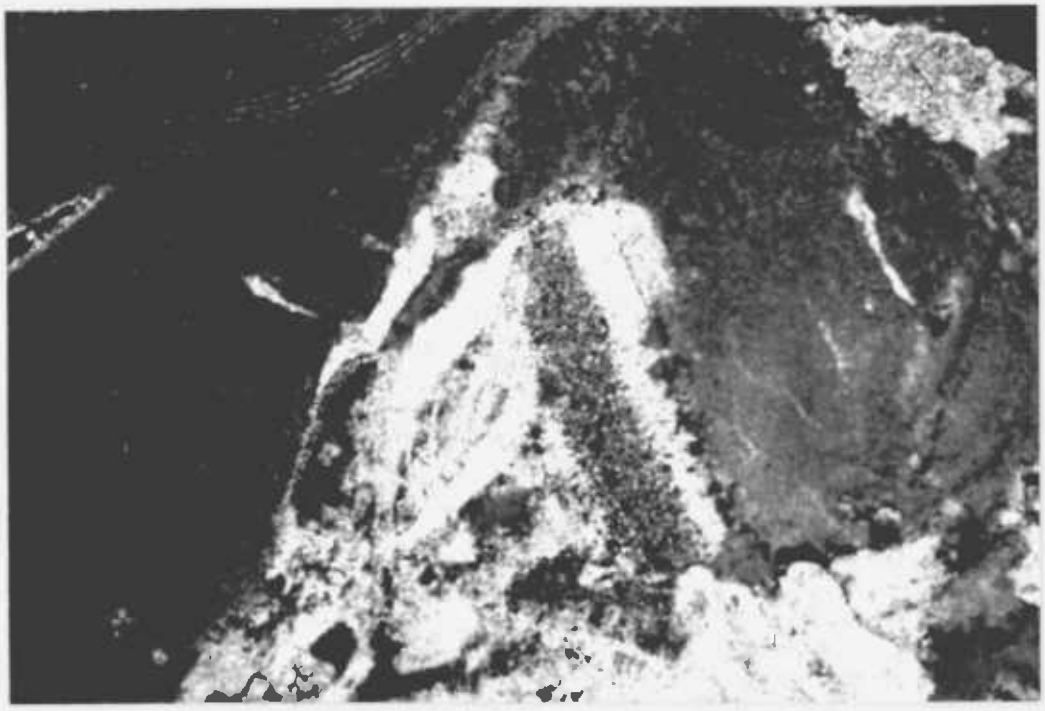


FIGURE 50 Photomicrograph showing that syntaxial overgrowth on the echinoid fragment appears to have replaced part of the cellular structure of a coralline algae. The rock is micritic and it is thought that the syntaxial rim was formed by neomorphic replacement of the micrite. 'c_1' Member, Do-Baradar section. (x 45).

Bathurst (1958) contended that, where syntaxial rim cement around echinoderm fragments penetrates the fabric of other skeletal particles or embays the surfaces of pelloids, the rim is of neomorphic origin. He also suggested that where syntaxial overgrowths on echinoderm debris are seen in carbonate mud supported limestones, the overgrowths formed by recrystallization of the mud. Both these occurrences are encountered in the Qom limestones but, while it is believed that the syntaxial rims may have formed by recrystallization of the carbonate mud, they are not believed to be the products of grain growth. It might be suggested that the syntaxial rims formed during the initial stages of compaction by pressure dissolution of micrite next to the echinoderm fragment accompanied by redeposition of the calcium carbonate from solution.

The second phase sparry calcite cement in the oolitic rocks comprises subequant coarser crystals of calcite. In the bioclastic rocks the calcite crystals grow larger away from the pore walls and fill the intergranular as well as intragranular interstices.

4.7 Recrystallization

In this thesis the term 'recrystallization' is used in the sense of change in the fabric of the carbonate minerals, where crystals grow larger: i. e. 'aggrading neomorphism' as defined by Folk (1965). Both terms carry no implication of the original mineralogical composition of the carbonates, nor of the nature of the processes which were involved.

The matrix of the Qom limestones, where present, is low magnesium calcite, but there is sometimes accessory fine grained terrigenous detritus. In many thin sections, the carbonate matrices are present as semi-opaque microcrystalline mosaics of calcite which could be primary fabrics. However, in most of the samples the fabrics of the matrices do not appear to be primary, and it is concluded that they are products of 'recrystallization'. The matrices appear in

part as irregular patches of fine to medium grained sparry calcite, intimately mixed with micrite. The distribution of crystal sizes in the sparry calcite is also irregular. The overall fabric of the matrix is therefore 'blotchy', and the term 'leopard skin pattern', used by Schlanger (1964), aptly describes it. In the more coarsely crystalline parts the fabric is very similar to that of the cement, but it lacks the characteristics of pore filling spar and contains small patches of micrite which float in it (Fig. 51). Grumeleuse textures similar to those described and illustrated by Cayeux (1935, pp. 211, 308, pl. XVIII, Figs. 67-69) occur occasionally. The origin of the clotted structure is uncertain. In some thin sections of the 'c_1' and 'f' Members, bioclastic fragments appear to float in the granular sparry calcite. Fossil fragments, such as algal debris, have been transected by the sparry calcite and appear as disconnected relics. Many algal fragments are recrystallized around their margins (Fig. 52). Irregular masses of coarsely crystalline calcite with a roughly circular outline may record former fossil fragments in which no trace of the original structure remains. This texture occurs more often in the mud supported rocks where the looseness of packing of the allochems, as well as relics of micrite, preclude the possibility that the calcite was an interstitial cement.

In the mollusc shells, traces of yellowish 'fibres' are occasionally seen in the mosaics of otherwise irregular sparry calcite. The mosaic of calcite crystals is clearly not the original crystal fabric, and the shell therefore appears to have been aragonite in life. The yellowish material traces out the former structure of the shell, and it appears therefore that the replacement of aragonite by calcite must have taken place on a piecemeal basis with dissolution of aragonite accompanied by concommitant precipitation of calcite. (Hudson, 1962).

As with present day carbonate muds, those of the Qom limestones were probably mostly bioclastic in origin and the constituent carbonate grains were probably formed by comminution of skeletal

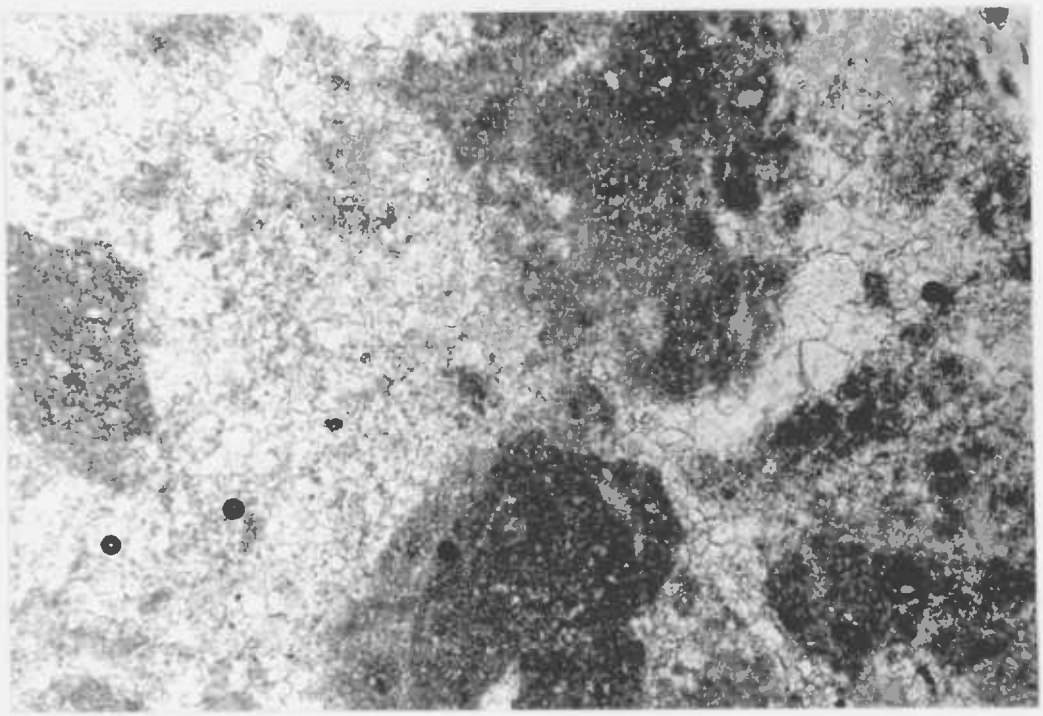


FIGURE 51 Photomicrograph showing the recrystallization of the carbonate mud matrix in a wackestone. Relic patches of micrite in the sparry calcite suggest that sparry calcite was produced by recrystallization of an earlier carbonate mud. 'f' Member, Do-Baradar section. (x 48).

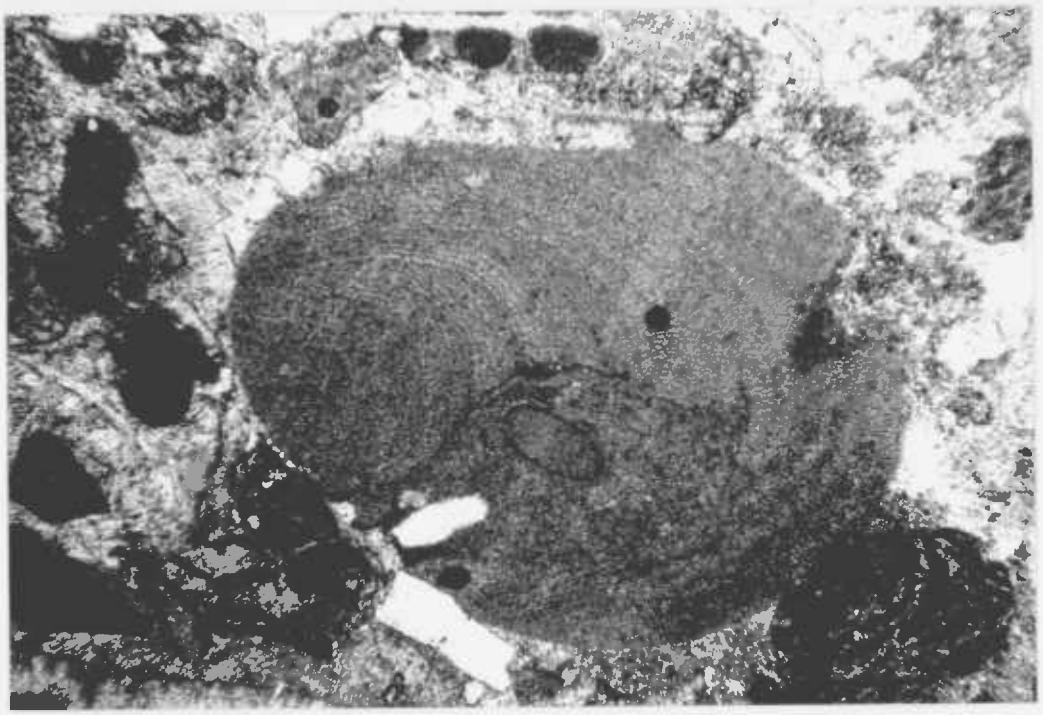


FIGURE 52 Photomicrograph of an algal fragment recrystallized around its margin. 'f' Member, Do-Baradar section. (x 48).

materials. The comminution was possibly the result of biological erosion, caused by the vital activities of various organisms, each of which eroded and comminuted the carbonate substrate in different ways. Boring and burrowing organisms in search of food and shelter penetrate calcareous substrates, and thus weaken and erode them.

Certain blue-green algae, green algae, some sponges and certain gastropods attack carbonate substrates primarily by chemical secretions, which in some boring animals such as gastropods are produced by specific boring organs. Boring and burrowing by other animals, like worms and echinoids, are achieved by mechanical means. Some herbivorous animals like certain fishes, gastropods and echinoids find their foods within the carbonate substrate and break it down by trituration. At the present day some starfish, which feed on corals, are destroying them wholesale in various parts of the world. Some fishes eat shelled invertebrates and 'crunch' the shells into small fragments. Mechanical abrasion of the carbonate grains must also produce micron-size debris. The likelihood is that the original mud matrices were deposited as mixtures of aragonite and high-magnesium calcite, the composition of the mud being dependent on the composition of the skeletons of the contributing organisms. Obviously, the main diagenetic alteration which would affect the matrices would have been the change of aragonite and high-magnesium calcite to low magnesium calcite.

As previously mentioned, the matrices as presently seen in some specimens consist of lithified muds in which the original fabrics appear to be preserved apparently without loss of details. However, in the majority of the thin sections, the crystal fabrics are so anomalous that they can only be explained by 'recrystallization'.

Apart from the textures described above, other occurrences of recrystallized fabrics, such as those associated with syntaxial overgrowths on echinoderm fragments, are similar to some of those described and illustrated by Bathurst (1958, 1975).

4.8 Dolomitization

Prior to this study, no dolomite had been reported from the Qom limestones. The presence of dolomite was not noticed during the field work, but was only revealed in the course of petrographic study of thin sections and by X-ray diffraction. Although most dolomite crystals can be easily recognized by their rhombic outlines, study of the distribution of dolomite in the Qom limestones was facilitated by differentially staining the thin sections with alzarin red-S.

Dolomitization is generally restricted stratigraphically to the lowermost and uppermost limestone members. It occurs in the 'a' and 'f' limestone Members only. In the 'a' Member it was found principally in the Idaghchi and Nardaghi sections and, in the 'f' Member, in the Do-Baradar section only. It must, however, be mentioned that in the 'a' Member of the Do-Chah and Do-Baradar sections, rare isolated rhombs of dolomite can occasionally be detected by differentially staining the thin sections. The intensity of dolomitization varies from bed to bed and also within a single bed, but in no sample studied did dolomite exceed 80 percent.

In the Idaghchi section, the dolomite was found in the lower part of the 'a' Member and most of it is concentrated in the oolitic grainstones and oolitic packstones. In the Nardaghi section, however, it appears to increase upwards from the lower part of the 'a' Member into the upper part, where a large proportion of the rock is dolomitized, and then to decrease again towards the top. The distribution of the dolomite in the 'f' Member is generally rather uniform throughout the whole section.

Dolomite in the Qom limestones is of diagenetic origin. As seen in thin section it appears to be present either as a simple cement or as a replacement. However, where it appears to represent an original cement, i. e. as a simple void -filling, the possibility has

to be considered that it may in fact have formed as a replacement of an earlier carbonate mud matrix, and that replacement went to completion so that no relics of the original matrix remain. Where the dolomite appears to be present as cement it can be as partial or total infilling of intergranular and intragranular spaces (Fig. 53).

Because the limestones of the Qom Formation are only partially dolomitized, the original textures of the rocks and the fabrics of the skeletal and nonskeletal structures are still discernible in most samples. Only in a few thin sections have the organic structures been obliterated by replacement dolomite, but even then some traces of the original structure can still be seen (Fig. 54). Some of the details of the dolomite vary with the depositional fabric and with the fabric elements of the host limestone.

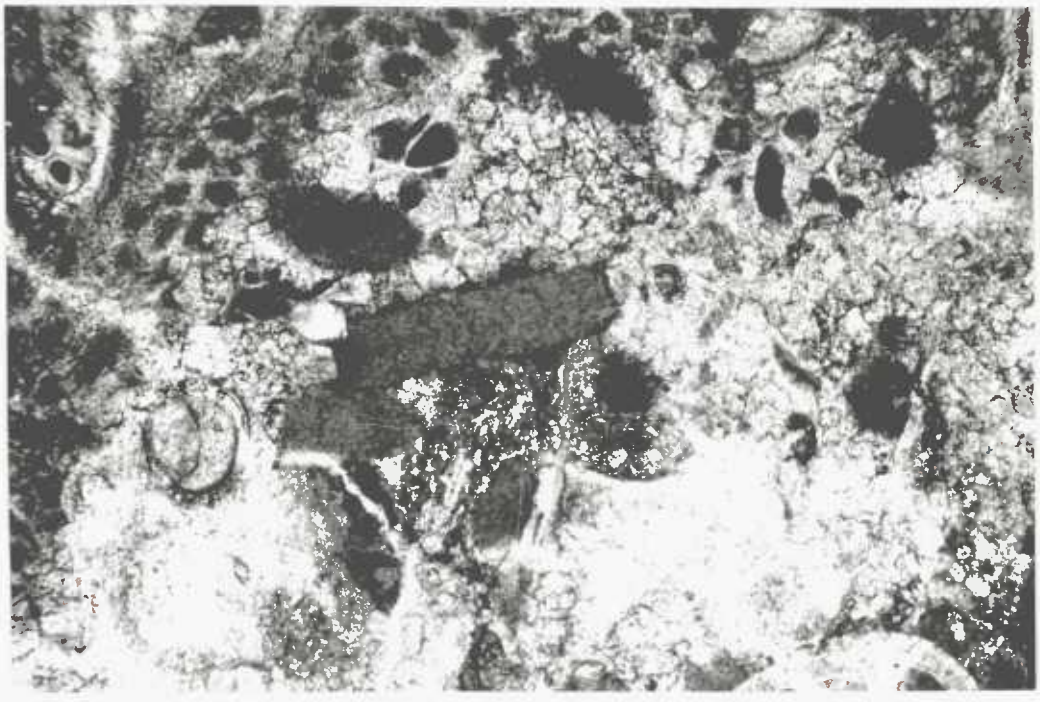
Where partial replacement has occurred, certain preferences can be seen. Dolomite rhombs occur most commonly as a replacement of micrite. Preferential replacement of micrite by dolomite has been reported by several authors (Murray, 1960, p. 73; Lucia, 1962, p. 856; Murray and Lucia, 1967) and these observations are confirmed by this study. The micritic rocks apparently were more susceptible to dolomitization due to the very large surface areas offered by the minute grains.

Dolomite crystals are found scattered in carbonate mud. They occur as isolated rhombs or as groups of rhombs within the micrite matrix (Fig. 55). In these instances the dolomite was either replacive or displacive. The latter could only have been possible if the mud was soft and wet, in which case emplacement of the dolomite would have to have been penecontemporaneous with deposition. This is thought to be unlikely.

The dolomite crystals are between .02 and 0.3 mm. in diameter and isolated crystals are euhedral. Some crystals exhibit zoning which appears as reddish brown or dark lines parallel to the rhombohedral faces of the crystals. Katz (1971) suggested that the zoning

FIGURE 53 a) Photomicrograph of a dolomitized algal-bryozoan packstone. The dolomite formed either as cement or a replacement of intergranular carbonate mud. There is some marginal impingement of skeletal fragments by the dolomite. Thin section treated with alizarine red-S, 'a' Member, Nardaghi section. (x 48).

FIGURE 53 b) Photomicrograph of a dolomitized algal-bryozoan packstone. The dolomite appears superficially to be a cement, but it is thought that it did in fact replace an earlier micrite matrix. The dolomite has also embayed the margins of the skeletal fragments. Thin section treated with alizarine red-S. (x 48).



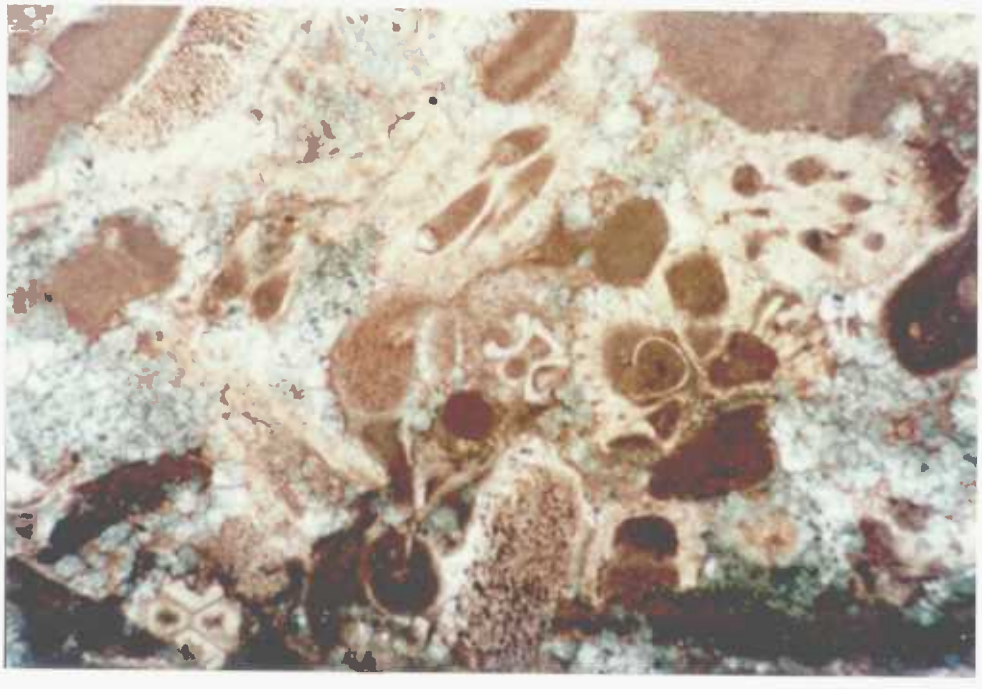


FIGURE 54 Photomicrograph of a highly dolomitized limestone. Thin section treated with alizarine red-S. 'a' Member, Nardaghi section. (x 40).

FIGURE 55 Photomicrograph showing replacement of carbonate mud by dolomite. Individual rhombs are rimmed by reddish brown iron oxide. 'a' Member, Nardaghi section. (x 64).

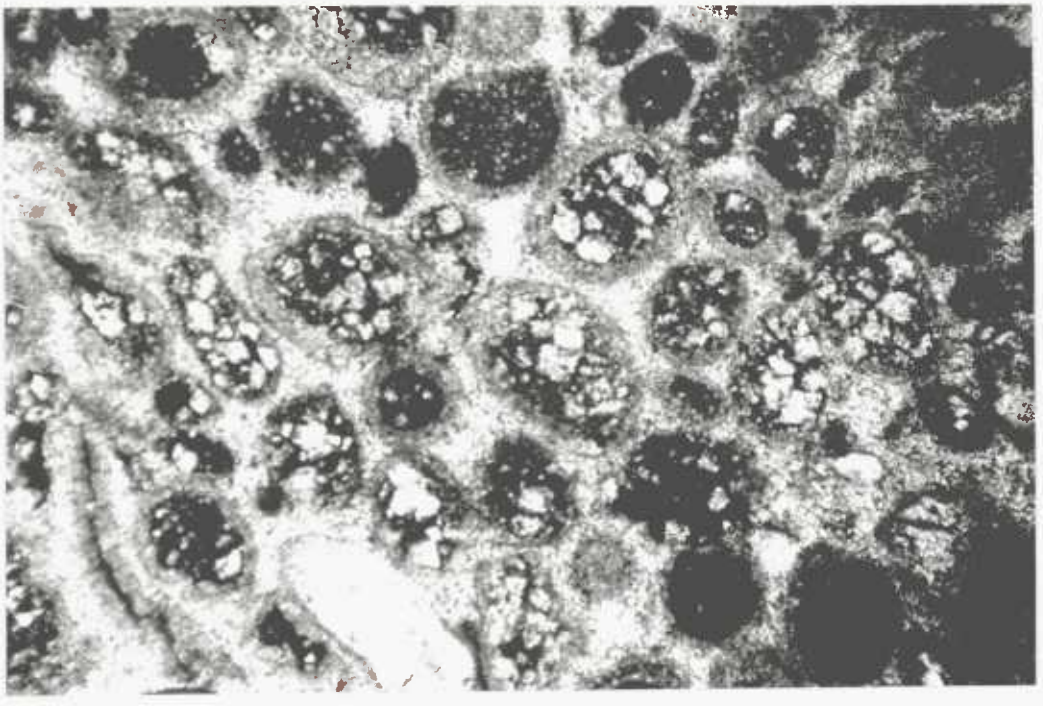
might record variations in the composition of the dolomitizing fluids. Other rhombohedra are devoid of any inclusions and thus appear as clear crystals. Many rhombs are outlined with a deep red iron oxide stain associated with rich iron-stained zones of the rocks (Fig. 55). In some samples the centers of many of the crystals are marked by dark 'muddy' inclusions and resemble frog-spawn. These muddy centers might be due to inclusions of the original carbonate mud trapped within the dolomite. Some rhombs are wholly or partially present as voids.

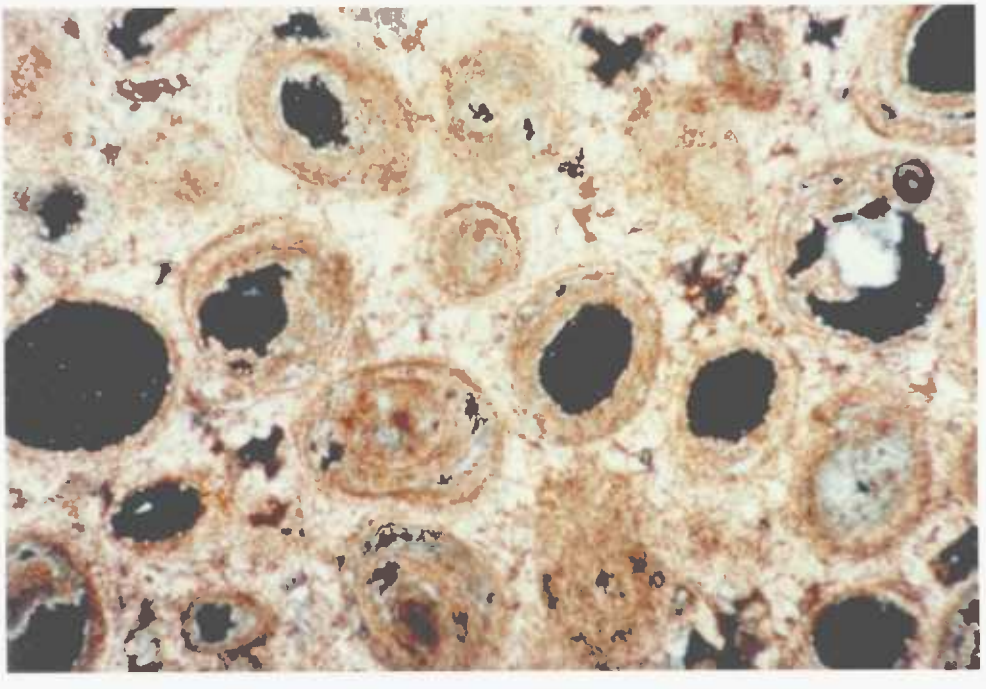
In the argillaceous mud-supported wackestones and some of the packstones tiny rhombs of dolomite are concentrated in masses and stringers. Clusters of larger crystals also occur. Rhombs are prominent but, due to mutual interference during growth, many of them are incomplete and the result is a mass of interlocking euhedral and anhedral crystals.

Among the various carbonate grains, ooliths were the most susceptible to replacement by dolomite. Ooliths are commonly the only type of replaced grains and are the only kind of grains found as ghosts. In dolomitized oolitic grainstones it is only the ooliths which are dolomitized and these are cemented by crystals of sparry calcite (Fig. 56). The dolomitized ooliths may be put in two groups. In one group both the cores and their surrounding oolitic coatings are entirely dolomite and the original concentric structure of the ooliths can only vaguely be seen (Fig. 56). In the second group the cores of the ooliths appear to have been affected in three ways. In some the cores have been entirely dissolved to leave a void which is surrounded by dolomitized oolitic shells (Fig. 57). In others, part of the core is occupied by one large or few smaller dolomite rhombs and the remaining part is void. In the third type, the core of the ooliths is completely occupied by a group of coarsely crystalline dolomite rhombs (Fig. 56). In this second group of ooliths, the oolitic coatings consist of shells of very finely crystalline anhedral

FIGURE 56 Photomicrograph of a dolomitized oolitic grainstone. In some ooliths only the nuclei are replaced by dolomite rhombs. In others dolomitization affected almost the whole of each oolith and only a few outer shells remain visible. Thin section treated with alizarine red-S. 'a' Member, Idaghchi section. (x 64).

FIGURE 57 Photomicrograph of a dolomitized oolitic grainstone. The oolitic shells are dolomitized in an alternating pattern. Some shells are not completely replaced. Most of the carbonate nuclei have been dissolved out. Thin section treated with alizarine red-S. 'a' Member, Idaghchi section. (x 64).





dolomite which alternate with darker concentric layers of granular calcite (Fig. 57). Individual calcite grains are rimmed with reddish brown stain. It is thought that both the cores and the concentric shells of these ooliths were originally aragonite. In some samples, however, the composition of the oolitic shells varies from layer to layer. Some layers stain pink with alizarine red-S and are calcite; others remain unstained and are dolomite, although some of those which do not stain are mostly dark brown with some clear patches. It is likely that the cores of the ooliths were formed of pelleted carbonate mud or fossil fragments and that both the cores and oolitic shells were originally aragonite. In the course of dolomitization the aragonite of the cores of some ooliths was completely dissolved to leave voids. In others the cores were partially or wholly dolomitized. In the partially dolomitized cores the undolomitized parts were left as voids (Fig. 57). The fact that dolomite rhombs in the oolitic layers are very small, anhedral and are arranged in concentric layers suggests that the fabric of the dolomite was influenced by the internal structure of the oolith. It is possible that the concentric layers of organic matter, which are known to be present in both modern and ancient ooliths, may have acted as templates which guided the dolomite fabrics. Where voids are present in the ooliths, it is believed that they represent undolomitized parts where unreplaced aragonite was subsequently dissolved out. Where ooliths are associated with bioclastic materials, it is only the ooliths which are dolomitized. These various lines of evidence suggest that in these rocks the aragonite was selectively dolomitized.

Amongst the calcitic bioclasts, dolomite is most commonly found in the fragments of coralline algae; most of the rhombs occur at the margins of the fragments and in between the laminae of the structure (Fig. 58). However, some are scattered randomly. In foraminifera and bryozoans dolomite is usually present as infillings of the chambers. Few rhombs of dolomite were observed at the margins of echinoderm

FIGURE 58. Photomicrograph of a dolomitized algae. 'f' Member, Do-Baradar section. (x 48).

fragments and only in rare instances was dolomite found in overgrowths. Although the rhombs often transect skeletal grains, they are generally restricted to the margins (Fig. 53). This type of marginal replacement was called impingement by Lucia (1962, p. 856). He stated that the impinging rhombs nucleated outside the skeletal grains and, once nucleated, were able to replace part of the fossil during growth. Replacement of the skeletal grains is confined mainly to marginal impingement. Even in highly dolomitized samples, the rocks commonly contain a diverse assemblage, the skeletal materials of which still retain their original structure.

In some skeletal chambers dolomite is present with a geopetal arrangement. The lower part of the former chamber is occupied by carbonate mud, on top of which groups of dolomite rhombs have grown. These are followed in turn by sparry calcite cement (Fig. 59). It is probable that subsequent to the partial filling of the lower part of the cavity with mud, dolomite rhombs started to grow as cement, but these did not fill the whole cavity and the remaining space was later occupied by calcite 'cement'.

The mechanism of dolomitization by seepage reflux, proposed by Adams and Rhodes (1960), has been considered in the case of the Qom limestones. In this process, evaporation of sea water leading to precipitation of gypsum would produce brines with a high Mg to Ca ratio. These dense brines would then seep down into the underlying sediments and promote dolomitization. There is no evidence of former intertidal environments in the Qom limestones, most of which are bioclastic grain supported micritic packstones, evidently deposited in an open marine environment. Thus one cannot easily postulate penecontemporaneous intertidal or supratidal dolomitization. Furthermore, the Qom limestones are only partially dolomitized and the dolomite tends to occur in the carbonate muds rather than in the grains. The dolomite crystals are characteristically coarsely

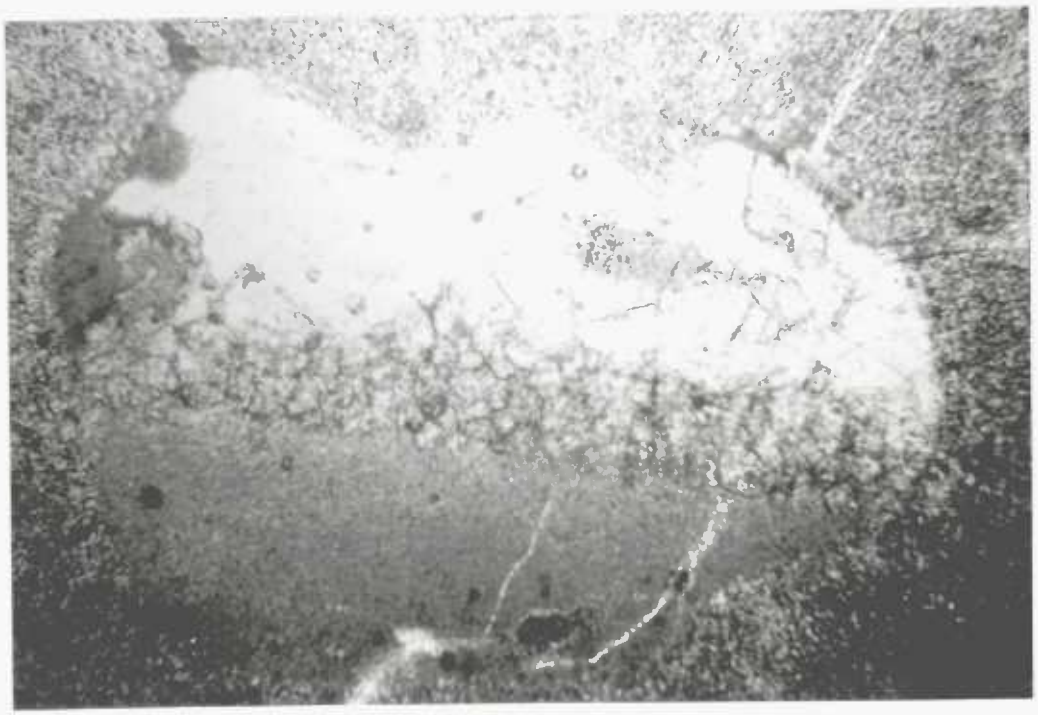


FIGURE 59. Photomicrograph showing the geopeal fabric in an echinoid hollow. The pore is filled with carbonate mud, dolomite rhombs and sparry calcite in succession from bottom to top. Thin section treated with alizarine red-S. 'a' Member, Nardaghi section. (x 64).

crystalline and euhedral, and it will be recalled that Folk (1959, 1974) noted that dolomite rhombs of diagenetic origin are coarser than those which are syngenetic. Some dolomite rhombs are zoned and the zones probably record changes in physico-chemical conditions (Katz, op. cit.). On the basis of these various lines of argument, it is perhaps reasonable to suppose the limestones were dolomitized after burial.

4.9 Dedolomitization

Dedolomitization in the Qom limestones was first noticed in the course of this research by the differential staining of thin sections and was confirmed by close examination of the textures and crystal fabrics. Two of the dedolomitization textures described by Shearman et al. (1961) are found in these rocks: (1) One type is seen in samples of the 'f' Member where the rocks contain abundant isolated dolomite rhombohedra. In these there are rhombs which at first sight appear to be dolomite but, when the thin section is differentially stained with alizarine red-S, are seen to be calcite (Fig. 60). Under the microscope each rhomb is seen to consist of a mosaic of small calcite crystals. These composite calcite rhombs are evidently pseudomorphs after dolomite. In the same rocks some of the dolomite rhombs have cores of fine grained calcite thought to represent early stages in calcitization of the dolomite. On the other hand, there is always the possibility that the latter texture represents incomplete dolomitization; however, the calcite in the core of the rhombs is slightly coarser grained than the carbonate mud groundmass (Fig. 60), and this tends to argue against incomplete dolomitization.

(2) The second type of dedolomitization texture is found in the algal-bryozoan packstones in which the cement consists of coarsely crystalline sparry calcite. In this cement and in some of the fossil fragments rhombic ghosts can be seen outlined in iron oxides. Under

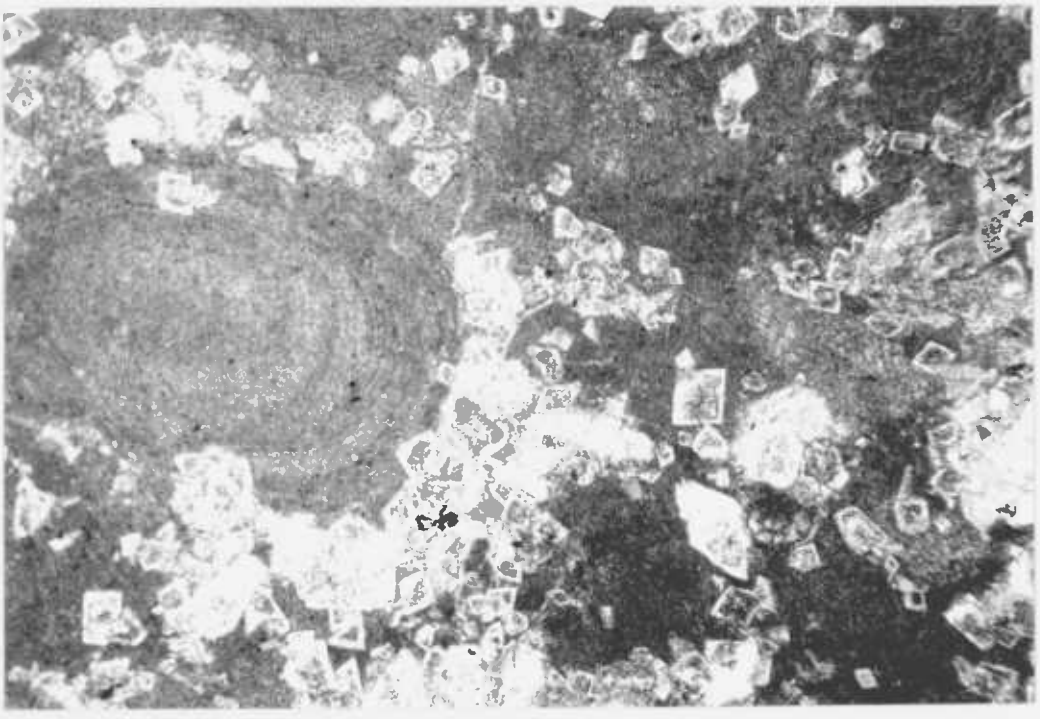


FIGURE 60 Photomicrograph of a partially dedolomitized rock. The core of each rhomb is occupied by small calcite crystals. These crystals are coarser grained than the surrounding carbonate matrix and this precludes their being residual undolomitized calcite. Thin section treated with alizarine red-S. 'f' Member, Do-Baradar section. (x 48).

crossed polars each part of these rhombic ghosts is part of a different calcite crystal. They are similar to examples described by Shearman et al. (op. cit.) and by Evamy (1967), where rhombic zones of ferric oxides are found within the calcite of the pore filling mosaic. These authors concluded that dedolomitization had regenerated the earlier texture of the rock. They also suggested that the ferric oxide stain was a product of calcitization of an iron rich dolomite. Such an argument can be applied to the examples from the Qom limestones.

A third type of dedolomitization texture is the selective replacement of dolomite by calcite in zones parallel to the original rhomb faces. This type of dedolomitization produces a box-in-box appearance (Fig. 61). In some occurrences, however, individual zones are not completely altered. The possibility is that selective dedolomitization of particular zones records subtle differences in the composition of the original dolomite.

Occurrences of rhombs which are partially or wholly void are not uncommon in some samples. These are usually present in association with composite calcite rhombs and/or zoned dedolomite rhombs. Evamy (1967) suggested that the pores were produced by selective leaching of the calcite which had replaced the dolomite. The evidence Evamy put forward for this suggestion (pp. 1212-1215) is not applicable in the case of the Qom limestones, in which it is believed that the pores were produced by dissolution of the residual dolomite.

In the Qom limestones there is no evidence which allows the time of dedolomitization to be determined. It could equally have been relatively recent or ancient. However, most authors relate dedolomitization to the effect of calcium sulphate bearing groundwater. In the Qom limestones such solutions could have been produced from the underlying and overlying gypsiferous red beds, and from gypsum beds which are present in the Qom limestones.

FIGURE 61 a) Photomicrograph of a partially dedolomitized rock. Dedolomitization has produced calcite zones parallel to the rhomb faces. Centers of some rhombs are voids or contain partly dissolved dolomite. Thin section treated with alizarine red-S. 'f' Member, Do-Baradar section. (x 48).

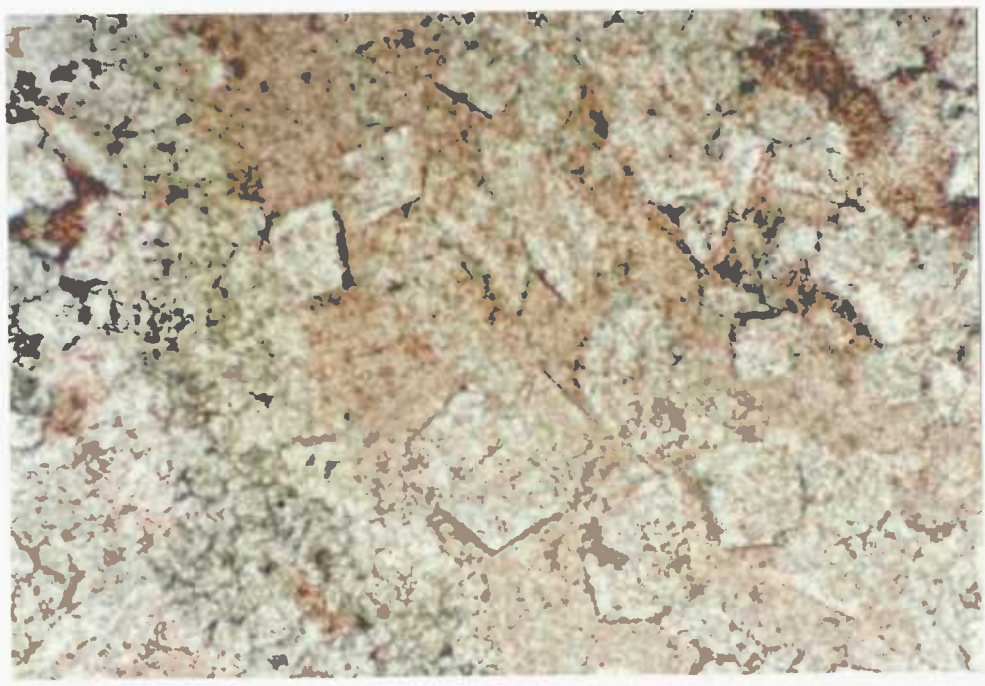


FIGURE 61 b) Photomicrograph of a partially dedolomitized rock. The red-stained parts of the crystals are calcite and greenish parts are dolomite. The rhombs are rimmed by reddish brown iron oxide. Thin section treated with alizarine red-S. 'a' Member, Nardaghi section. (x 96).

4.10 Silicification

Silicification was observed occasionally in various limestone members, but it is most common in the 'f' and 'c_1' Members. The silica either replaces skeletal components and the carbonate mud matrix or the carbonate matrix alone. Some pelecypod fragments are virtually wholly replaced by silica (Fig. 62), and minute relics of the original calcite are only occasionally preserved. The original fibrous structure of pelecypod valves can still be seen in the silica, presumably being outlined by the organic matter of the former shell. The common replacement of the pelecypod fragments by silica indicates that, for some reason, the shells of these organisms were very susceptible to replacement by silica. The mode of replacement of the gastropod shells is different. The gastropods are set in a microcrystalline calcite matrix and their chambers are also filled by microcrystalline calcite. Replacement of the gastropod shells by silica proceeded from the matrix into walls of the shells, and it is only occasionally that silicification has extended into the carbonate mud which occupies the chambers (Fig. 62). Furthermore, in some cases the gastropod shell is marginally replaced along only one side while the other side is unaffected. This suggests that 'nucleation' of silica started in the matrix and moved into the shell. Corals are also found completely replaced by silica. In some thin sections chambers of foraminifera are occupied by silica. There are also instances where silica has cut through fragments of calcareous algae, and apparently replaced both fossils and the cement in a random fashion.

Chert nodules have been found in the 'f' limestone Member. They are elliptical, lenslike, or irregular in shape. The nodules are brownoutside and light reddish brown inside. They range in their largest dimension from 15 millimetres to more than 250 millimetres. The plane of flatness of individual lenslike nodules and the long axis of elliptical nodules are roughly parallel to bedding in otherwise massive limestones. Nodules occur as a layer which

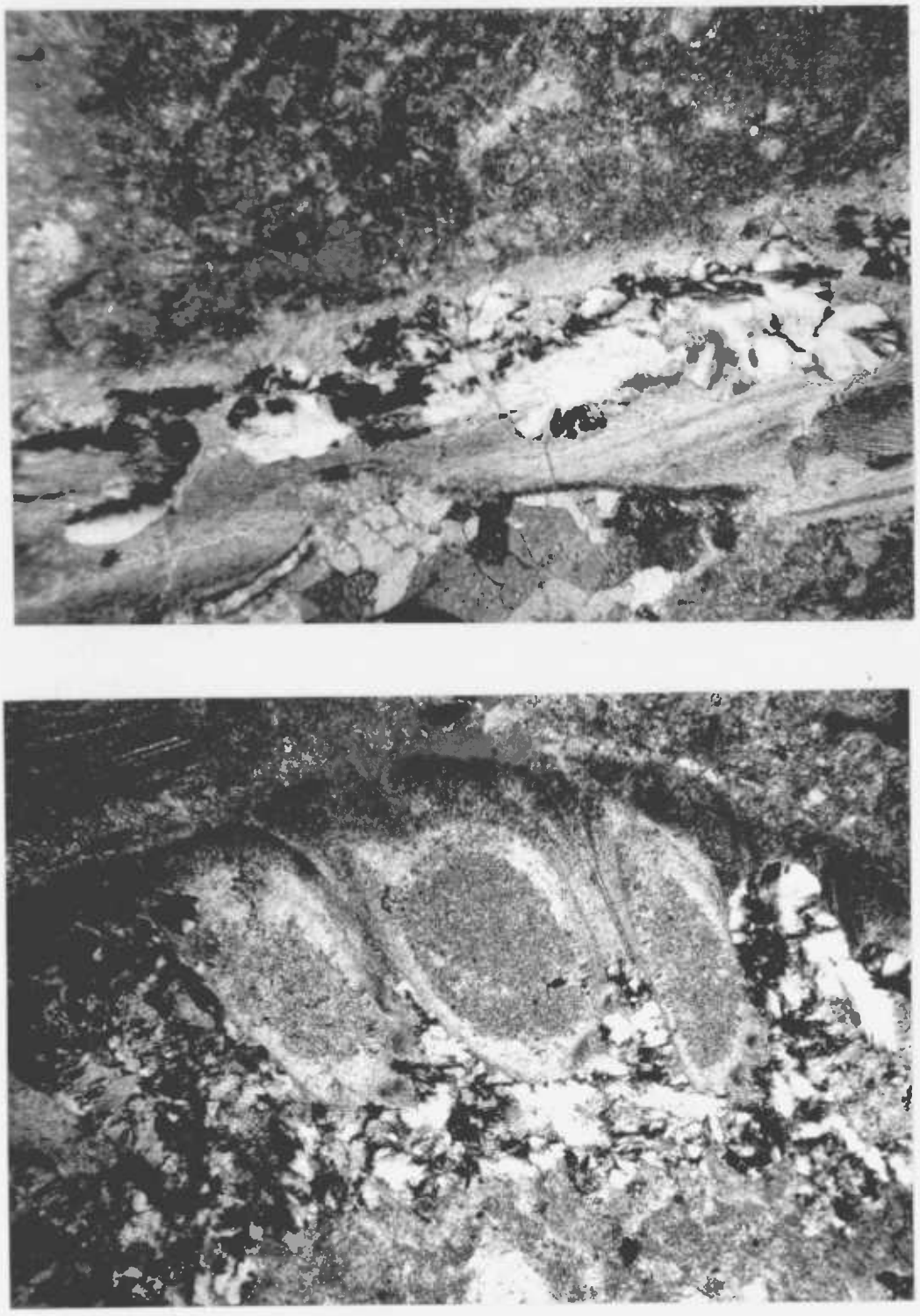


FIGURE 62 Photomicrographs of silicified mollusc shells.

a) Silica developed in a pelecypod shell.

b) Silica replaced the carbonate mud matrix with marginal corrosion of a gastropod shell.

Crossed polars. (x 35).

extends along the outcrop for distances of several metres, and were found at three horizons each a few metres apart. They occur in the lower part of the 'f' Member in Nardaghi mountain only.

Evidence for the origin of chert is scant. It is probable that silica was derived from volcanic rocks in the vicinity of the basin. As was mentioned earlier, the Qom limestones carry detrital materials of volcanic origin in the sand, silt and clay size grades. It is possible that the silica for the chert was supplied by diagenetic corrosion of the detrital fragments, as was suggested by Peterson and von der Borch (1965) for modern occurrences in some Australian ephemeral lakes.

Part of the silica may have been derived from sponges, as some sponge spicules are occasionally found in the thin sections of the 'f' limestone member. Decomposition of the organic parts and reorganization of silica were probably critical in determining whether or not recognizable sponge remains persist.

4.11 Celestite $SrSO_4$

Celestite ($SrSO_4$) was found in the limestones of the 'c_1' Member in three of the four measured sections, but only in one thin section from each locality. The occurrence of celestite was confirmed in one sample by X-ray diffraction. Celestite can be seen in thin sections as large areas of unit extinction under crossed polars. In all the samples, celestite is present as cement. Crystals are subhedral and very coarsely crystalline, such that one crystal spreads through several adjacent intergranular and intragranular pore spaces and may extend over an area up to 2 centimetres in diameter (Fig. 63).

Possible sources of the strontium may have been aragonitic skeletal fragments or other aragonitic constituents. The overlying gypsiferous member could also have been a source.

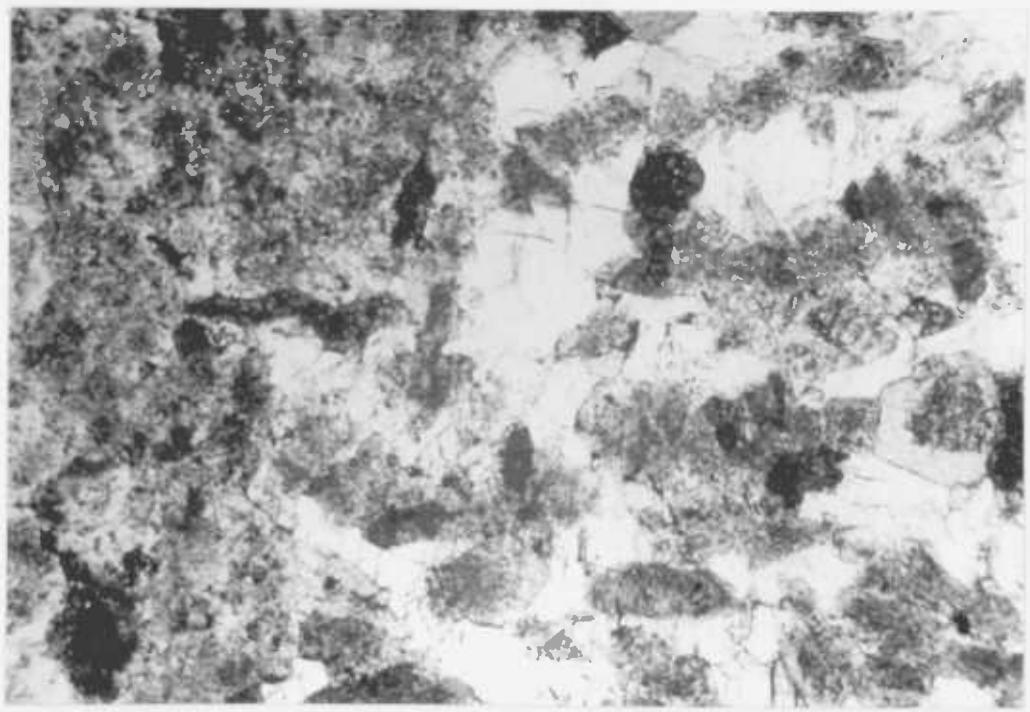


FIGURE 63 Photomicrograph of colorless poikilitic celestite in a wackestone. 'c_1' Member, Do-Baradar section. (x 35).

4.12 Stylolites

Stylolites run roughly parallel to the bedding and are present as parallel or subparallel sets with up and down zig-zag extensions (Fig. 64). The spacing of the seams varies from bed to bed, but most are closely spaced. The amplitudes of the peaks also vary, but average about five millimetres. They cut through grains, matrix and cement, but more often they pass over or under allochems rather than cutting across them. The stylolites have concentrations of fine grained reddish brown or dark gray opaque material along the seams. Accessory fine grained detrital material is abundant in the matrix of some of the Qom limestones, and it seems that the occurrence of stylolites is most common in those rocks which have very fine grained terrigenous detritus in the matrix.

The stylolites cut through all other diagenetic structures and textures and are only interrupted by joints and fractures. They are thus late features. The fact that stylolites transect the cement indicates that they were formed after lithification and are thus similar to those described by Dunnington (1954) in the subsurface rocks of north Iraq.

4.13 Minor fractures

Fractures in the Qom limestones were probably produced by tectonic activity during the Pliocene. They can be seen in nearly all of the thin sections from all of the limestone members. Fractures are present as parallel or subparallel groups, as well as intersecting sets which cut one another at different angles. Some of the fractures are wide as well as long and extend across the whole of a thin section; others are short and narrow. These various fractures cut across allochems, matrix and cement, and are healed by sparry calcite (Fig. 65). In a few samples, fractures of one set are displaced on opposite sides of an intersecting fracture. This clearly indicates fractures of two different generations.

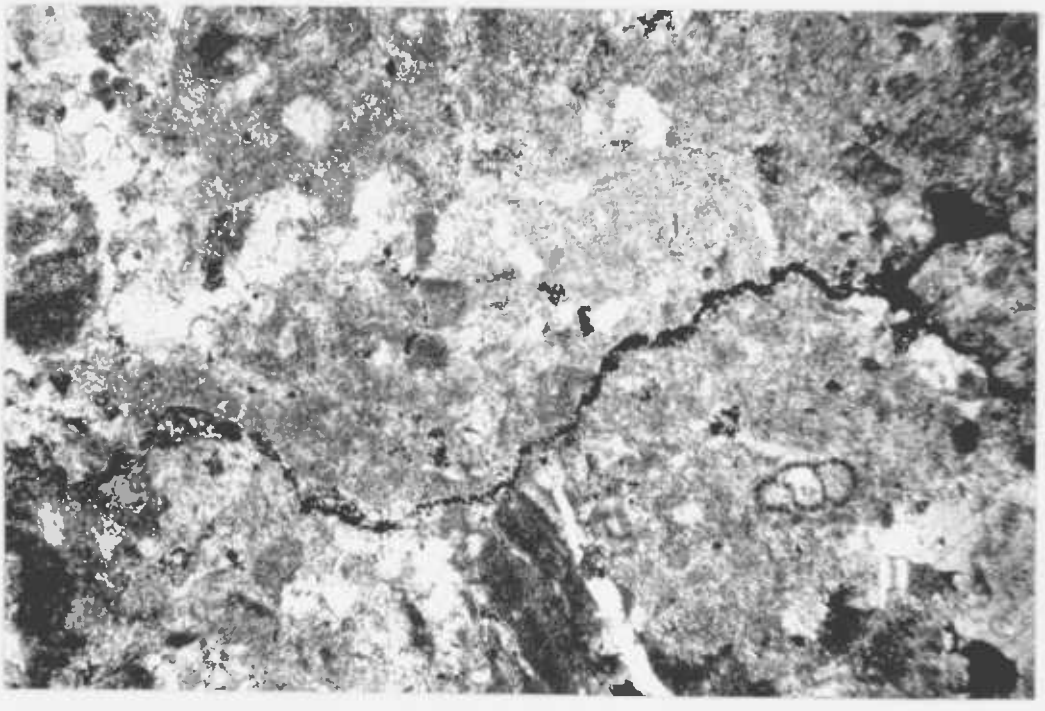


FIGURE 64 Photomicrograph of microstylolites. 'f' Member, Do-Baradar section. (x 45).

FIGURE 65 Photomicrograph showing late calcite-filled fractures. 'f' Member, Do-Baradar section. (x 45).

4.14 Sequence of Diagenesis

In the previous pages postdepositional changes in the mineralogy and fabrics of the Qom limestones have been described, and it is now necessary to put the various diagenetic changes into a time sequence. Evidence for the paragenetic relations between two or more authigenic components is commonly conjectural. Emplacement of any one component may have taken place over a period of time which may have overlapped partially or wholly the replacement of another component. Likewise the time span or continuity of any one process is usually ambiguous. It is therefore often difficult to define the sequence of diagenetic events in any rock with complete confidence. The sequence which has been aimed for the Qom limestones is illustrated in Figure 66. The relative order of events is based mainly on textural and fabric relationships seen, but it is in part subjective.

The formation of the glauconite in the chambers of fossils and as isolated grains is considered to be the earliest process. It must have been penecontemporaneous with deposition. Some of the grains of glauconite may have formed elsewhere and then been transported to the site of deposition.

Development of micrite envelopes around skeletal fragments must also have been penecontemporaneous with deposition. The extent of micritization of many of the skeletal fragments indicate that a considerable period of time must have elapsed between death of the organism and final burial of its skeletal remains, since the micritization apparently resulted from the boring activities of the blue-green algae. These algae are unlikely to have operated after burial of the sediment.

The first postdepositional event was the introduction of first phase sparry calcite cement. This was emplaced either as syntaxial

overgrowths on echinoid fragments or as a rim of fibrous crystals around other grains.

High-magnesium calcite skeletal debris probably lost its magnesium at this time or shortly afterwards. The manner in which the magnesium was lost is still unknown, but it was achieved without any apparent change to the crystal fabrics of the skeletal structures which are now present intact in low-magnesium calcite. Replacement of aragonite by low-magnesium calcite took place concommitant with the transformation of high-magnesium calcite to low-magnesium calcite. This change resulted from complete dissolution of the aragonite of the skeletal fragments. The micrite envelopes and the first phase of calcite cement probably provided the support necessary to prevent the moulds from collapsing. The moulds were then filled with sparry calcite so that the original fabric of the fossils was completely lost. Preservation of the original concentric structure of ooliths was probably aided by the shells of organic matter which were inherent in them and rearrangement of the crystals to radial structure took place by progressive dissolution of the former aragonite and simultaneous deposition of calcite.

Recrystallization of the carbonate mud matrix probably occurred either concurrently with or after the change of aragonite to calcite. Recrystallization of the fragments of calcareous coralline algae also took place at the same time, because the recrystallized margins of the algal fragments merge with the matrix and show a similar texture.

In situ fragmentation of skeletal materials and compaction with pressure welded contacts between most of the grains probably occurred slightly before or after the formation of the first phase cement.

Emplacement of the second phase of sparry calcite cement which

filled all the remaining pore spaces was clearly a later event, but how much later is uncertain. The cement filled the intergranular spaces and also the moulds, which were formed by dissolution of former aragonitic skeletal fragments.

It is probable that dolomitization took place over a long period of time, and in separate episodes. Among the allochems, ooliths are often extensively dolomitized whereas other components were not affected. The ooliths were probably originally aragonitic, and the possibility arises that dolomitization of the ooliths took place early, before replacement of aragonite by calcite. However, the presence of occasional rhombs of dolomite in the intergranular cement of some of the algal-bryozoan packstones is suggestive of late dolomitization of these particular rocks.

It is difficult to explain how silicification occurred and impossible to determine the exact time of silicification. It is thought that the replacement by silica may have taken place at different times. Some of the silica is obviously of late diagenetic origin because it fills stylolites and minor fractures.

Dedolomitization took place some time after lithification of the rocks. This is suggested by the occurrence of calcite pseudomorphs after dolomite rhombs in the intergranular calcite cement. Dedolomitization is considered to be a near surface process by most authors, e. g. Evamy (1967). In the Qom limestones it probably occurred after uplift and exposure of the rocks.

The dissolution voids which cut randomly across allochems, matrix and cement must also have been very late.

The Qom limestones are strongly folded, and in many places they are overturned. One of the questions which arises is: at what stage in the diagenetic history did the folding take place? Was it before

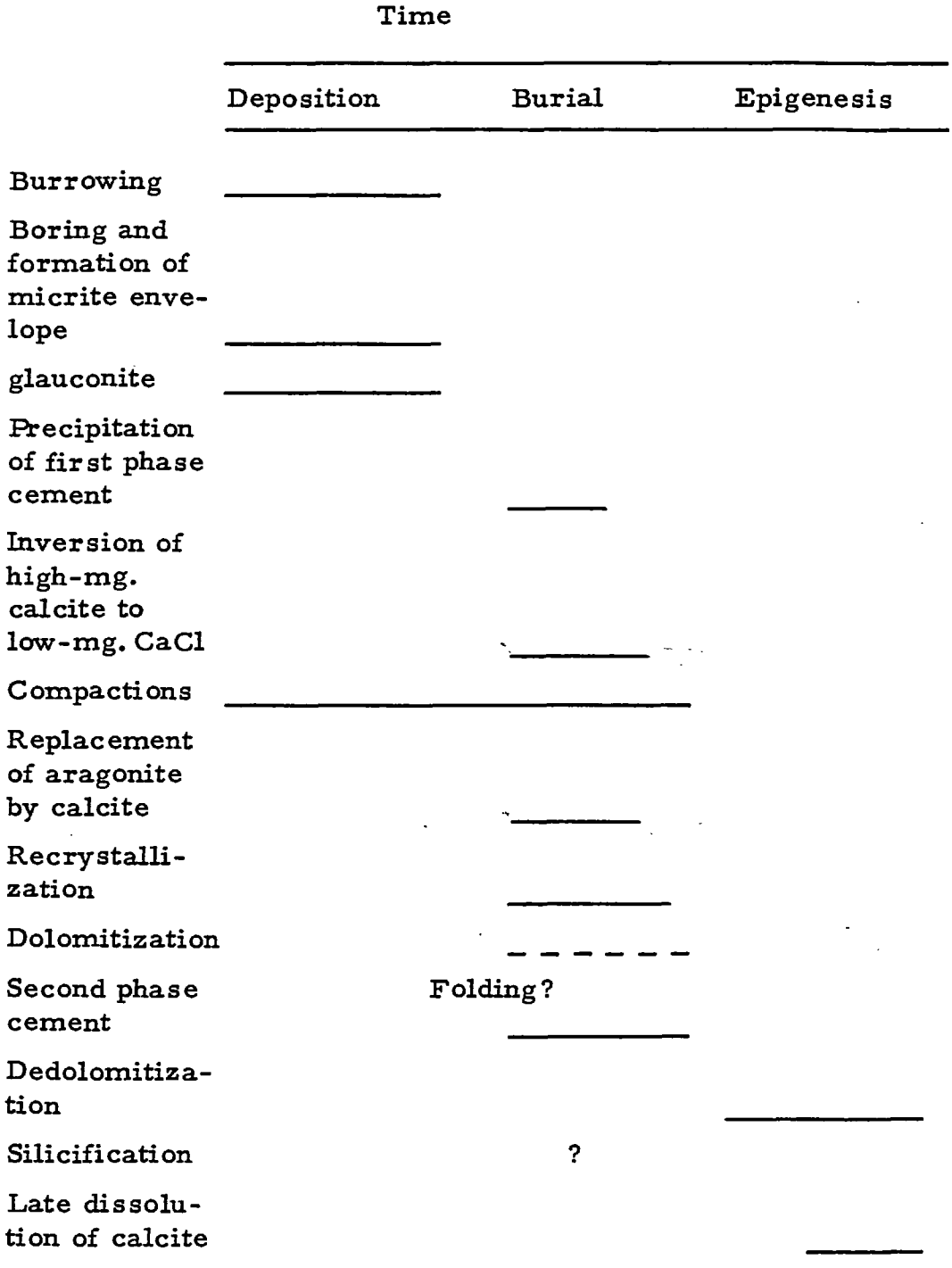


FIGURE 66 Diagram of inferred diagenetic sequence of the limestones of the Qom Formation

or after complete lithification? The fact that almost all grain contacts are pressure welded and that the welded contacts occur in all directions and not in the plane of bedding suggests that they were not simply the result of compaction due to overburden load. The calcite crystals of late phase of cement do not show any obvious strain or deformation, yet in many places the beds are strongly folded and inverted. These various features forcefully suggest that the folding of the rocks took place before emplacement of the second phase of cement.

CHAPTER 5

DESCRIPTIONS OF MEASURED SECTIONS

Four stratigraphic sections of the Qom Formation were measured and sampled. They are described in this chapter, and field and laboratory data are integrated in the descriptions. The locations of the four sections are shown on the geologic map (enclosure 1).

5.1 Do-Chah Section (Enclosures 2 and 3)

Do-Chah section was measured on the northern overturned flank of the anticline, which forms the Do-Chah range (Fig. 67). The strike of the beds is approximately east-west and the dip is about 80° overturned to the south. The section was measured south-east of the abandoned village of Do-Chah which is located on the contact between the 'e' marl member of the Qom Formation and the upper Red Formation. Because of the fact that access to the outcrop was only possible from the northern part of the section, the section was measured and sampled stratigraphically from top to bottom, but is described from bottom to top. The total thickness of the measured section is 1117 metres.

It starts with the 'a' limestone Member which is 84 metres thick. On the basis of comparison with the colour chart the rocks are medium gray (N5) on fresh surfaces and light brownish gray (5YR 6/1) to brownish gray (5YR 4/1) on weathered surfaces

The basal 0-7 metres of the unit consist of cross bedded oolitic-pelletic-bioclastic limestones. The limestones are moderately well cemented. They are more pelletic and oolitic at the base and grade upward into sandy bioclastic rocks. The ooliths at the base have been deformed, presumably by compaction. In the field the change of lithology from the basal oolitic-pelletic rocks into the more bioclastic types is not easily seen. Skeletal components comprise algal

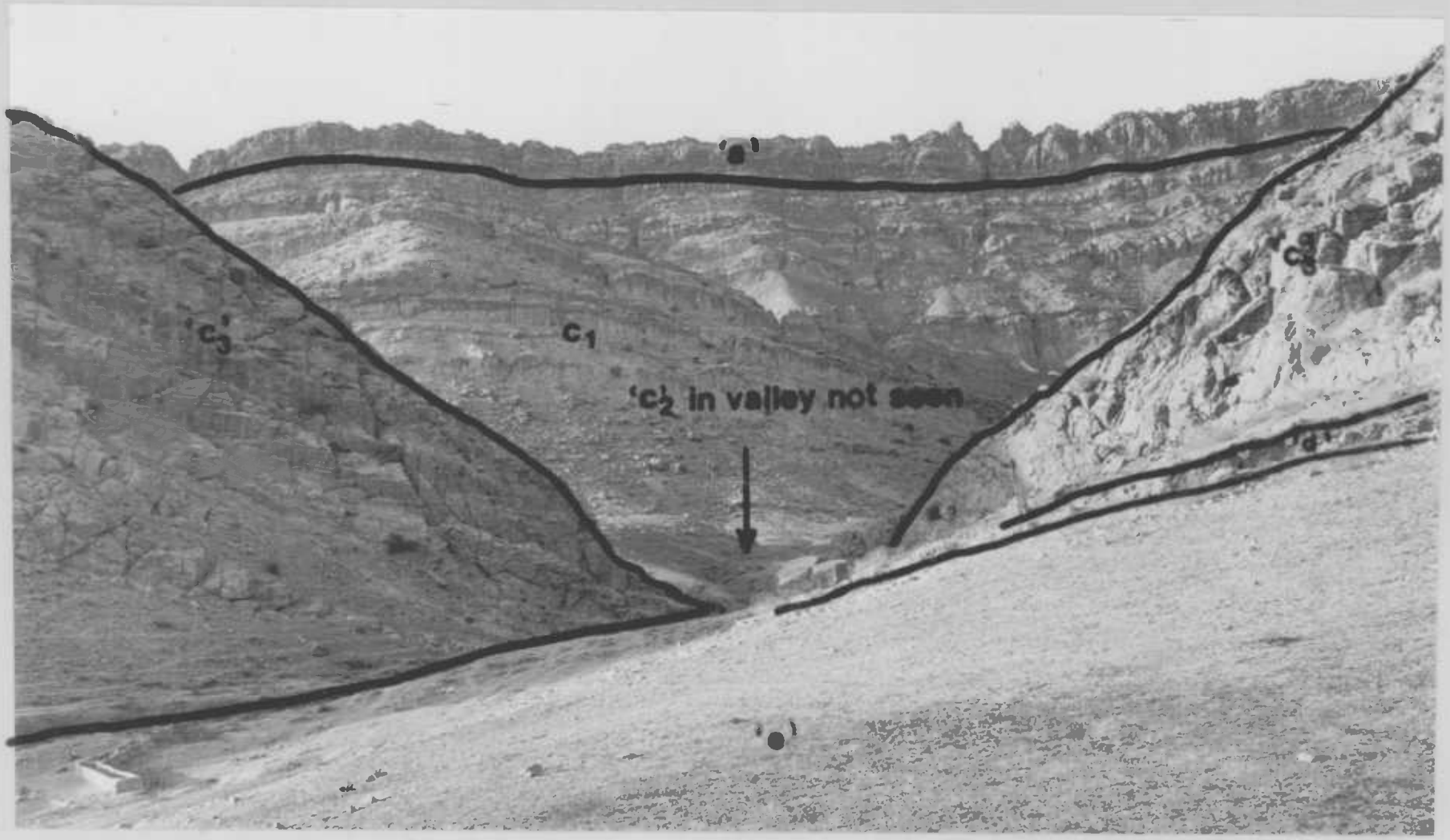


FIGURE 67 A general view of part of the Do-Chah range showing characteristic appearance of the limestones and marls of the Qom formation. N. B. The beds are overturned and nearly vertical. Looking south.

FIGURE 67 A general view of part of the Do-Chah range showing characteristic appearance of the limestones and marls of the Qom formation. N. B. The beds are overturned and nearly vertical. Looking south.

debris, tests of small foraminifera and a lesser proportion of other fossils. Abundant pelloid types of intraclasts are present. Iron staining is a common feature.

The basal part is followed by 10 metres of medium to thick-bedded algal-foraminiferal packstones. Some beds are sparsely fossiliferous, whereas in others fossils are more abundant. The packstones have a microcrystalline calcite matrix which is often recrystallized. These rocks are medium light gray (N5) on fresh surfaces and weather into light brownish gray (5YR 6/1).

The next 49 metres of the 'a' Member consist of porous algal bryozoan packstones. The rocks are medium light gray (N6) and weather into light brownish gray (5YR 6/1). The lower part of this unit is formed of thick beds which are alternately marly. Some of the beds of packstones contain considerable proportions of sparry calcite and grade into grainstones. The packstones are present as calcarenites and calcirudites, and frequently one type passes into the other. Likewise the fossil content of the various beds varies within them. In the lower part, pelecypods are abundant and in the upper 22 metres bryozoans become predominant. The packstones are sandy and there is an increase in sand content towards the top of the unit.

The 'a' Member terminates with 19 metres of calcareous fossiliferous sandstones. The sandstones are thick bedded dark greenish gray (5GY 4/1) and weather to a brownish gray color (5YR 4/1). They are fine grained and contain patches of clayey material. Abundant echinoids, mostly whole-skeletons, lie parallel to bedding planes. They are locally concentrated and often form discrete layers within a bed. They are usually more concentrated near the lower part of each bed.

Passage from the sandstones into the overlying 'b' Member is

transitional. The basal 2 metres of the 'b' Member are formed of thin-bedded, moderately indurated pale reddish brown (IOR 5/4) sandy limestones. The limestones weather grayish red (IOR 4/2).

The 'b' Member is formed of 108 metres of sandy fossiliferous glauconitic marls and calcarenite. They are poorly bedded and in higher parts of the member they show no bedding. The rocks are not well cemented, and are greenish gray (5GY 6/1) when frensh and weather to a light olive gray (5Y 6/1). They contain abundant tests of small foraminifera, some bryozoan debris and echinoid spines.

Two intercalations of sandstone, and one of limestone occur. The first is at 42 metres above the base of the member. It is 4 metres thick, brownish gray (5YR 4/1), and thin to medium bedded. It comprises calcareous glauconitic fine grained sandstone. The second intercalation is found following the next 38 metres of calcarenite. It is 2 metres thick and is a thin-bedded silty sandstone. The sandstone is light olive gray (5Y 6/1) and weathers to the same color. The third intercalation occurs after the next 18 metres of calcarenites. It is formed of 4 metres of sandy bioclastic limestones. They are thin-bedded and medium light gray (N6), but weather to grayish organice (10YR 7/4). They carry fragments of coralline algae and tests of benthonic foraminifera. The member is 120 metres thick.

The basal 25 metres of the 'c_1' Member, which immediately overlie the top of the 'b' Member, are formed of thin to medium bedded sandy bioclastic limestones. The lowermost part contains some intraclasts. Towards the upper part the rocks are sandy. They are medium gray (N5) in color and weather into grayish orange (10YR 7/4).

The bioclastic limestones pass up into alternations of marls and limestones which, with minor variations in thickness and composition,

continue for 255 metres. The limestones comprise foraminiferal-bryozoan packstones in which the fossil contents are essentially similar. Either bryozoans or foraminifera and sometimes algae predominate, but in some beds pelecypods become an important constituent. Encrustations of coralline algae and bryozoans are fairly common.

The packstones comprise both calcarenites and calcirudites and are mostly coarse grained. At some levels alternating limestone and marl beds become thin and closely spaced. In those parts, the limestones are more argillaceous. All of the limestones show extensive fracturing, and the fractures are filled with clear sparry calcite. The limestones are mostly medium dark gray (N4) and their weathered color is grayish orange (10YR 7/4). They are thin to thickly bedded. The marly beds tend to become eroded out, and covered by debris of the limestones. The marls are massive to thick bedded, generally dusky yellow green (5GY 5/2), which weather into grayish yellow green (5GY 7/2). Their faunal content is more or less similar to those of the associated limestones. In the lower parts of the member some marly beds contain abundant tests of large benthonic foraminifera. Some of the limestone and marl beds are also crowded with oyster shells.

The top of the 'c_1' Member consists of 70 metres of thin to partly nodular-bedded marls. The marls are dusky yellow green (5GY 5/2) and weather to pale yellowish green (10GY 7/2). Their fossil content is sparser than that of the interbedded marls. The total thickness of the member is 350 metres.

The 'c_2' Member is 75 metres thick. The lowermost 8 metres of the Member, which overlies the marls of the top of the 'c_1' Member, consist of thin to very thin-bedded platy limestones. The limestones are generally yellowish gray (5Y 7/2), but some thin beds show different colors. The platy limestones show various lithologies ranging from micrite to recrystallized and pelletoidal limestones.

Above the limestones, lies 7 metres of thin-bedded silty marl. The marl is dusky yellow green (5GY 5/2), and it weathers to grayish yellow green (5GY 7/2). Above the marls 1 metres of gypsum appears and is followed by 6 metres of marls. Another 1 metre of gypsum lies on top of the marls and this in turn is followed by 10 metres of gypsiferous marls.

Above the marls a series of calcareous haematitic siltstones and very fine grained sandstones makes up the remaining 43 metres of the member. The siltstones are very thin bedded in the lower parts but towards the top they show wavy and lenticolor bedding. The uppermost part is formed of fine grained sandstones which are rippled and easily split into thin layers. The color of the siltstones and sandstones varies from grayish olive green (5GY 3/2) which weather to grayish yellow green (5GY 7/2), to pale reddish brown (10R 5/4), which on weathering retain the same color.

The 'c_3' Member is 75 metres thick. The base of the member is marked by 4 metres of oolitic bioclastic grainstones and packstones. The lower surface of the lowest bed of packstone is marked by the casts of symmetrical ripples on the underlying sandstone. The rocks are medium gray (N5) and the weathered color is dark yellowish orange (10YR 6/6). The next 26 metres are formed of thick-bedded bryozoan packstones. They are mostly coarse grained, i.e. they are calcirudites, but calcarenites are also present. Some are tightly packed but, where packing is loose, considerable proportions of lithified carbonate mud are present. Echinoid and pelecypod debris and tests of foraminifera are also abundant. At 24 metres above the base, the limestones become marly and continue as such for about 6 metres. The color of these limestones is similar to that of the underlying rocks. On top of the marly limestone comes 4 metres of yellowish marls, which are followed by 20 metres of bryozoan packstones. Above the packstones lie 4 metres of marl which is partially covered by limestone debris. The top of the

member is formed of 17 metres of bryozoan packstones. The packstones are medium to thick bedded, medium gray (N5) on freshly broken surface but they weather grayish orange (10YR 7/4).

The 'c_4' Member consists of 37 metres of silty marls. The marls are thin bedded, pale olive (10Y 6/2) and weather to yellowish gray (5Y 7/2).

The 'd' Member is formed of 18 metres of gypsum which stands as a rounded ridge between the overlying and underlying marl members.

The 'e' Member is 342 metres thick. It is uniformly formed of calcareous marls. It is grayish green (5G 5/2) and weathers to moderate greenish yellow (10Y 7/4). The marls do not show distinct bedding although some parts are nodular-bedded.

In the upper parts of the marls, five intercalations of bioclastic calcarenites occur. These are between 30 centimetres and 2 metres thick and they are all slightly different in lithology. The calcarenites are each separated by 8 to 22 metres of marl. The first intercalation appears 220 metres above the base of the member and the last one occurs 22 metres from the top of the member and is followed by marls. The calcarenites carry fragments of bryozoans and echinoids, tests of foraminifera, and occasionally pelecypod shell debris. The rocks are sandy, and iron staining is common. Near the top of the member there is a bed of ferrugenous mudstone. It is possible that some of these marls may in fact be the lateral equivalents of limestones designated as the 'f' Member in other sections.

5.2 Idaghchi Section (Enclosures 2 and 4)

Idaghchi is a westerly plunging asymmetrical syncline (Fig. 68). Extension of the syncline to the west was truncated by a fault. A complete section of the Qom Formation was measured on the southern limb of the syncline. On this limb the strike of the beds

FIGURE 68. A general view of part of the Idaghchi syncline. Looking north.

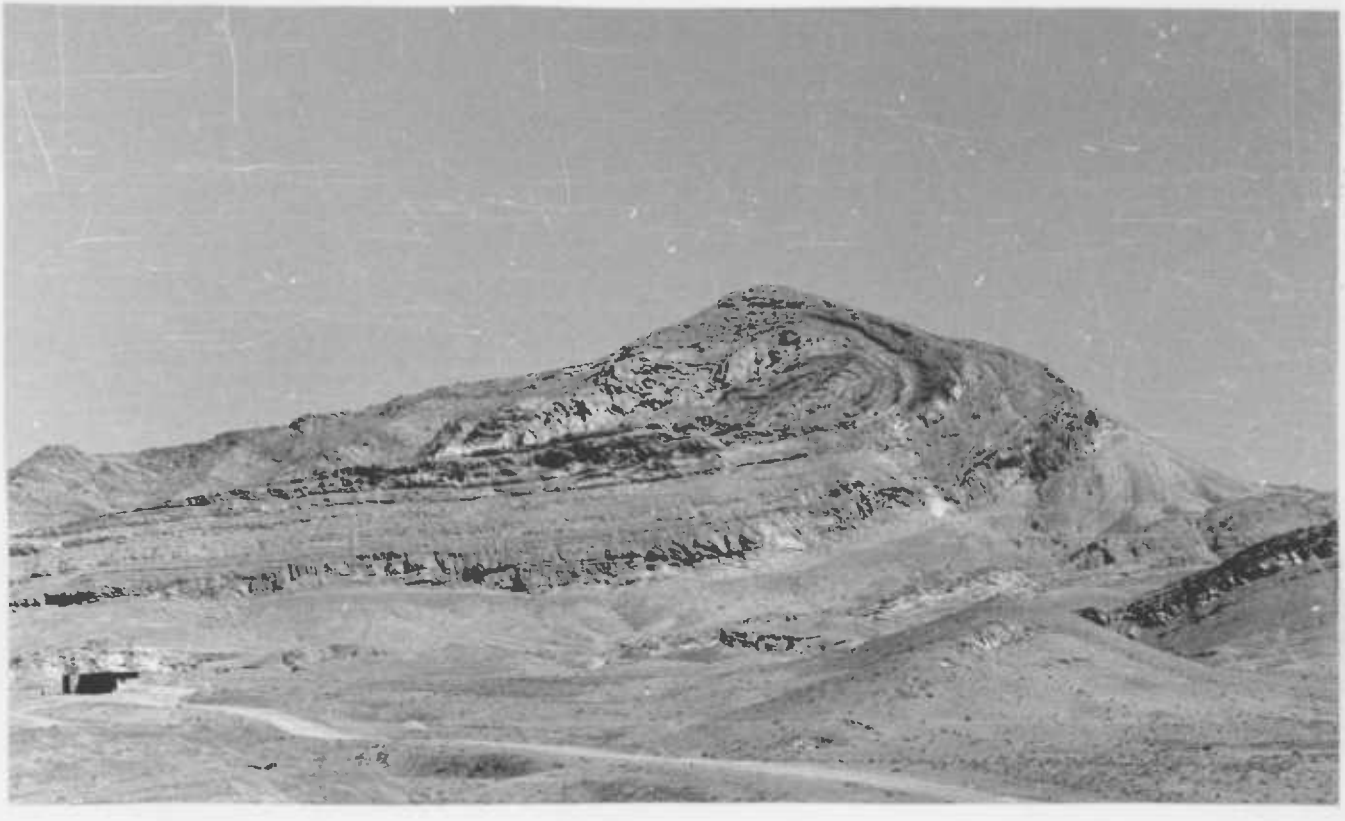


FIGURE 68. A general view of part of the Idaghchi syncline. Looking north.

is northwest-southeast and the dip is 40° to the northwest.

The section commences with the limestones of the 'a' Member overlying the Lower Red Formation. The 'a' Member at Idaghchi is 70 metres thick. Freshly broken rocks are medium gray (N5) in color and they weather to grayish orange (10YR 7/4). They are thick-bedded and cliff forming. The lower part of the member consists of 10 metres of algal-foraminiferal packstones. Laterally the lower part shows distinct facies variation in a short distance from this location and changes from algal-foraminiferal packstones to oolitic grainstones, which are white in color (N9) and planar cross bedded. The basal 5 metres of the packstones are sandy. Sparry calcite becomes abundant in some packstones; however, it is difficult to separate a grainstone from packstone. The packstones are dominantly calcarenites but usually grade into calcirudites.

From 10 metres to 35 metres the rocks are algal-bryozoan packstones. The packstones are medium light gray (N6) and they weather to dark yellowish orange (10YR 6/6). Large fragments of coralline algae are abundant in these rocks. Bryozoans are of smaller size. Pelecypods are also common. Carbonate mud is an important element, and is present in nearly all of the rocks.

Above this unit lie 25 metres of interbedded algal-bryozoan packstones and algal-foraminiferal packstones in which other fossil debris is equally incorporated. The interbedded rocks are calcirudites and calcarenites respectively, and some of the calcarenites show small-scale graded bedding. Towards the upper part, the limestones become more sandy.

The top 10 metres of the member grade from highly sandy rock types of the immediate lower part to calcareous fossiliferous sandstones. They are not well indurated and the color is light gray (N7)

to medium gray (N6) weathering to pale yellowish brown (10YR 6/2).

The 'b' Member is 165 metres thick and almost the whole of it consists of sandy marls. It is rather deeply eroded and largely covered by rock debris. The marls are medium bluish gray (5B 5/1) and they weather into light olive gray (5Y 5/2). At 13 metres above the base, a 4.1 metres thick intercalation of highly calcareous sandstone occurs which is light olive gray (5Y 6/1) and weathers to yellowish gray (5Y 8/1). Above the sandstone lie 7 metres of sandy marls which in turn are overlain by a 2.5 metre thick bed of sandy limestone. The rest of the 'b' Member is formed of uniform sandy marls. The faunal content consists of tests of smaller foraminifera, some bryozoan debris and echinoid spines.

The 'c_1' Member is formed of alternations of limestones and marls. The lower 22 metres consist of sandy-bioclastic packstones. At the base, the rocks are pelletic but towards the upper part they become argillaceous and sandy. The packstones are thin to thick-bedded, medium gray (N5) in color and they weather light greenish gray (5GY 6/1).

The packstones are followed by 60 metres of moderately indurated calcareous marls. About 10 metres from the top of the marls, a 50 centimetres thick intercalation of sandy bioclastic limestone occurs.

The next 147 metres of the succession are formed of alternations of limestones and marls, with thicker marl and thinner limestone units. The limestones are generally medium light gray (N6) to medium dark gray (N4) on fresh surface and their weathered color is generally dark yellowish orange (10YR 6/6). The marls are greenish gray (5GY 6/1) and their weathered color varies from olive gray (5Y 6/1) to yellowish gray (5Y 8/1).

The limestones consist of porous sandy bioclastic packstones and

bryozoan foraminferal packstones. These rocks are followed by 68 metres of alternations of limestones and marls in which both rocks occur as thinner units. The limestones are foraminiferal-bryozoan packstones. They are mostly calcarenites and some show loose packing.

The 27 metres of upper part of the member consist of poorly indurated calcareous marls, greenish gray (5GY 6/1) on fresh surface and greenish orange (10Y R7/4) on weathered surface. They carry fewer fossils than the marls of the lower part. The total thickness of the member is 324 metres.

The 'c_2' Member is 82 metres thick. The basal part of the member immediately overlying the marls is 2 metres of very thin bedded platy limestone, which are light gray (N7) and weather yellow gray (5Y 8/1). They are harder than the underlying rocks and are exposed as a low ridge. Above the limestone follow 7 metres of gypsum which is light bluish gray (5B 7/1) and does not show distinct bedding. Overlying the gypsum are 6 metres of marls, the lower 4 metres of which are gypsiferous. On top of the marls lie 2 metres of ridge-forming gypsum. The section is followed by 23 metres of thin bedded, moderately indurated, silty marls. The marl is light olive gray (5Y 6/1) on fresh surface and yellowish gray (5Y 8/1) on weathered surface. The top of the member is formed by 3 metres of gypsum.

The 'c_3' Member is 24 metres thick. The base is characterized by 2 metres of sorted, porous oolitic grainstone and packstone. The rocks pass up into bryozoan packstones, 16 metres thick, medium gray (N5) in color and weathering grayish orange (10YR 7/4). In the packstones, large fragments of bryozoans are embedded in a dense carbonate mud. The packstones also contain echinoid plates and spines, mollusc shell debris and tests of foraminifera. Four metres of marl sit on top of packstones. It is greenish gray (5GY 6/1) on fresh surfaces and yellowish gray (5Y 8/1) on weathered surfaces.

The lowest part of the section is formed of well sorted algal-foraminiferal packstones, which exhibit abundant subparallel fractures filled with sparry calcite. Towards the upper part, the packstones become coarser grained and poorly sorted. About 10 metres above the base, the rocks become dominantly algal and the succeeding limestones are formed of interbedded algal-foraminiferal packstones and algal-bryozoan packstones. In the latter rocks algae become an important element and some packstones are dominantly algal. Near the middle of the section pelecypod and gastropod shells are abundant, and the gastropod shells are smashed by compaction. The echinoid Scutella, which in other sections is common in the sandstones, in this section is found equally in the limestones. The limestones are dolomitized and dolomite rhombs occur in all of the intergranular and intragranular pores, sometimes exceeding 80 percent. Towards the top, the limestones become sandy and pass up into calcareous fossiliferous sandstones, which are highly stylolitic.

The upper limit of the 'a' Member is marked by the appearance of the sandy marls of the 'b' Member. The member is 265 metres thick and, except one intercalation, the whole of it is formed of sandy marls. The marls are greenish gray (5G 8/1) and weather yellowish gray (5Y 8/1); they are soft and poorly indurated. An intercalation of calcareous sandstone 10.8 metres thick occurs 137 metres above the base of the member. The sandstones are greenish gray (5GY 6/1) and cross-bedded. They are very fine grained and glauconitic.

The sandy marls gradually pass up into the sandy bioclastic limestones of the 'c_1' Member which, in the upper parts, becomes interbedded with marls. The 'c_1' Member at the Nardaghi section is 254 metres thick, largely formed of marls which are greenish gray (GY 6/1) and weather also the same. Alternating limestones and marls occur in lower part of the member and are about 76 metres

thick. The limestones are mainly algal-foraminiferal wackestones. About 67 metres below the top of the member an intercalation of algal-bryozoan packstone and wackestone occurs. The rocks are sandy and contain abundant mud matrix. The intercalation is 3 metres thick and is cliff forming.

The base of the 'c_2' Member is marked by 3 metres of very thin bedded platy limestone. The limestones are medium light gray (N6) to light gray (N7) and their weathered color is yellowish gray (5Y 7/2). They pass up into silty marls 49 metres thick and poorly indurated. Above the marls lies a 2 metres thick bed of gypsum which is in turn followed by 4.5 metres of marls. Another 1.5 metre thick bed of gypsum sits on top of the marls and the member terminates with 30 metres of soft silty marls. The marls are generally greenish gray (5GY 6/1) on fresh surface and yellowish gray (5Y 8/1) on weathered surface. The member is 90 metres thick.

The 'c_3' Member at Nardaghi section is 22 metres thick, and is mainly formed of alternations of limestones and calcareous marls. The marl units are between 25 centimetres and a maximum of 3.10 metres thick. The thickness of the limestone units ranges from 25 centimetres to a maximum of 4.5 metres. The thickest limestone unit occurs on top of the member. The basal 1.4 metres of the 'c_3' Member consist of oolitic pelloidal packstones and grainstones. These rocks are well sorted and contain abundant pelloid intraclasts. Towards the upper part, the rocks become coarser grained, are poorly sorted and are composed of bryozoan packstones in which mollusc and echinoid debris is also abundant. The rocks are in general medium gray (N5) and their weathered color is grayish orange (10YR 7/4).

The sequence is followed by poorly indurated silty marls of the 'c_4' Member. The marls are greenish gray (5G 6/1) and they weather into light greenish gray (5G 8/1). They are 126 metres thick. The fossil content is confined to the tests of small planktonic foraminifera.

An intercalation of calcareous sandstone occurs about 80 metres above the base; it is thin-bedded and 3 metres thick.

On top of the marls sit 21 metres of gypsum of the 'd' Member. The gypsum shows thin layers and stringers of clayey material.

The 'e' Member is composed of monotonous poorly to moderately indurated calcareous and silty marls. The marls are light olive gray (5Y 6/1) and they weather yellowish gray (5Y 8/1). They contain abundant tests of small foraminifera and some echinoid debris. The marls are 157 metres thick and are partially covered by the rock debris.

The 'f' limestone Member in the Nardaghi Section is a build-up and its petrology was discussed earlier. (Page 101). It is thick to massive-bedded. The limestones are bluish white (5B 9/1) and weather a very pale orange (10YR 8/2). They are intermittently formed of chalky foraminiferal mudstone, bioclastic packstone and wackestone, foraminiferal-algal packstone and other various rock types of the build-up. Silicification of the fossils is observed at various horizons and chert nodules occur in 3 horizons in the lower part of the member. The thickness of the member at this location is up to 300 metres.

5.4 Do-Baradar Section (Enclosures 2 and 6)

Do-Baradar is a large westerly plunging syncline in the south-eastern part of the area of study. A complete section of the Qom Formation was measured on the northern flank of the syncline. The section represents the development of the Qom Formation in the extreme southeastern part of the area of study.

The Formation commences with 2 metres of sandy fossiliferous conglomerates of the base of the 'a' Member. The conglomerates grade into bioclastic conglomeratic limestones. The rocks are

dark reddish brown (10R 3/4) and they weather a similar color. They are followed by algal-foraminiferal packstones, which are oolitic and pelletic in the lower part and become fossiliferous upwards. The packstones are yellowish gray (5Y 8/1) and they weather into dark yellowish orange (10 YR 6/6). A few metres above the packstones and towards the upper part of the member, algal-bryozoan packstones are developed. Some beds are rich in algae and some layers are largely formed of large algal debris. On top of the packstones, 3 metres of calcareous fossiliferous sandstones are present. Whole skeletons and debris of the echinoid Scutella are scattered through the sandstones which are pale olive (10Y 6/2) and weather moderate brown (5YR 4/4). The member is 32 metres thick in this section.

The 'b' Member is 178 metres thick and the bulk of it at Do-Baradar consists of 152 metres of silty marls. The marls are poorly indurated and partially covered by rock debris; they are greenish gray (5GY 6/1) and their weathered color is grayish orange (10YR 7/4). The marls are overlain by 26 metres of argillaceous calcareous sandstones, moderately to poorly indurated, thick-bedded and cross-bedded. They are light brownish gray (5YR 6/1) to greenish gray (5GY 6/1) and their weathered surfaces are pinkish gray (5YR 8/1) to yellowish gray (5Y 8/1). They are fine grained and are composed mostly of volcanic rock fragments and feldspars. The sandstones laterally pass to coarser grained conglomerates to the west of this section.

The 'c_1' Member is formed of alternations of limestones and marls. The base consists of 6 metres of thin to medium bedded highly sandy bioclastic limestones. The rocks are very pale orange (10YR 8/2) on fresh surface and grayish orange (10YR 7/4) on weathered surface. The limestones pass up into algal-foraminiferal packstones and the sequence is then continued by the alternations of limestones and marls. In the lower part of the member, the limestones are

thicker and are interbedded at fairly regular intervals. Towards the upper part the marls become thicker and limestones are thinner. The limestones are pale greenish yellow (10Y 8/2) on fresh surface and yellowish gray (5Y 8/1) to grayish orange (10 R 8/2) when weathered. The marls are generally poorly indurated, with no distinct bedding. They are light olive gray (5Y 6/1) on fresh surface, and yellowish gray (5Y 8/1) on weathered surface. Limestones are thin to thickly bedded and comprise algal-foraminiferal packstones and wackestones which, in the lower part of the section, are finer grained, sandy and glauconitic. Towards the upper part, some limestone beds become more fossiliferous and bryozoans occasionally become predominant. Tests of large benthonic foraminifera, however, are the most abundant fossil. The limestones in some beds are slightly silicificed. The total thickness of the 'c_1' Member at Do-Baradar is 285 metres.

The 'c_2' Member is 28 metres thick. The base of the member is marked by 2 metres of platy limestones, which are light olive gray (5Y 6/1) on fresh surfaces and yellowish gray on weathered surfaces. The limestone is overlain by 8 metres of gypsiferous marls, which pass up into silty marls 18 metres thick. The marls are yellowish gray (5Y 8/1) and weather to the same color.

The 'c_3' Member is 20 metres thick. At the base it is an oolitic-pelletic packstone but the upper part is formed of bryozoan packstone. The packstones also carry pelecypod shell debris, echinoid fragments and spines, and the tests of foraminifera. The limestones are granular and thin to thickly bedded. They are medium gray (N5) on fresh surface and weather orange pink (5YR 7/2).

The limestones are followed by 50 metres of silty marls of the 'c_4' Member. They are soft, yellowish gray (5Y 8/1) on fresh surface and very pale orange (10YR 8/2) on weathered surface.

The 'd' Member is formed of 10 metres of gypsum and is overlain

by 32 metres of marls of the 'e' Member. The marls are poorly indurated, light olive gray (5Y 6/1) to greenish gray (5GY 6/1) on fresh surface and yellowish gray on weathered surface. Towards the top, the marls are moderately indurated and assume a chalky appearance. They are followed by the limestones of the 'f' Member, which is 40 metres thick. The limestones are thick to massive-bedded, white (N9) to pinkish gray (5YR 8/1) on fresh surface and very pale orange (10YR 8/2) to grayish orange (10YR 7/4) on weathered surface. The limestones are mainly algal-foraminiferal packstones with abundant carbonate mud matrix. The limestones are dolomitized and some are slightly silicified.

Generally, the compositional and textural characteristics of the limestones of the 'a' Member remain constant throughout the area and it is only the thickness of the member that varies considerably. The 'c_1' and 'f' Members show considerable lateral variation. There is a general progressive tendency for the development of massive limestones towards the southeastern part of the study area, where the Kuh-e-Da-Baradar build-up is formed of the limestones of the 'c_1' Member and the Kuh-e-Nardaghi build-up of the 'f' limestone Member. Dolomitization of the limestones has also occurred in the southern outcrops.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Local orogenic movements near the end of the Lower Oligocene allowed a shallow sea to invade the central basin of Iran from the south and led to the deposition of the Qom Formation. The Qom Formation is formed of alternations of limestones and marls with some intercalations of sandstone, shale and gypsum.

The regional depositional environment of the limestones was essentially a shallow, warm sublittoral sea, which spread from the south and encroached upon the low lands to the north. The waters were shallow enough to permit sunlight to penetrate to the sea floor and this allowed a bottom dwelling fauna and flora to thrive. The skeletal remains of these organisms produced the thick bedded limestones of the 'a', 'c_1', 'c_3' and 'f' members. They also constructed the two distinct limestone build-ups of the 'c_1' and 'f' Members and formed the scattered limestone masses of the 'f' Member.

Terrigenous detritus entered the sea at varying rates, and it is not evenly distributed through the sediments. The detritus was produced as the weathering products of surrounding Eocene volcanics and Oligocene sediments.

The limestones are formed of various combinations of skeletal debris, carbonate mud and terrigenous detritus. The skeletal components consist of calcareous coralline algae, bryozoans, foraminifera, corals, echinoids, pelecypods, gastropods, ostracods and calcareous green algae.

The faunal and floral constituents of the limestonesof the various members are relatively constant throughout the formation, but their proportions vary both laterally and vertically.

In spite of their very strong topographic expressions, the limestone build-ups of the Qom Formation show no true framework structure. They are bioclastic skeletal limestones, and they are similar in composition and texture to the open shoal-reef, and fore-reef transitional limestone facies of Iraq defined by Henson (op. cit.).

The platy limestones of the 'c_2' Member stand apart from the other limestones in that they are devoid of fossils. It is suggested, by comparison with similar present day sediments, that they were deposited in lower intertidal lagoonal environments. The 'c_2' Member as a whole represents a regressive phase of the Qom Sea.

The oolitic grainstones of the 'a' Member are a shoal facies which developed on topographic highs, whereas the oolitic grainstones and packstones of the 'c_3' Member were formed in the course of a transgression in littoral to sublittoral environments.

All of the carbonate components of the limestones have been affected to some extent by diagenetic alteration. The distribution and crystal fabrics of the minerals formed during diagenesis are sometimes moulded on depositional fabrics and fabric elements.

Many rocks show cementation by sparry calcite which grew from the grain surfaces into the pore spaces. A first phase of fine grained cement can be recognized in most samples: overgrowths around echinoid fragments are extensive and constitute a large proportion of the cement.

The mud matrices are usually highly recrystallized to a coarser crystal mosaic of calcite. Gradations from lithified carbonate mud

to relatively complete recrystallization are present. Amongst the calcitic fossils coralline algae were the most susceptible to recrystallization. The high-magnesium calcite of calcitic organisms inverted to low-magnesium calcite, apparently without change of the crystal fabrics.

Dolomite preferentially replaced the carbonate mud matrices rather than the grains or sparry calcite. Dolomite in the matrices ranges from a few scattered rhombs to such abundance that the rhombs form an interlocking mosaic representing complete replacement of the matrix. Amongst the various grains, ooliths were the most susceptible to dolomitization and in some samples only ghosts of the concentric shells of former ooliths are visible. Within the skeletal grains, dolomite rhombs are usually found between the laminae of coralline algae and around the margins of echinoid fragments and other fossil debris. Only in some instances do dolomite rhombs replace the intergranular sparry calcite cement.

The total amount of silicification is small. Where it occurs the silica preferentially replaces skeletal grains and it also replaces the carbonate mud matrices of some rocks. Silica is sometimes found in the chambers of tests of foraminifera; it is uncertain whether it is a simple chamber filling or whether it replaced carbonate mud which formerly filled the chambers.

Celestite was found in three of the measured sections, but only in the 'c_1' Member. It is present as large crystals which poikilitically spread through several intergranular pores. It is possible that it may have replaced a carbonate matrix or calcite cement rather than being a simple void filling.

Fracture and breakage of fossil components due to early compaction, and pressure dissolution contacts are widespread and in some samples they totally obliterate porosity. The pressure dissolution contacts do

not show any relation to the bedding and this suggests that the dissolution was not related to overburden pressure; the grain to grain pressure dissolution contacts suggest rather that the rocks were folded before they were fully cemented, i. e. between the first and second phases of cementation.

Fractures and stylolites occur in all the rocks and are thought to be postlithification features.

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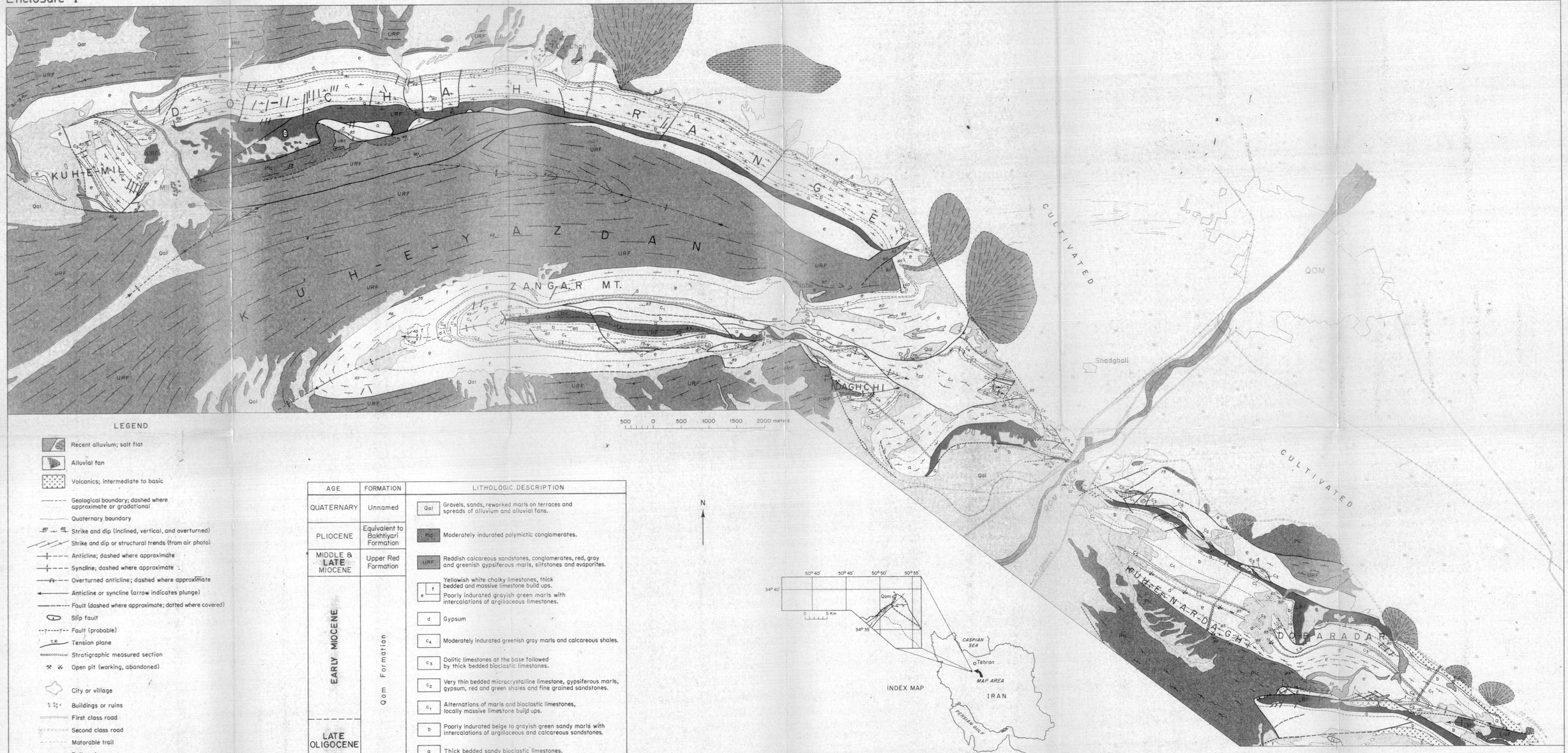
Enclosure I



LEGEND

- Recent alluvium; salt flat
- Alluvial fan
- Volcanics; intermediate to basic
- Geological boundary; dashed where approximate or gradational
- Quaternary boundary
- Strike and dip (inclined, vertical, and overturned)
- Strike and dip or structural trends (from air photo)
- Anticline; dashed where approximate
- Syncline; dashed where approximate
- Overturned anticline; dashed where approximate
- Anticline or syncline (arrow indicates plunge)
- Fault (dashed where approximate; dotted where covered)
- Slip fault
- Fault (probable)
- Tension plane
- Stratigraphic measured section
- Open pit (working, abandoned)
- City or village
- Buildings or ruins
- First class road
- Second class road
- Motorable trail
- Railroad
- Stream channel
- Cultivated area

AGE	FORMATION	LITHOLOGIC DESCRIPTION
QUATERNARY	Unnamed	Qal — Gravels, sands, reworked marls on terraces and spreads of alluvium and alluvial fans.
PLIOCENE	Equivalent to Bakhtiyari Formation	Pic — Moderately indurated polymictic conglomerates.
MIDDLE & LATE MIOCENE	Upper Red Formation	URF — Reddish calcareous sandstones, conglomerates, red, gray and greenish gypsiferous marls, siltstones and evaporites.
EARLY MIOCENE	Qom Formation	f — Yellowish white chalky limestones, thick bedded and massive limestone build ups.
		e — Poorly indurated grayish green marls with intercalations of argillaceous limestones.
		d — Gypsum
		c_4 — Moderately indurated greenish gray marls and calcareous shales.
		c_3 — Oolitic limestones at the base followed by thick bedded bioclastic limestones.
		c_2 — Very thin bedded microcrystalline limestone, gypsiferous marls, gypsum, red and green shales and fine grained sandstones.
		c_1 — Alternations of marls and bioclastic limestones, locally massive limestone build ups.
LATE OLIGOCENE		b — Poorly indurated beige to grayish green sandy marls with intercalations of argillaceous and calcareous sandstones.
		a — Thick bedded sandy bioclastic limestones.
MIDDLE OLIGOCENE	Lower Red Formation	LRF — Red and greenish shales, siltstones, claystones, very fine grained sandstones, gypsiferous marls and some evaporites.

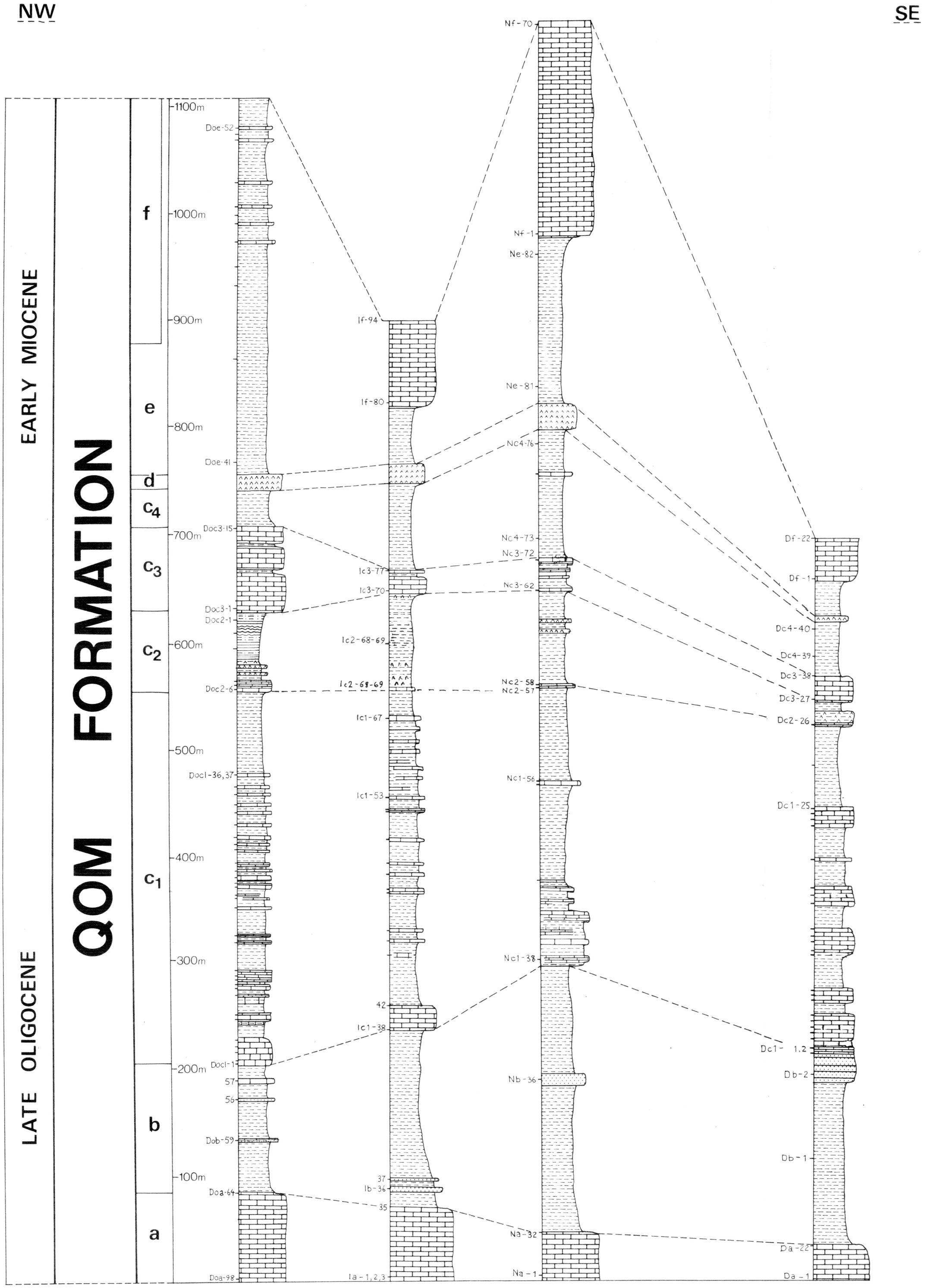
GEOLOGICAL MAP OF QOM AREA

(Modified from M. Nowgole Sadat, 1973)

1978

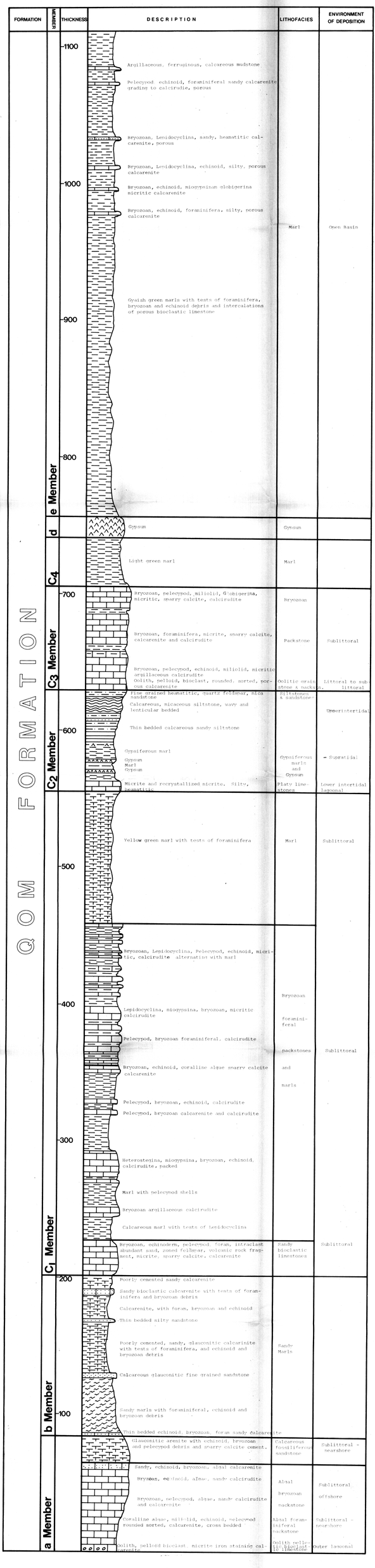
Enclosure 2

LOGS OF THE STRATIGRAPHIC MEASURED SECTIONS OF THE QOM FORMATION



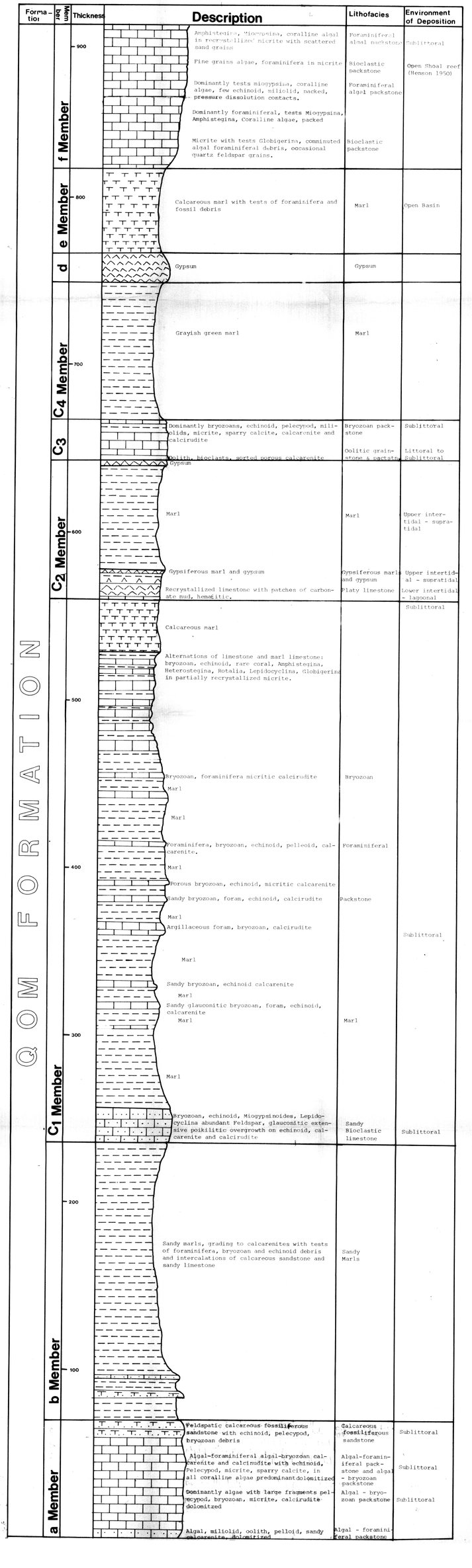
Enclosure 3

DO-CHAH SECTION



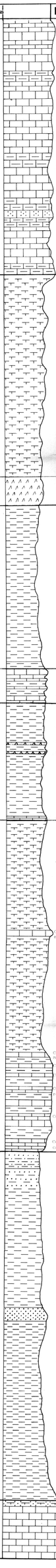
Enclosure 4

IDAGHCHI SECTION



Enclosure 5

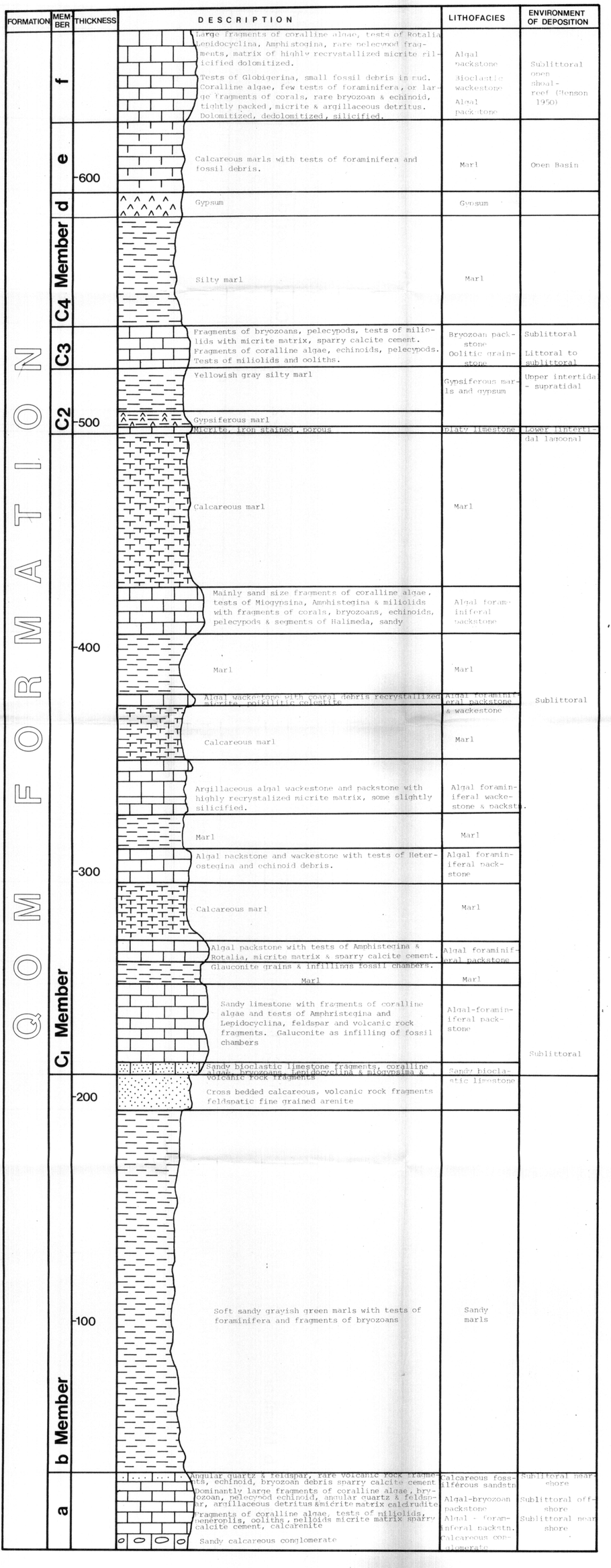
NARDAGHI SECTION



Formation	Member	Thickness	Description	Lithofacies	Environment of deposition
QOM FORMATION	f Member	1100	Fragments coralline algae, bryozoan, pelecypod, echinoid, miliolid, volcanic rock fragments in partly recrystallized micrite.	Bioclastic	Fore-reef
			Pelecypod, algae, coral in a matrix of the same fossil debris and micrite.	packstone	transitional
			Chalky limestone with echinoderm debris	and	zone
			Coralline algae, echinoderm, pelecypod in a partly recrystallized micrite.	wackstone	of
			Coralline algae, small gastropod, echinoid, miliolid, Globigerina, in a partly recrystallized micrite.	(various	an
			Coralline algae, coral, bryozoan, pelecypod, miliolid in recrystallized micrite, silicified.	rock	open
			Globigerinid, mudstone with minor proportion of minute fossil debris	types)	shoal-reef
			Chalky feldspatic limestone with tests of Globigerina		(Henson, 1950)
			Foraminifera, coralline algae, small gastropod in recrystallized micrite		
			Sandy foraminiferal mudstone		
			Globigerina mudstone with echinoid spine		
			Chalky silty Globigerina mudstone		
			Foraminiferal - algal packstone with tests of Lepidocyclina, sandy		
			Fine grained algal - foraminiferal packstone		
			Foraminiferal - algal packstone with matrix of the same smaller grains - large tests aligned.		
			Silty Lepidocyclina, bryozoan packstone		
			Bryozoan coralline algae, echinoid, Foram packed in micrite. Dominantly coral with algal debris in micrite		
			Chalky micrite with tests of Globigerina and minute fossil debris and gastropod cast.		
	e Member	900	Calcareous marl with tests of foraminifera, mollusc shells and echinoid debris	Marls	Open basin
	d		Gypsum	Gypsum	
	C4 Member	800	Grayish green marl	Marl	
	C3	700	Bryozoan, pelecypod, miliolid calcarenite and calcirudite alternating with marl	Bryozoan packstone	Sublittoral
			Oolith, pelloid, bioclast sorted calcarenite	oolitic grain stn. & Packstn	Littoral to sublittoral
	C2 Member		Marl		
			Gypsum	Gypsiferous	Upper
			Marl	marls	intertidal
			Gypsum	and	- supratidal
			Marl	gypsum	
			Pelletoidal limestone	Platy limestones	Lower intertidal - lagoonal
	C1 Member	500	Calcareous marl		
			Coralline algae, bryozoan, Heterostgina in partly recrystallized mud		
			Calcareous marl	Algal	
				foraminiferal	Sublittoral
				packstone	
		400	Coralline algae, pelecypod, Lepidocyclina in partly recrystallized micrite		
			Coral, in partly recrystallized micrite, poikilitic celestite		
			Coral, coralline algae, bryozoan in partly recrystallized micrite		
			Coralline algae, pelecypod, rare echinoid, Miogypsina in partly recrystallized micrite		
			Coralline algae, pelecypod, Lepidocyclina calcirudite		
			Coralline algae, Lepidocyclina, Miogypsina highly sandy micritic calcarenite and clacirudite	Sandy bioclastic limestn.	Sublittoral
	b Member	300			
		200	Highly sand marl with tests of foraminifera, fragments of a echinoids and intercalation of sandstone	Sandy Marls	
		100			
	a Member		Echonoid, bryozoan, pelecypod, Feldspatic arenite	Calcareous fossiliferous sandstone	Sublittoral
			Algal, mollusc, bryozoan, calcirudite and calcarenite highly dolomitized.	Algal bryozoan packstone	
			Algal, miliolid, echinoid, pelecypod, rounded calcarenite, dolomitized	algal, foraminiferal packstone	Sublittoral

Enclosure 6

DO-BARADAR SECTION

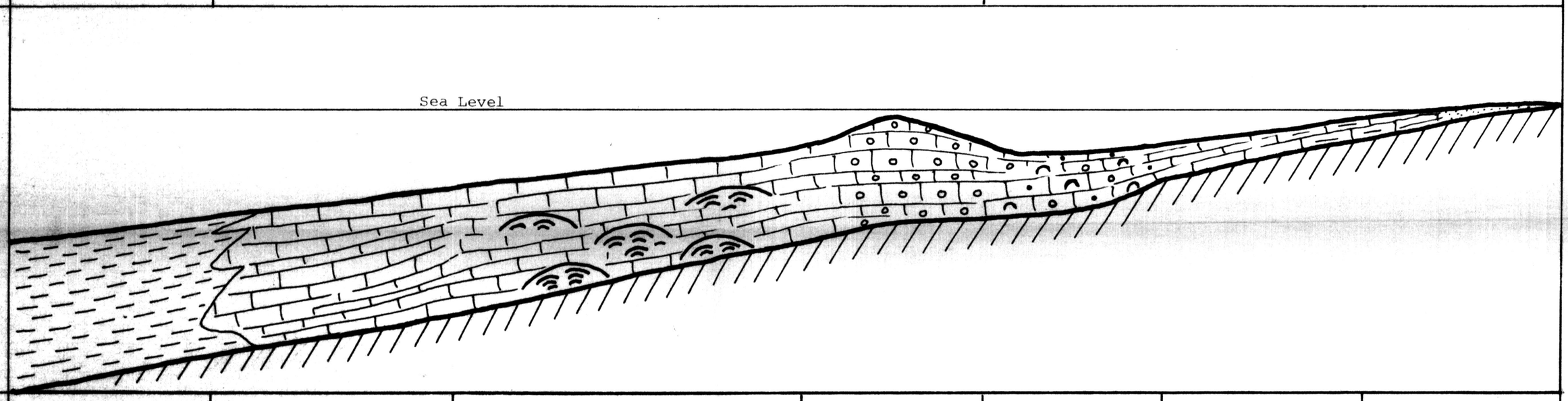


ENCLOSURE 7

A Schematic Model of the Environments of Deposition and Facies of the Limestones of the Qom Formation

Environment	Open Marine	Sublittoral: Offshore ⟷ Nearshore	Littoral: Intertidal ⟷ Supratidal

Schematic Cross-section



Facies	Open Marine	Fore reef and fore-reef transitional	Nearshore to offshore with open shoal reefs	Shoal	Outer lagoonal	Lower intertidal lagoonal	Upper intertidal and supratidal
Lithology	Marl	Mainly foraminiferal algal packstones and wackestones, fossiliferous mudstones and Globigerina mudstones	Algal foraminiferal packstones Algal-bryozoan packstones Calcareous fossiliferous sandstones Sandy bioclastic limestones Bryozoan-foraminiferal packstones Algal-foraminiferal packstones and wackestones Algal-foraminiferal-bryozoan packstones Bryozoan packstones Marls	Oolitic grainstones	Oolitic, pelletic, bioclastic limestones	Pelletoidal limestones and micrites. Recrystallized limestones. Oolitic grainstones and packstones	Gypsiferous marls, gypsum, Calcareous siltstones & sandstones
Bedding and Sedimentary Structures		Thickly bedded often > 1 metre	Thin to thickly bedded, generally < 1 metre. Cross bedded. Some binding of grains by algae and bryozoans. But build-ups generally massive.	Planar cross-bedded	Medium bedded	Mostly very thinly bedded ± 3 cms, but oolitic rock generally thickly bedded < 1 metre.	Marls are thinly to non-bedded, Siltstones are thin and wavy bedded, sandstones are thinly bedded and rippled
Terrigenous Detritus	Mainly fine grained clay and silt, with some coarser sand grains	Occasional quartz and feldspar grains	Mainly sandgrade and silt: less than 2% in buildups, up to 20% in some packstones, and more than 50% in sandstones.	Sand occasionally present as cores to ooliths.	Quartz and feldspar sand grains occasionally present	None	Quartz and feldspar comprise the bulk of siltstones and sandstones
Biota	Benthonic and planktonic foraminifera and small mollusc shells	Abundant whole and fragmented tests of large benthonic foraminifera, and diverse bioclastic debris	Mainly indigenous organisms with some insitu colonies. Various algae, bryoans, benthonic foraminifera, echinoids, corals and molluscs	Fossils scarce, rounded fragments of mollusc, algae, etc.	Mainly miliolid forams, and mollusc, algae, etc.	Mostly barren, but oolitic rocks carry miliolids with fragments of molluscs, algae etc.	Barren