JOURNAL OF THE PALAEONTOLOGICAL SOCIETY OF INDIA
VOLS. 21 & 22, 1978 pp. 78—95. (*For* 1976-77).

MICROFACIES, PETROGRAPHY AND MINERALOGY OF THE TERTIARY ROCKS OF GUAR NALA NEAR NARAIN SAROVAR, KUTCH, INDIA, AND THEIR PALAEOECOLOGICAL SIGNIFICANCE

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ABSTRACT

Microfacies, insoluble residue, clay mineralogy, carbonate mineralogy and petrography of the Tertiary succession of Guar Nala in Western Kutch are studied in order to interpret the depositional environment and palaeoecology. On the basis of fossil content, mineralogical characteristics, insoluble residue content the succession has been subdivided into five zones; namely, Zone A, B and C (Middle Kirthar = Middle Eocene), Zone D (Nari = Oligocene), Zone E (Gaj- = Lower Miocene). Biomicrite is the most abundant microfacies of the succession and shows many variants, i.e., low matrix biomicrite, high matrix biomicrite, glauconitic biomicrite, dolomitized biomicrite, sandy biomicrite. Other microfacies present are clay, sandstone, calcareous sandstone and sandy biosparite. Dolomitization is the most common diagenetic process, which is dominantly early diagenetic. The dolomite has been formed in three stages : early stage making $< 5\ \mu$ dolomite rhombs in the lime matrix, intermediate stage showing development of 30-100 μ dolomite rhombs associated with recrystallization, and late stage patchy dolomitization showing larger anhedral grains. Glauconite is a significant diagenetic mineral formed in minor amounts in Zone A and in abundance in Zone D. In Zone D glauconite formation is accompanied by the illite neoformation during diagenesis. Other diagenetic minerals present are goethite and pyrite. The diagenetic changes have taken place in exclusively alkaline milieu and broadly aerobic conditions, where eH-value fluctuated from slightly—ve to slightly+ve. Terrigenous material of zone A, B, C and D has been derived mostly from the soils of Deccan Trap ; while the terrigenous material of zone E is derived from mainly a metamorphic-granitic terrain, along with some contribution from Deccan Trap soils. The succession under study was laid down in an open shelf of a shallow sea. Deposits of zones A, B, C, and D are characteristically deposits of the shallow part of shelf, while zone E sediments are deposits of shallow part of shelf to transition zone with increased sand supply.

INTRODUCTION

The region of Kutch has a well-developed succession of Mesozoic, Tertiary, and Quarternary sediments. In small patches older rocks, i.e. Pre-Cambrian crystallines are also exposed. The Mesozoic rocks are made up of transitional-coastal deposits, mainly terrigenous in nature. The change from Mesozoic to Tertiary is marked by a widespread volcanic activity represented by Deccan Traps. The Tertiary and Quarternary sediments are mainly exposed more or less continuously fringing the Western, Southern and Southeastern coastal parts (Fig. 1). There are also a few exposures of Tertiary rocks in the North and Northeastern parts of Kutch.

The Tertiary sediments unconformably overlie the Deccan Traps ; and at places even on the Jurassic and Cretaceous sediments. The total thickness of Tertiary sediments reaches values of several hundred metres.

The Tertiary sediments of Kutch have attracted the geologists since last century. Wynne (1872) gave first detailed account of the geology of Kutch (For detailed bibliography see Tewari, 1960 ; Tandon, 1966 ; Singh, 1967). After the early investigations related to systematic geological mapping and establishing of stratigraphy work began on the biostratigraphy and foraminifera of the Tertiary rocks. Tewari (1960) made a detailed study of the foraminifera and biostratigraphy of the Tertiary sediments.

Important contributions on the biostratigraphy and foraminifera have come from Tewari, Sengupta, Poddar,

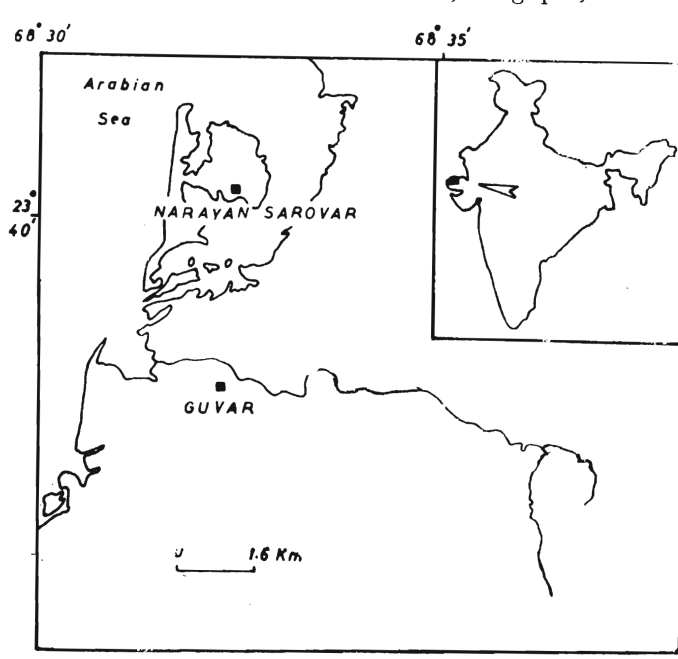

Fig. 1. Location map.

Biswas, Tandon, and Singh etc. Exhaustive list of references are given by Tandon (1966), and Singh (1967). Biswas (1965, 1971) has reviewed the litho and biostratigraphy of Kutch. (Sen Gupta, 1959, 1964), Poddar (1963), Tewari (1952, 1957, 1960), Tandon (1962, 1970, 1976) provide good information on the biostratigraphy of the Tertiary rocks of Kutch. However, no attempt has so far been made to investigate the petrography and mineralogy of the Tertiary rocks of Kutch.

In the present paper microfacies, petrology, and mineralogy of a section located in Guar Nala near Narain Sarovar, W. Kutch are discussed. The samples were collected by Dr. M. P. Singh, Geology Department, Lucknow University, who placed the samples at the author's disposal. Singh (1971) gave a preliminary account of the mineralogy and petrography of the Tertiary rocks of this profile.

GUAR NALA SECTION NEAR NARAIN SAROVAR

The Tertiary rocks of Kutch have been traditionally subdivided into Laki, Kirther, Nari and Gaj. General palaeogeographical considerations suggest that the Tertiary sequence in the Eastern part of Kutch is thicker (600—700 m) than in the Western part of Kutch (area of study), where it is condensed to about 100 m thickness.

Guar Nala is located about 8 km from Narain Sarovar and flows from East towards West cutting across the Tertiary succession (Fig. 2). Another section at Kanoj-Sehe, about 15 km from Guar Nala has been investigated in detail for foraminifera by Singh (1967), where he has been able to establish three major palaeontological breaks : Laki/Kirthar unconformity, Kirthar/Nari unconformity, and Nari/Gaj unconformity.

Detailed foraminiferal studies of the Guar Nala section have not yet been finished. However, preliminary thin-section identification of the foraminifers reveals that the lowest most samples of the profile belong to the lower part of Middle Kirthar. The succession under study has been subdivided into five units, on the basis of foraminifers seen in thin-section, insoluble residue content, mineralogy and petrography. The lower three zones correspond to the Middle Kirthar, the Upper two

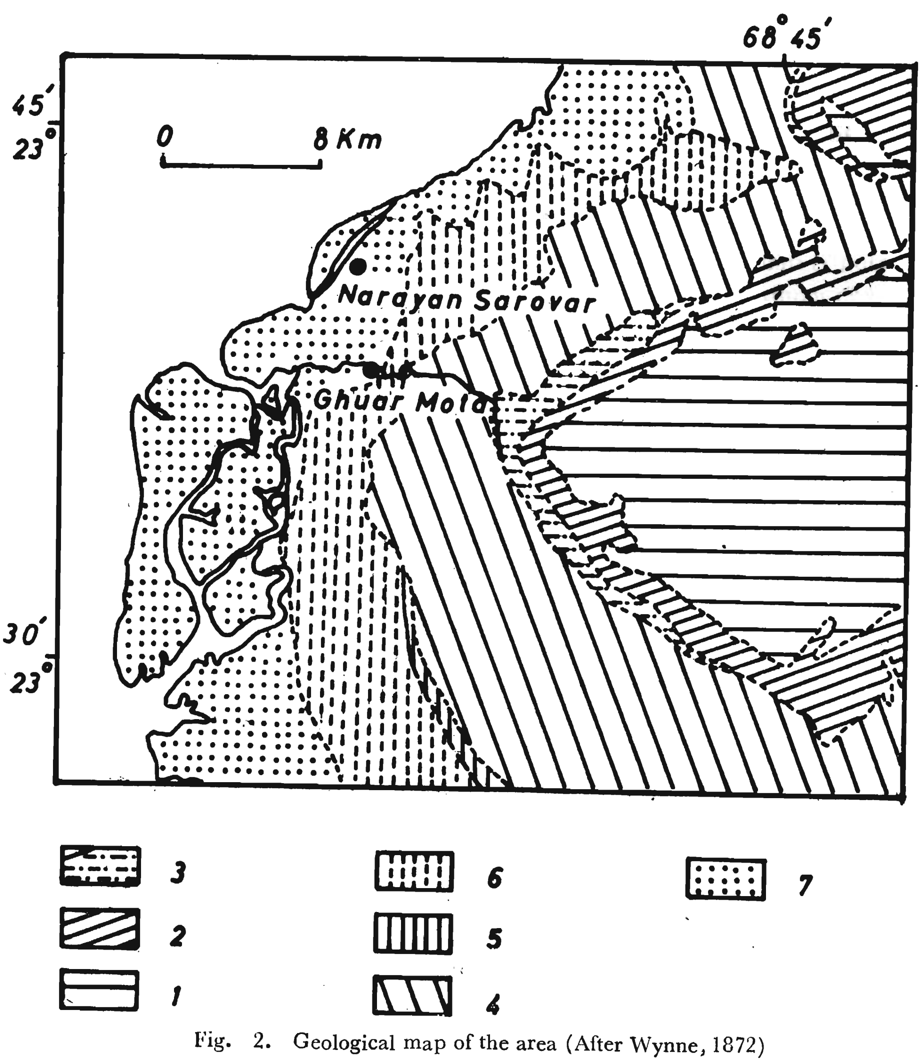

Fig. 2. Geological map of the area (After Wynne, 1872)

zones correspond to Nari and Gaj respectively (Table 1).

Zone A—This is mainly shale-rich succession, characterized by *N. perforatus*, and *Nummulites* sp. with *Discocyclina* in the upper part. This zone corresponds to the lower part of Middle Kirthar.

Table 1—Lithostratigraphy of the Tertiary rocks in Guar Nala section, Kutch

Stratigraphic Units of Guar Nala section	Age and standard subdivisions
Zone E	Gaj=Lower Miocene
Zone D	Nari=Oligocene
Zone C	Middle Kirthar
Zone B	=Middle Eocene
Zone A	

Zone B—This is mainly a carbonate (foraminiferal limestone) succession with abundant foraminifers and characterized by *Discocyclina*, *Nummulites*, and *Assilina cancellata*.

Zone C—This is also made up of foraminiferal limestone, characterized by *Asterocyclina*, *Nummulites*, and *Discocyclina* and corresponds to the upper part of Middle Kirthar.

Zone D—This succession is made up of foraminiferal limestone with abundant glauconite in the lower part. It contains reticulate *Nummulites* (*N. fischteli*, *N. intermedius*) and few Lepidocyclines. This zone corresponds to the Nari succession (Oligocene).

Zone E—This succession is characterized by the presence of abundant sand fraction and few sandy horizons. The sediments contain *Miogypsina*, *Lepidocyclina* and rotaloids. Near the top of this zone calcareous algae is commonly present. This zone corresponds to the Gaj succession (Lower Miocene).

METHODS OF STUDY

Thin-section study—Thin sections of all the samples were prepared and studied with the help of polarization microscope and microfacies established. Thin-sections of the carbonate rocks were stained by Alizarin-red-S following the procedure of Friedman (1959) to differentiate between dolomite and calcite.

Insoluble residue study—For determination of insoluble residue 50—100 gm of the crushed sample was dissolved in dilute HCl. After the completion of reaction the residue was filtered, washed, air dried and weighed to obtain the wt. % of the insoluble residue which was further sieved through 63 μ sieve, in order to separate sand from silt+clay. A suspension was prepared of the fraction <63 μ and silt and clay fractions were separated and their percentages determined by sedimentation in Atterberg cylinders. In the case of sand-rich samples sand fraction was sieved through a set of sieves (2.0, 1.0, 0.63, 0.315, 0.2, 0.125, 0.063 mm) to obtain various size fractions. Cummulative curves were plotted and Trask's statistical parameters were calculated, From the sand fraction grain slides were prepared and studied under a polarisation microscope.

Carbonate mineral study—Identification of calcite and dolomite and their inter-relationship was done in stained samples. Moreover, the powdered samples were scanned in a X-ray diffractometer. Calcite/Dolomite ratios were determined using the method proposed by Tennant and Berger (1957). In this method intensities were measured for the 3.03 Å. Calcite line and the 2.88 Å dolomite line. The Phillips diffractometer with conditions also used for clay mineral study was employed. For the calculation of peak areas peak height×peak width at the half peak height was taken as a measure.

$$\text{Calcite/Dolomite ratio} = \frac{\text{Calcite peak area} \times 0.846}{\text{Dolomite peak area}}$$

Clay mineralogy—For the study of clay minerals, oriented slides of clay fraction were prepared by placing a few drops of suspension slurry on a glass slide. X-ray determination were made on a Phillips (Müller Mikro II) diffractometer under the following conditions : CuK α_1 as source, Ni filter, beam slit 1°, detection slit 0.1°, 40 KV, 20 mA, goniometer speed 1/2°/Min, paper speed 600 mm/hr. Three diffractograms were prepared for each clay fraction : air dry, glycolated, and heated to 550°C. Quantitative estimation of clay minerals was done on diffractograms of glycolated samples. Peak areas were measured and weighted peak area percentages were calculated according to the method suggested by Biscaye (1965).

Silt fraction study—The separated silt fraction was gently ground before making a thick slurry from which oriented slides were prepared. The slides were placed in a X-ray diffractometer. For the identification of minerals, peaks on the diffractograms were indexed and various minerals were identified.

MICROFACIES

As already mentioned most of the rocks of the succession under study are foraminiferal limestones ; only few bands of shale and sandstone are present. An attempt has been made to distinguish and characterize the carbonates on the basis of the nature of allochemical and orthochemical constituents (Folk, 1959, 1968). Most of the limestones fall in the category of biomicrite. For detailed identification of the microfacies other petrological and mineralogical parameters have also been utilized ; namely, amount and nature of dolomite, degree of recrystallization, nature of fossils and their abundance, sand fraction content, glauconite content.

Zone A

Sediments of Zone A show three microfacies. The fossils do not show any sorting or preferred orientation.

(i) Shale microfacies—They are fine-grained shales, which in thin-section appear as fine-grained clayey matrix with silt-size quartz grains scattered throughout (samples G/91-92, G/79).

(ii) Low-matrix biomicrite microfacies (Plate I—1)—This facies is made up of dominantly fine-grained carbonate matrix in which micro-forams, e.g., *Textularia*, *Quinquiloculina*, small shells of gastropods and lamellibranches are inter-sperced. Matrix/bioclast ratio is rather high. Matrix shows few dolomite crystals ; fossils are only feebly dolomitized. Grain size of the micritic matrix is about 5-6 μ.

(iii) Glauconitic biomicrite microfacies—This microfacies is quite similar to the low-matrix biomicrite microfacies, except for the presence of glauconite pellets in considerable amount in the matrix. Fossils are gastropods, lamellibrachs and few algal remains. Foraminifers are less common.

Zone B

The sediments are made up exclusively of carbonates, showing high fossil content and feeble to low dolomitization. Fossils do not show any sorting and preferred orientation. The samples belong to the following single microfacies :

Low-matrix biomicrite microfacies (Plate I—2, 3)—This microfacies is characterized by very high content of fossils, which include larger forams, i.e., *Discocyclina*, *Nummulites*, *Assilina* along with smaller forams, bryozoa, and rare algal fragments. The matrix is fine-grained micrite with low content of dolomite. In patches the matrix is dark-coloured due to high iron content. Degree of recrystallization of the dolomitized matrix is very low and local. Fossils have escaped dolomitization, except along the borders. The recrystallized dolomite grains are 50-100 μ in size.

Zone C

The sediments are made up of carbonates, which show variation in amount and nature of the fossils and degree of dolomitization. Larger forams are abundant, along with smaller fossils. Fossils do not show any preferred orientation and sorting. Following microfacies have been recognized.

(i) Low-matrix biomicrite microfacies (Plate II—5, 6)—This microfacies is similar to the facies of the Zone B. The larger foraminifera are common, i.e., *Asterocyclina*, *Nummulites*, *Discocyclina* with few bryozoa and algae. The matrix is fine-grained, showing strong dolomitization and recrystallization. Fossils show only little effect of dolomitization.

(ii) High matrix biomicrite microfacies (Plate I—4 ; Plate II—7)—This microfacies differs from the previous microfacies in high content of matrix and low content of fossils. The matrix is highly dolomitized. In patches dolomitized matrix is recrystallized, made up of euhedral dolomite crystals in the size range of 30-40 μ. Rarely, recrystallized dolomite crystals attain size up to 100 μ. Fossils show considerable effect of dolomitization. Sometimes, forams have been completely dolomitized. However, the fossils mostly have preserved their original texture.

Zone D

This zone is also made up exclusively of carbonates. However, a characteristic feature of the sediments of this zone (especially in the lower part) is the presence of glauconite. The rocks are mostly biomicrite, but show much variation in the nature of matrix and fossils. Larger forams are commonly present—*Nummulites*, *Operculina*, *Lepidocyclina*, Miliolids. However, the variety of larger forams is lesser than in the zones B and C. Microforams are commonly present. Algal fragments are present in almost all the samples. Fossils do not show any preferred orientation and sorting. Following microfacies are recognized :

(i) Low-matrix biomicrite microfacies—Broadly this microfacies is similar to the microfacies of the zones B and C. In the micritic matrix very minute crystals of dolomite are present. In some cases small forams have been completely dolomitized forming aggregate of large dolomite crystals. Some of the fossils show recrystallization to sparry calcite, and show little effects of dolomitization.

(ii) High-matrix biomicrite microfacies—This facies is similar to the microfacies of the zone C. The matrix shows considerable dolomitization ; the foraminifera sometimes show patchy dolomitization.

(iii) Glauconitic biomicrite microfacies (Plate II—8; Plate III—9, 11, 12)—This microfacies is quite similar to the low-matrix biomicrite microfacies, except for the presence of the glauconite in considerable amount. The glauconite is developed mostly in the chambers of the forams ; however, it is also present as small grains in the matrix, The glauconite in the chambers of the forams is sometimes associated with dolomite. It may be pointed out that the samples containing glauconite show low content of dolomite. Nevertheless, the glauconite bearing samples contain low matrix. Rarely, the matrix is also recrystallized into larger dolomite rhombs ; in one case zoned rhombs are present.

(iv) Dolomitized biomicrite microfacies (Plate III—10) —This microfacies is characterized by a high degree of dolomitization, leading to extensive dolomitization of even fossils making the identification of the fossils impossible. Few remains of fossils are made up of sparry calcite, and patchy dolomite. The matrix is made exclusively of dolomite crystals ; very little calcite is present. In the matrix dark-coloured patches representing iron minerals are present. It is considered that the rock was originally a biomicrite, which upon strong dolomitization has led to obliteration of even the original components.

(v) Sandy biomicrite microfacies (Plate IV—13)—This microfacies is similar to low-matrix biomicrite microfacies, except for a considerable content of sand. The matrix contains much quartz grains. The matrix is mostly calcitic with scanty dolomite crystals. The fossils are mostly larger forams, smaller forams and algal remains.

Zone E

This zone corresponds to the Gaj succession and is characterized by the presence of sandstone and shale along with biomicrite and biosparite. Moreover, the biomicrite and biosparite invariably contain considerable amount of quartz grains. The fossils are foraminifers, pieces of molluscs and algae. Content of algae is high in the samples from the upper most part of the succession. Following microfacies are recognized :

(i) Dolomitized biomicrite microfacies—This microfacies is similar to the microfacies of the zone D. Matrix is strongly dolomitized, in some cases showing complete obliteration of the fossils due to dolomitization. Few quartz grains are present.

(ii) Sandstone microfacies (Plate IV—16, VII—33) —They are pure sandstone, almost orthoquartzitic in composition with mostly silica cement.

(iii) Calcareous sandstone microfacies (Plate IV—14)—This microfacies is made up of quartz grains cemented with a calcitic cement. Rare fossils fragments are also present.

(iv) Shale microfacies—This microfacies in thin-section shows scattered minute quartz grains embedded in a clayey matrix.

(v) Sandy biosparite microfacies—This is the most abundant microfacies of the zone E, and is characterized by the high content of quartz grains along with the fossil fragments. Fine-grained micritic calcite/dolomite matrix is almost absent. The rock is cemented by the sparry calcitic cement. Depending upon the nature of fossil fragments this microfacies can be further distinguished into three varieties, namely—

(*a*) Sandy algal biosparite—made up of mostly algal fragments,

(*b*) Sandy molluscan biosparite (Plate IV—15)—made up of dominantly molluscan fragments,

(*c*) Sandy foraminifera biosparite—made up of mostly foraminifera.

PETROLOGY OF THE CARBONATES

PETROGRAPHY OF THE DOLOMITE :

As already discussed in the microfacies analysis, dolomite is an important constituent in most of the carbonate rocks of the succession.

An important feature of this succession is that beds with slightly dolomitized matrix alternate with beds showing strongly dolomized matrix.

In all the cases, first the matrix has been affected by dolomitization. Mostly the fossils have not been affected or only feebly affected by dolomitization. Only in the samples showing strong dolomitization, allochems (forams, algal remains etc.,) have been dolomitized. Thus, the amount of dolomite in most of the samples is more or less directly proportional to the content of matrix. The fossils are made up of microcrystalline calcite showing well-preserved micro wall-structure. Invariably, the chambers of the foraminifera are filled with dolomitized lime-mud barring few cases where the borders of the forams (both from outside and inside of the chambers) are partially replaced by dolomite (Plate VI—26, 27). However, in few samples, the fossils have been extensively dolomitized along with complete dolomitization and recrystallization of the matrix, sometimes producing zoned dolomite crystals (Plate VI—23).

The sediments of zone A show moderate dolomitization of the matrix and foraminiferal chambers, and feeble dolomitization of the fossils along the borders. The dolomite mostly occurs as 5-6 μ size crystals and do not show any recrystallization (Plate V—17, 18). However, due to low matrix content in the samples, total dolomite content of the samples is very low.

The samples of zone B show moderately dolomitized matrix showing dolomite grains of 5-10 μ size. Locally the dolomitized matrix has undergone patchy recrystallization producing dolomite crystals of 50-100 μ size (Plate V—19, 20, 21).

The samples of zone C exhibit strongly dolomitized matrix, which has been invariably recrystallized making 30-40 μ size dolomite cyrstals. The fossils have been considerably affected by the dolomitization (Plate V—22, VI—23, 24). Even patchy dolomitization is present showing dolomite crystals of 100 μ size (Plate V—22). The fossils often show recrystallization into sparry calcite, which has been dolomitized with preference over the microcrystalline calcite (Plate VI—24). Often recrystallized fossils are left as unidentifiable rests of sparry calcite. Thus, there seems to be an increase in the dolomitization towards the top within the Middle Kirthar succession (Zone A, B and C). The topmost sample of the Middle Kirthar succession (sample G/31-32) exhibits strong dolomitization, where both the matrix and the fossils have been dolomitized to produce a dolomite rock.

The samples of zone D (Nari=Oligocene) show moderate to strong dolomitization of the matrix (Plate VI—25). Chambers of the forams are filled with sparry calcite, which has been partially dolomitized. In rare cases, portions of matrix have been recrystallized into sparry calcite. Patchy dolomitization (Plate VI—28), recrystallized dolomitic matrix with zoned dolomite crystals are also present. In the upper part of this zone degree of dolomitization is very low.

In the samples of zone E (Gaj=Lower Miocene) dolomite rocks are present in the lower part, showing completely dolomitized matrix and fossils with dolomite rhombs of 20-30 μ (Plate VII—31, 32, 34). In the upper part of this zone dolomitization is feeble to absent. In one sample detrital grains of dolomite are present.

Thus, in the succession under study following types of carbonates have been identified :

(i) Original fine-grained lime-mud (calcite/aragonite) and microcrystalline calcitic fossils.

(ii) Minute dolomite rhombs (5-6 μ in size) developed in the micritic matrix (Plate VII—29, 30).

(iii) Recrystallized sparry calcitic matrix, sparry calcitic fossils and sparry calcite filling the foraminiferal chambers.

(iv) Recrystallized dolomite rhombs of the matrix (30-100 μ size), sometimes even zoned.

(v) Patchy dolomitization showing larger, anhedral dolomite grains, replacing the fossils and matrix without any preference.

CALCITE/DOLOMITE RATIO

The staining reveals that almost all the samples contain some dolomite, though its content varies from insignificant to high. However, the samples with very low dolomite content fail to exhibit any peak in the X-ray diffractograms. Calcite/dolomite ratios are given in Table 2.

The samples of zone A do not show any dolomite in the X-ray study because of its low content. Samples of zone B show highly variable dolomite content. The samples of zone C shows much fluctuations in the dolomite content. The calcite/dolomite ratios of zone D show even greater fluctuations from sample to sample. Horizons of high dolomite content alternate with horizons of very low to negligible dolomite content. The samples of zone D show high dolomite content in the lower part, while in the upper part dolomite is absent or very low in amount (not detectable in the X-ray study).

A look at the calcite/dolomite ratio curve shows that vertically in the succession dolomite content exhibits high degree of fluctuations, without any gradual increase or decrease in the dolomite content upwards in the profile.

In the literature, attempts have been made to correlate the insoluble residue content with the calcite/dolomite ratios. Few workers point to a positive correlation (Fairbridge, 1957 ; Murray, 1960; Schmidt, 1965), while others fail to get any significant correlation (Zenger, 1965 ; Lumsden, 1974). In the present study of the tertiary succession of Kutch there is no definite correlation between insoluble residue content and calcite/dolomite ratio.

DOLOMITIZATION PROCESS IN THE SUCCESSION

Though, dolomite is a stable mineral in warm shallow marine waters, normally dolomite in the carbonate rocks is not precipitated directly, but formed due to change of $CaCO_3$ (Calcite/Aragonite) into dolomite [CaMg (CO_3) 2]. Some workers believe that primary dolomite can be formed in evaporitic facies, whereas others believe that direct precipitation of dolomite is not possible even in the evaporites. The process of dolomitization is distinguished into two types.

(i) Early diagenetic dolomitization (before consolidation of the sediment).

(ii) Late diagenetic dolomitization (after consolidation of the sediment).

In the last few decades there have been much discussion on the early diagenetic dolomite, and many theories have been proposed. Though, early diagenetic dolomite associated with evaporites and supratidal zone deposits have been properly explained, most of the theories fail to satisfy the early diagenetic dolomitization of the shallow continental shelf carbonates. The more important theories about dolomitization are: Evaporation model (Illing *et al.*, 1965), density gradient (Bonaire model) (Deffeyes *et al.*, 1965), hydrostatic head model (the ground water model) (Hanshaw *et al.*, 1971). Cannibalization model (Goodell and Garman, 1969), seepage refluxion (King, 1947 ; Friedman and Sanders, 1967). More recently, (Badiozamani 1973) has proposed Dorag dolomi-

Table 2—Calcite/dolomite ratio in carbonate rocks of Guar nala section, Kutch. G-glauconite-bearing samples.

Geological unit	Sample No.	Calcite/Dolomite ratio
Zone E	G/4-5d	No dolomite
	G/16-17	No dolomite
	G/18-19b	1.02
	G/19-20	0.23
Zone D	G/22-23	No dolomite
	G/25-26	No dolomite
	G/26-27A G	1.60
	G/26-27B G	No dolomite
	G/27-28A G	12.88
	G/27-28B G	Traces of dolomite
	G/28 G	Traces of dolomite
	G/29 G	11.80
	G/30 G	No dolomite
Zone C	G/31-32	0.64
	G/32-33	9.92
	G/34	4.69
	G/36-37	Traces of dolomite
	G/38-39	1.36
	G/42	3.91
	G/47	2.34
	G/54	1.40
	G/57	1.10
	G/57-58	19.23
Zone B	G/59	7.17
	G/62-63	No dolomite
	G/64-65	Traces of dolomite
	G/68	Traces of dolomite
	G/70	No dolomite
	G/73-74	12.87
Zone A	G/78-79	No dolomite
	G/79	No dolomite
	G/93	No dolomite
	G/97-98	No dolomite

tization model for explaining the dolomitization of the off-shore sediment, which lack any evidence of supratidal origin or evaporite association.

Mg^{2+} ions released from recrystallization of the Mg-rich fossils (Chave, 1954) and Mg^{2+} ions absrobed on the clay minerals (Kahle, 1965) are important factors in the supply of Mg^{2+} ions during dolomitization. It may be pointed out that in the succession under study main clay mineral is montmorillonite, which is rich in Mg ions and possess strong property of adsorption. Thus the role of clay minerals must have been significant in contribution of Mg ions.

Development of small-sized, scattered dolomite crystals (0.01—0.02 mm) in the matrix of the most of the samples, and alternation of dolomite-rich and calcite-rich layers without any systematic increase or decrease in dolomite content from bottom to top in part or in whole of the succession indicate early diagenetic origin of the dolomite (Laporte, 1967; Füchtbauer and Müllar, 1970). Nevertheless, some dolomite was also formed during late diagenesis producing larger crystals and minute vugs due to reduction in volume during dolomite formation (Weyl, 1960).

The Tertiary succession under study represents deposits of shallow part of continental shelf, below wave base, where dolomite content of the samples is rather low. For most of the samples Mg^{2+} released by breaking up of high-magnesian calcite and Mg^{2+} available from the clay minerals must suffice to explain the extent of early dolomitization. Moreover, there are evidences of precipitation of gypsum in the marginal part of the basin resulting into increased Mg^{2+} concentration in the water. This water might have also partly contributed to the early dolomitization of the matrix.

There are two horizons of extensive dolomitization, where the rock is almost a dolomite rock, namely the sample G/31-32 (topmost part of Zone C), and sample G/19-20 (basal part of Zone E). It is quite likely that these horizons represent horizons of regression, which led to extensive dolomitization by Mg^{2+}—rich ground water.

PETROLOGY OF GLAUCONITE

The glauconite is present in one sample of zone A, and in the lower part of zone D. The glauconite of zone A is present in the form of well developed pellets, which are intensively bottle green in colour (Plate V—17). X-ray study of the pellets reveals that they are made up of true glauconite mineral. It seems that this glauconite has been formed due to *in situ* glauconitization of small clay pellets or due to localized glauconitization of the matrix at places where matrix is rich in iron. Such areas appear as dark patches in several samples. Another possibility is that the glauconite was formed in the chambers of the foraminifers, and later released and transported up to the site of deposition ; though there is no direct evidence for this mode of genesis.

The sediments of zone D (Oligocene) are characterized by the common presence of glauconite in significant amounts in most of the samples.

Often the chambers are completely filled by glauconite (Plate VI—26). In few samples the chambers contain glauconite along with some dolomite (Plate VI—27). It shows that glauconite developed during diagenesis syngenetically with the dolomite. X-ray study of the separated glauconite in few samples (e.g. G/26-27A) show that it is made up of mixture of glauconite, illite and biotite. It is interesting to note that the clay fraction of the samples containing glauconite depict an increase in the 10A° illite group of minerals at the cost of montmorillonite (see under clay mineral study). Another significant aspect of the samples containing glauconite is that these samples show a low degree of dolomitization. The Mg^{2+} ions are needed for the formation of both glauconite and dolomite. Due to limited availability of Mg^{2+}, and its partial consumption in the genesis of glauconite, only little amount of Mg^{2+} was available for the dolomite formation.

In the sediments under study first dolomitization of the matrix during early diagenesis started. However, in the foraminiferal chambers glauconite developed synchronously to the dolomite formation. The process of dolomitization was arrested at an early stage due to generation of glauconite, which seem to have even partly replaced the dolomite. However, in few cases dolomite in the chambers appear to have developed after the genesis of glauconite.

GENESIS OF GLAUCONITE

Glauconite is a characteristic mineral of the sedimentary rocks and occur almost exclusively in the marine sediments of continental shelf zone. Various aspects of glauconite genesis, its distribution etc., are discussed by Burst (1958a, b), Cloud (1955), Pratt (1963), Borchert and Braun (1963), Porrenga (1967), Millot (1970).

The glauconite can develop both by neoformation as well as by replacement of earlier minerals, e.g., biotite (Millot, 1970). Burst (1958a) considers redox-potential as the most critical factor in glauconite formation, as it occurs in local reducing milieu.

The glauconite generally develops in association with organic matter in an overall aerobic milieu in areas of low rates of deposition. The occurrence with both organic matter and dissolved oxygen, formation at the sediment-water interface, and high Fe^{3+}/Fe^{+2} ratio all suggest that glauconite is stable in an environment of intermediate, and probably fluctuating, redox potential (Berner, 1971).

In the succession under study organic matter was available in abundance mainly in the foram chambers, and partly in the matrix. The overall aerobic conditions are indicated by the abundance of fossils. Thus, glauconite developed where iron was available from the clay minerals. The main clay mineral in the succession is montmorillonite, which has good adsorption properties. Porrenga (1966) shows that glauconite develops in the continental shelf sediments of the Niger delta, where kaolinite and montmorillonite are the main clay minerals along with some illite.

GENESIS OF IRON OXIDE AND IRON SULFIDE

The sediments under study contain goethite and pyrite in most of the samples. Few samples contain only pyrite, whereas some contain goethite, pyrite and glauconite, or glauconite and pyrite or only goethite as opaque mineral. Pyrite is stable in pH 7.2-9, Eh 0.2-0.5 V, while goethite is stable in pH 7.2-8.5, Eh 0.05 to 0.4V. Glauconite has stability field similar to that of goethite.

Accordingly, pyrite is stable in negative Eh-values, while iron oxide is stable in positive Eh-values. However, Berner (1964) pointed out that in marine environment pH value and CO_2 partial pressure is relatively constant, and the stability of the iron minerals strongly depends upon Eh and pS (sulphur activity). Thus, according to Berner (1964) iron oxide can be precipitated in slightly reducing environment in case pS (sulphur content) is low ; if pS is high pyrite is precipitated at the same Eh value. This explains the simultaneous occurrence of goethite and pyrite in the same samples.

DIAGENETIC EVENTS

Carbonate rocks are highly susceptible to the early diagenetic changes, almost penecontemporaneous to the sedimentation. The changes taking place before lithification of the sediments are generally recognized as early diagenetic changes, while the changes taking place after the lithification are late diagenetic changes. Authigenesis denotes neoformation of minerals, which in the sediments under study include dolomite, glauconite, pyrite, goethite and illite.

As already discussed the succession under study is above all dominated by recrystallization and neoformation of the carbonate minerals-calcite and dolomite. The process of silicification is completely absent in the rocks. This suggests that during diagenesis the pore water maintained an alkaline milieu, so that carbonate minerals were very actively formed (see Pettijohn *et al.*, 1972). Development of dolomite further demands that along with the high pH value, concentration of Mg^{2+} ions was also high in the pore waters responsible for diagenesis. Genesis of pyrite, goethite and glauconite also demand an alkaline milieu during diagenesis.

To sum up, the diagenetic changes took place in an alkaline milieu (pH 9) in broadly aerobic conditions with eH value more or less zero at the sediment water interface and which kept on fluctuating. Eh value changed to negative side wherever organic matter was present or sometimes changed to positive side due to increased aeration.

Following sequence of events in the diagenetic changes have been recognized in the rocks under study, though these changes are not observable in a single thin-section. It is assumed that originally a microcrystalline calcareous matrix was deposited, made up of calcite/aragonite only, along with the calcitic micro-crystalline skeletal remains. There is no evidence to favour a primary precipitation of dolomite.

(i) Development of minute dolomite rhombs in the fine-grained lime-mud matrix. The size of the rhombs is 5 μ or even less. This is the result of very early dolomitization of the lime mud, almost penecontemporaneously to the sedimentation.

(ii) Dolomitization of microcrystalline chamber walls of the larger foraminifera and complete dolomitization of the smaller foraminifera.

(iii) Development of sparry calcite in the matrix, fossil fragments, and in the chambers of forams. It is mostly due to recrystallization of the micritic matrix.

(iv) Dolomitization of the sparry calcite of the chambers of the foraminifera possessing dolomite crystals of 30-50 μ size.

(v) Authigenesis of glauconite, illite, pyrite and goethite (time sequence of the genesis of these minerals is not very clear ; most probably genesis of these minerals started very early in the sediments, almost penecontemporaneous to the sedimentation, and continued even after the lithification of the sediments).

(vi) Recrystallization of the fine-grained dolomitic matrix into coarser dolomitic matrix possessing dolomite rhombs of 30-100 μ size.

(vii) Patchy dolomitization showing large, anhedral crystals of dolomite in the size range of 100 μ or more.

Thus, there are three definite stages of dolomite formation during diagenesis.

(i) Early stage dolomitization of lime mud making <5-6 μ size dolomite rhombs.

(ii) Intermediate stage dolomitization affecting sparry calcite and recrystallization of early formed dolomite into 30-100 μ size dolomite rhombs.

(iii) Late stage dolomitization or patchy dolomitization producing irregular patches of dolomite made up of anhedral, large dolomite grains (100 μ or more).

INSOLUBLE RESIDUE STUDY

Percentages of the insoluble residue of various samples are plotted in Fig. 2. and also given in Table 3 and 4.

The samples of zone A are marked by a rather high insoluble residue content in which clay fraction dominates. The change from zone A to B is marked by a very significant decrease in the percentage of the insoluble residue. In zone C, insoluble residue content shows a slight increase from 1-2% to 5-6%. The zone D is characterized by a further slight increase in the insoluble residue (8%). It may be pointed out that the sand fractions of zones, A, B, C and D are made up of mostly authigenic minerals, i.e. glauconite, pyrite and goethite. The zone E is marked by a sudden and conspicuous increase in the insoluble residue (42%), which is mostly made up of sand-size quartz particles. Thus, except for zone E, whole succession is very poor in sand-size particles.

Table 3—Percentage of insoluble residue, and sand, silt, clay percentages of theins oluble residue, Tertiary rocks of Guar nala section, Kutch. G-glauconite-bearing sample.

Geological unit	Sample No.	Insoluble residue—%	Sand %	Silt %	Clay %
	G/1-2	15	69	13	18
	G/4-5A	22	6	38	56
	G/4-5B	50	71	9	20
	G/4-5C	68	60	12	28
	G/4-5D	49	66	13	21
Zone E	G/4-5E	82	27	21	52
(Gaj)	G/4-5F	53	74	9	17
	G/8-9	98	1	68	31
	G/12-13	22	30	21	49
	G/16-17	60	95	4	1
	G/18-19A	99	72	24	4
	G/18-19B	8	20	67	13
	G/19-20	15	10	66	24
	G/22-23	12	65	10	25
	G/25-26	4	1	23	76
	G/26-27A	6G	7	53	40
	G/26-27B	2G	4	15	81
Zone D	G/27-28A	9G	12	52	36
(Nari)	G/27-28B	16G	1	44	55
	G/28	10G	9	59	32
	G/29	12G	3	36	61
	G/30	2G	4	24	72
	G/31-32	7	2	52	46
	G/32-33	6	4	25	71
	G/34	4	4	24	72
	G/36-37	6	2	36	62
Zone C	G/38-39	6	3	22	75
(Kirthar)	G/42	5	4	18	78
	G/47	7	1	16	83
	G/54	6	3	16	81
	G/57	7	1	37	62
	G/57-58	1	38	9	53
	G/59	3	2	23	75
	G/62-63	1	4	13	83
Zone B	G/64-65	1	10	38	52
(Kirthar)	G/68	1	6	20	74
	G/70	1	12	29	59
	G/73-74	2	15	36	40
	G/78-79	7	5	20	75
	G/79	40	9	13	77
Zone A	G/91-92	96	(0.35)	11	89
(Kirthar)	G/93	16G	30	14	56
	G/97-98	19	(0.29)	10	90

Table 4—Average distribution of insoluble residue, and sand, silt, clay percentages in the insoluble residue of Tertiary rocks of Guar nala section.

Geological Unit	Insoluble residue %	Sand %	Silt %	Clay %
Zone E	41.61	46.2	28.0	25.7
Zone D	8.11	11.8	35.1	53.1
Zone C	5.5	6.2	25.5	68.3
Zone B	1.5	8.2	26.5	65.3
Zone A	35.6	8.9	13.6	77.4

MINERALOGICAL COMPOSITION OF THE SAND FRACTION OF THE INSOLUBLE RESIDUE

Zone A—The insoluble residue of this zone is characterized by a low content of sand fraction, except in sample G/93, where sand fraction is high and made up mainly of glauconite. Otherwise sand fraction contains mostly opaque minerals, which is dominantly goethite. Sample G/78-79 contains some pyrite. Content of quartz grains is rather low, and mostly in size 0.125—0.063 mm. Quartz grains make only 5-10% of the sand fraction of a given sample. Some samples (G/93, G/91-92, G/79) are characterized by the presence of gypsum grains sometimes as big as 0.5 cm, which are irregular in shape showing effects of transportation. Few gypsum grains show well-developed crystal forms and gypsum flower suggesting their *in situ* growth within the sediment.

Presence of gypsum grains as detrital grains suggests that within the basin of sedimentation, areas of increased salinity were present, probably high tidal flats and lagoons where gypsum precipitation took place. The gypsum layers from these areas were reworked penecontemporaneous with sedimentation and transported to the site of deposition as detrital grains. *In situ* precipitation of gypsum also took place on a minor scale.

Zone B—The sand fraction is made up of mostly opaque grains, which are dominantly pyitre, showing partial oxidization into iron oxides. Quartz grains are few and very angular in fine-sand size. Some samples contains gypsum grains.

Zone C—The sand fraction is quite similar to that of zone B. The opaque grains are made up of both pyrite and goethite. Gypsum is present in minor amounts.

Zone D—The sand fraction consists of mainly opaque iron minerals, with rare occurrence of pyrite. Most of the samples in the lower part of this zone contain glauconite in appreciable amounts. In these samples quartz grains are very few and of fine sand size and angular shape. In the topmost samples of this zone amount of quartz grains increases.

Zone E—The sand fraction is made up of dominantly quartz grains of medium to fine sand size. Sometimes quartz grains up to 1 mm size are present. Opaque minerals are present, but always very low in content. Coarser sand fractions often contain clay pellets and well-rounded grains of opaque minerals showing smooth surface. Opaque grains are sometimes abundant in the finer fractions (G/19-20, G/18-19B), while in the other samples they are abundant in the coarser fractions (G/12-13, G/4-5). In most of the samples mica is present in minor amounts. In the samples of the upper part of zone E, the medium sand fraction is characterized by the presence of greenish quartz grains (G/4-5B, G/4-5C). Gypsum grains are present in few samples in the lower part of Zone E (G/19-20, G/8-9).

GRAIN SIZE ANALYSIS

The samples containing sufficient amount of sand-size insoluble residue were subjected to grain size analysis.

Zone A—The cumulative curves for the two samples are shown in fig. 3. The curve marked with G contains glauconite in abundance. As already discussed, the glauconite in the sample has been produced authigenetically, the statistical parameters need not be calculated for the purpose of environmental interpretation. The other sample is basically a clay, but contains sand size particles showing wide size distribution.

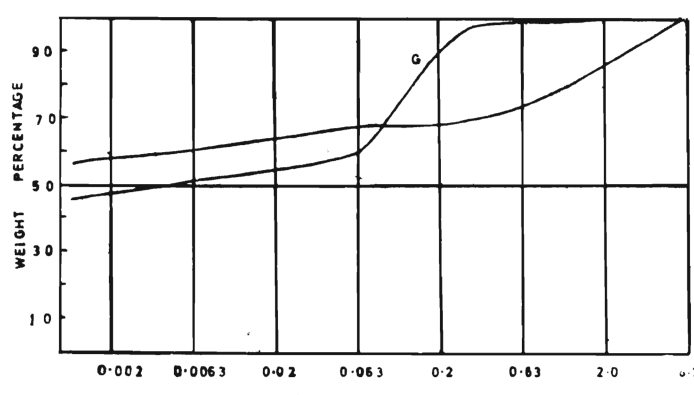

Fig. 3. Cummulative curves of two samples of zone A. G—glauconite-bearing sample.

Zones B and C—No sample contains sufficient sand for the purpose of grain size analysis.

Zone D—The cumulative curve of two samples are shown in fig. 4. However, the curve marked with G contains mainly glauconite in the sand fraction. The other sample is a medium sand with Md-0.135, and So—13.2, indicating very poor sorting of the detrital material.

Zone E—This zone is marked by the abundance of terrigenous clastic material. The cumulative curves of

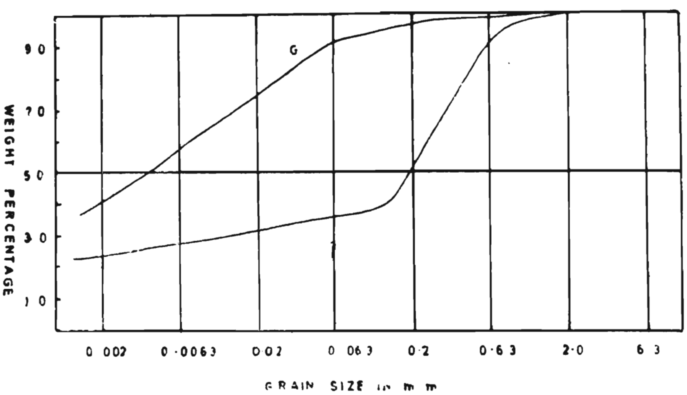

Fig. 4. Cummulative curves of two samples of zone D. G—glauconite-bearing sample.

the sandy samples are plotted in fig. 5 ; while those of clayey samples are plotted in fig. 6. The clay-rich samples show that their detrital material is poorly sorted, showing mixed type of grain size populations exhibiting much variation in the grain size distribution. Md-value ranges from 0.018 mm to <0.002 mm, i.e., the samples fall in the range of clayey silt to silty clay.

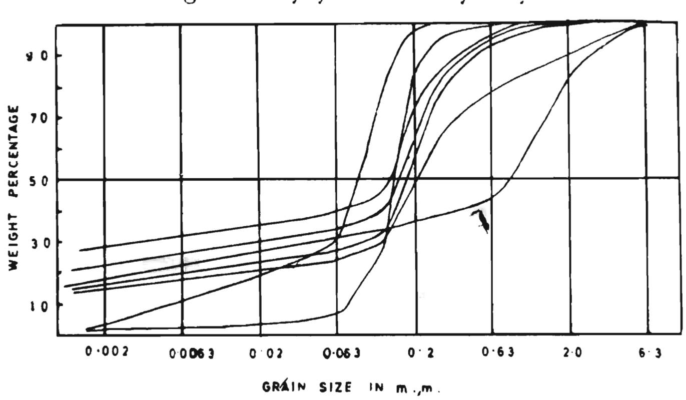

Fig. 5. Cummulative curves of the sand-rich samples of zone E.

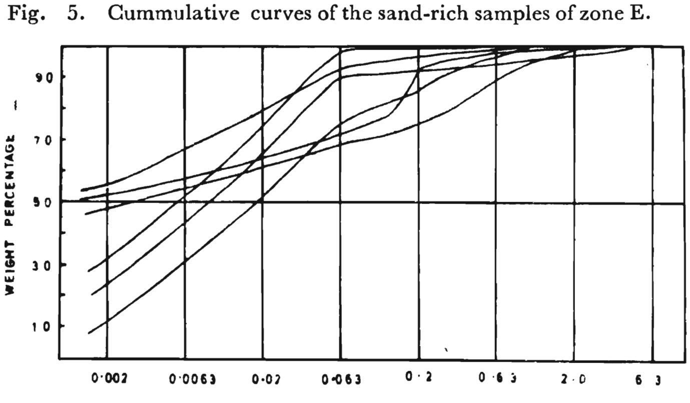

Fig. 6. Cummulative curves of the clay-rich samples of zone E.

The sand-rich samples fall in the category of fine sand to medium sand. Md and So of different samples are given in table 5. The sorting of these samples is rather poor because of the high content of clay fraction. Only one sample (G/16-17) shows moderate sorting.

Table 5--Md and So of the sand-rich samples of the Gaj sediments, Guar Nala section, Kutch.

Sample No.	Md	So
G/1-2	0.88	10.33
G/4-5 B	0.21	2.58
G/4-5 C	0.14	13.54
G/4-5 D	0.159	6.32
G/4-5 F	0.18	2.76
G/16-17	0.15	1.24
G/18-19 A	0.087	1.74

No hydrodynamic interpretations leading to the environmental reconstruction can be made on the basis of the grain-size data of the insoluble residue of the carbonates. It is due to the fact that these samples contain considerable amount of carbonate grains, especially the fossil fragments which have been deposited as detrital grains, and dissolved during acid treatment. Thus, the grain size data of these samples does not reflect the true grains size distribution. Nevertheless, this data does provide information about the nature of terrigenous clastic material, coming to the basin of deposition.

CLAY FRACTION STUDY

The clay fraction of the samples is made almost exclusively of clay minerals, i.e., montmorillonite, kaolinite and illite. Only in few samples quartz is determinable in low amounts in the clay fraction. However, in the evaluation of the mineralogical composition of the clay fraction only the clay minerals have been considered. Weighted peak area percentages of various clay minerals in the samples are given in Table 6, 7 and shown in fig. 2.

Montmorillonite--It possesses a characteristic basal peak at 14°A which expands to 17°A upon glycolation. On ignition up to 550°C montmorillonite structure collapses, and the 14°A peak shifts to the 10°A position. In few samples small amount of mixed-layer mineral may be present ; however, they are included in the broad group montmorillonite. Height of the peak above background (p) and the depth of the valley (v) on the low-angle side of the peak were measured and v/p has been taken as a measure of determining the crystallinity of the montmorillonite (Biscaye, 1965), and calculated for all the samples. Montmorillonite is extensively produced during soil formation in alkaline milieu with poor drainage, in the presence of Ca^{2+} and Mg^{2+} ions.

Illite—It gives characteristic reflections at 10°A, 5°A and 3.3°A. These peaks remain unaffected upon glycolation and heat treatment.

It may be pointed out that the palygorskite-attapulgite give a major peak at 10.5°A, interfering with the 10°A peak of illite, making identification of both the

Table 6—Percentages of clay minerals (weight peak area) in clay fraction ($< 2\mu$) of carbonate free-residue of Tertiary rocks of Guar nala section, Kutch. G—glauconite-bearing samples.

Geologcial unit	Sample No.	Weight peak area in %		
		Montmorillonite	Illite	Kaolinite
	G/1-2	27	23	50
	G/4-5A	38	21	41
	G/4-5B	61	10	29
	G/4-5C	44	14	42
	G/4-5D	49	18	33
	G/4-5E	46	15	39
Zone E	G/4-5F	57	14	29
	G/8-9	57	22	21
	G/12-13	44	23	33
	G/16-17	46	15	39
	G/18-19A	35	65	
	G/18-19B	59	23	18
	G/19-20	43	29	28
	G/22-23	69		31
	G/25-26	75	17	8
	G/26-27A G	72	16	12
	G/26-27B G	37	62	1
Zone D	G/27-28A G	70	29	1
	G/27-28B G	14	85	1
	G/28 G	78	15	7
	G/29 G	52	44	4
	G/30 G	55	39	6
	G/31-32	100		
	G/32-33	85	3	12
Zone C	G/34	83		17
	G/36-37	91	2	7
	G/38-39	78		22
	G/42	75	5	20
	G/47	78	4	18
Zone C	G/54	75		25
	G/57	64		36
	G/57-58	57		43
	G/59	53		47
	G/62-63	72	8	20
Zone B	G/64-65	88	12	
	G/68	89	11	
	G/70	90	6	4
	G/73-74	100		
	G/78-79	75	10	15
	G/79	71		29
Zone A	G/91-92	57	11	32
	G/93 G	32	19	49
	G/97-98	7	76	17

minerals difficult. Electron-microscope study may be helpful in its identification (Singh, 1974).

Again, most of the samples in the succession under study show a rather broad 10°A, peak with values often more than 10.5°A. This observation indicates that

Table 7—Average clay mineral composition of the clay fraction of Tertiary rocks of Guar nala section

Geological Unit	Clay mineral composition (weighted peak area percentage)		
	Montmorillonite	Illite	Kaolinite
Zone E	46	23	31
Zone D	58	34	8
Zone C	79	1	20
Zone B	82	6	12
Zone A	49	23	28

either the crystallinity of the illite is very poor, and/or else it contains appreciable amount of attapulgite-palygorskite along with illite. Illite (mica) minerals develop extensively either by mechanical degradation of mica or weathering of felspars. It also develops extensively in the marine waters during sedimentation and also during diagenesis. Glauconite is an important mica mineral which is formed authigenetically in the basin of deposition.

Kaolinite—Kaolinite gives strong reflection at 7.2°A (001) and 3.6°A (002). These/reflections remain unaffected upon glycolation. The reflections disappear on heating upto 550°C ; Kaolinite is typically a land-derived clay mineral, produced in soils with good leaching in an acidic milieu. It is incapable of being formed in marine waters.

DISTRIBUTION OF CLAY MINERALS IN THE SUCCESSION

Distribution of clay minerals in different stratigraphic zones is discussed below :

Zone A—Clay mineral composition of this zone shows much variation. The average composition of this zone is :—

Montmorillonite	..	..	49%
Illite ..	..	..	23%
Kaolinite ..	..	..	28%

Though montmorillonite is the most abundant mineral, illite and kaolinite are also present in appreciable amount. Crystallinity of montmorillonite is poor in the lower part ; but improves in the upper part. The 10°A peak is rather broad suggesting probable incorporation of attapulgite-palygorskite.

Zone B—The clay mineral association is uniform in all the samples showing dominance of montmorillonite ; illite and kaolinite are present in minor amounts. One sample is monomineralic and is made up of only montmorillonite. The average composition is :

Montmorillonite	..	..	82%
Illite ..	..	..	12%
Kaolinite ..	..	..	6%

Crystallinity of montmorillonite is very good in all the samples of this zone (v/p=0.8—0.9). The illite peak shows a rather high °A value, mostly >10.3°A, and a broad peak.

Zone C—The clay mineral association in the samples of this zone are characterized by overdominance of montmorillonite, and presence of kaolinite in minor amounts. Illite is either absent or present in negligible proportions. One sample is made up of montmorillonite only. The average composition is :

Montmorillonite	79%
Illite	20%
Kaolinite	1%

Crystallinity of montmorillonite is good in all the samples of this zone (v/p)=0.8—0.9) like that of zone B. The illite peak shows a rather high spacing value (10.8°A).

Zone D—Clay mineral association of this zone is characterized by dominance of montmorillonite with illite in significant amounts. Kaolinite is present in negligible proportions. The average composition is :

Montmorillonite	58%
Illite	34%
Kaolinite	8%

Crystallinity of the montmorillonite is usually good to moderate, showing much fluctuations (v/p=0.6—0.9). The illite peak shows a high spacing value (10.3—10.9°A), and a rather broad peak suggesting poor crystallinity. The samples showing high illite content are also rich in glauconite in sand fraction.

Zone E—Clay mineral composition of the sediments of this zone shows a marked change from those of the underlying sediments. The clay mineral composition is more or less uniform in all the samples of this zone. Montmorillonite is still the main mineral ; but illite and kaolinite are also present in appreciable amounts. The average composition is :

Montmorillonite	46 %
Illite	31 %
Kaolinite	23 %

Crystallinity of the montmorillonite show much fluctuations ranging from poor to vrey good (v/p= 0.4—0.9). The illite peak shows its characteristic d-spacing values ranging from 9.9—10.2°A, suggesting presence of well-defined mica minerals, though the peak is broad indicating poor crystallinity.

SIGNIFICANCE OF THE CLAY MINERAL ASSOCIATIONS

It is a widely accepted fact that clay minerals of the sedimentary rocks can originate in the following three ways (see Millot, 1970 ; Singh, 1974).

(i) Inherited clay minerals, derived from the provenance.

(ii) Transformed and neoformed clay minerals developed in the basin of deposition.

(iii) Transformed and neoformed clay minerals during diagenesis.

Deposition of the Tertiary rocks of Kutch took place in an open shallow marine basin densely populated by benthonic foraminifera, receiving some detrital material including clay minerals from the ajdoining source area. In such marine basin some neoformation and transformation of clay minerals can take place.

The sediments of zone A contain abundant montmorillonite and some kaolinite, both land-derived minerals. Illite, which is also present in appreciable amounts, can be land-derived or noeformed in the basin of deposition. As the illite peak shows a higher d-spacing value, it is quite likely that at least partly it is neoformed at the cost of montmorillonite and larger d-spacing is because of the presence of montmorillonite-illite intermediate lattice.

Loughnan (1962) has shown development of illite from 14°A mineral in marine waters of Australia. Whitehouse and McCarter (1958) have shown in the laboratory studies that montmorillonite in marine waters can change to illite.

During deposition of zone B sediments source area and climate of the source area was most favourable for the genesis of montmorillonite with minor amounts of kaolinite, and illite as in the case of the sediments of zone A. Good crystallinity of the montmorillonite further confirms the favourable conditions for its genesis in the provenance. Illite shows a broad peak and high d-spacing suggesting neoformation at least in part.

Clay mineral association of zone C is identical to that of zone B, suggesting that the source area and climate of zone B continued into zone C sedimentation.

Sediments of zone D show montmorillonite as main mineral, along with illite in good amounts and kaolinite in very low contents. The montmorillonite, kaolinite, and some illite is land-derived. However, major part of illite has been formed during diagenesis along with glauconite. This zone is characterized by the neoformation of 10°A mineral (illite and glauconite).

The sediments of zone E show a marked change in the clay mineral assemblage in comparison to that of underlying zones A, B, C and D. In this zone along with montmorillonite, both illite and kaolinite are important constituents of the clay fraction. The illite of this zone shows normal d-spacing, in contrast to the higher d-spacing of illite of the underlying zones, and appear to be almost exclusively land-derived ; no neoformation of illite seem to have taken place during diagenesis. It appears that the sediments of zone E have been derived from a different source with different set of soil formation processes than the rest of the succession. This is also supported by the sand-rich insoluble residue of this zone.

It is likely that the terrigenous material of zones A, B, C and D is derived from the Deccan Trap area ; while that of zone E is supplied mainly from a metamorphic and granitic terrain, along with some material from the Trap country. During sedimentation of Middle Kirthar sediments (Zones A, B, C) mainly montmorillonite was supplied along with little kaolinite and illite. Diagenetic effects on the clay minerals are negligible and are restricted to the formation of illite only. During deposition of Nari sediments (zone D) same material was supplied but neoformation of illite extensively took place. In Gaj sediments (zone E) illite and kaolinite were supplied in good proportions along with montmorillonite ; no neoformation of clay minerals took place.

SILT FRACTION STUDY

The study is confined to the qualitative determination of various minerals by X-ray, and no detailed study of this fraction has been undertaken. In all the samples some clay minerals are present, mostly illite, montmorillonite ; and sometimes kaolinite (in zone E), showing their characteristic peaks. Quartz is present in all the samples in abundance. Sometimes felspars are also present in minor amounts. Zone A shows mostly quartz, rarely K-felspar ; zone B shows dominantly quartz with K-felspar in minor amounts ; zone C also shows dominantly quartz with K-felspar in minor amounts ; zone D shows dominantly quartz with both K-felspar and plagioclases in minor amounts ; zone E shows almost exclusively quartz in abundance, negligible amount of K-felspar is present in one sample.

DEPOSITIONAL ENVIRONMENT

In last two decades the Tertiary rocks of Kutch have been investigated by many workers for its fauna, especially the foraminifera (for example, Tewari, 1960 ; Tandon, 1966 ; Singh, 1967). These authors have discussed the palaeoecology of these sediments, and agree that sediments of the western part of Kutch are deposits of an open, warm shallow sea of normal salinity. Few horizons of gypsiferous sediments indicate increased salinity, while some horizons of coal bands and fresh water vertebrate remains indicate low salinity. Probably, in the Tertiary succession of Kutch there are several minor regressions representing periods of non-deposition, which are not readily recognizable.

The fauna of the Tertiary rocks of Kutch is dominated by the benthonic larger foraminifera ; though planktonic forms are also present in considerable amount. This suggests a rather open, extensive shallow continental shelf, where planktonic forams could freely come in the shallower parts of the continental shelf. Besides, these sediments also contain lamellibranchs : *Ostrea*, *Turritella* and *Mytilus ;* and benthonic echinoderms. These organisms usually inhabit the littoral zone, transition zone and shallow parts of the shelf mud. *Turritella* in present-day sea lives in the shelf mud zone (Hertweck, 1971) while *Ostrea* lives from intertidal zone to few tens of metre depth. *Mytilus* also lives in intertidal zone and to a lesser degree in the shelf mud zone. Calcareous algae—*Lithothamnia*, *Archaeolithothamnium* are also quite abundant in these sediments, especially in the Oligocene to Lower Miocene sediments (Nari and Gaj zones D and E).

These faunal elements are indicative of a shallow warm sea. On the basis of faunal evidences it can be said that the deposition of these sediments took place mainly in the upper part of the continental shelf of an open sea ; the maximum depth of deposition reaching up to about 40-50 m. However, the major part of the succession represents deposition in a much shallower regime (5-20 m water depth), especially the horizons rich in molluscs and echinoids and with little planktonic foraminifers.

The zone A of the succession under study make a few metre thick succession at the base and made up of mainly shale and biomicrite, containing mostly smaller forams, molluscs and some algae. The insoluble residue is mainly fine-grained silt and clay. Gypsum is present as detrital grains. These parameters indicate that the sediments of zone A are deposited in a rather low-energy environment of a shallow sea, where mostly clay material was coming from the land. In the shallower parts of the basin (intertidal and supratidal zone) gypsum was precipitated under hypersaline conditions and reworked to produce detrital grains. The sedimentation of this zone mainly took place in the shallower parts of continental shelf, below wave base in an embayment of the sea.

The sediments of zone B are made up of only biomicrite containing mainly larger, benthonic foraminifera. Few planktonic forams and rare algal remains are also present. The content of the insoluble residue is very low (1.5%). The Forams do not show any sorting effects or preferred orientation. These features suggest that site of deposition was a shallow open sea shelf, situated at some distance from the coast, out of reach of the coastal currents and below wave base. Only very small amount of suspended silt and clay reached the site of deposition. Rate of sedimentation was low, and due to rich food available, population of benthonic forams was high.

The sediments of zone C are very similar to those of zone B, and must have been deposited under very similar set of conditions. The only difference seen is that the sediments of zone C are characterized by a higher content of insoluble residue (6%) than the sediments of zone B. The site of sedimentation for zone C also must have been shallower part of the continental shelf situated at some distance from the coast.

The sediments of zone D are also similar to those of zone B and C, and made up of mostly biomicrite. However, these sediments show extensive development of glauconite and algal fragments are almost present. The insoluble residue content is about 8% (this high value is mainly due to content of glauconite). The zone D sediments also represent deposits formed under conditions similar to those of zones B and C, i.e., in a shallow shelf out of reach of wave and current action, situated at some distance from the coast. Abundance of glauconite in these sediments indicate presence of much organic matter in the sediment and slow rate of sedimentation. At the top of zone D, there is a change in the conditions of sedimentation. These samples contain considerable amount of sand, indicating that sand could be brought in the site of sedimentation ; though the regime of sedimentation was not directly affected by wave or current activity.

The sediments of zone E are characterized by sandy biomicrite, sandstone and shale. The fossils are mostly benthonic forams, pieces of molluscs and algae. The insoluble residue content is rather high and marked by the dominance of sand fraction. The sediments represent deposits of a shallower part of shelf and transition zone. The site of sedimentation was located quite near the sandy coast line. The sand from the coastal part was occasionally transported up to the site of deposition, where benthonic forams lived in lime mud sediments. Parts of the succession seems to represent deposits of the coastal part itself, which was affected directly by wave and current action.

To sum up, the Tertiary rocks of Guar Nala section of W. Kutch represent predominantly shallow-water, shelf-type carbonate deposits, laid down in a warm open sea with normal salinity, and dense population of benthonic foraminifera. The site of deposition was located at some distance from coast, for most of the time out of reach of the coastal currents and waves.

Because the succession under study represents near shore sediments, there must be several periods of non-deposition in response to the eustatic sea-level changes. However, such horizons are not identifiable with the help of petrological and mineralogical studies. It may be pointed out that within the succession there are horizons of highly dolomitized rocks, made up of dolomite, which may represent regressive phases of the sea. Detailed palaeontological studies may confirm these breaks in sedimentation and may also reveal many more such horizons of non-deposition in the succession. In other sections of Tertiary of Kutch, breaks in deposition have been recorded.

CONCLUSION

1. The Tertiary succession of Guar Nala in western part of Kutch represents shallow-water shelf-type carbonate deposits laid down over Deccan Traps during Middle Eocene to Lower Miocene period (Middle Kirther, Nari and Gaj succession). On the basis of fossil content mineralogical characteristics, insoluble residue content the whole succession has been subdivided into five zones, namely, A, B, C, D and E, out of which zone, A, B, C corresponds to Middle Kirthar (Middle Eocene), zone D to Nari (Oligocene), and zone E to Gaj (Lower Miocene).

2. Zone A sediments show three microfacies, shale, low matrix biomicrite and glauconitic biomicrite. The insoluble residue content is high (av. 36%) and is mainly silt and clay ; only few grains of quartz along with detrital grains of gypsum occur in the sand fraction. Biomicrites, are characterized by negligible to low dolomite content, matrix shows moderate to low dolomitization. The clay fraction shows variable composition ; however, montmorillonite is the main mineral along with illite and kaolinite in appreciable proportions.

3. Zone B sediments are made exclusively of foraminiferal limestone (low-matrix biomicrite). The insoluble residue content is extremely low (av. 1.5%) and is made up of predominantly clay and silt fraction. Dolomite content is low to moderate affecting mostly the matrix, which has also been sometimes recrystallized. The clay fraction shows montmorillonite as dominant mineral with kaolinite and illite in minor amounts.

4. Zone C sediments show two microfacies, namely low-matrix biomicrite and high matrix biomicrite. The insoluble residue content is low (av. 6%), made up of predominantly clay and silt fraction. The sand fraction contains pyrite and goethite along with few grains of quartz in fine sand size. Matrix of both the microfacies shows strong dolomitization. The dolomite content is relatively high throughout this zone. The clay fraction shows montmorillonite as dominant mineral along with kaolinite in minor amounts, and illite in negligible proportions.

5. Zone D sediments (Nari=Oligocene) show following microfacies : low-matrix biomicrite, high-matrix biomicrite, glauconitic biomicrite, dolomitized biomicrite, and sandy biomicrite. The content of insoluble residue is low (av. 8%), though more than in zone C. Most of the samples show authigenic glauconite. Degree of dolomitization is low to moderate (less than in Zone C), but both matrix and fossils have been dolomitized. In the topmost part biomicrite contains quartz grains in appreciable amounts. The clay fraction shows montmorillonite as dominant mineral with illite in good proportions, and kaolinite in very minor amounts.

6. Zone E sediments are made up of carbonates, sandstone and shale and show following microfacies : dolomitized biomicrite, sandstone, calcareous sandstone, shale, sandy biosparite. The content of insoluble residue

is high (av. 41%) and marked by the abundance of sand fraction made up of mostly medium to fine-sand size quartz grains. Dolomite is absent to low, except in the lower most part, where it is very high. The clay fraction shows montmorillonite as main mineral along with kaolinite and illite in good proportions.

7. It is suggested that during deposition of the sediments of Zone A, B, C and D, terrigenous clastic material was derived from the soils developed on the Deccan Traps, while during sedimentation of zone E sediments terrigenous clastic material was mainly supplied from a source area with sedimentary rocks, or granitic and metamorphic rocks, bringing much quartz sand and mica. Soils of Deccan Traps also contributed in minor amounts during deposition of zone E sediments.

8. The environment of deposition for the succession under study seems to be an open shelf with carbonate precipitation. The zone A sediments were laid down in a low energy environment of a shallow sea where sufficient supply of fine-grained terrigenous material (clay) was available due to vicinity of the coast. Sediments of zones B, C and D were deposited in a shallow, open shelf, situated at some distance from the coast beyond the reach of active current and wave activity in the sediment bottom. There was little or negligible supply of clay material. Throughout the succession the sediments were densely populated by benthonic foraminifera and some molluscs. The sediments of zone E were laid down in upper shallow part of shelf and transition zone quite near the coast line so that sandy material in appreciable amounts could reach the site of deposition.

9. The succession has been subjected to diagenetic changes, where early diagenetic processes have dominated. The diagenesis took place exclusively in an alkaline milieu with mainly aerobic conditions, though eH value fluctuated from slightly + Ve to —Ve values.

10. Diagenesis has especially affected the carbonates leading to very early diagenetic dolomitization. Three diffrent stages of dolomitization are recognizable.

11. Glauconite has been extensively formed during diagenesis mostly in the zone D sediments. Illite has also been formed diagenetically in the samples containing glauconite. Pyrite and goethite are the other diagenetically formed minerals present in the succession.

ACKNOWLEDGEMENTS

The author expresses his sincere thanks to Dr. M. P. Singh, Geology Department, Lucknow University who supplied the samples for this study. Thanks are extended to Prof. H.-E. Reineck and Dr. S. Gadow, Senckenberg Institut, Wilhelmshaven, W. Germany for providing the facilities to undertake the X-ray analysis of the samples. Help of Dr. K. K. Tandon, Lucknow University in the thin-section identification of the forams and in fixing of petrological zones is acknowledged. Encouragement given by Prof. R. C. Misra, Lucknow during this study is gratefully acknowledged. Thanks are also expressed to Prof. S. N. Singh, Geology Department, Lucknow University for providing the facilities of the department. The author is thankful to Dr. S. Kumar, Lucknow University; for the help and suggestions during writing up of this paper.

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EXPLANATION OF PLATES

PLATE I

1 Low-matrix biomicrite microfacies. Few larger forams are present; otherwise microforams are embedded in a finegrained matrix. Zone A, sample No. G/93. 1 div. of scale = 1 mm.

2 Low-matrix biomicrite microfacies showing abundant larger forams. Zone B, sample No. G/73-74. 1 div. of scale = 1 mm.

3 Low-matrix biomicrite microfacies. Matrix is moderately dolomitized, in parts patchy dolomitization. Zone B, sample No. G/70. 1 div. of scale = 1 mm.

4 High-matrix biomicrite microfacies. Patchy dolomitization of the matrix. Zone C, sample No. G/54. 1 div. of scale = 1 mm.

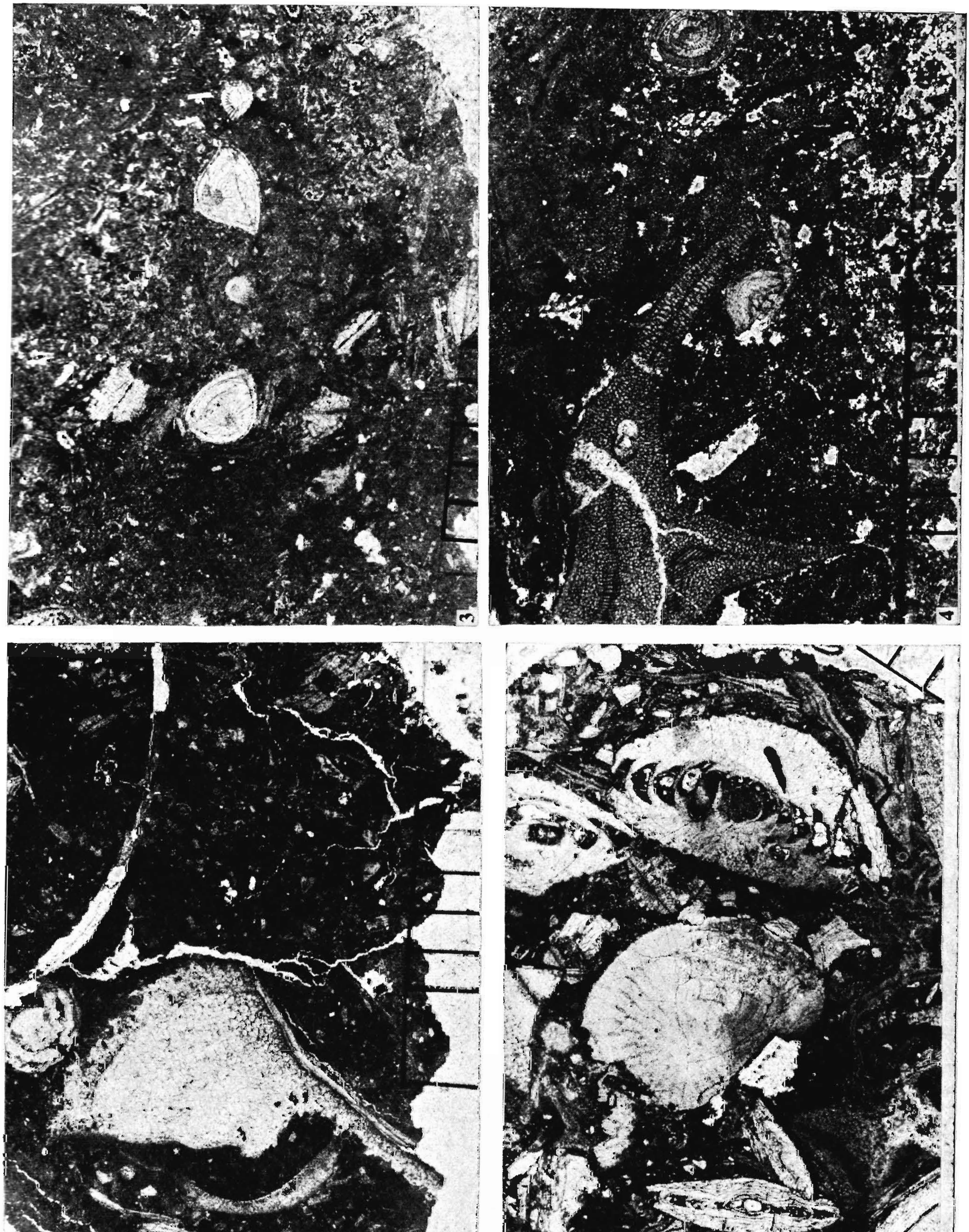
PLATE II

5 Low-Matrix biomicrite, microfacies. Matrix is dolomitized and recrystallized. Fossils also show partial dolomitization. Zone C, Sample No. G/38-39. 1 div. of scale = 1 mm.

6 Low-matrix biomicrite microfacies. Matrix content is very low, patchy dolomitization of the matrix and borders of the fossils. Zone C, sample No. G/34, 1 div. of scale = 1 mm.

7 High-matrix biomicrite microfacies. Strongly dolomitized; fossils have been partly obliterated. Zone C, sample No. G/31-32. 1 div. of scale = 1 mm.

8 Glauconitic biomicrite microfacies. Chambers of the forams are filled mostly with glauconite. Patchy dolomitization. Zone D, sample No. G/29. 1 div. of scale—1 mm.



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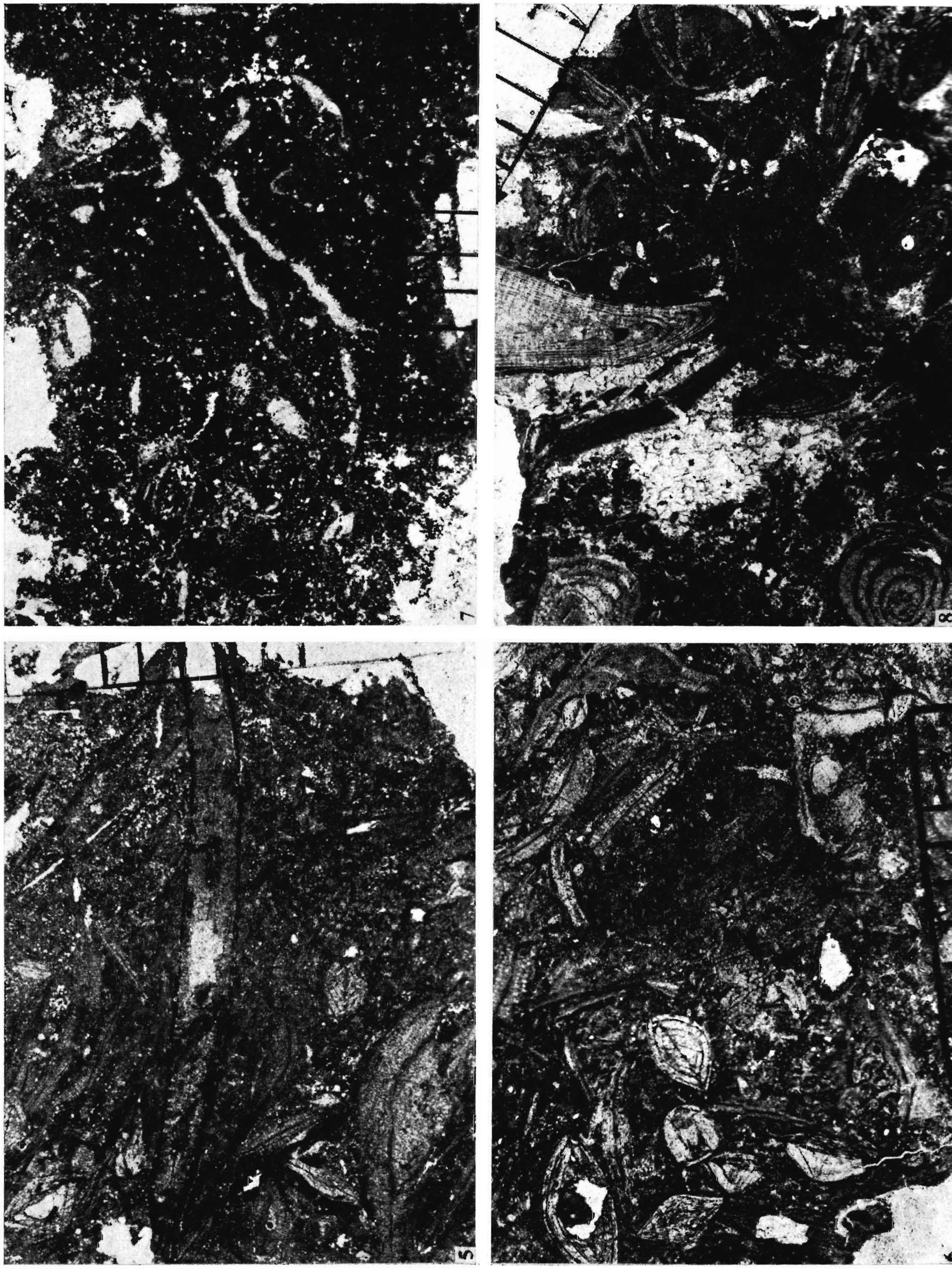

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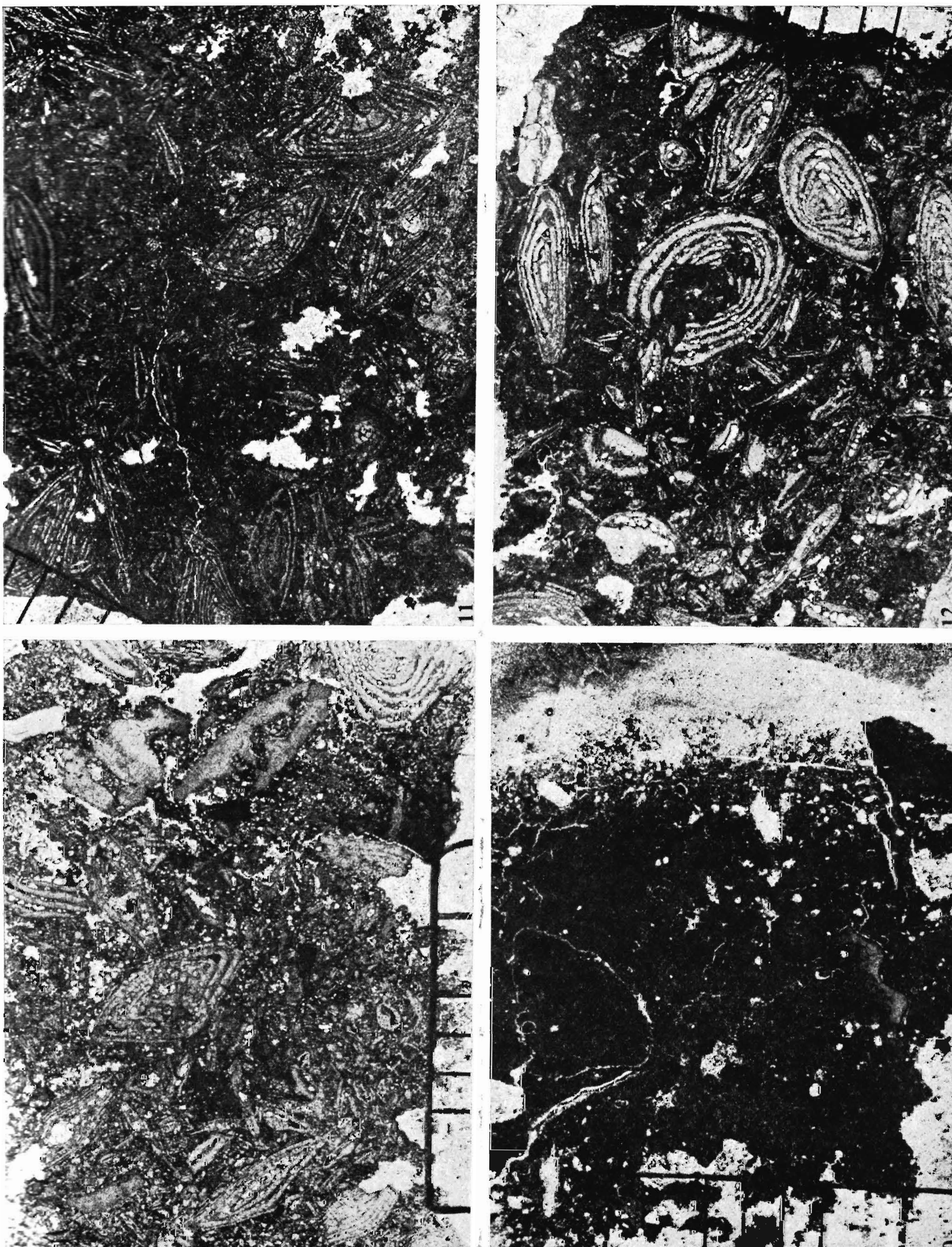

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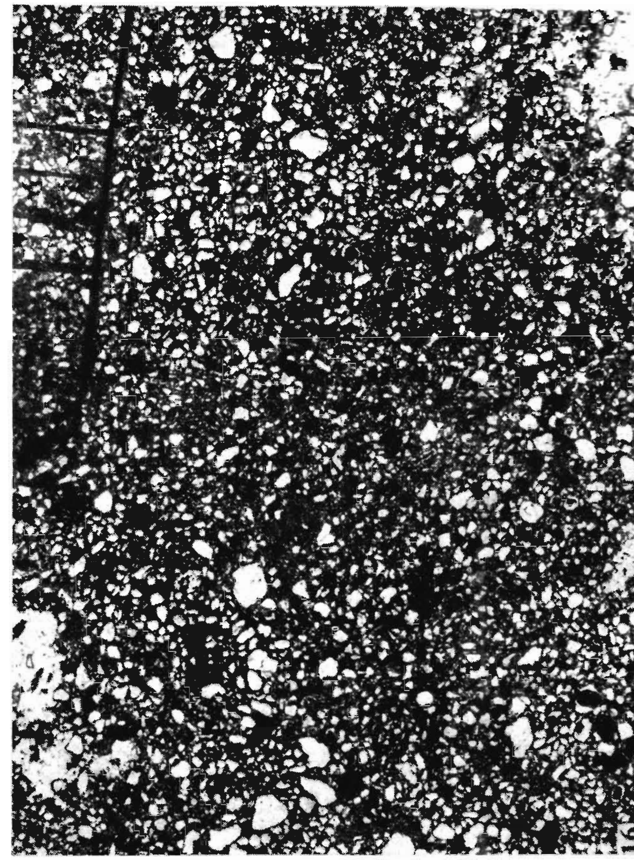

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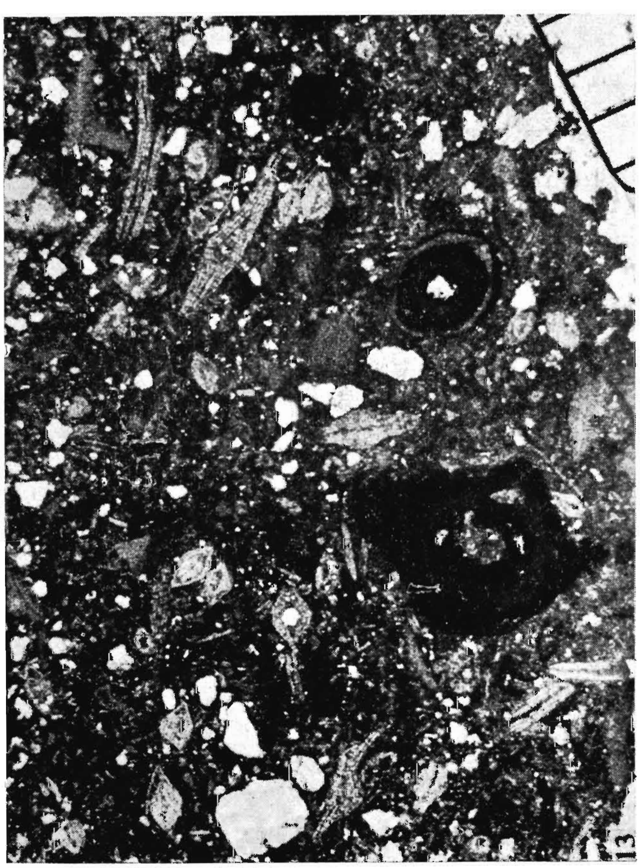

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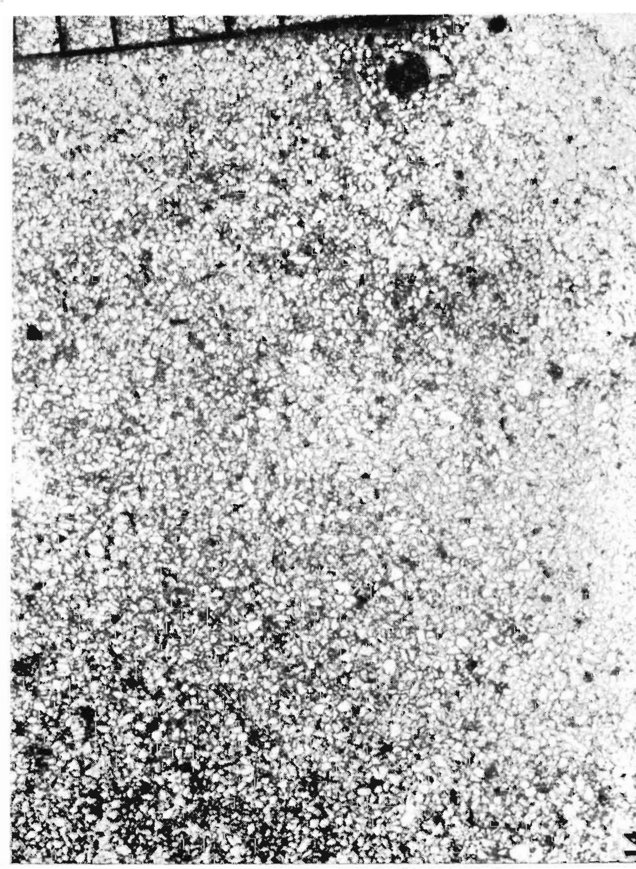

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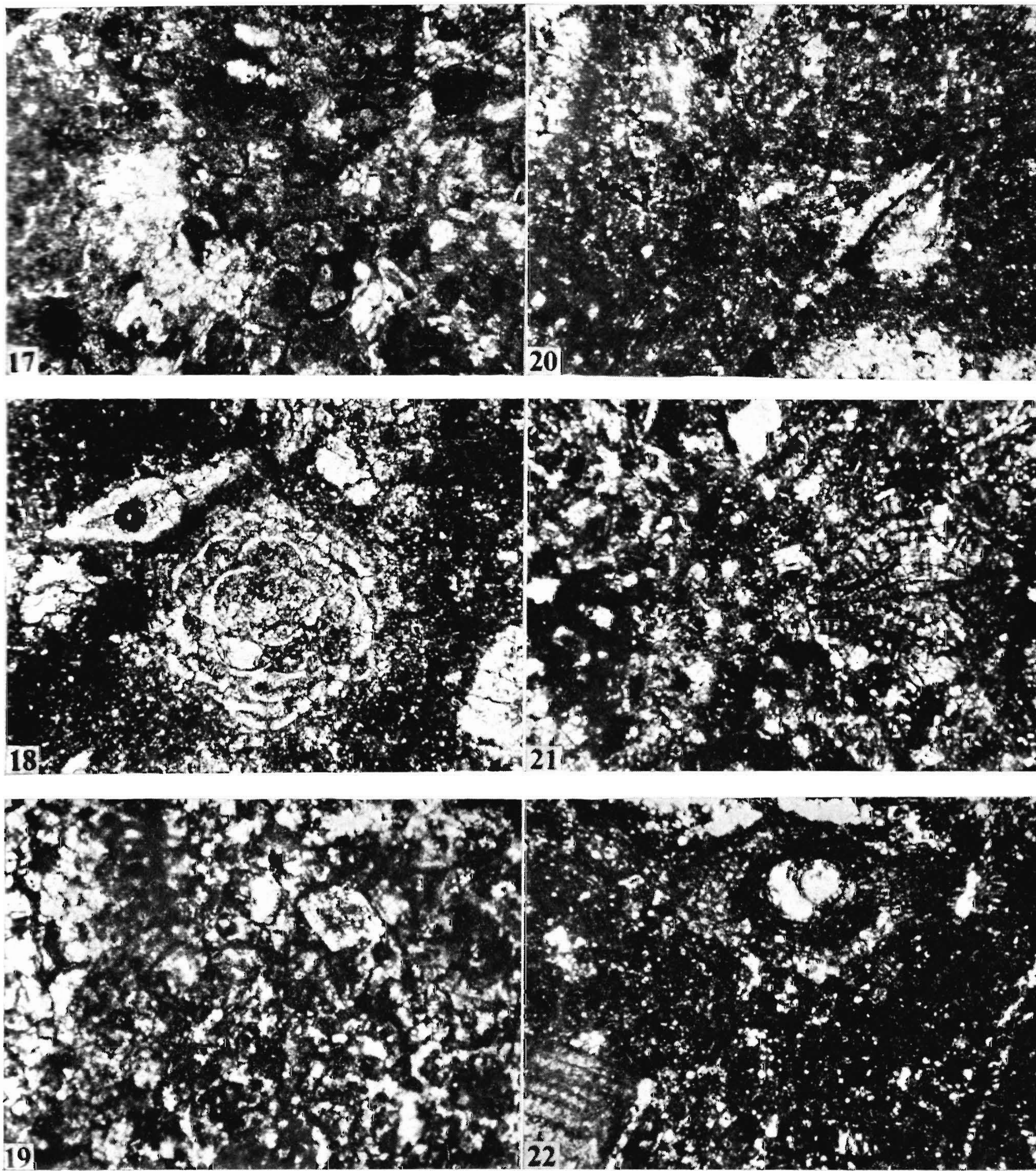

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PLATE III

9 Glauconitic biomicrite microfacies. Strongly dolomitized affecting also the fossils. Zone D, sample No. G/28, 1 div. of scale= 1 mm.

10 Dolomitized biomicrite microfacies. The rock is made up of almost exclusively of dolomite. Zone D, sample No. G/27-28B, 1 div. of scale 1 mm.

11 Glauconitic biomicrite microfacies.Matrix contains much dolomite, also some patchy dolomitization. Zone D, sample No. G/27-28A. 1 div. of scale=1 mm.

12 Glauconitic biomicrite microfacies. Chambers of larger forams are filled with glauconite and some dolomite. Little patchy dolomitization. Zone D, sample No. G/26-27 A. 1 div. of scale=1 mm.

PLATE IV

13 Sandy biomicrite microfacies. Quartz grains and algal remains are very common. Zone D, sample No. G/22-23. 1 div. of scale=1 mm.

14 Calcareous sandstone microfacies. Quartz grains are cemented by calcite. Zone E, sample No. G/16-17. 1 div. of scale=1 mm.

15 Sandy molluscan biosparite microfacies. Rounded to subrounded quartz grains and molluscan shell fragments are common. Zone E, sample No. G/4-5 t .1 div. of scale—=1 mm.

16 Sandstone microfacies iron and little calcitic cement are present. Zone E, sample No. G/4-5c. 1 div. of scale=1 mm.

PLATE V

17 Microphotograph showing glauconite pellets in a slightly dolomitized calcitic matrix. Zone A, sample No. 93. Magnification × 39.

18 Forams embedded in a carbonate matrix, which shows minute dolomite rhombs (about 5 μ in size). Zone A, sample No. G/78-79. Magnification × 126.

19 Recrystallized and dolomitized matrix. Smaller rhombs are about 5 μ in size, while larger ones are 40-50 μ in size and sometimes show zoning. Zone B, sample No. G/64-65. Magnification × 126.

20 General view of slightly dolomitized matrix showing dolomite grains of two sizes. Fossils are embedded in the matrix. Zone B, sample No. G/64-65. Magnification × 39.

21 Three types of dolomite,viz. minute rhombs (5 μ), recrystallized rhombs (50 μ) and anhedral grains in the matrix. Forams have been partly affected by dolomitization. Zone B, sample No. G/59. Magnification × 126.

22 Partially dolomitized forams embedded in a moderately dolomitized matrix. Zone C, sample No. G/54. Magnification × 39.

PLATE VI

23 Strongly recrystallized dolomitic matrix made up of mainly large dolomite rhombs. Zone C, sample No. G/36-37. Magnification × 126.

24 Dolomitized foraminfera showing large dolomite rhombs. The matrix contains both large and small rhomgs. Zone C, sample No. G/32-33. Magnification × 39.

25 Fine-grained dolomitized matrix containing glauconite pellets and darker-coloured iron rich pellets. Zone D, sample No. G/30. 'Magnification × 126.

26 Chambers of a foraminifera filled with glauconite (dark-coloured) and some dolomite (colourless). Zone D, sample No. G/29. Magnification × 39.

27 Foraminifera showing glauconite pellets and dolomite in the chambers. Dolomite has also replaced the chamber walls and made irregular patches. Zone D, sample No. 29, Magnification × 39.

28 Patchy dolomite (colourless) replacing both forms and matrix without any preference. Zone D, sample No. 28. Magnification × 39.

PLATE VII

29 Fine-grained carbonate matrix showing minute dolomite crystals. Few patches of patchy dolomite. Zone D, sample No. G/27-28 A. Magnification × 39.

30 Microforams embedded in moderately dolomitized fine-grained matrix (grain size approx. 5 μ). Zone D, sample No. G/27-28 B. Magnification × 126.

31 An algal remain embedded in a dolomitic and sandy matrix. Zone D, sample No. G/22-23. Magnification × 39.

32 A dolomite rock showing larger dolomite rhombs, sometimes exhibiting zoning. Zone E, sample No. G/19-20. Magnification × 126.

33 A sandstone made up of subrounded quartz grains and iron-oxide cement. Zone E, sample No. G/18-19A. Magnification × 39.

34 Algal fragment embedded in a fine-grained dolomitic matrix. Patchy dolomitization is visible. Zone E, sample No. G/18-19 B. Magnification × 39.