THE EVOLUTION OF AN ATOLL: THE DEPOSITIONAL AND EROSIONAL HISTORY OF ALDABRA

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[Plates 33—38; pull-out map]

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The earliest sediments identified of late Pleistocene age are quiet-water calcarenites, containing abundant molluscs but few corals. As waters shallowed these were replaced by emergent intertidal sediments, probably colonized by mangroves. Further emersion into subaerial conditions resulted in cementation and solution of the limestones to form a dissected karst topography. Perhaps concurrent with this, phosphates, probably originally derived from sea birds, were deposited in open cavities. Further marine withdrawal caused the erosion and re-deposition of these phosphatic sediments at a lower level. A succeeding event was the formation of a sand cay at the western end of the atoll. Its emergent surface was colonized by tortoises, birds, crocodiles and snails, and the youngest deposits indicate the presence of at least seasonal bodies of standing fresh water.

This terrestrial interlude was followed by inundation by a sea, perhaps 2–3 m higher than the present level, in which was deposited a fairly uniform limestone over the whole area of proto-Aldabra. The limestone consists largely of calcareous algae set in a calcilutite-calcarenite matrix, in which both corals and molluscs are low in numbers and diversity. The emergence that followed caused widespread erosion and the island formed, surrounded by low cliffs, was subject to solution fretting and a limited deposition of soils. Renewed submergence carved proto-Aldabra into a broad shallow bank, with an almost flat ring-like rim around the periphery, while re-emergence allowed deposition on this bank of a series of sandbanks, beaches and terrestrial soils.

These deposits were truncated by a marine erosion surface which marked the beginning of a sea-level rise that continued to a level at least 8 m above present datum, proto-Aldabra (125000 years B.P.) then consisting of a shallow bank covered by coral-rich calcarenite. Coral growth was more prolific around the rim, but coral knolls were also common within the rim to the northwest, where both coral and mollusc diversities are highest. The dominant sediment in the southeast is a *Halimeda*-rich sand with relatively little coral growth, but the presence of abundant *Acropora* around the southeast rim suggests that the dominant wind was from this quarter. Early in the deposition of this rock unit a sea-level oscillation resulted in temporary emergence, causing a change in facies or a break in deposition.

A subsequent drop in sea level resulted in the cutting of a terrace at about 8 m and a more conspicuous terrace at around 4 m. Aldabra then stood as a ring of narrow, low, rocky islets surrounding a broad shallow lagoon. Deposits with a land-fauna including crocodiles, tortoises and lizards possibly date from this period. Continued depression of the sea level as a result of the Wurm/Wisconsin glaciation left Aldabra as a steep-sided rocky island, perhaps up to 100 m high. This was well vegetated, and a high rainfall caused much solutional erosion. Sea level, in response to post-Glacial climatic warming, has risen to its present position, a principal consequence being the breaching of the land rim and the flooding of the lagoon to reduce the land area by almost 60 %. Small cavity-fill deposits, caves, and stromatolitic coatings have been formed since the last interglacial, but it is difficult to place them in sequence.

A restless history, of changes in the size, shape and character of Aldabra had important effects upon both the marine and terrestrial biotas. The giant tortoise, *Testudo gigantea*, was eliminated and has recolonized the area on at least two occasions; and the faunas and floras characterizing the sediments of each marine event are very different in composition.

The evidence presented does not accord with the popular view of reef growth as steady accretion. The limestones were formed as discrete increments, often with dramatic facies changes between one unit and the next.

Introduction

The atoll of Aldabra (lat. 9° 24′ S, long. 46° 20′ E) has recently received much scientific attention (Westoll & Stoddart (eds.) 1971; Stoddart & Wright 1967), mainly concerned with the insular character of the biota (see Peake 1971), the most spectacular element of which is the giant tortoise *Testudo gigantea*. Little attention has so far been paid to the geological history of the atoll, although, in providing a picture of the evolving morphological and sedimentological framework it is of fundamental importance to the understanding of the character of the present-day fauna and flora. Many discussions on the reasons for high marine species diversity in the tropics (Sanders 1968; Valentine 1969, 1971) have assumed an environmental stability, over long periods; but on Aldabra the evidence shows the effect of environmental transcience in promoting successive colonizations by new marine and terrestrial biotas throughout late-Pleistocene times.

The general geological background and setting of Aldabra has been described by Stoddart, Taylor, Fosberg & Farrow (1971); previous geological work includes the perceptive account by Fryer (1911) and a brief report by Baker (1963). Aldabra is one of a group of slightly elevated coral islands to the north of Madagascar; they are the subaerial tips of individual seamounts rising from the floor, 4000 to 4300 m deep, of the Somali Basin. B. R. Rosen (personal communication) has pointed out that these raised islands lie to the west of a major tectonic line consisting of the Owen fracture zone, the Amirantes trench, and the faulted east coast of Madagascar (Francis, Davies & Hill 1966; Fischer, Engel & Hilde 1968). Coral islands to the east of this line are all low sandy cays and are in contrast to the Aldabra group and other high

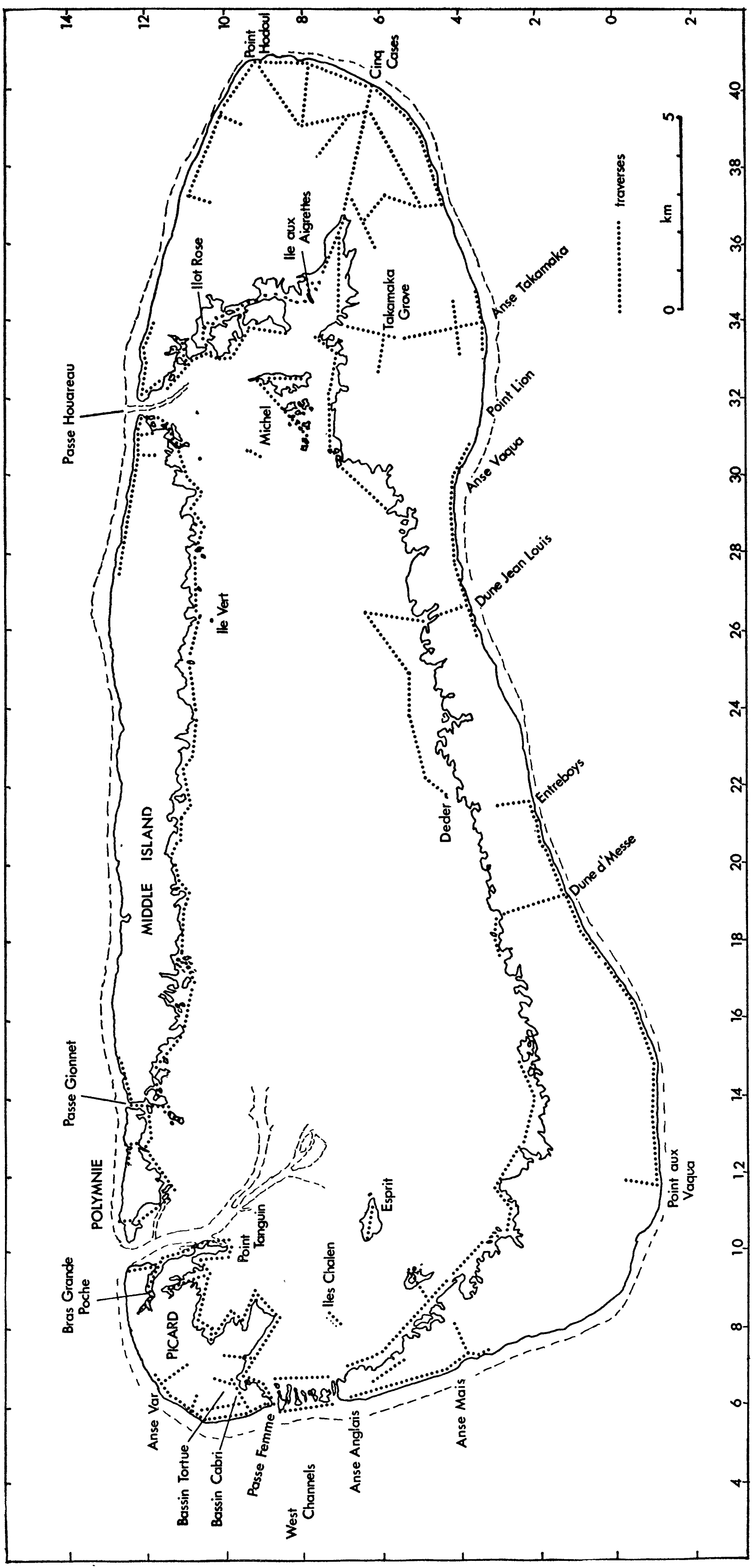


FIGURE 1. Map of Aldabra showing grid, localities mentioned in text and the main traverses worked by the geological party.

limestone islands to the west of it, possibly a reflection of differences in tectonic history. Locally volcanic basement may lie as shallowly as 0.32 km below the surface on Aldabra (Williams 1971); and Fischer *et al.* (1968) have dredged basalt from the margins of the Amirantes ridge.

At the present day Aldabra consists of an annular land rim surrounding a shallow lagoon (figure 1). Four main islands rise about 8 m above sea level and vary in width from 0.25 to 5 km; the total land area is approximately 155 km^2, a little less than half of the area of the atoll.

The seaward margins of the islands are generally steep cliffs, fronted by an intertidal and shallow subtidal platform of varying width that ends abruptly in a steep slope that plunges with minor interruptions, to abyssal depths. The lagoon is drained by four channels which breach the land rim. The lagoon itself is very shallow and, except in the vicinity of the channels, is usually not more than about 5 m deep. The lagoon floor is generally remarkably flat, but slopes slightly towards the deeper centre. The cover of Recent sediments is thin and the rock beneath has a slightly pitted planed-off surface. Other geomorphological information may be found in Stoddart & Wright (1967) Stoddart *et al.* (1971).

Field work on Aldabra occupied the months of June to September 1969, forming phase 8 of the Royal Society Aldabra Expedition. The specific objectives were to describe the geology of the atoll outlining the sedimentological, diagenetic and palaeontological characteristics of the sedimentary units recognized in surface outcrop, and their relationships to each other. More detailed studies of the petrology and the molluscan and coral faunas will be reported upon elsewhere.

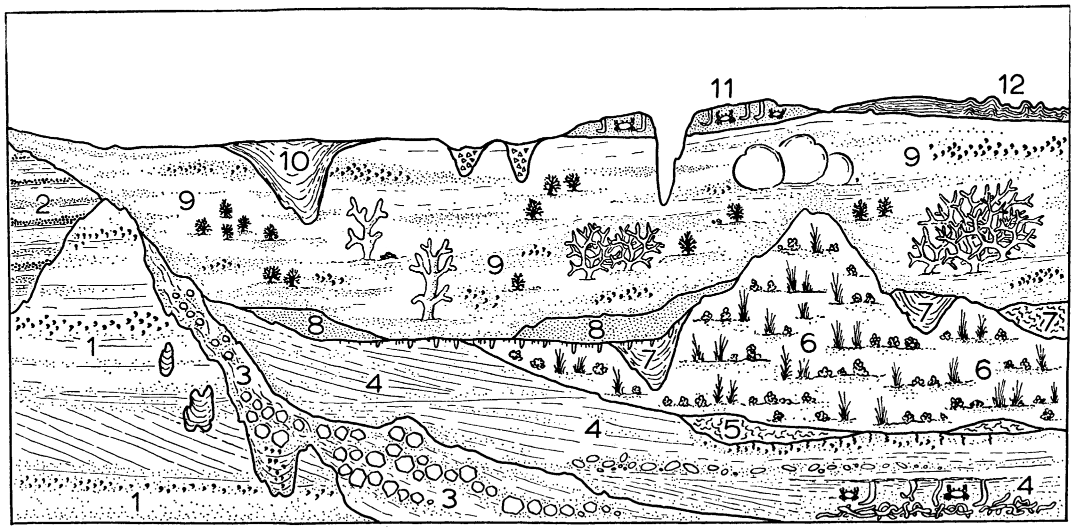
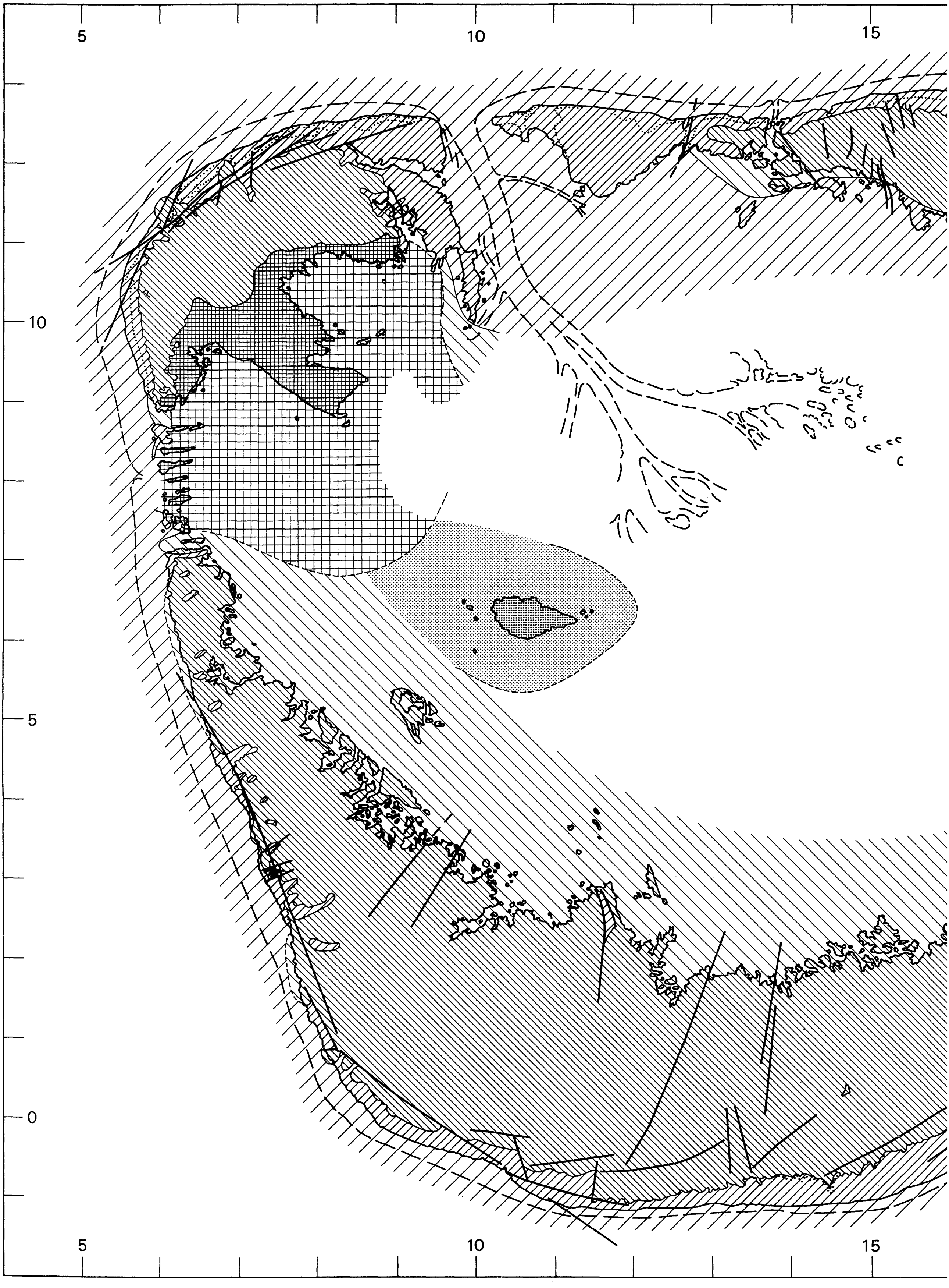


FIGURE 2. Stratigraphic 'column' of the exposed rocks of Aldabra, showing the vertical and lateral relationships. Lateral scale approx. 10 km vertical scale 9 m. Bed thicknesses not to scale. 1, Esprit limestones; 2, Esprit Phosphorites: oolites; 3, Esprit Phosphorites: conglomerates; 4, Picard Calcarenites; 5, Picard Calcarenites; – 'soils' with *Succinea*; 6, Takamaka Limestone; 7, soils filling subaerial solutional fretting; 8, hard calcarenites, containing *Strombus* and *Polynices*; 9, Aldabra Limestone; 10, solution pits and fillings; 11, crab burrowed calcarenites; 12, algal stromatolites.

STRATIGRAPHY

The nature of the depositional and erosional events recognized is such that no single deposit is found over the entire area of Aldabra. Indeed, some deposits are, and perhaps were, merely a few square metres in area and a few centimetres in thickness. For this reason the stratigraphic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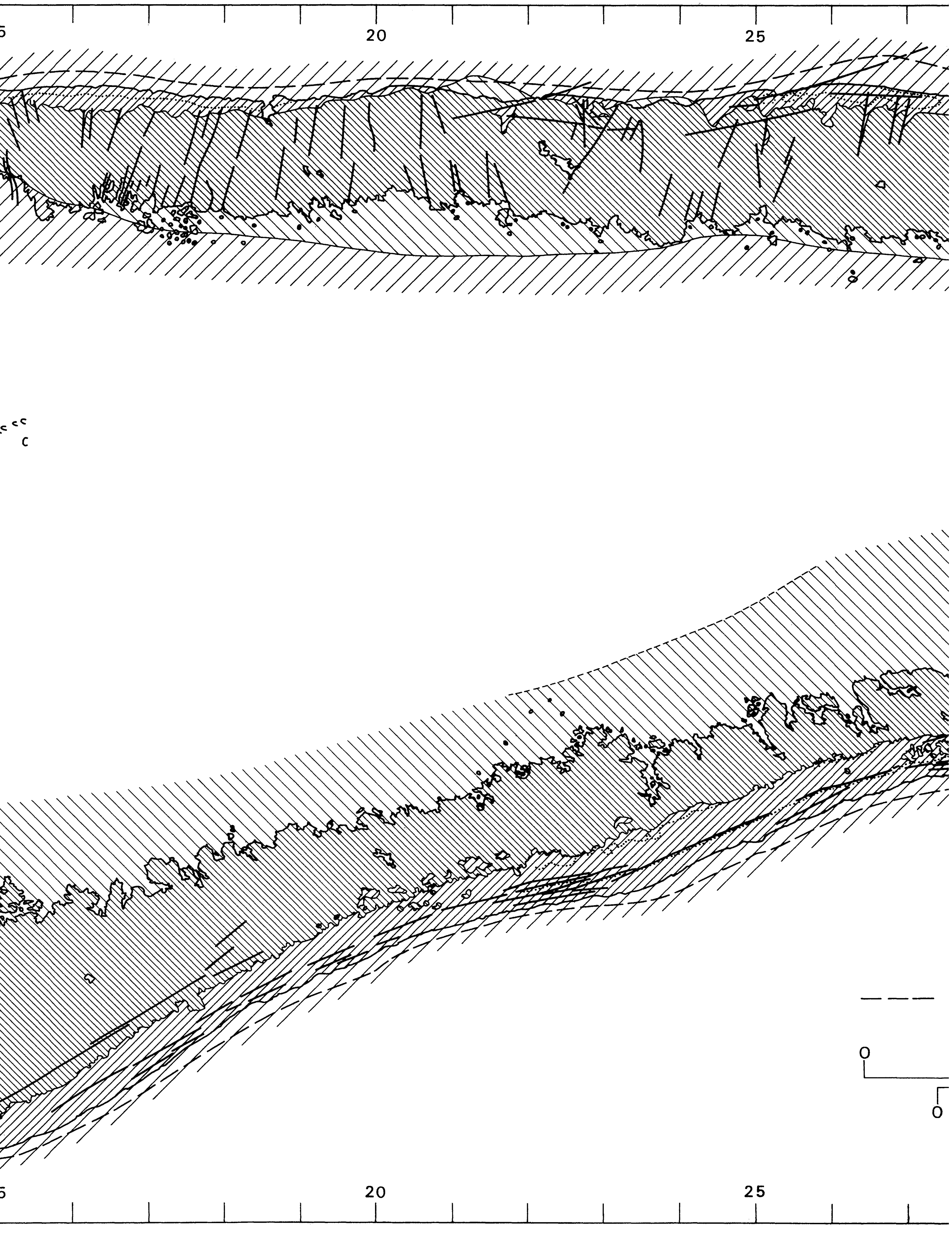
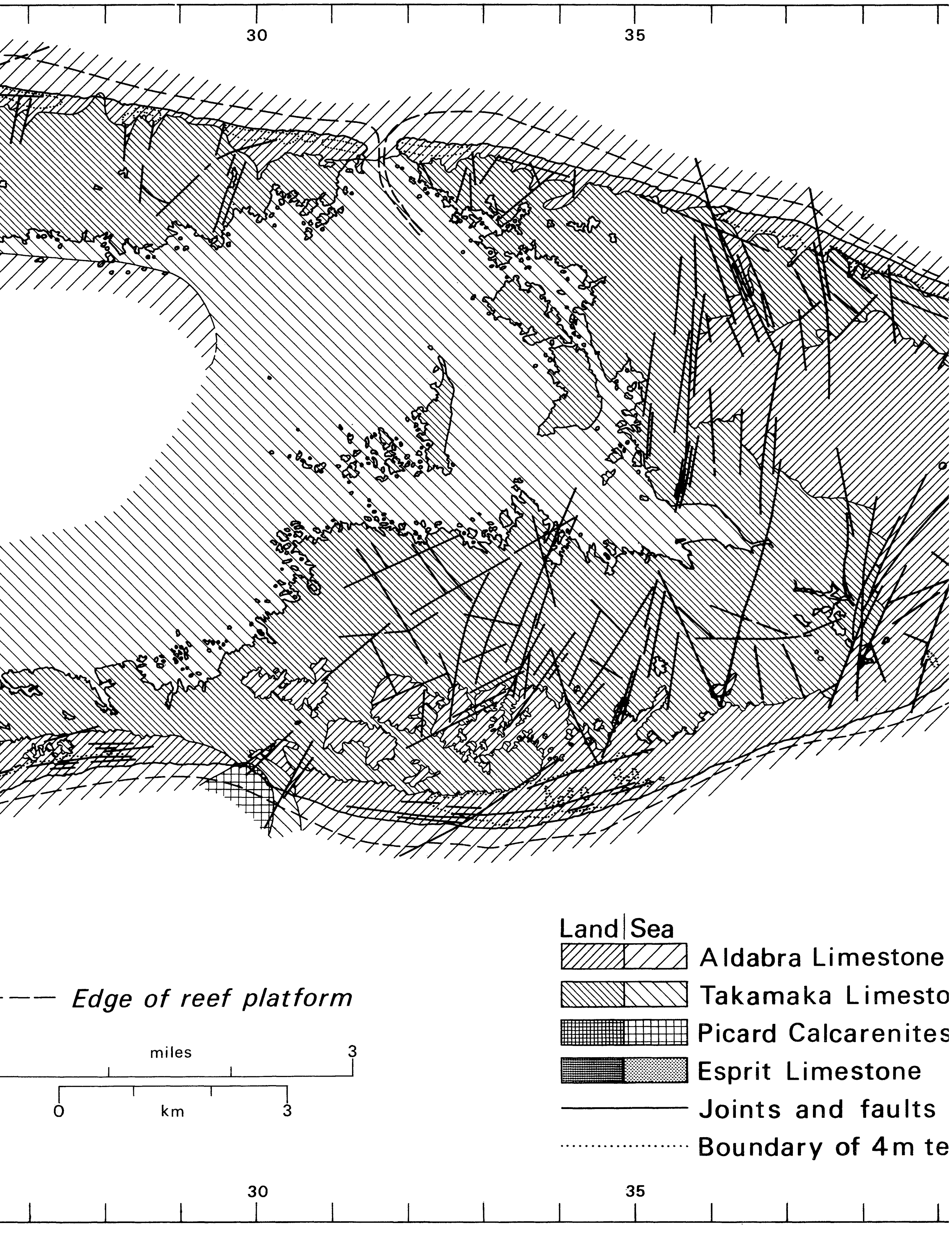


FIGURE 3. Geological map of Aldabra.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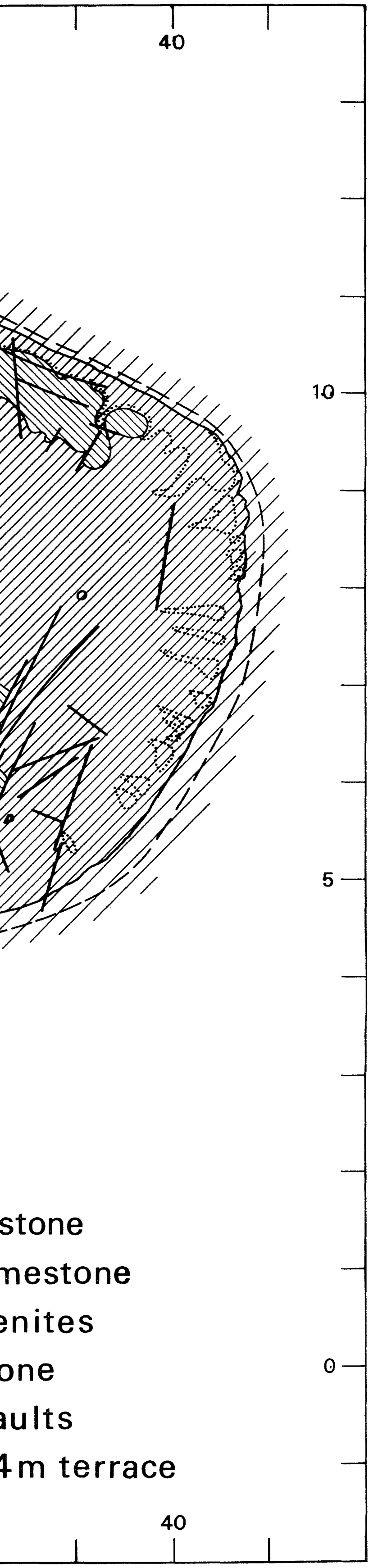
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'column' (figure 2) is necessarily a composite summary of age relationships for the whole of Aldabra and does not represent a succession at any one site. Some of the relationships shown are uncertain but the column is nevertheless useful as a basis for discussion. The geological map (figure 3) is a photo-interpretation based upon a ground survey. Its limits controlled by accessibility and time are shown in figure 1. Some boundaries must be treated as conjectural and may be revised if further ground control becomes available. Some stratigraphic units are too thin, or are of too limited areal extent to be shown on the map; but they add to the difficulties of determining the margins of major units in some areas.

The features and supposed conditions of formation of each of the eleven depositional units and intervening erosional events recognized are discussed in turn below.

The Esprit Limestone

Although of relatively small area (0.34 km^2) the island of Esprit (grid ref. 1060, 0625), reaching to about 8 m above sea level, appears to contain the oldest rocks exposed on Aldabra.

The sequence is largely of thick-bedded, cross-bedded calcarenites, predominantly fairly fine grained, but locally coarsening into coquinal calcirudites, which are normally concentrated into thin discontinuous bands. These sediments are normally hard and tightly cemented, but there are some diagenetic differences between upper and lower horizons. Within the highest limestone, primary cavities are selectively lined with phosphates, leaving secondary cavities produced by solution of fossils either as open voids or filled with coarse crystalline calcite. Lower in the sequence, fossil moulds are also lined with phosphate, and such differences might be correlated with ground water levels at the times of phosphate emplacement. It is perhaps significant that the limestone surface has been dissected by solution which is believed to have been subaerial.

This complex diagenetic history has resulted in fossils being poorly preserved. However, by the use of silicon rubber casts, a fairly diverse fauna of 56 species of molluscs has been extracted. Bivalves are numerically the most important element comprising 88 % of individuals found. The dominant species are *Glycymeris* cf. *tenuicostatus*, *Fragum fragum*, *Trachycardium* sp. and *Dosinia* spp. Gastropods are much less common; they include *Cassis cornuta*, *Terebellum terebellum*, *Strombus* sp., and *Natica* sp. Corals are found at some levels; they tend to be very badly preserved but include small rounded colonies of *Goniastrea* and *Favia*. A number of epifaunal molluscs occur at these coral horizons, but the molluscan assemblage generally is interpreted as a predominantly sublittoral soft-substrate fauna inhabiting clean-washed sand. Good indicator species and genera suggests a water depth at the time of deposition of up to about 20 m.

Towards the top of the succession the appearance of the gastropods *Cerithidea*, *Terebralia palustris* and *Cerithium morum* indicate a shallowing of the water, conditions of restricted circulation, and the presence of mangroves.

In summary, the Esprit Limestone was deposited in a shallow-water (up to 20 m), open sandy-floor environment not subject to strong wave action, with very little coral growth. In time the water shallowed and the exposed sediments were colonized by mangroves. The size of the total area of deposition is not known.

The limestones were cemented and diagenetically altered before the formation of the Esprit Phosphorites and probably were also subject to subaerial solution.

The Esprit Phosphorites

The Esprit Phosphorites occurring primarily on the highest points of Esprit, range up to a maximum of 2 m thickness. They include fine-grained, regularly laminated sediments, with thin oolitic horizons (figure 45, plate 38) and with cavitous layers, implying several cycles of erosion and deposition. Fragments of laminated sediment occur within floor deposits as intraclasts. A few cavities contain bioclasts, either as discrete shells or as small amounts of phosphate-cemented calcarenite similar to that described by Braithwaite (1968). Others are filled with laminated phosphatic sediment or oolite. A possible origin as deposits in caves or in some similarly enclosed environment is suggested, but petrographic work which might provide further evidence is not yet complete.

There is no doubt that the beds described above rest upon an eroded and pinnacled limestone surface (figures 8 and 9, plate 33) and extends into low-roofed cavities. It is not, however, clear what the relief was at the time of phosphorite deposition. Phosphates are at present distributed over more than 8 m, but those occurring at sea level are different from those described above. They include cavity fillings packed with shells and corals which are crusted with phosphate (carbonates removed by solution), and oolite-conglomerates. The last are best preserved in the 5 m above sea level at the eastern end of the island. These sediments consist of massive jumbled blocks, some up to a metre in diameter, formed largely of red-brown oolitic-phosphates, with individual ooliths up to 2 mm in diameter. It is clear that the beds from which these rocks were derived were much thicker than, and lithologically distinct from, any of those visible in present surface outcrops on the island. Bedded phosphates are not seen within the large vertical solution pipes and their formation probably predated both the emplacement of the shelly phosphates within these pipes and the deposition of the conglomerates.

It is presumed that the original source of the phosphate in these sediments was provided in the form of guano by ground-nesting sea birds. However, the deposits seen on Esprit are different from those described by Braithwaite (1968) and Roy (1970) from Remire and Fanning Island respectively.

The phosphatic sediments form an important marker horizon; the occurrence of their lithologically distinctive fragments within the Picard Calcarenites (see below) enables these to be dated with confidence as younger, even though no direct contact between the two units has been observed. Individual phosphatic ooliths and pebbles are relatively common in the lower parts of the Picard Calcarenites (Bassin Tortue 0660.1010). These are probably lithoclasts and suggest that the formation of the younger phosphatic conglomerates on Esprit may be partly synchronous with the calcarenites on Picard.

The Picard Calcarenites

The main outcrop of the Picard Calcarenites is in the Bassin Cabri area on Picard (0635.0990) and on islets as far south as Iles Châlen. They are predominantly well-bedded, laminated calcarenites (figure 11, plate 33); some beds are more massive but in a typical outcrop, 1 cm thick laminae dip in a general west–southwesterly direction at 7 to 10°. A few sections show trough cross-bedding or other current bedding features, but these are not common. At Bassin Tortue the total thickness of calcarenites is at least 3 m. The upper part of the unit consists of massive unlaminated calcarenites whose upper margin contains plant rootlets, tortoise bones and articulated skeletons, bird bones, a crocodile tooth, and abundant terrestrial gastropods

(*Trophidophora*). Pebbles derived from the distinctive Esprit Phosphorites are also common, probably signifying transport from the southeast. This is, however, in conflict with the general southwesterly accretion shown by cross-laminae. Shark and puffer fish teeth found are presumed to have originated from corpses which had floated ashore. Within the sequence in the West Channels area (0625.0863) there are two additional bone-bearing horizons. One is particularly widespread, normally occurring about 30 cm above mean low water mark and containing very large numbers of tortoise scutes and bones, disarticulated but not severely broken, usually appearing on the outcrop surface as moulds. Some 20 cm above these bone beds there is a well-defined horizon containing rootlet moulds and *Trophidophora* (figure 10, plate 33) and overlain by laminated calcarenites.

The bone-bearing horizons are important in judging rates of deposition. Large numbers of bones in general indicate low rates of deposition which are also reflected in the breakage suffered by skeletons. On the other hand, a number of groups of bones were found around Bassin Cabri which seemed to belong to nearly complete animals. Observations on the *post mortem* dispersal of modern tortoise remains suggest that these could only have been preserved by rapid burial, perhaps as a result of storm overwash (cf. McKee 1959).

At a few sites in the Bassin Cabri area the calcarenites are overlain by a 10 cm thick band of dark brown porcellanous limestone that appears to lie below the Takamaka Limestone. Although thin, it consists of three distinct units. The lowest is micritic and contains large numbers of ostracods and foraminifera and is penetrated by tubules, some of which are probably rootlet moulds. The second unit (5–15 mm thick) is a dense biomicrite and rests on an erosion surface. Bioclasts in it include coral and molluscan shell fragments, calcareous algae and small pieces of bone that suggest the sediment represents a normal marine incursion, perhaps resulting from a storm. The upper unit with rootlets and burrows is brownish in colour and rich in ostracods and (at its lower margin) foraminifera. A nearby outcrop slightly separated from the latter contains about 15 cm of porcellanous limestone equated with the upper unit containing ostracods and foraminifera, together with abundant specimens of the gastropod *Succinea*. The presence of rootlet moulds suggests that these sediments acted as soils, and the gastropods suggest formation in rather wet areas.

The Picard Calcarenites appear to have been built up as part of a prograding system, analogous to a sand cay rising to above sea level from some near-surface platform. The emergent vegetated islet was probably not more than 2 to 3m above sea level and was populated by seemingly abundant tortoises and terrestrial gastropods (*Trophidophora*) accompanied by birds and crocodiles, though these may only have been present in small numbers. In the higher parts of the sequence the presence of freshwater ostracods and the snail *Succinea* indicates at least seasonal bodies of standing fresh water. The concentrations of tortoise bones and the presence of rootlet horizons containing terrestrial snails, suggest that emersion of the sand cay took place on at least two occasions, with the sediment of the newly formed land surface functioning as an azonal soil.

The eastern lagoon shore of Picard (west of Point Tanguin, 0913.1100) includes a moderately widespread burrowed calcarenite (figure 4). At one locality a basal unit 2 m thick contains large numbers of small-diameter burrows which show angular directional changes and branching similar to those produced by some modern callianassid shrimps. Towards the upper surface the sediments are less disturbed and a number of larger-diameter tubes are present which are comparable with burrows of the crab *Ocypode*. These sediments are overlain abruptly by a coarse calcirudite which is probably equivalent to the Aldabra Limestone. This sequence, if correctly interpreted, suggests prograding of a sub-beach across an intertidal sand flat environment; such a pattern is consistent with the progression envisaged for the Picard calcarenites and these beds are considered to be an eastern facies of that unit.

Other facies variations are to be seen in the West Channels area. As the calcarenites are followed to the west they contain progressively more coral and algal fragments. At the same time bedding becomes less distinct and, at the limits of outcrop, corals appear in the growth position (figure 5). These sediments presumably accumulated before the bulk of the Picard Calcarenites.

The outcrop of the sediments described above is almost restricted to that defined on the map, but other calcarenites which are believed to be equivalent in age are exposed in cliff sections

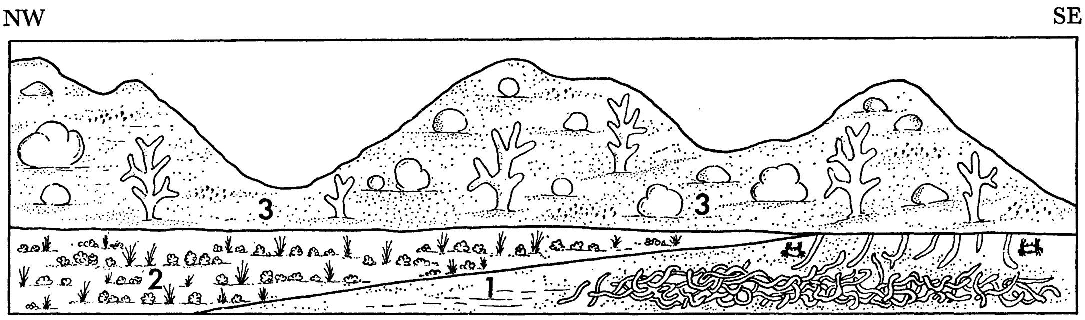


FIGURE 4. Stylized section in Bras Anse Grande Poche, showing stratigraphic relationships. Lateral scale about 400 m, vertical scale 9 m. 1, crab burrowed calcarenites; 2, Takamaka Limestone; 3, Aldabra Limestone.

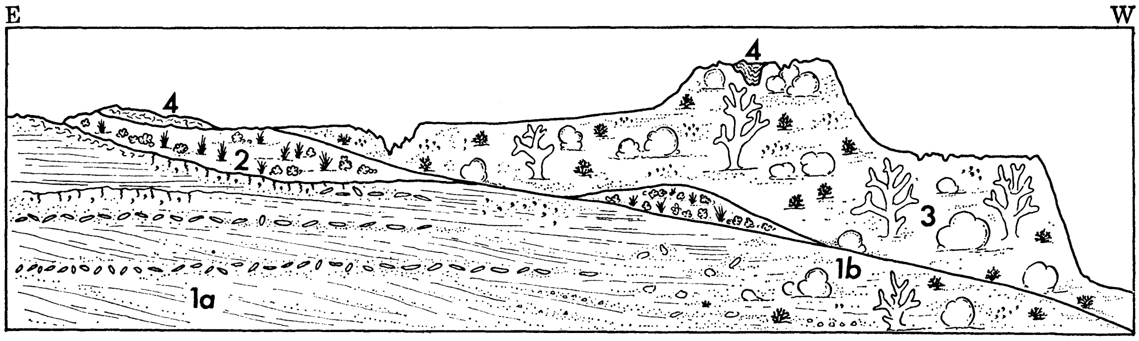


FIGURE 5. Section (E–W) along the north side of Passe Mili showing stratigraphic relationship and lateral facies changes within the Picard Calcarenites. Horizontal scale about 100 m, vertical about 8 m. 1*a*, Picard Calcarenites, containing tortoise and turtle bones, and terrestrial snails; 1*b*, Picard Calcarenites, containing corals; 2, Takamaka Limestone; 3, Aldabra Limestone; 4, cavity fill deposits.

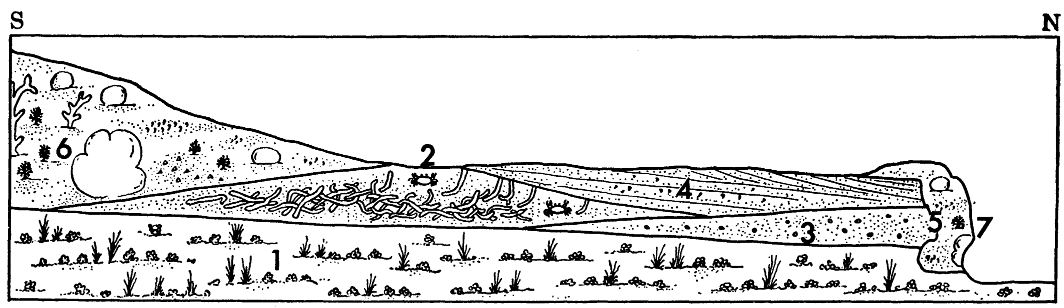


FIGURE 6. North–south section along the western shore of Passe Houareau. Horizontal scale about 200 m, vertical about 8 m. 1, Takamaka Limestone; 2, calcarenites with crab burrows; 3, calcarenites with molluscs; 4, beach calcarenite; 5, cliff cut into previous deposits; 6, Aldabra Limestone; 7, present-day cliff.

west of Point Lion (2920.0408) on the south coast. These comprise about 3 m of a massive cross-bedded unit which laminae dip at 32 to 35°, overlain by a 40 cm unit with gently dipping laminae. The sediments are well sorted and contain an unusually high percentage of alcyonarian spicules. They closely resemble sands at present accumulating in dunes on the south coast. The relatively high-angle laminations and sorting characteristics seem consistent with a wind blown origin. Since part of the upper surface of the deposit is truncated by erosion there is no evidence of the area which it might originally have occupied; it seems reasonable to suggest that deposition was related to a slightly lower sea level than that surmised for the youngest Bassin Cabri deposits (figure 7).

The Takamaka Limestone

The Takamaka Limestone unit is typified by the presence of large numbers of nodose, red calcareous algae, although it was not formed primarily by the activities of these organisms. It is possible that the lower portions of the sequence are interbedded with the upper margins of the Picard Calcarenites, and that the two facies are in part contemporaneous.

At Anse Anglais (0613.0675) cliffs of this limestone are 2–3 m high. The sediment varies from coarse calcarenite or even calcirudite to what is virtually a calcilutite, the fine-grained lithology being typical of wide areas of the southwest of the atoll. At one locality on a lagoon islet the calcilutite matrix has obviously been added to a sediment which consisted largely of algae, for in some smaller cavities it forms geopetal layers with flat or gently sloping surfaces, leaving open spaces above. This is critical since it shows that there was a disparity in times of deposition of the two components, and once the voids became full, as elsewhere, there is no way of knowing that this was so. An unusual development of shrimp-burrowed calcarenites occurs on an island in the southwest lagoon.

Calcareous red algae are ubiquitous irrespective of the grain size of the matrix. They occur as papillate heads, foliose masses, encrusting sheets or broken debris, but it is only in a few places that growth can be interpreted as a constructional framework. The dominant forms are species of *Lithothamnion* particularly *L. funafutiense*, but *Lithophyllum kotschyanum*, *Dermatolithon*, and *Melobesia* are also common. The branching genera *Jania* and *Amphiroa* are found as debris in the sediment matrix, and moulds of *Halimeda* segments are abundant in the fine-grained matrix of the southern area.

Although very few species of corals have been found, they may locally be fairly common. In general they are rather more abundant in the limestones to the east and southeast of the present lagoon. Identification is generally difficult because of extensive alteration, but those occurring most frequently include rounded heads of *Goniastrea* (colonies up to 50 cm diameter); *Favia*, *Platygyra*, *Millepora*, *Porites* cf. *nigrescens*, stagshorn *Acropora*, and *Acropora palifera*. Moulds of delicate *Seriatopora* branches are sometimes abundant in the matrix of the fine-grained sediments.

Molluscs are generally rare or uncommon but in eastern outcrops they become both more numerous and more diverse. The characteristic feature of the assemblage is the numerical dominance of Archaeogastropoda (66 % of all individuals found). The most common species are *Trochus maculatus*, *T. radiatus*, *Tectus mauritianus*, *Clanculus limbatus*, *Phasianella* and *Haliotis*. Bivalves are much less common but include *Cardita variegata*, *Barbatia*, and occasional large *Tridacna gigas*. Infaunal bivalves have been found at only one or two sites and about 70 % of the molluscs found are epifaunal species normally associated with hard substrates.

In general the limestones show little facies variation. Such changes that do occur mainly involve differences in the abundance of calcareous algae and corals, and variations in the grain size of the matrix. At one locality on Picard (0608.0950) the exposed top of the unit consists of a little over 1 m of well-rounded calcirudite: a clean-washed pea-gravel with a mean grain size of about 5 mm.

The conditions of deposition of the Takamaka Limestone are not easily interpreted, partly because of the anomalous relationships between organisms and sediment, and partly because of the unusual character of the biota itself. The presence of abundant calcareous algae suggests deposition in an environment of strong wave action, but this usually results in the production of an algal frame. By contrast, the fine grained matrix in this limestone indicates quiet-water deposition without significant wave action. A third unusual feature is the widespread occurrence of the facies; the most common Recent environments in which abundant calcareous algae occur, are narrow, sharply delimited, zones. Finally, the paucity and low diversity of the associated molluscs and corals seems to point to some environmental stress.

One Recent environment which has features which might explain the situation has been observed at Shimoni on the East African (Kenya) coast by J. D. Taylor. Here, large areas are colonized by the marine phanerogam *Thalassodendron ciliatum*. This plant is common in sublittoral environments in the Indian Ocean and, in contrast to other phanerogams, it can live in areas of considerable wave action, colonizing rock and cobble surfaces. It does not require or form the large sediment accumulations commonly associated with other sea grasses. The long ligneous stems of *Thalassodendron* allow back-and-forth movement in surge, and beneath the leaf canopy there are frequently masses of red calcareous algae. These may grow as cushions, papillate heads, foliose sheets, encrustations and free cobbles, and may be accompanied by other forms such as *Jania* and *Amphiroa* which coat the grass stems. The algae do not, therefore, form a constructional framework, but beneath their cover fine sediment, perhaps derived from *Halimeda*, is able to accumulate interstitially. Thus a low energy environment exists only centimetres from one of high energy. The comparability of this situation with the deposition of the Takamaka Limestone is strengthened by the isolated observation of internal sedimentation noted above and by the fact that in *Thalassodendron* habitats both coral and molluscan diversity is usually low. Trochid gastropods and *Phasianella* are relatively frequent, while bivalves are uncommon. The large area of the Aldabra deposit seems not to be a problem, since Recent areas of *Thalassodendron* with calcareous algae which occur around Coetivy Island in the Seychelles and on the East African coast are of similar size.

Deposition of the Takamaka Limestone was followed by a period of emergence during which solution took place resulting in the production over wide areas of a delicately pitted surface comparable with that of the present champignon (see appendix 3). This surface, with an attendant buff-coloured, soil-like, cavity filling, is exposed over wide areas along the south and southeastern shore of the lagoon. Cliffs which were probably eroded at this time are now exposed at Passe Houareau (3143.1193) and Anse Vaqua (2920.0408) where they are seen as step-like features about 2 m high with their bases less than 1 m above present low-water mark (figure 16, plate 34). They have been buried by later deposition of the Aldabra Limestone (figures 6, 7).

At one locality in the Bassin Cabri area an irregular fretted surface of Takamaka Limestone is overlain by a brown fossil soil consisting largely of rounded glaebules loosely packed in a sparry calcite cement. In addition to altered lithoclasts and marine bioclasts the sediment contains shells of three species of terrestrial gastropods including *Truncatella*. It is overlain by a darker brown laminated crust which is also glaebular, and by a further soil horizon (which might be appreciably younger) also containing rounded pellets and bone fragments and modified by burrows and rootlet moulds.

It is not known how far sea level lay below the present datum at this time but it was probably not more than a few metres. When it rose again it was to a point not more than 3 to 5 m *above* the present level. The submergence resulted in marine erosion of the lithified algal limestone. The surface produced is normally of low relief, in contrast to terrestrial surfaces, and is characteristically bored by *Lithophaga*, *Cliona*, polychaetes and *Tridacna crocea*. (figures 14, 15, plate 34), while corals, encrusting calcareous algae and serpulids are locally seen growing upon it.

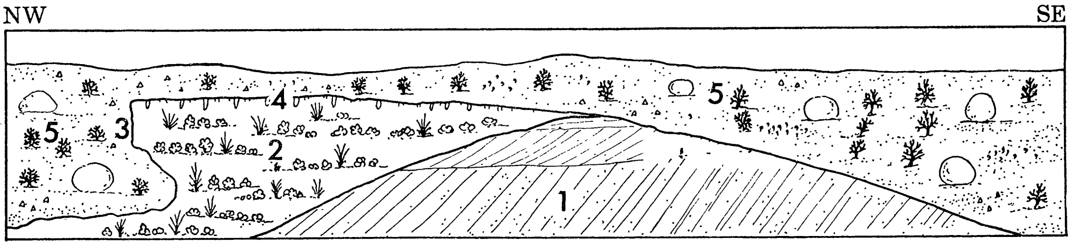


FIGURE 7. Section (NW–SE) between Anse Vaqua and Point Lion. Horizontal scale about 200 m, vertical 4 m. 1, aeolionite; 2, Takamaka Limestone; 3, cliff cut into Takamaka Limestone; 4, *Lithophaga* bored surface of Takamaka Limestone; 5, Aldabra Limestone.

The erosional surface cuts completely through the Takamaka Limestone in some areas and extends onto the Picard Calcarenites at West Channels. It is exposed on the cliffs of Anse Mais (0665.0483), over wide areas south of Takamaka (3400.0475), and on the northern lagoon shore. It seems to have formed a broad annular rim to the platform and seaward dipping ramps (figure 12, plate 33) are exposed at Anse Mais, Passe Gionnet (1390.1250), and Passe Houareau, while a lagoonward slope, rather less steep, is seen on Polymnie (1265.1218), Passe Gionnet (1375.1216) and elsewhere. Islands probably projected above this surface at Esprit, Bassin Cabri and many small ones close to the present lagoon shore at Dune Jean Louis (2623.0438).

In detail the surface is mainly planar, but in some areas distinctive grooves are cut into it. These are best seen south of Takamaka (3420.0388) where they are typically shallow (30 to 40 cm), tapering at either end and reaching a maximum of 2 m in width and 20 to 25 m in length. A few meander slightly and have tributary branches, but most (in this area) strike north of northwest, at right angles to the presumed coast. Similar channels (figure 13, plate 33) are seen in section on the Anse Mais cliffs (0665.0483), but there is no evidence to indicate whether or not larger channels comparable with the modern passes were present, or to suggest how far the central area lay below the present lagoon floor.

In many western localities the Takamaka Limestone is directly overlain by the Aldabra Limestone. To the east, however, a number of stratigraphic variations are noted which are best considered together below.

Unassigned calcarenites

A number of isolated calcarenite deposits occur principally around the eastern end of the present lagoon. Although they appear to occupy a stratigraphical position between the Takamaka Limestone and the succeeding Aldabra Limestone, exposures are of such small extent and fragmentary nature that it is not clear whether they are remnants of contemporaneous deposits. For this reason they are best discussed individually.

On the western shore of Passe Houareau a gently dipping Takamaka Limestone surface, without borings but having truncated corals, is overlain by three calcarenite units (figure 6).

In the lowest unit the internal structures are blurred, possibly as a result of burrowing, but the sediment is characterized by the presence of rounded fragments of coral and limestone pebbles among the coarser clasts. The molluscan fauna is quite varied and includes *Cerithium morum*, *Quidnipaqus palatam*, *Asaphis dichotoma*, *Conus* spp., and a number of other forms that seem to indicate a shallow, near-shore, sandy-floor environment. These sediments do not exceed about 50 cm in thickness, and taper laterally in a northerly direction.

There are no direct contacts between this unit and a wedge occurring a few tens of metres to the north, of fine-grained burrowed calcarenite about 1.5 m thickness. There are four more or less well-defined horizons in which burrows are particularly common. The burrows range from less than 1 cm to about 5 cm in diameter; some are branched but others are simple low-angle structures resembling crab burrows.

Overlying these two, a third wedge can be seen to thicken from about 10 to 100 cm or more within a distance of 50 m to the south (relations shown in figure 6). It is well sorted with well-rounded grains and pebbles of limestone and is cross-laminated with low-angle depositional dips facing north. A distinctive molluscan fauna includes specimens of the limpet *Siphonaria*, *Nerita polita*, *Nerita* sp., *Littorina* sp., *Conus ebraeus* and the chiton *Acanthopleura*, all forms which inhabit the eulittoral zone of intertidal rocky shores. Sedimentary and palaeontological evidence thus indicates that this is a beach deposit with a rocky cliff-line close by. These three calcarenites are therefore interpreted as being a shallowing-upwards sequence culminating in the emergence of sandy beaches and rocky promontories.

Southeast of Passe Houareau, on Ile aux Aigrettes (3455.0787), and on islands immediately adjacent, calcarenites are exposed up to 3 m in thickness. The lower 1.5 to 2 m rocks are fairly fine grained and are characterized by low-angle (? beach) cross-laminae and occasional pebble-size fragments of corals and calcareous algae. The overlying rocks are less well sorted and recognizable fossils are generally rare. Towards the top, however, there are a few thin horizons with poorly preserved moulds of *Cerithium* sp., *Fragum* sp. and a *Turbo* operculum, while scattered in the calcarenites are occasional fragments of coral (*Tubipora*, *Millepora* and *Goniastrea*). On Ile aux Aigrettes the uppermost sediments exposed include curious brown laminated crusts, some of which have been eroded and re-sedimented. These resemble terrestrial crusts seen in other areas and, if this sequence is to be compared in any way with that at Passe Houareau, it might be equated with the final emersion of a shallowing-upwards sequence.

Description of plate 33

Figure 8. Eroded pinnacle (2 m high) of Esprit Limestone surrounded by boulders of Esprit Phosphorite. Ile Esprit (1060.0625).

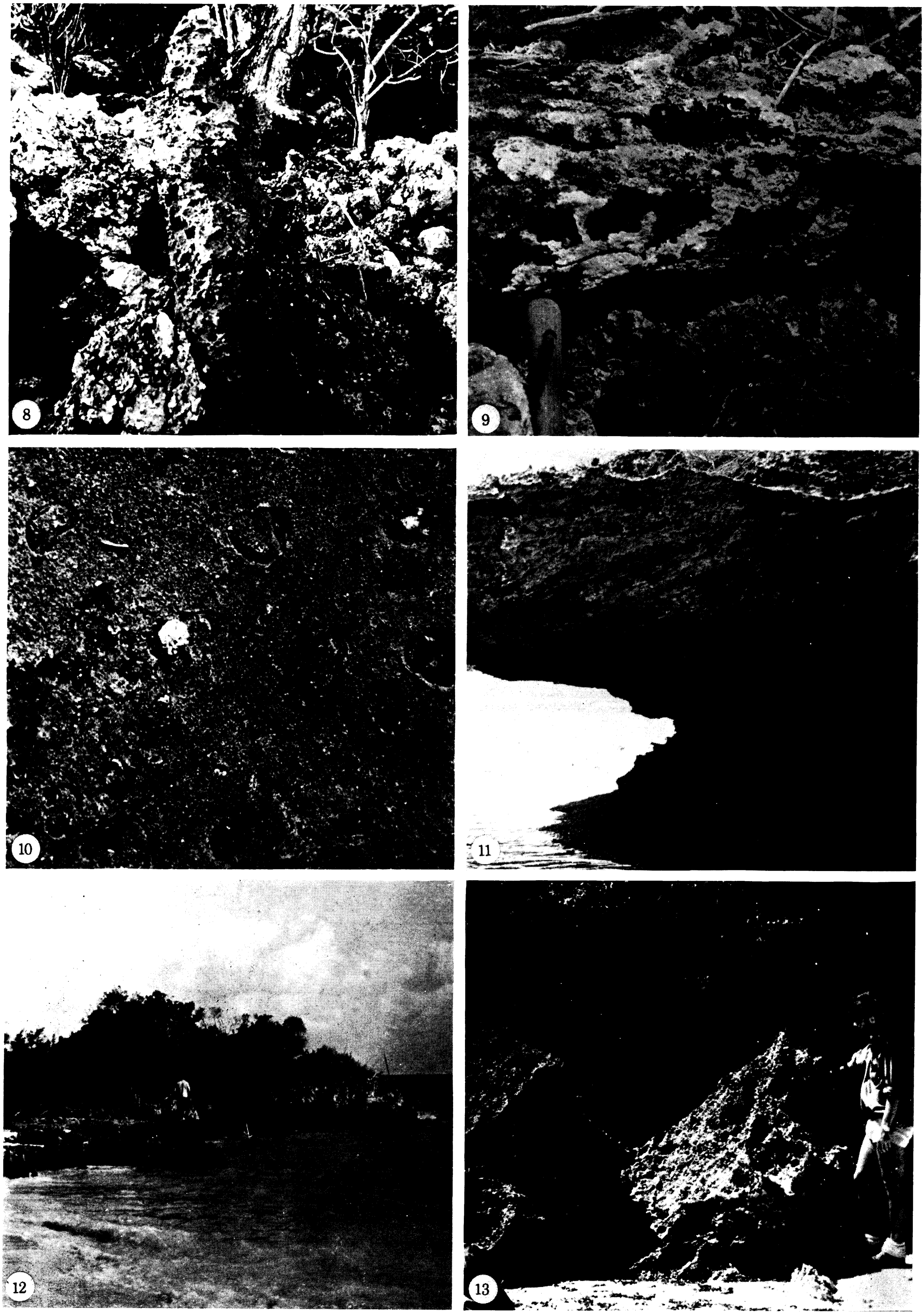
Figure 9. Unconformity between the Esprit Limestones and the overlying, laminated Esprit Phosphorites. Ile Esprit (1060.0625).

Figure 10. Eroded surface of the Bassin Cabri Calcarenites showing sections of abundant terrestrial gastropods (*Trophidophora*). Bassin Cabri (0635.0990).

Figure 11. Undercut cliff, showing about 3 m of cross-laminated Bassin Cabri Calcarenites; the upper part of which contains tortoise and bird bones with terrestrial gastropods. Lagigi (0625.0863).

Figure 12. Takamaka Limestone cut by a seaward dipping ramp (arrowed) and overlain by Aldabra Limestone. Anse Anglais (0613.0675).

Figure 13. Takamaka Limestone cut by a surge channel and infilled by Aldabra Limestone. Anse Badamier (0625.0475).



FIGURES 8–13. For legends see facing page.

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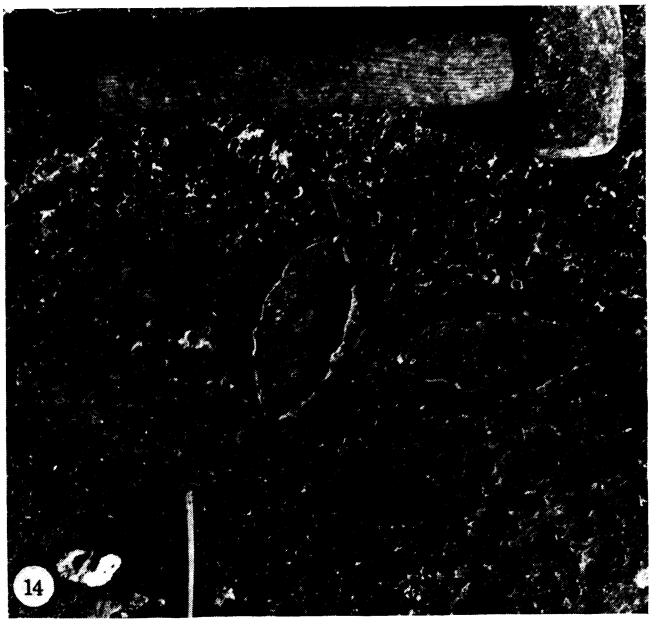

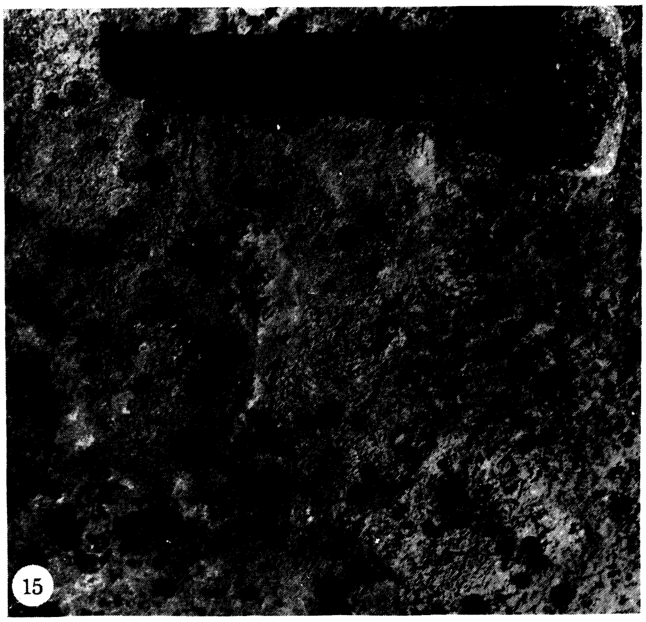

FIGURES 14–19. For legends see facing page.

At some sites these calcarenites unequivocally overlie the Takamaka Limestone, but elsewhere relationships are ambiguous so that sediments 'above' and 'below' the boundary may be in part contemporaneous.

A further key deposit (figure 20) is to be seen near Dune Jean Louis (2633.0418). Here the surface of the Takamaka Limestone is bored by *Cliona*, *Lithophaga* and polychaetes. The larger of the cavities produced by these organisms are filled with a tightly cemented fine-grained calcarenite rich in *Halimeda* fragments. This is presumed to be marine but it passes upwards without any significant break into a soft chalky deposit containing terrestrial snails (figure 44, plate 38) particularly *Trophidophora*, but also *Truncatella*, *Melampus* and the freshwater *Neritina*. More than one depositional event may be represented in the unit, whose upper margin is clearly terminated by a sharp but irregular surface, the cavities in-filled by a well-cemented marine sediment. This in turn has been eroded by a later event so that its upper margin, together with that of the same terrestrial sediment, exposed from beneath has been bored by *Cliona* and is encrusted with calcareous algae (*Lithoporella*?) and foraminifera (figure 42, plate 38). The overlying sediment is undoubtedly marine and contains numerous fragments of *Halimeda*, *Amphiroa*, *Millepora*, echinoderm plates, coral and algal fragments. Terrestrial gastropods very similar to those in the above sequence have also been found in small deposits at Passe Houareau and south of Takamaka.

It is possible that all of the deposits so far discussed in this section formed part of one large sand cay extending from Passe Houareau to Dune Jean Louis and near the sea at Takamaka, and including the calcarenites found near Ile aux Aigrettes. They can be interpreted as a sequence, shallowing-upwards in which subtidal sand areas, broken by rocky islets, were replaced in time by low sand banks and, finally, by land areas with beaches.

The Aldabra Limestone

At present the Aldabra Limestone unit forms an annular feature around the entire atoll, occupying the high ground and extending (presumably) below sea level where the Takamaka Limestone surface slopes sufficiently steeply. It thus has an overall thickness of about 8 m with the greatest values reached around the seaward margins. Most of the present lagoon was probably once covered by this limestone and remnants of its former extent can be seen on the islets of Deder (2168.0435) and Michel (3250.0910).

The rock is basically a coral limestone which accumulated in a broadly 'reef' environment. Exposed surfaces are cemented to a depth of several centimetres by case hardening, but beneath,

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Description of plate 34

Figure 14. Planated Takamaka Limestone surface, bored by *Tridacna crocea* at the base of the Aldabra Limestone transgression. Near Takamaka Grove (3420.0388).

Figure 15. As above but the borings are of *Lithophaga*, clionid sponges and polychaetes.

Figure 16. Cliff cut into the Takamaka Limestone (right) and overlain by Aldabra Limestone (left). Cliff is now exhumed by recent erosion. Passe Houareau (3140.1193).

Figure 17. Large colonies of *Acropora palifera* which dominate the northeastern facies of the Aldabra Limestone. Northeast shore of Middle Island (3020.0918).

Figure 18. Corymbose and spray *Acropora* colonies separated by *Halimeda* – rich calcarenite. This facies is typical of the outermost southeastern facies of the Aldabra Limestone. Anse Takamaka (3418.0340).

Figure 19. Detail of above, note the lack of continuous frame growth and the tumbled nature of some of the colonies.

the rocks are generally soft, unconsolidated and friable. The sediment varies from a fine calcisiltite through calcarenites to coarse algal-encrusted calcirudites, the finer sediments usually containing larger bioclasts. Corals and molluscs are particularly abundant and generally well preserved, the latter commonly retaining their original coloration. The standard of preservation, however, varies considerably from place to place and depends upon diagenetic environments which are sometimes rather localized.

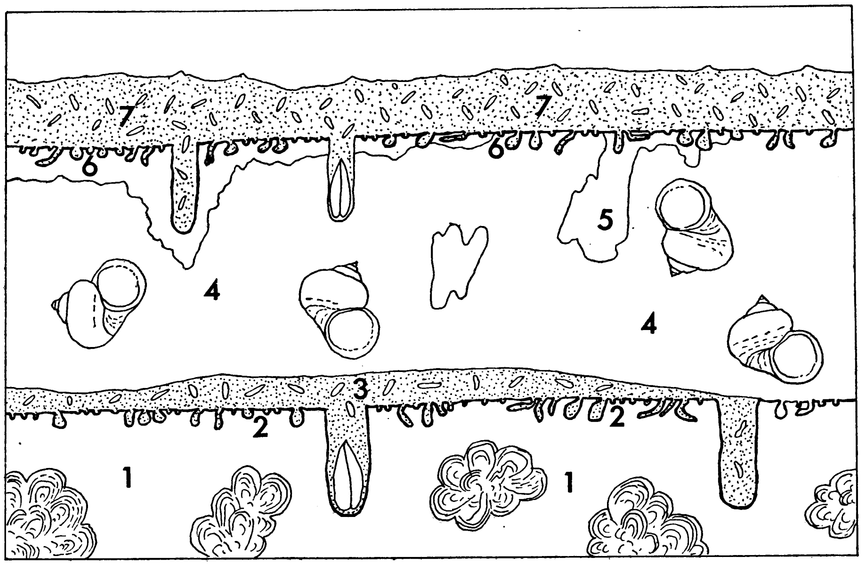


FIGURE 20. Section through rocks overlying the Takamaka Limestone at Dune Jean Louis. Vertical scale about 25 cm. 1, Takamaka Limestone; 2, *Cliona* and *Lithophaga* bored surface of Takamaka Limestone; 3, *Halimeda* rich calcarenite; 4, calcarenite containing terrestrial gastropods *Trophidophora*; 5, infilled cavities; 6, *Cliona* and *Lithophaga* bored surface; 7, *Halimeda*-rich calcarenite.

1. *Sedimentation*

It is clear that sedimentation took place over an extended period of time and that it did not follow any uniform pattern. Evidence is often conflicting and in particular localities may indicate very rapid or very slow deposition. In many areas corals are well preserved with intricate details of calices still visible. On Picard (0583.0913) and at other localities well-preserved spicular skeletons of alcyonarians strongly suggest rapid burial, but all of the evidence, even at these localities, is not wholly consistent. At Bras Grande Poche (0923.1185), Point aux Vaquas (1065.0087) and Entreboys (2225.0225) some corals have extensively bored surfaces crusted with algae, locally so extensively as to make identification of the corals difficult, and at Point aux Vaquas algal crusts were sometimes 5 to 10 cm thick. Similar evidence of slow deposition is also seen in the relations between individual corals and sediment, as in thin sheets of coral (*Millepora*) crusting a sediment surface on Picard (0583.0913), and in groups of corals with their growth related to a particular sediment level (non-depositional surface) within the sequence. At localities on Polymnie (1265.1218) Point Tanguin (1005.1040) and Passe Femme (0625.0863) large colonies (2 to 2.5 m diameter) of *Porites* form 'micro-atolls' containing one or more abraded surfaces, usually bored by *Lithophaga* and bearing in some cases crusts of calcareous algae and small colonies of *Favia*, *Porites* and *Pocillopora damicornis*. Such eroded colonies often occur in groups with the planed surface accordant from colony to colony, although the surrounding sediment may give no indication of any break in deposition. The growth of these assemblages has clearly been closely controlled by their relationship to a water level taken to be that of low-water spring tides. Colonies with more than one erosion surface suggest that sea level was changing in a positive sense more slowly than the coral grew but at a non-uniform rate.

The same colonies also raise an important issue in the depth of water they indicate which, in some cases, must have been less than 1 m at low tide. This evidence is clearly incompatible with that at some localities on the south coast and west of Passe Houareau (2823.1268) where individual colonies of *Acropora palifera* may be 2 to 3 m (or sometimes more) in height (figure 17, plate 34). These presumably had water of rather more than that order of depth to grow in, and we must assume that their growth could not have begun until some substantial period after that of the planated *Porites* colonies low in the succession.

Facies changes that involve species composition and abundance of the coral and molluscan faunas, and the character of the sediment matrix, appear to have been related to the geometry of the bank at the time of deposition. Variations may be seen both around the circumference of the present exposures and in a radial direction towards the centre of the atoll, the main differences being shown in figure 21.

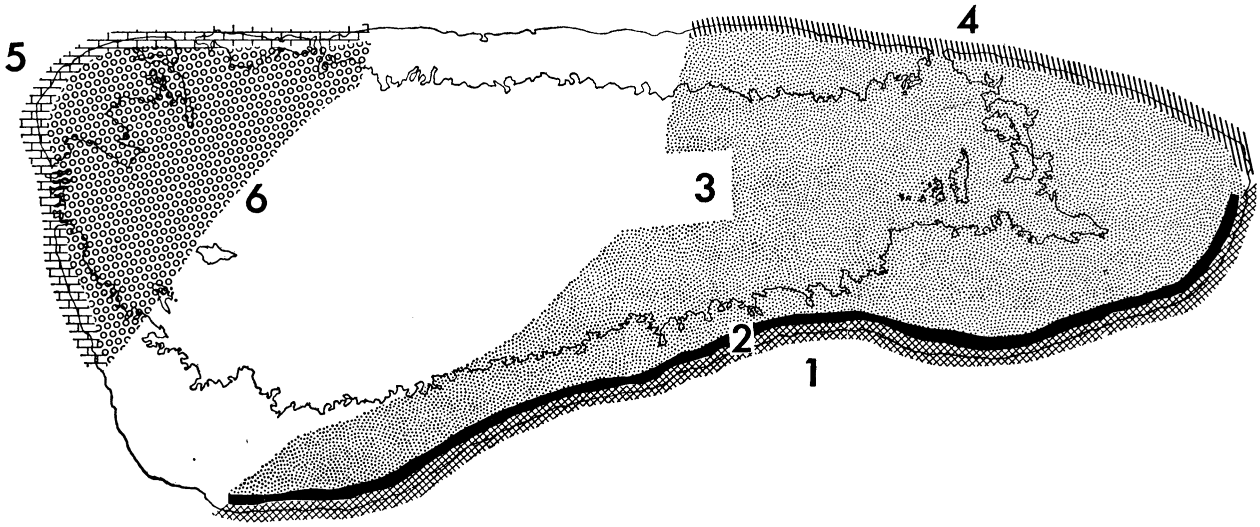


FIGURE 21. Reconstruction of the distribution of the major facies of the Aldabra Limestone. See text for details. 1, facies dominated by colonies of digitate *Acropora*; 2, facies dominated by rounded *Goniastrea* colonies; 3, *Halimeda*-rich calcarenite with coral patches and knolls; 4, facies containing abundant clubby growths of *Acropora palifera*; 5, facies consisting of knolls and pinnacles with faviid corals particularly abundant; 6, facies of mollusc-rich, calcarenite with frequent coral knolls, *Porites* common.

2. *Facies changes around the circumference*

Along the south and southeast shores (Dune d'Messe to Cinq Cases), the coral assemblages are characterized by an abundance of species of *Acropora*, particularly digitate corymbose colonies of 30 to 45 cm diameter (figures 18, 19, plate 34), but accompanied by smaller and less common *Acropora* in sprays, *A. humilis* and large *A. palifera*. Other corals include *Goniastrea*, *Favia*, *Galaxea*, *Hydnophora*, *Fungia* and *Platygyra*, but these are less common. Coral density is very variable along this coast and patches of high density may be separated, sometimes by tens of metres, by calcarenites containing large numbers of *Halimeda* segments and spines of *Heterocentrotus*, but with few corals. It is significant that areas of constructional frame are rare and often small, and in some sites coral colonies are tumbled and disorientated. Within these limits, however, this 20 km of coast generally shows a remarkably uniform facies.

To the north and northeast (on the seaward coast adjacent to Passe Houareau) the coral fauna is dominated by large *Acropora palifera* (colonies up to 3 m high), with stagshorn *Acropora*, *Favia*, *Goniastrea*, *Galaxea* and occasional massive *Porites* (figure 17, plate 34; figure 23, plate 35). Apart from the colonies of *A. palifera*, which sometimes extend throughout the section, it is usually only at the cliff top that any dense constructional framework is to be seen. The rest of the vertical rock exposure generally consists of *Halimeda*-rich calcarenites with scattered corals, but within this same section there are also some of the coarsest detrital sediments found, consisting of rolled coralgal cobbles of 10 to 15 cm diameter crusted with calcareous algae. These occur towards the top of the cliff and are presumed to reflect deposition in a higher-energy environment than that of the sediments around them. They again raise the problem of contemporaneity of events (figure 26, plate 35).

At the west and northwest end of the atoll the coral assemblages consist mainly of faviid corals (figure 29, plate 36), *Favia*, *Platygyra*, *Leptoria* and *Symphyllia*, but these are accompanied by species of *Acropora*, *Pocillopora* and *Millepora*. Branching forms of *Acropora* such as *A. palifera* and the stagshorn and corymbose varieties do occur, but the overall impression is one of rounded (massive) coral growths. More good frame growth is seen in this northwest quadrant than in any other area around the present exposures. At Anse Var (0688.1208) patches are generally a few metres in diameter and may include contributions from *Favia* spp., *Favites*, *Porites*, *Montipora*, *Galaxaea* and small *Acropora*. Between these knolls, which are sometimes widely spaced, the sediments are poorly sorted calcarenites and calcirudites packed with comminuted coral and molluscan fragments.

Coral growth knolls are also found south of the settlement on Picard, but here, towards the top of the cliff, the dominant corals are *Millepora platyphylla* and some *Acropora* but also include species such as *Acanthastrea echinata* and *Stylophora mordax*. The associated molluscs at both localities includes coral-living genera from pinnacle surfaces and sand-dwelling genera indigenous to the sediment. This association is typical of shallow, high-energy situations on Mahé, described by Taylor (1968, p. 175) and Rosen (1971, p. 172).

In contrast the assemblage at Anse Anglais is dominated by very large *Porites* colonies (some 4 m diameter), accompanied by *Goniastrea*, *Favia* spp. *Platygyra* and others; but there are few branching forms and the general appearance of the fauna is in keeping with Rosen's (1971, p. 174) quiet water association.

Description of plate 35

Figure 22. Erosion surface truncating Bassin Cabri Calcarenites and colonized by a *Porites* colony of the overlying Aldabra Limestone Passe Mili (0625.0863).

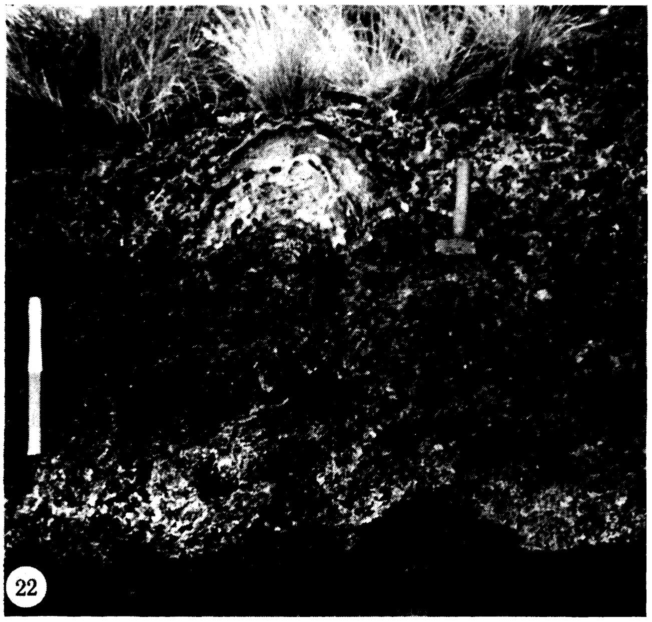
Figure 23. Large colony of *Acropora formosa*? in the Aldabra Limestone. Northeast shore of Middle Island (3020.0918).

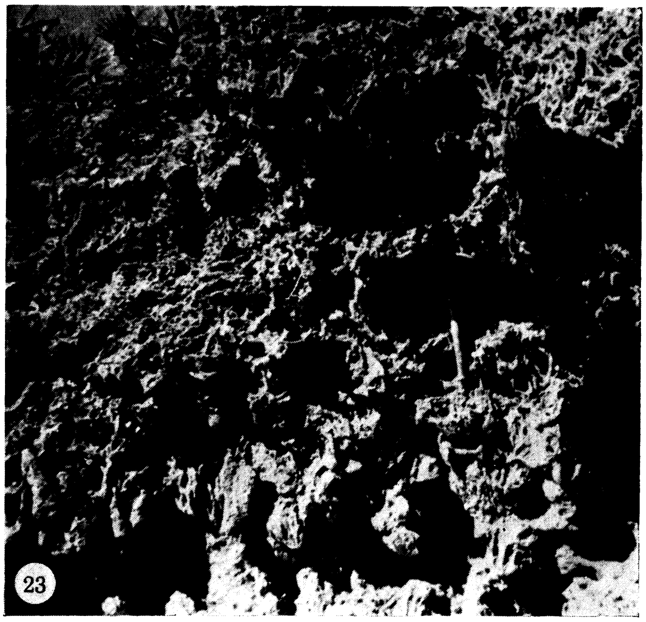
Figure 24. Large colony of *Porites* (3 m in diameter) in the Aldabra Limestone (north-west knoll facies) resting upon Takamaka Limestone erosion surface. Bras Anse Grande Poche (0940.1098).

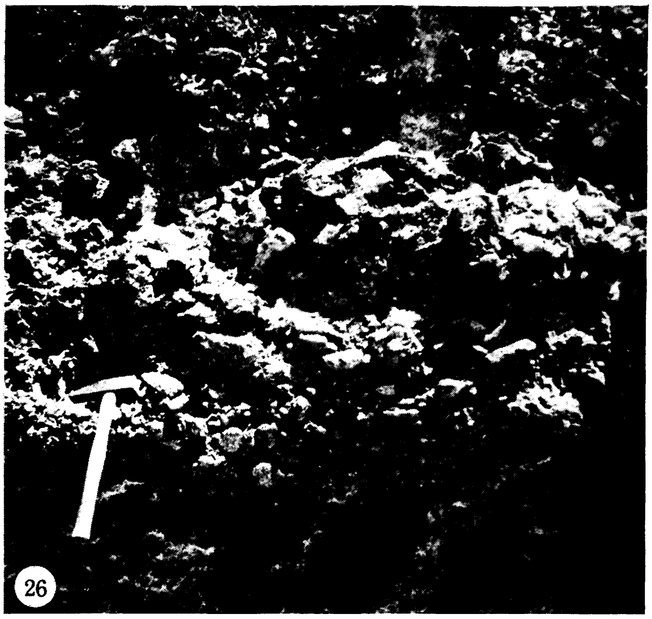
Figure 25. Cliff section of Aldabra Limestone showing horizontal plates of *Acropora hyacinthus* (in fact, broad conical bowls) separated by coarse calcarenite. Polyrnnie (1063.1235).

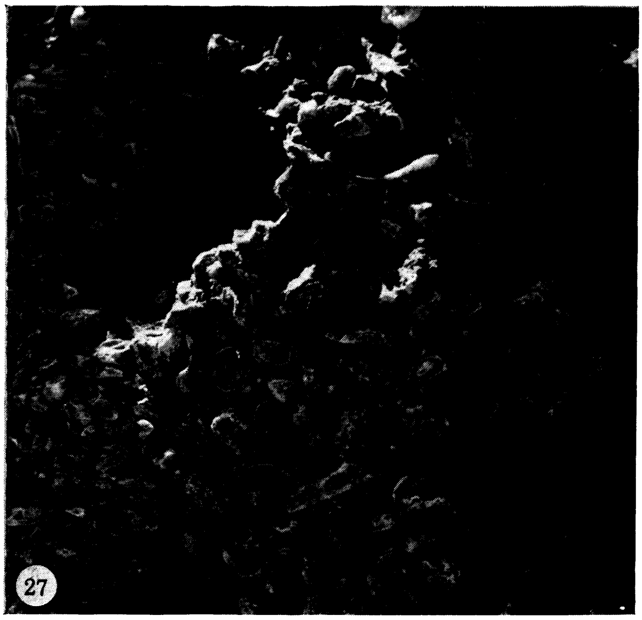
Figure 26. Facies of Aldabra Limestone consisting of large rounded blocks of coral debris. Near Passe Houareau (3250.1215).

Figure 27. Calcirudite of Aldabra Limestone consisting mainly of echinoid (*Heterocentrotus*) spines and rounded coral debris. Anse Takamaka (3418.0340).









FIGURES 22–27. For legends see facing page.

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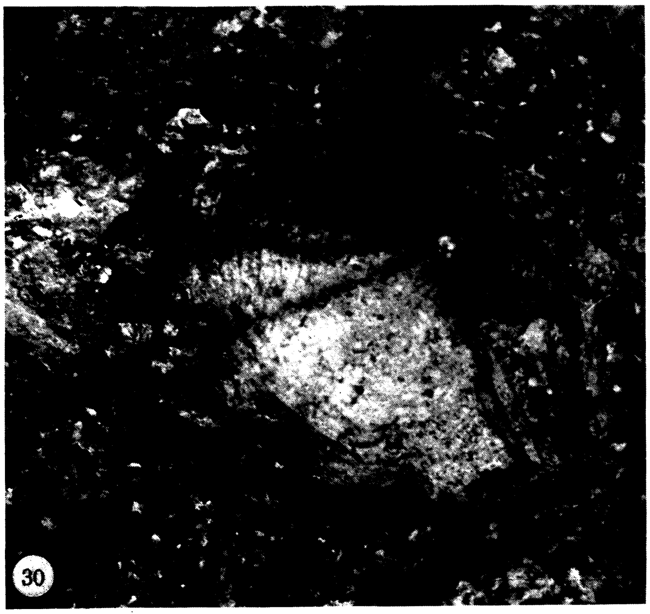

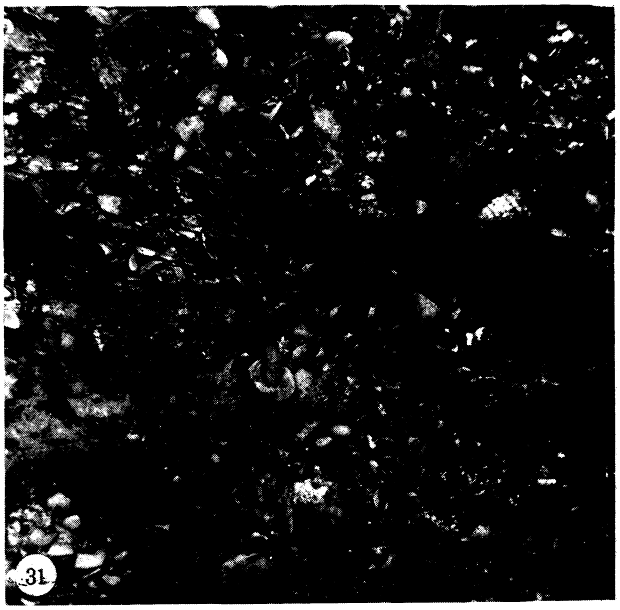

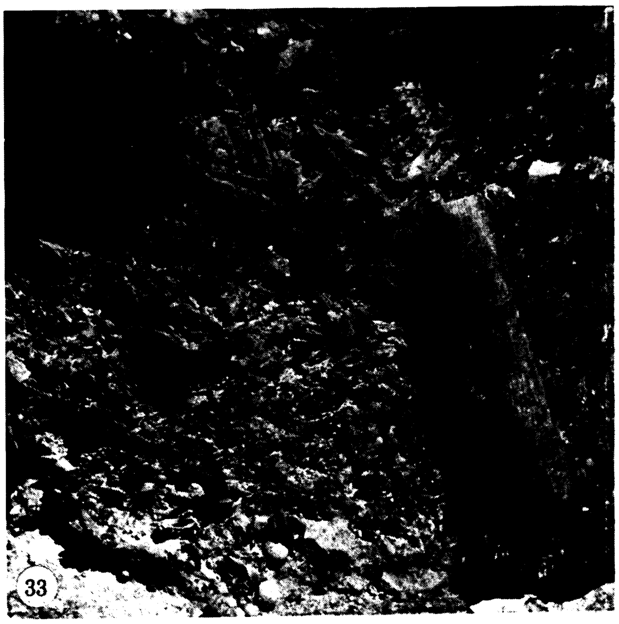

FIGURES 28–33. For legends see facing page.

In only one of the outcrops examined is there much rigid frame growth suggestive of an edge-zone environment. Even in this case the impression is more one of a mixed environment with good circulation in which coral knolls are separated by sand patches. This would seem to lie within a few metres of the surface but not usually to subject violent wave action.

The above facies differences have been described as circumferential, but they may in part be a result of differential rates of erosion acting on facies variations which are primarily radial.

3. *Radial facies changes*

The most obvious of the radial facies changes is a general decrease in coral abundance towards the centre of the atoll, but there are also clearly defined changes in species composition and in the morphology of growth forms.

The coral assemblage visible on the seaward coast in the south and southeast is dominated by species of *Acropora*. These are replaced inland by *Goniastrea* which appears in colonies up to 1 m in diameter, and is often almost the only coral present. Other corals tend to have similar rounded growth forms: they include *Favia* and *Platygyra*, while *Millepora*, *Tubipora*, and species of *Acropora*, where present, form small compact colonies. Between the coral heads, which are sometimes widely separated, areas of calcarenite include masses of *Halimeda* segments packed in a finer matrix. Further 'inland' the corals again decrease in numbers, *Goniastrea* is still common, but forms such as *Acropora palifera*, stagshorn *Acropora*, massive *Porites* and *Millepora* occur as isolated colonies. Other forms such as the corymbose *Acropora*, *Hydnophora* and faviids occur only in small coral patches. Wide areas of the southeast corner of the atoll, away from the present coast, consist of *Halimeda* – rich calcarenite with more or less isolated coral colonies of a few species, together with small coral patches displaying greater diversity.

Similar changes are seen in the northwest area where the seaward faviid-dominated assemblage grades inwards into an area of coral knolls separated by calcarenites. The transition is well seen along the western shore of Bras Grande Poche where coral knolls are relatively large and today form positive features in an undulating topography that may in part reflect original relief. Although the knolls represent sites of prolific coral growth and the faunas are often quite diverse, growth frameworks probably play a subordinate role. Corals important in the knolls include massive *Porites*, often several metres in height and diameter (figure 24, plate 35), large colonies of *Acropora palifera*, branching *Porites*, corymbose *Acropora*, and sometimes faviids such as *Favia*, *Platygyra* and *Symphyllia*. *Fungia* and *Seriatopora* are common in the calcarenites immediately around the knolls. Close to this facies on the southwest shore of Polymnie and on the

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DESCRIPTION OF PLATE 36

FIGURE 28. Cliff section of Aldabra Limestone showing depositional break within the sequence (arrowed). Polymnie (1265.1218).

FIGURE 29. Western facies of Aldabra Limestone with many *Favia* colonies separated by coarse calcarenite. Anse Var (0648.1195).

FIGURE 30. *Tridacna squamosa* surrounded by coral. Aldabra Limestone, Anse Var (0648.1195).

FIGURE 31. Facies of the Aldabra Limestone consisting dominantly of molluscan shells in a fine calcarenite matrix. Camp Frigate (1760.1088).

FIGURE 32. Crustacean burrows in facies of Aldabra Limestone. Near Passe Gionnet (1505.1158).

FIGURE 33. Solution-pipe, cavity-fill deposit, consisting almost entirely of broken tortoise and crocodile bones. Point Hodoul (4025.0930).

eastern shore of Grande Passe conical sheets of *Acropora* (*hyacinthus* group) are associated with masses of debris which represent stagshorn *Acropora* colonies 2 to 3 m in diameter and small colonies of a number of other coral species (figure 25, plate 35). These corals are all embedded in a coarse calcarenite matrix but seem to represent a rather different environment from that of any other area of the atoll. The change in facies from the north to the south coast of Polymnie is among the most rapid observed.

4. *Vertical facies changes*

The time sequence of changes that took place during the deposition of the Aldabra Limestone have already been briefly referred to. At a number of areas the base of the formation is not represented by coral-bearing sediments. At Anse Mais the lowest 1.5 m of the cliff consists of crudely bedded calcarenites and calcirudites, and when corals appear above they are massive slow-growing forms with a relative paucity of branching genera. At localities in Bras Grande Poche, Point Tanguin and Anse Takamaka (3418.0340) the lower parts of the succession include intensively burrowed calcarenites, corals being infrequent and generally broken. Within 1 or 2 m upwards these sediments are replaced by the extensive coral growths.

In the Passe Femme area the base of the Aldabra Limestone includes low banks formed almost entirely of nodose calcareous algae which are in general relatively uncommon in the unit. Similar banks occur north of Point Hodoul, where the topmost metre of the cliff is almost entirely algal frame, and on the coast about 800 m southwest of Cinq Cases, where algal rich sediments 30 to 40 cm thick extend inland as a thin sheet at the top of the succession.

In a section 4 m high at the eastern end of Middle Island (3005.1225) the lower part of the cliff consists almost entirely of *Halimeda* calcarenites with very few corals. Above them, large growths of *Acropora palifera* are abundant, together with stagshorn and spray *Acropora*, while in the upper 0.75 m these are replaced by small rounded growths of *Goniastrea*, *Platygyra*, *Favia* and Porites, many with flattened tops which suggest growth in very shallow water. Other corals present are *Stylophora*, *Millepora*, *Pocillopora* (*danae-meandrinae* type) and *Acropora humilis*. The sequence therefore suggests a gradual shallowing of the water from a depth of perhaps several metres to within a few centimetres of low spring tides. Such a change could have been produced as a result of coral growth and sedimentation, by a change in sea level, or by a combination of both.

A more marked facies change, and further evidence of the disparity in age between parts of the Aldabra Limestone, is shown by occurrences of a distinctive hard calcarenite, whose stratigraphical relationships are, however, sometimes ambiguous. At a number of localities, along both the northern and southern lagoon shores and around Takamaka, the surface of the Takamaka Limestone (bored by *Cliona* and *Lithophaga*) is overlain by a fine-grained, tightly cemented, calcarenite packed with well-preserved molluscs (figure 41, plate 38) including *Strombus gibberulus*, *Polynices mammilla*, *Fragum fragum*, *Pyramidella sulcata* and tellinids. It is usually 10 to 15 cm thick and is overlain by friable coral-rich sediment typical of the Aldabra Limestone. In contrast, over wide areas around Cinq Cases, an almost identical calcarenite with a well-preserved *Strombus–Polynices* fauna, here including *Phasianella*, *Cerithium rostratum*, *Scissulina*, *Pinguitellina* and *Bulla*, overlies a laminated brown (? terrestrial) crust which has been eroded and bored by *Cliona*, but rests upon undoubted Aldabra Limestone.

The distinctive lithology and widespread occurrence of these essentially similar sediments have led to the belief that they represent a single depositional event. There are some faunal variations within the bed; the Cinq Cases occurrences in general contain a fauna typical of a *Thalassia* environment (see Taylor 1968), while in other localities fossils are more indicative of shallow-water unvegetated sands, but these are minor variations.

Some evidence of another depositional break is seen in the occurrence of a similar hard calcarenite east of Passe Gionnet. This, however, is in a slightly different stratigraphical situation. The Takamaka Limestone surface is overlain by about 1 m of calcarenite, which contains numerous burrows of 2 to 3 cm diameter forming a vertically disposed system with nodular swellings believed to represent turning areas (figure 32, plate 36). Because of mutual interference the extent to which these structures branch is not clear; they may have been formed by crustaceans and resemble, in some respects, burrows figured by Farrow (1971, pl. 10) and ascribed to *Albunea*. They are accompanied by many small-diameter (5 cm) branching structures which produce a more continuous interwoven mass and which are probably best ascribed to burrowing shrimps. Immediately above the burrowed unit is about 50 cm of hard calcarenite, similar to the calcarenites of Takamaka and Cinq Cases, with abundant well-preserved molluscs including *Scissulina*, *Jactellina*, *Pinguitellina* and *Strombus gibberulus*. This is overlain by a thin brown laminated crust (terrestrial ?) upon which a coral and mollusc-rich calcarenite, the Aldabra Limestone, rests. Similar burrowed sediments are visible on adjacent islands, and in one case six burrowed subunits were identified which presumably represent successive positions of the depositional surface. These burrowed calcarenites thus overlie the Takamaka Limestone and pre-date a supposed terrestrial event which was followed by the deposition of typical Aldabra Limestone. All three of these facies, the burrowed sediments, the hard calcarenite and the friable coral-bearing sediments, are interpreted as lying within the Aldabra Limestone formation.

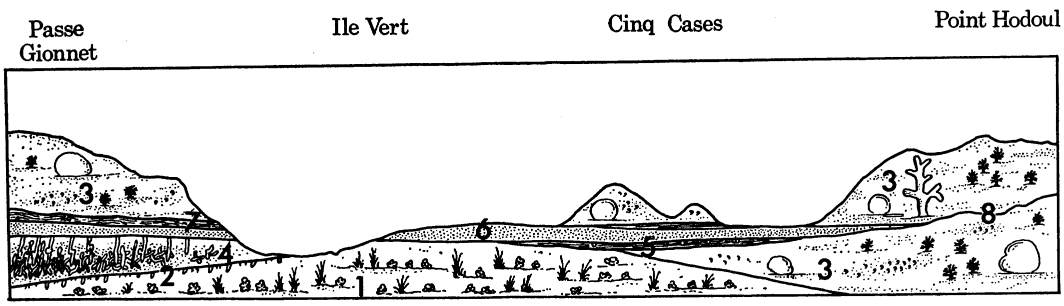

FIGURE 34. Stylized section (W–E) from Passe Gionnet–Ile Vert–Cinq Cases–Point Hodoul, to clarify stratigraphic relationships. Horizontal scale about 25 km, vertical 4 m. 1, Takamaka Limestone; 2, surface bored by *Cliona* and *Lithophaga*; 3, Aldabra Limestone; 4, burrowed calcarenite; 5, subaerial crust (bored); 6, hard *Polynices–Strombus* calcarenite; 7, subaerial crust; 8, depositional break within the Aldabra Limestone.

The differences in stratigraphical relationships at each of the three locations can be explained by suggesting that the formation of the Aldabra Limestone was a discontinuous process. After an initial period of deposition, emersion, from whatever cause, resulted in the formation of terrestrial crusts and, in some areas, the uncovering of the Takamaka Limestone surface by erosion. Subsequent submergence allowed deposition of the *Strombus–Polynices* sediments and, as waters deepened, of the coral-rich calcarenites of the Aldabra Limestone. The distinctive cementation of the *Strombus–Polynices* calcarenite raises the possibility of another break in deposition and an emergence, but recent descriptions by Shinn (1969) and others of submarine lithification leave this open to argument. Much stronger evidence is seen in the Gionnet occurrence where a laminated crust *overlies* the calcarenite.

Sediments which may be equivalent to the *Strombus–Polynices* rock are also to be seen at Bassin Flammants (3908.0800), where there are exposed areas of a coquinal calcarenite made up almost entirely of shells of *Fragum fragum*. They are apparently overlain by a thin surface crust and about 30 cm of calcarenite with *Fragum* and *Halimeda* which might be equated with the 'typical' Aldabra Limestone at Gionnet.

At a number of sites around the atoll indistinct irregular bedding planes can be seen (figure 28, plate 36). Their precise significance is not known, but, with the sediments described above and a thin laminated crust within the Aldabra Limestone on Polymnie (1265.1218), they may be explained as a product of an emergence.

The relationships proposed for all of these sediments are illustrated in figure 34.

5. *The molluscan fauna*

The molluscan fauna of the Aldabra Limestone is very diverse, including about 400 species. In general distribution and in broad facies variation they match the corals. Around the outside of the atoll species associated with exposed hard substrates and with corals are generally dominant, while sand-dwelling forms are less common. Away from the present coast the increase in the area occupied by calcarenites is paralleled by an increase in the numbers of sand-living species. As with the corals, by far the greatest diversity is found at stations in the northwest quadrant of the atoll, notably fewer species being found in the *Halimeda* sands of the southeast.

6. *Conditions of deposition*

Taken as a whole the evidence indicates that the Aldabra Limestone was deposited in shallow waters, probably never exceeding 10 m in depth and covering the broad annular platform which had been formed from the eroded surface of the Takamaka Limestone and whatever calcarenites may have been deposited on it. The sediment complex that built up consisted at times of coral pinnacles and knolls concentrated around the margins and rising from a generally sandy floor. Water circulation was generally good; there is no evidence of areas of restricted circulation, reduced salinities, or other extreme environments. The dominance of species of *Acropora* to the south and southeast suggests onshore winds and free water movements in that

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DESCRIPTION OF PLATE 37

FIGURE 35. Elevated cliff line post-dating the deposition of the Aldabra Limestone. Scale figure is standing on the floor of a former channel through the atoll rim. Cinq Cases (3938.0527).

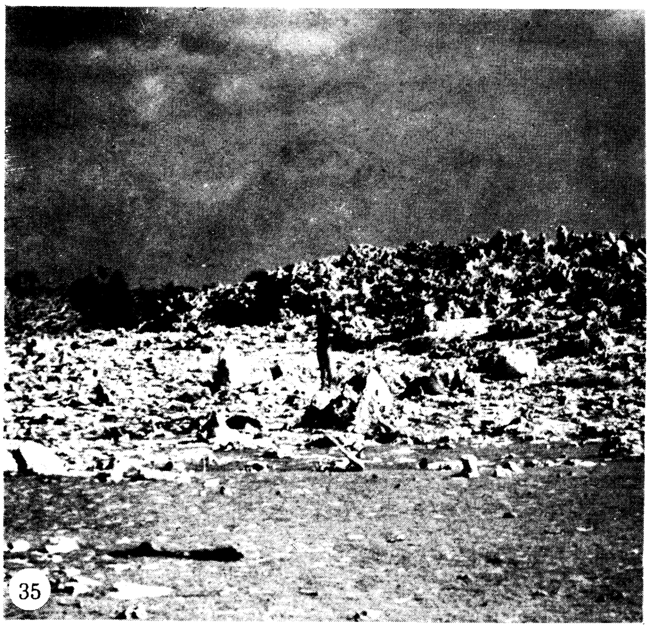
FIGURE 36. Common type of laminated cavity-fill deposit, consisting of a buff-coloured 'soil' with laminae draping over the cavity walls. Anse Var (0648.1195).

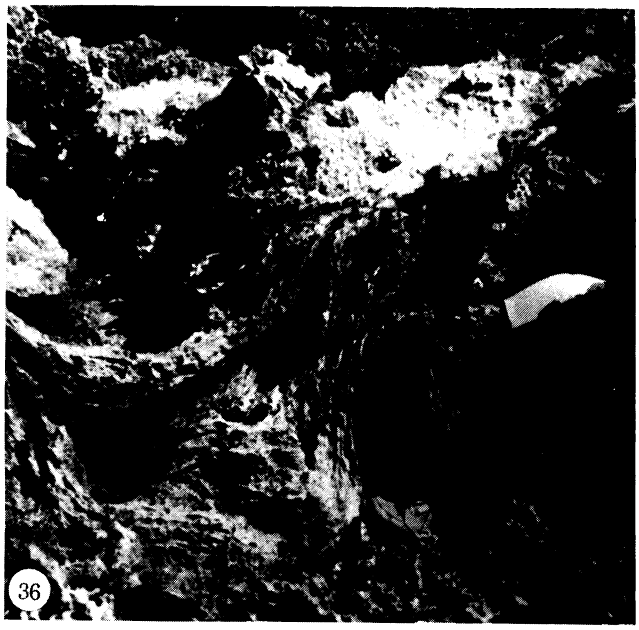
FIGURE 37. Brown calcarenite, burrowed by *Uca*, overlying Aldabra Limestone. This deposit may have been formed at a sea level slightly higher than the present. Cinq Cases (3805.0610).

FIGURE 38. Mammillated pavement of algal stromatolites, overlying the Aldabra Limestone. Cinq Cases (3908.0573).

FIGURE 39. Recent stromatolites in a high intertidal pool in lagoon. Cinq Cases (3800.0630).

FIGURE 40. 'Recent' laminated crust, overlying the Aldabra Limestone. Near Passe Gionnet (1265.1218).





FIGURES 35–40. For legends see facing page.

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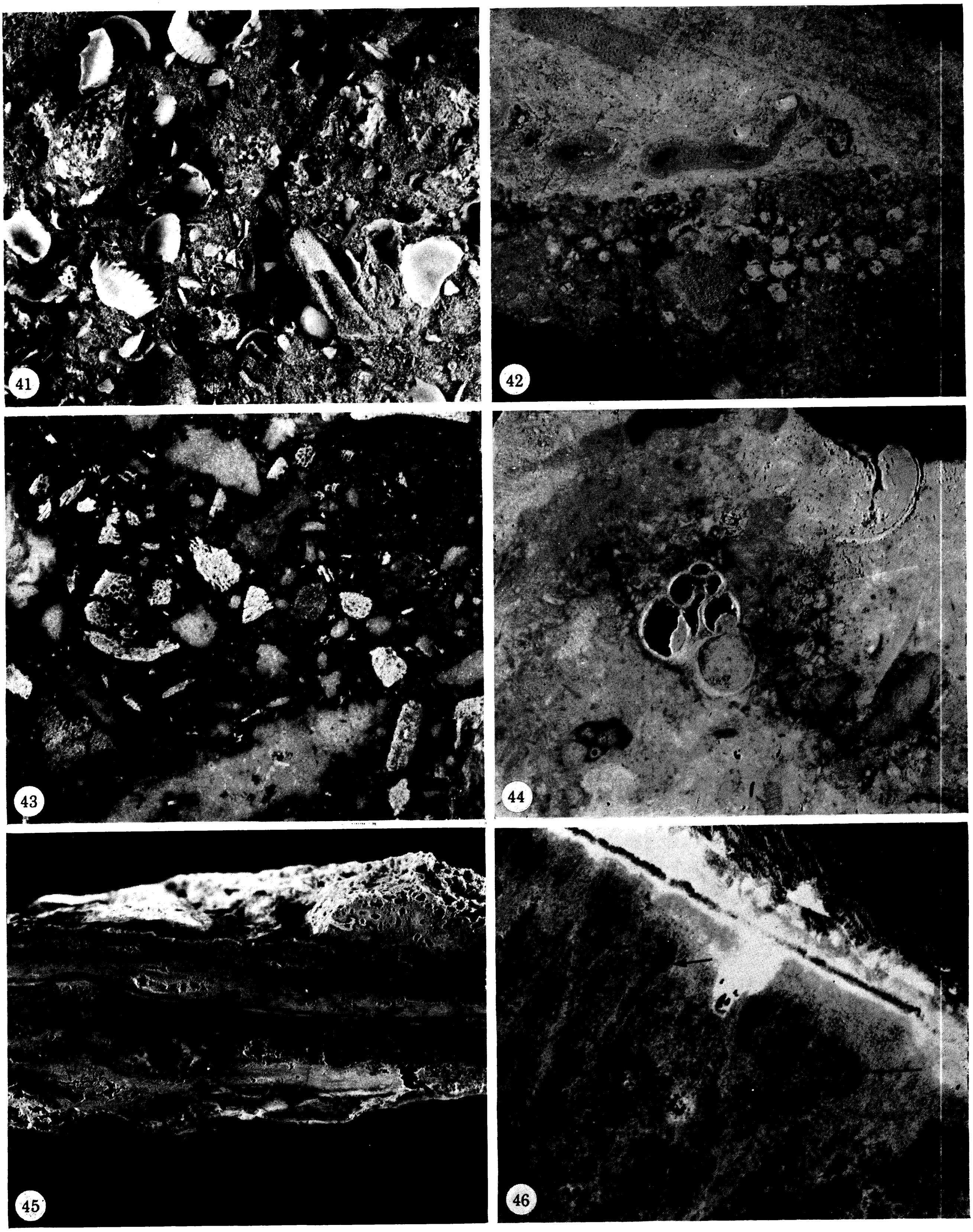

FIGURES 41–46. For legends see facing page.

area, but the presence of good frame growth also suggests fairly good circulation at the north western end of the atoll. There may thus have been a seasonal SE/NW wind system at this time, similar to that of the present day.

In general the extent of rigid frame growth is more limited than might be expected, although corals are fairly abundant all round the outer rim of the atoll. Within the outer coral rim quieter conditions prevailed and, over most of the present exposure, the Aldabra Limestone consists of calcarenites containing isolated corals. In the northwest coral knolls rise from the calcarenite floor, supporting a high diversity of corals and molluscs. These are not represented to the southeast, where the coral and molluscan abundance and diversity are very much lower and there is a vast area of relatively barren *Halimeda*-rich calcarenites which are generally finer grained than in the northwest. It is suggested that these differences reflect variations in wind strengths. The postulated southeast winds were perhaps the stronger, causing greater circulation in the northwest corner of the bank and promoting the accumulation of nutrients (cf. von Arx 1954).

The form of some of the corals suggests growth in very shallow water, and there is evidence of a general shallowing of water up the sequence. This could be the result of a drop in sea level, tectonic uplift, a reduction in the rate of sea-level rise, or a still-stand.

Despite the evidence of very shallow water there is very little suggestion of terrestrial deposits. The sort of land expected would be low sandy islets similar to those found around the rim of present-day low atolls. No distinctive sand cay accumulations have been found, although the supposed terrestrial crusts within the Aldabra Limestone at Cinq Cases and Polymnie may represent land. There is no evidence of the biota of this, and of the area that it might have occupied. It was certainly low lying and, must have been completely inundated by the later submergence that obliterated any terrestrial organisms present.

Evidence of deposition in relation to sea level is sometimes conflicting, and some facies changes are difficult to explain. These differences, and the breaks in deposition, may all be accommodated in a general statement that deposition of the unit represents an extended time period. This means that sediments at the top of the sequence in one area may have been deposited at the same time as those appearing at the base elsewhere. The deposits within the unit have only general contemporaneity.

Description of plate 38

Figure 41. Hard calcarenite from within the Aldabra Limestone sequence; this specimen contains abundant fragments of the bivalve *Fragum fragum*.

Figure 42. Terrestrial? crust (bottom), from within the Aldabra Limestone sequence, the upper surface of which is perforated by clionid sponge borings and overlain by a coral/algal rich calcarenite.

Figure 43. Cavity-fill deposit (type 2), consisting of tortoise bone fragments, limestone intraclasts and a red brown matrix containing abundant ovoid glaebules (crab faecal pellets?).

Figure 44. Coarse calcarenite containing terrestrial gastropods (*Trophidophora*) from the Unassigned calcarenites which lie stratigraphically between the Takamaka and Aldabra Limestones. Dune Jean Louis (2630.0418).

Figure 45. Laminated phosphorite from the summit of Ile Esprit (1060.0625).

Figure 46. Enlarged aerial photograph of the Cinq Cases area showing the 4 m terrace and the elevated cliff line (arrowed) with former islets and channels.

7. *Dating*

The Aldabra Limestone is the only formation which has so far yielded material well enough preserved for radiometric dating. Corals from growth assemblages 2 to 7 m above present sea level were dated by the $^{230}Th/^{234}U$ method. The ages obtained (Thompson & Walton 1972) ranged from 118 to 136 ± 9 ka.

These ages thus place the deposition of the Aldabra Limestone in the last interglacial period. The dates are in good agreement with those obtained from coralline limestones from other parts of the world (Veeh 1966; Broeker & Thurber 1965; Stoddart 1971). The ^{14}C dates of 33000 years previously obtained from the same deposits and interpreted as indicating deposition during an interstadial (Stoddart *et al.* 1971; Stoddart 1971, p. 27) are regarded as spurious.

Depositional and erosional events post-dating the Aldabra Limestone

A number of erosional and depositional events post-date the formation of the Aldabra Limestone. Deposits are principally cavity fillings, always small and usually obscure in origin, linked with the erosional events which have produced the present-day land forms, and which must be interpreted in the context of sea-level changes of the last 100000 years. The time span embraces the last glaciation (Würm-Wisconsin) and its accompanying world-wide depression of sea level, and the post-glacial sea-level rise. Unfortunately, it is at present impossible to state the ages, or sometimes even relative ages, of most of these sediments or events, although some can be related to specific sea-level positions.

Depositional events

A number of distinctive types of cavity filling may be recognized:

1. The most common deposits are yellow-brown in colour, and although case-hardened are generally soft and friable below the surface. They are usually laminated, with laminae each several millimetres thick (figure 36, plate 37) draping across walls and floors to a thickness which in some cases may reach more than a metre. Some still have glossy botryoidal surfaces and it seems possible that, at least in their later stages, sediment was carried into the cavity in water films adhering to the surface. This is in addition to any more substantial rain-wash transport of residual soils. Deposition might have been aided by evaporation or by the intercession of filamentous algae or other organic trap.

The central areas of some cavities contain masses of intermeshed branching tubules which are probably the moulds of rootlets. Terrestrial snails occur in a few of these cavity fillings, but are generally rare. There is no clear evidence of the sea level at the time of formation of these cavities, but the abundance and volume of their deposits suggest a prolonged period of emergence and, probably, high rainfall.

2. Less common, but distinctive, are types of cavity fillings which occur principally as residual pinnacles around the atoll and are typified by the occurrence at Ilot Rose (3380.1028).

In most the matrix is orange brown in colour and, apart from its hardness, is soil-like in appearance (figure 43, plate 38). It contains large numbers of tortoise-bone fragments, blocks of recrystallized limestone and blocks of travertine-coated limestone, the latter probably representing fragments of the walls of the original cavity. In thin section the matrix is seen to be made up of relatively structureless areas which alternate with accumulations of ovoid amorphous glaebules, set in a sparry calcite cement. Some areas contain what appear to be the remains of algal filaments, while related fillings contain terrestrial molluscs which strengthen interpretation as a subaerial environment. The deposits are analogous to the soils of contemporary solution pits occupied by the land crab *Cardisoma carnifex*. Remnants of the fossil deposits are found all around the atoll at sites up to about 2.5 m above present sea level, and comparisons with the distribution of modern *Cardisoma* suggest that this would accord with a sea level 1 to 2 m higher than the present.

3. Only one deposit of this type was found, situated near Passe Houareau. The sediment consists of a dark brown, diagenetically hardened, 'soil' within which are packed large numbers of a large ribbed species of *Trophidophora* and many other smaller species of land snails, some of them identical with ground-dwelling forms at present found in scrub and forests on other islands in the Western Indian Ocean.

4. A group of bedded cavity fillings at Point Hodoul (4025.0930) appears to be restricted to this area (figure 33, plate 36). They contain great numbers of bone fragments of *Testudo gigantea*, *Crocodylus niloticus*, some bird bones and possibly the vertebra of a varanid lizard. Land snails including *Trophidophora* sp. occur in the matrix. Some of these deposits extend below low tide mark.

The fauna can be presumed to have required a land area rather larger than that at present. It is clear that such a land mass with this fauna is unlikely to have risen to any great height above a sea level which was probably not significantly lower than the present.

5. At many southeastern localities there are laminated coatings (figure 40, plate 37) on the margins of present pools and cavities. Moulds of algal filaments have been found within these earthy sediments which are sometimes stromatolitic. Near Takamaka Grove (2928.1090) there are extensive mammillated surfaces with stromatolites ranging from a few centimetres up to 20 to 30 cm in diameter, with composite structures reaching 50 cm in height. They occupy an area of several thousand square metres and, since they appear to have been little modified by erosion, may represent some fairly recent event, when water level lay perhaps 1 to 5 m above the present. Similar but smaller stromatolitic deposits (figure 38, plate 5) are to be seen in the Cinq Cases area (3908.0573). At Takamaka Grove laminated fillings, apparently associated with the stromatolites, contain coral and gastropod fragments including *Succinea*, *Melampus*, and other terrestrial snails.

6. A number of other small developments of calcarenite also seem to be the result of Recent events. Near Cinq Cases (3805.0610) a thickness of 15 to 20 cm of orange-brown calcarenite overlies laminated crusts and eroded limestone surfaces (figure 43, plate 38). Large numbers of simple burrows weathered out on the exposed surface are similar in general appearance to that of Recent burrows inhabited by the fiddler crab *Uca*, but only a single crab chela was found. Close to this locality specimens of *Terebralia palustris* and *Melampus* occur at a similar level in hardened sediment coating a cavity in the limestone surface. Other crab-burrowed calcarenites were discovered in cavities in the cliffs west of Passe Houareau (3005.1225). Taken together, these sediments might be related to deposition at a sea level about 1.5 m above the present datum.

Erosional events

Several erosional events post-date the formation of the Aldabra Limestone. At about 8 m above present sea level there is an erosional terrace which generally forms the highest parts of the land rim. This is fairly flat, but hummocky areas and residuals are present, particularly along the south coast. It is significant in terms of relative age that this feature truncates some terrestrial deposits resting in cavities in the Aldabra Limestone.

Below the 8 m terrace the most conspicuous element in the morphology is a second terrace at about 4 m above present sea level seen around most of the circumference of the atoll, (figure 46, plate 38), and bounded by well defined cliffs cut into the 8 m platform. The cliffs are most conspicuous on the seaward side and their profiles are closely comparable to those of the present shores in the same areas. This suggests that patterns of exposure at the time of formation were similar to those operating today. Cliffs along the old lagoon shore are less well defined and the coastline was obviously low and indented. Offshore islands can be recognized in some areas (Bassin Cabri). The surface of the 4 m terrace on the seaward side is generally flat, rising slightly towards the cliff-line. At a number of localities on the south coast elongate grooves extend at right angles to the shore. These are less than 1 m in depth and generally 10 m or so in length; they resemble abrasion grooves cut in the present mid-littoral platform in this area and their fresh appearance supports the suggested recent origin of the terrace.

It is probable that some stromatolitic crusts were formed around the margin of the lagoon during the period of terrace cutting or as sea level fell a little.

At the time of formation of the 4 m terrace, proto-Aldabra (about 50 km^2 in area) consisted of a series of linear, low, rocky islets forming an almost continuous land rim along the north and northwestern coast but broken by many channels to the east and southeast. The broad lagoon floor extended over most of the area of the present 'platin'.

Evidence from outside of Aldabra of widespread glacio-eustatic sea-level changes (Milliman & Emery 1968) indicates a depression of sea level of over 100 m during the last glacial maximum. Such an event would have left Aldabra as a high, steep-sided limestone island, probably with a rimmed shallow depression at the summit. The rainfall was probably higher than at present and the flutes (grooves and buttresses) on the seaward slope (Barnes *et al.* 1971, p. 90) particularly prominent on the north coast, might well have been cut by solution at this time (cf. Guilcher 1971).

Although it is tempting to suggest that the main lagoon drainage channels originated at this time, Stoddart *et al.* (1971) suggest positive evidence to the contrary. The main cavity fillings of type 1 and the isolated occurrence of type 3 may have been deposited at this time.

In the Bassin Tortue area (0660.1010) there are a number of old caves which are being exposed by present erosion. They seem to have been a predominantly horizontally disposed system. In a few cases thick (20 cm) coatings of fibrous crystalline calcite occur along floors but are absent from walls. Other deposits include buff-coloured flinty calcilutites which are sometimes marked by well-defined desiccation cracks. Areas of collapse which may be associated with similar cave systems have been noted in a number of localities, principally to the east of Passe Gionnet and southeast of Passe Houareau on the lagoon shore. Marine solution cannot be discounted and these caves might have been formed by the aggressive surface waters of the sea standing at a level 1 to 2 m above the present, but freshwater solution is in general more effective. This would require a much higher rainfall than the present. We have no information which would enable us to place this solution event accurately on a time scale.

Large numbers of joints in some areas, particularly at the eastern end of the island group, may from apparent displacement of outcrops, include true faults. They are probably gravity structures, resulting from slight movements downslope of the unconsolidated and relatively unsupported carbonate sediments during and as a result of the maximum low sea-level stand.

The lack of mechanical strength of these limestones is well illustrated by block faulting along high cliff faces, particularly north of Point Hodoul where the subtidal platform in front of the cliff is especially deep and accentuates the unsupported cliff height.

Sea level has been rising towards its present level since about 13000 years ago although it slowed considerably at about 5000–7000 years B.P. (Milliman & Emery 1968; Bloom 1971). The major event affecting Aldabra during this period was the breaching of the land rim by the sea and the flooding of the central depression to form the present lagoon, although sea water also probably had access to the lagoon through solution cavities. Evidence of sea levels substantially higher than the present (Fairbridge 1961), are regarded as questionable (Stoddart 1968, 1971).

Minor fluctuations in sea level are suggested by the fresh appearance of the stromatolitic deposits in the Takamaka and Cinq Cases areas; by the ambiguous occurrence of shallow-water *Nerita* spp., *Chama* and *Saccostrea* high on cliff faces associated with deeper water forms (e.g. Polymnie, 1063.1235); and by the occurrence of *Sacccostrea* with *Tubastrea* and *Dendrophyllia* above present high-water mark in Passe Femme.

The present seaward platform varies in width from 100 m in the east to 460 m in the west, it is an erosional feature whose form is apparently related to present sea level and to a landward retreat of the cliffs, but when did this erosion take place? Measurements taken recently on the seaward cliffs of Aldabra (Trudgill 1972) record a maximum erosion rate of 3 mm per annum from cliff faces. If it is assumed that sea level has been approximately the same as at present for about 5000 years then this rate of recession can account for only 15 m of the seaward platform. It is thus likely that much of the present platform was cut at some other time when sea level stood at a similar level, or, that the rate of cliff retreat has not been constant. Similar problems are associated with the size of the present lagoon.

Present-day sedimentation and coral growth

The following notes on present-day environments may be used with the accounts of Stoddart & Wright (1968) and Stoddart *et al.* (1971) of present morphology to establish a picture of the contemporary phase in the development of the atoll.

Coral growth is considered to be active on the seaward slopes only in one small area off Picard, at the western end of the atoll. The assemblage is generally of a rather mixed character in shallow waters, but is zoned with increasing depth. Along the northern shore corals are still fairly abundant, but elsewhere they are generally sparse and it seems that they always grow on an inherited (eroded) surface. In the lagoon, coral growth is largely confined to areas immediately around the channels draining to the sea. The shallower parts of the channel margins support fairly dense frame growth, but away from these, corals are sparse and separated by large areas of calcarenite.

Sedimentation on the seaward platform is limited; at the western end coarse calcarenites are fixed by growth of sea grasses but generally along the south and eastern shores sands are confined to pockets and depressions in a rocky surface. In the lagoon, sediment is accumulating around channels, as mobile sand-banks and more stable bodies bound by plant growth; the greater area of the floor has only a thin cover of fine sediment over a relatively flat rock bottom.

Terrestrial sediments are similarly of very limited extent. True soils are absent and most of the land area consists of rock surfaces in various stages of dissection, although there are localized pockets of forest litter. The most extensive terrestrial accumulations are the nearly continuous perched beaches and the occasional sand dunes of the south and southeasterly shores.

Beach-rocks occur intermittently around the atoll, principally along sandy coasts. In a number of areas they are firmly emplaced in cliff undercuts, illustrating the changing pattern of erosion and deposition.

Fine sediments occur in the brackish and freshwater pools of the southeastern area and Recent stromatolites may be seen in one small area in Bras Cinq Cases (figure 39, plate 37).

Discussion and conclusions

Comparison with other areas

There is good reason for supposing that Aldabra has been tectonically fairly stable during the late Pleistocene. This is suggested by the general correspondence of the Aldabra Limestone with coral limestones found at 6 and 9 m around the granitic Seychelles and dated by Veeh (1966) at 140000 ($\pm$ 30) years. Both sequences indicate deposition in relation to a sea level about 10 m above the present, and this is the figure suggested on general evidence by Shackleton (1969 p. 149), as the height of the sea level during the maximum warming of the last interglacial.

It is interesting, however, to compare this supposedly stable area with the contrasting situations of progressive subsidence on Eniwetok (Schlanger 1963) and progressive elevation on Barbados (Mesolella, Sealy & Matthews 1970).

At Eniwetok, tectonic subsidence has meant that the sediments of glacio-eustatic events are only preserved in the subsurface limestone column and do not outcrop at the surface. They can therefore only be investigated by means of boreholes (Ladd & Schlanger 1960; Schlanger 1963). The results of periods of subaerial emergence can be recognized in the sequence at solutional unconformities.

At Barbados, continuous uplift has been at a more rapid rate than glacio-eustatic sea-level changes with the result that well-separated constructional reef tracts, developed at various stages in the late Pleistocene, have been elevated, sequentially, high above the present sea level.

By contrast Aldabra has apparently remained tectonically stable while the glacio-eustatic sea-level changes of the late Pleistocene have fluctuated about it. Each sea-level stand has produced erosion, or deposition, or both, depending upon situation, and the results are thus rather complex. Erosional events often completely obliterated previous deposition and relationships are thus not as clear-cut as at either Eniwetok or Barbados. The terraces on Barbados, for example, represent constructional reef tracts (Mesolella *et al.* 1970), and are dated by the sediments forming them, while those on Aldabra are erosional and generally bear no sediment.

In spite of the considerable differences in control there is evidence in all three of these places of extensive coral growth taking place between 100000 and 130000 years ago. This is part of a pan-tropical pattern of prolific growth at this time (Stoddart 1968, 1971).

Correlation with the extensive Pleistocene succession of the East African coast is difficult in the absence of reliable absolute age dating. All coral samples so far collected from the Kenya Pleistocene have been too altered for dating. The African coast has apparently been tectonically active during the Pleistocene (Kent, Hunt & Johnstone 1971, p. 86) and correlation merely by elevation is therefore liable to error. The effects of several depositional and erosional events can be recognized within the East African limestones (A. Crame, personal communication) and on general faunal and diagenetic grounds it seems likely that the bulk of the exposed succession is equivalent to the Aldabra Limestone and thus dates from the last inter-glacial. There are also minor deposits, associated with solution pits, which are probably comparable in age with similar sediments on Aldabra. Comparison with continental East African successions is tenuous and at the moment can only be attempted on the basis of climatic variations. Pollen analysis by Coetzee (1967) has suggested that, on higher ground in East Africa, there was a very cold period between 27000 and 14000 years B.P. when temperatures were 8.8 °C lower than at present. This period was followed by a gradual warming to between 4000 and 2090 years B.P., when the temperature may have been 2 to 3 °C warmer than present. This might be extrapolated to infer a slight rise in sea level at about this time. It was followed by a general cooling towards present-day temperatures. Such variations would not in fact have been so marked at coastal sites, but micropalaeontological and oxygen isotope analyses have suggested that equatorial surface sea-water temperatures may have varied by so much as 8 °C between glacial and interglacial periods (Emiliani 1971). Changes of this magnitude would have had important effects in areas close to the thresholds of coral growth but may also have influenced levels of activity in general (cf. Laborel 1969).

Summary history of Aldabra

The earliest event identified in surface outcrops is the deposition of marine limestones on Esprit. There is no evidence that Aldabra was other than a totally immersed shallow platform during this period. Deposition extended over an unknown interval and was accompanied by an effective shallowing of the water. A fall in sea level which followed, resulted in the lithification and erosion of the limestones. The size of proto-Aldabra at this time is not known but it could have been as large as 365 km^2 (the total area of the bank). The range of relief of the surface upon which the Esprit phosphorites rest is at least 8 m, but this need not have been a product of one event since the phosphatic sediments themselves imply two separate periods of deposition. It is important to note, however, that both groups of phosphorites contain marine fossils related to high sea-level stands of +8 m and +2 m. If correctly interpreted, therefore, the succession can be fitted to points in a sequence of sea levels, falling from a stand more than 8 m above the present datum.

At the time of deposition of the Bassin Cabri Calcarenites, Aldabra consisted of a broad subtidal platform, relieved by rocky islets in the region of Esprit. At a later date, supra-tidal accretion, prograding across a shallow-intertidal sand-flat burrowed by crustaceans, resulted in the formation of a sand cay around Bassin Cabri. This island, which approached 20 km^2 in area, was vegetated and populated by tortoises, crocodiles, birds and snails. Aeolian dunes, presumably also based upon a sand cay, were present at Point Lion, but the former extent of these deposits or of the islands they represent is unknown.

Re-submergence, to a level at least 4 m above present sea level, was accompanied by deposition of the Takamaka Limestone. At this time Proto-Aldabra was again a shoal area – a broad bank colonized by a fairly uniform cover of calcareous algae with few corals and, perhaps, extensive growths of *Thalassodendron*. Rocky pinnacles probably existed around Esprit. A subsequent fall in sea level resulted in a superficial lithification of these sediments and the initiation of a new terrestrial erosion cycle, with the formation of a fretted limestone surface and, in some areas, complex soils. The presence of these soils, and the intricacy of the eroded limestone surface, indicate that the lithification was probably subaerial. Sea level at this time was close to present datum, and cliffs associated with it can be seen at Passe Houareau and Point Lion. The land area was probably relatively large, perhaps approaching 300 km^2.

The marine planation surface limiting the Takamaka Limestone marks a rise in sea level to some point which may not have exceeded 3 to 5 m above present datum. Proto-Aldabra became a broad shallow bank with a ring-like ridge around its periphery. The surface was relatively flat, dipping more steeply outwards on the seaward margin and sloping gently towards the present lagoon, although we have no information on its ultimate termination in either direction. In some areas, for example West Channels, the Takamaka Limestone was completely removed by this erosion and there are only very limited marine sediments associated with the surface. The land flora and fauna must certainly have been eliminated at this time of total submergence.

Re-emergence is probably marked by the beach deposits at Passe Houareau, the terrestrial soils at Dune Jean Louis and sand banks around Ile aux Aigrettes. These are, however, terminated by a marine erosion surface.

The widespread deposition of the Aldabra Limestone between 137 000 and 114 000 years B.P., marked a sea-level rise to at least 10 m above present datum. Sedimentological data indicate that the rise was gradual and that many of the corals in the unit grew in rather shallow water. A local brief emergence, probably occurring early in the history of the unit, is suggested by the presence of irregular bedding planes sometimes coated with laminated terrestrial crusts and bored by *Cliona*. Sediments formed immediately after re-submergence seem often to have been a shallow-water facies (the *Strombus–Polynices* calcarenite). Later, however, Proto-Aldabra again appears to have been a totally submerged shallow bank with an annular rim of more prolific coral growth.

Following the last depositional event, there was a fall in sea level to produce the terrace seen at about + 8 m all around the atoll. A further fall in sea level with a still-stand (possibly in the late stages of the last inter-Glacial period) produced the prominent terrace at 4 m, with the raised cliff-line seen on lagoon and seaward shores. At this time Proto-Aldabra consisted of a narrow, low, rocky rim of islands with a shallow central lagoon, considerably larger than the present. It was once more open to colonization by a new terrestrial flora and fauna.

Further marine withdrawal may have been by as much as 100 m but we have no direct evidence for this extreme figure. It resulted in the formation of a high rocky island, probably approaching 400 km^2 in area and surrounded by steep cliffs. A shallow central depression was present at the summit of the island. This was a result partly of differential erosion of contrasted rock types and partly of case hardening (cf. McNeil 1954; Flint *et al.* 1953). Karst erosion and local deposition of residual terrestrial sediments took place on the summit, while the flanks were grooved and channelled by solution run-off. The sediments containing *Trophidophora* and other forest genera probably date from this time. It is not clear whether the occupation of the island by the Point Hodoul fauna of tortoises, crocodiles, birds and lizards took place before or after this low was reached. It seems obvious that such a fauna would have required a similar land area but could not have survived perched on 100 m high cliffs.

Since the maximum depression there has been a gradual rise of sea level to the present datum. There is some evidence of a post-Glacial level slightly higher than the present; this is seen particularly in the stromatolitic deposits around Takamaka and Cinq Cases and in some crab-burrowed calcarenites. These may have been formed by a sea level about 1–1.5 m above the present which could have occurred during the climatic optimum warming about 4000 years ago (Coetzee 1967).

One of the most significant events in the post-glacial history of Aldabra was the breaching of the land rim by the rising sea to form the present lagoon. This probably happened between 4000 and 5000 years ago and the present day, and it had the effect of reducing the land area by nearly 60 % with drastic effect on the composition of the terrestrial biota, causing widespread destruction of habitats and consequent extinction. Present-day erosion of Aldabra will result in continuing diminution of the land area. A summary of the relationships outlined is given in table 1.

TABLE 1. SUMMARY OF THE MAIN EVENTS IN THE GEOLOGICAL HISTORY OF ALDABRA SEEN IN THE SURFACE ROCKS

age	event	position of sea-level relative to present	land area and biota
	quiet water sands (10–20 m) shallowing upwards into intertidal mangrove covered sand flats	+ 8 m at least	no evidence
	emergence; phosphates deposited on subaerially eroded surface; further emergency caused erosion of phosphates to form phosphate conglomerates	+ 8 m falling to 0, still-stand at + 4 m?	Evidence of land only in Esprit area; no faunal data
	sand cay in Bassin Cabri area, prograding over subtidal sand flat; sand dunes on south coast	+ 1 to 2 m	at least 20 km², vegetated and with tortoises, crocodiles, birds, snails and freshwater ostracods
	submergence; colonization of Proto-Aldabra shallow bank by *Thalassodendron* and calcareous algae; few corals or molluscs	+ 4 m at least	no evidence, possibly no land
	emergence; lithification and erosion of cliffs	+ 0.5 to 1 m?	300 km²?
	submergence; Proto-Aldabra a broad shallow bank with a ring-like ridge around the periphery	+ 3 to 5 m	no evidence
	emergence; sand-cay, beaches and sand flats at east end	+ 2 m	25 km², land and freshwater snails
125 000 years B.P. absolute age	submergence; Aldabra a broad, shallow bank; corals abundant around the edges and *Halimeda*-sands and coral-knolls within; temporary emergence near the base of this deposit	+ 10 m	none, except temporary emergence near base
inferred age 80 000 years B.P.	emergence, cutting terraces at 8 m and 4 m; during the latter period Aldabra emerged as a ring of narrow, low rocky islands	+ 8 m and then 4 m	50 km², then increasing; colonized by tortoises, crocodiles, lizard, birds and snails
inferred age 27 000 years B.P.	continued emergence, Aldabra a high, steep sided, flat topped, rocky island; solution erosion of grooves and buttresses	− 100 m	400 km²; vegetated many snails and ? tortoises
13 000 years B.P. present day	submergence, flooding of lagoon (5000 years B.P.?) area to form present configuration	− 100 m to 0 (oscillation to + 0.5–1 m?)	155 km²; present biota

Implications of the study

Current textbooks of geology, and many papers, illustrate the growth of reefs and atolls as a continuous accretionary sequence. The main facies, reef-core, fore-reef, and back-reef, are shown as occupying the same relative positions over considerable periods of time. In contrast, the evidence on Aldabra clearly shows the piecemeal nature of accretion. Deposition is punctuated by erosion, and there are often major facies changes between increments, some of which do not represent 'reef' environments. Aldabra is not an atoll in the sense in which the word is usually understood. The lagoon is a rock-floored erosion feature produced by solution of raised limestones whose facies variations have had little influence on lagoon morphology. The present 'reef' (seaward platform) has had a long history. It is not there because of any coral reef growth, but as a result of erosion. Similarly, if the environment of deposition of the Aldabra Limestone can be described as having been a 'reef' (and this is arguable) it was only so because of a basic morphology inherited from erosion of the Takamaka Limestone beneath. Aldabra thus lends support to the inferences of atoll growth propounded by Flint *et al.* (1953) and McNeil (1954).

A pervasive view, among both zoologists and palaeontologists, is that coral reefs represent an ecosystem stable over many thousands or even millions of years. This stability is thought to account for the very high diversity of organisms associated with reefs, which act as refuges for forms driven out of more variable fluctuating environments (the 'diversity pump' of Valentine (1969)). Our evidence shows that the 'reef' habitats around Aldabra have altered dramatically in response to sea-level changes in the very short time span of the late Pleistocene, a conclusion that will probably be true for other atolls when these are investigated more fully, which is in contrast to the opinion of Newell (1971, p. 21) that Pleistocene sea-level changes had very little effect either upon the character of the size of habitats available. The changes in habitats on Aldabra have resulted in corresponding changes in the marine biotas. Thus, the four main marine events recognized (including the present) yield four very different assemblages of molluscs and corals. The deposits of three of these events have yielded fossils which are now absent from the Indian Ocean, an absence that indicates widespread late-Pleistocene zoogeographical changes in an area presumed to have been environmentally stable. Increasing attention to the global aspects of climatic variation and glacio-eustatic sea-level changes in the Pleistocene is revealing that changes in the tropical environment, although not as dramatic as those at higher latitudes, nevertheless had significant effects upon the biota.

The present terrestrial biota is but one of a series: the history of Aldabra, marked by successive emergences and submergences, records a pattern of repeated colonization by and extinction of land animals. The diversity of the fauna has, on each occasion, been controlled by the area of the land available to it, and three similar land masses, separated in time, have come to bear similar terrestrial biotas.

Appendices

The following notes are included for the benefit of non-geological workers on Aldabra and similar islands. They draw attention to points arising from this study which may influence their results.

The geological history of Aldabra and the present terrestrial biota

It is obvious from the summary history outlined above, that the size, shape and character of the islands has been constantly changing. Some of these changes have been fairly extreme, so that at various times Aldabra has been a sandy cay, a steep-sided rocky island, a low ring of rocky islets or totally submerged. This restless history is derived only from the exposed late-Pleistocene sequence; we have no record of events earlier in the Pleistocene which might have produced equally dramatic changes over a much longer period of time.

Any discussion on the origin and evolution of the present day terrestrial biota must take into account these changes, particularly those involving area and habitat. This is particularly so in view of the close correlation found between the area of an island and the number of species it can support (MacArthur & Wilson 1967; Peake 1969, 1971).

Some fossil terrestrial faunas found in the course of this work provide direct evidence of colonization, while extinction is inferred from their absence in overlying (marine) sequences. Tortoise bones have been found in nearly all of the terrestrial deposits and yet the atoll has probably been completely submerged at least twice in this history of occupation; once during the deposition of the Aldabra Limestone (approx. 125000 years B.P.) and once (more tentatively), during the deposition of the Takamaka Limestone. Land-living species must have been wiped out by each inundation, and we can only conclude that the land has been colonized by tortoises on at least three occasions. This may not be such a problem as it appears, for tortoises were once much more widespread on the islands of the Western Indian Ocean and, as shown by Gaymer (1968) and Grubb (1971) the marine dispersal of these animals is quite feasible.

Somewhat similarly, crocodile remains are found both in the Bassin Cabri Calcarenites and in deposits formed since 100000 years B.P. They are now locally extinct and were also, presumably, absent in the interval between these two sediments. The same kind of pattern applies to terrestrial gastropods, and several species of these are now extinct on the islands. These are particularly interesting since the number of species found in any deposit correlates well with our estimates of the land area at the time of its formation.

A direct influence of the geology upon the present fauna is seen in the choice of nest sites by the tropic birds *Phaeton lepturus* and *P. rubricauda*: Diamond (1971, especially Fig. 1) has described and classified the types of small lagoon islets chosen by these birds for nesting. Extrapolating from Diamond's diagram *P. rubricauda* nests only on high islets with substantial thicknesses of Aldabra Limestone, but *P. lepturus* nests preferentially upon islets either formed entirely of Takamaka Limestone, or with only small residual deposits of Aldabra Limestone.

The relation of geology to present vegetation patterns

The vegetation of Aldabra has been discussed by Stoddart & Wright (1967), Fosberg (1971), Renvoize (1971) and Grubb, (1971). Comparison of the geological map with the Aldabra vegetation map (D.O.S., 1:25000, 1970) shows the striking correspondence of the distribution of thick *Pemphis* scrub with that of dissected areas of the Takamaka Limestone. *Pemphis* scrub forms the most uniform and the most widespread of the Aldabra vegetation units. The correlation between rock type and vegetation is very close, for even small inliers of Takamaka Limestone, only a few metres in diameter and completely surrounded by Aldabra Limestone, support thick stands of *Pemphis*. The Takamaka Limestone is fairly uniform in lithology, lies between 1 and 2 m above sea level and is often extremely dissected. South of Takamaka Grove, however, exposures are usually of the exhumed erosion surface between the Takamaka and Aldabra Limestones. This dense and impermeable surface is often bare rock, but in general it supports a much more open and varied vegetation than the *Pemphis* scrub. The critical factors controlling the vegetation are unknown, but they may include porosity (availability of root-space) and the position of the water table.

The wide land area at the southeast of the atoll supports a very complex vegetation of scrub forest, mixed scrub, open grass and sedge swards (Grubb 1971, with map). The rock substrate in this area varies between normal Aldabra Limestone, the very hard *Polynices–Strombus* bed (within the Aldabra Limestone?), late depositional terrestrial crusts, stromatolitic mammillated surfaces and patches of Takamaka Limestone. Some higher residuals of Aldabra Limestone and more resistant cavity-fill deposits are also present, rising up to about 1 m above the surrounding level. There is little doubt as to the general correlation between the diversity of rock types and diversity of vegetation, and it seems likely that some vegetation types are very closely controlled by lithology and surface texture.

The influence of geology on geomorphology

The geomorphology of Aldabra has been summarized by Stoddart *et al.* (1971) and the terms *champignon*, *pavé* and *platin* have fallen into general usage applied to distinctive parts of what Fosberg (1969) considered as a genetically related sequence. It is admitted (Stoddart *et al.* 1971) that this classification is a gross over-simplication, but some simple organization of morphological types is clearly necessary in biological habitat description.

The investigation of the geology has revealed that present geomorphology depends upon a number of factors. These include, the original lithology and the diagenetic history of each formation, subsequent elevation-submergence history of each part of the atoll, and past and present weathering processes. The relative importance of any one of these factors can vary considerably in different areas, and has also changed with time. It is thought that, with our present state of knowledge, any increase in the detail of classification, as suggested by Stoddart *et al.* (1971), will result in confusion rather than greater clarity.

Areas now designated *platin* at the southeast corner of the atoll have the common property that they are fairly flat. In detail, however, their morphology varies considerably depending upon origin and history. Thus, the *platin* to the south of Takamaka Grove largely consists of an exhumed marine erosion surface limiting the Takamaka Limestone. This almost flat bench, bored by *Lithophaga* and *Cliona*, was eroded over 140000 years ago. It has been re-exposed by marine erosion during the cutting of the 4 m terrace (post-100000 years B.P.) and by post-Glacial and Recent subaerial processes. In contrast, the platin of Cinq Cases consists largely of Aldabra Limestone and, although 'flat', is generally less uniform than the Takamaka surface. It was eroded, possibly by solution, at the time of formation of the 4 m terrace, and has been modified in detail by subsequent subaerial erosional and depositional processes.

The general term *champignon* has been applied to severely dissected Esprit Limestone, Takamaka Limestone and Aldabra Limestone. In detail the morphologies produced on these three rock types are very different, and there may be considerable variation on a single rock unit as a result of exposure to different present day weathering processes. The Aldabra Limestone, for example, is much more severely dissected on an exposed cliff top than in a sheltered position further from the shore. Most of the *champignon* occupied by *Pemphis* scrub is formed by dissection of the Takamaka Limestone, partly by present-day rainfall-solution and partly, it seems, by the exhumation of a previous subaerial surface. The spectacular, pinnacled, dissection of the Esprit Limestone probably also results in part from the re-excavation of old weathering features.

The term *pavé* has been applied to the morphology on the summit of the 8 m ridge. This always consists of Aldabra Limestone but, as shown in the foregoing account, the top of this ridge is probably an old erosion surface and has had a much longer subaerial history than the lower areas.

The profiles of cliffs have been used as an index of energy of exposure (Stoddart & Wright

1967, p. 17; Taylor 1971, p. 176). This is a useful general principle, but with certain qualifications. It has been found that the very high vertical cliffs, such as at Point aux Vaquas and east of Anse Cèdres, occur where present-day cliff erosion intersects the 8 m terrace. In certain other places the unconformity between the Takamaka Limestone and the Aldabra Limestone occurs within the cliff face. At these sites differential erosion along this interface causes increased undercutting and sometimes collapse of the upper limestone, for example at Point Passe Femme (0583.0913). On the east side of Passe Houareau, some of the cliff features are caused by the exhumation of cliffs cut into the Takamaka Limestone before the deposition of the Aldabra Limestone.

It is thought that any genetic classification of land forms would be premature, while a purely morphological classification should be tailored to indidividual needs. The terms *champignon*, *platin* and *pavé* are useful general terms and should be retained with the qualification that each covers a multiplicity of forms, often of different origins and histories. Further subdivision of these categories becomes difficult or impossible to apply, and it is probably best that any more detailed classification be evolved only for individual research needs. These will certainly be different and tortoise workers, for example, may ascribe importance to particular landforms which seem of no consequence to a botanist.

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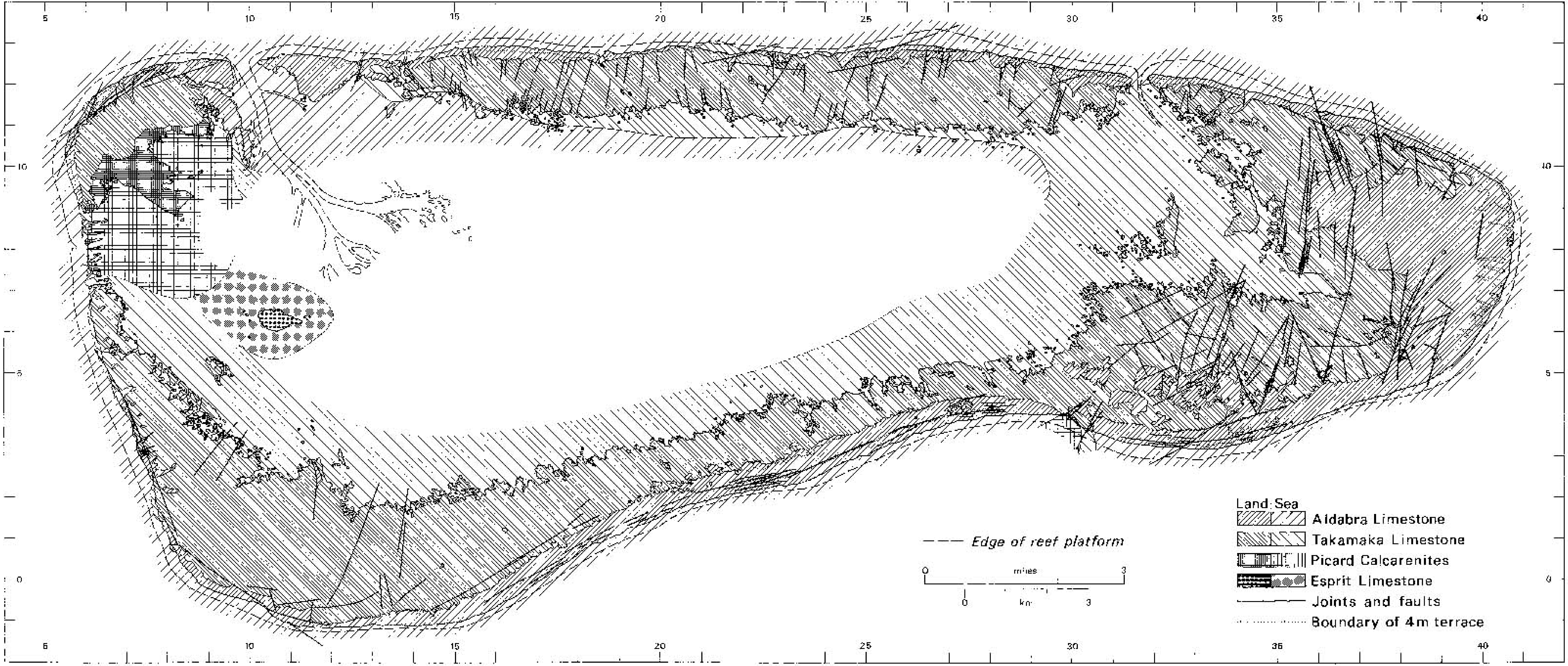
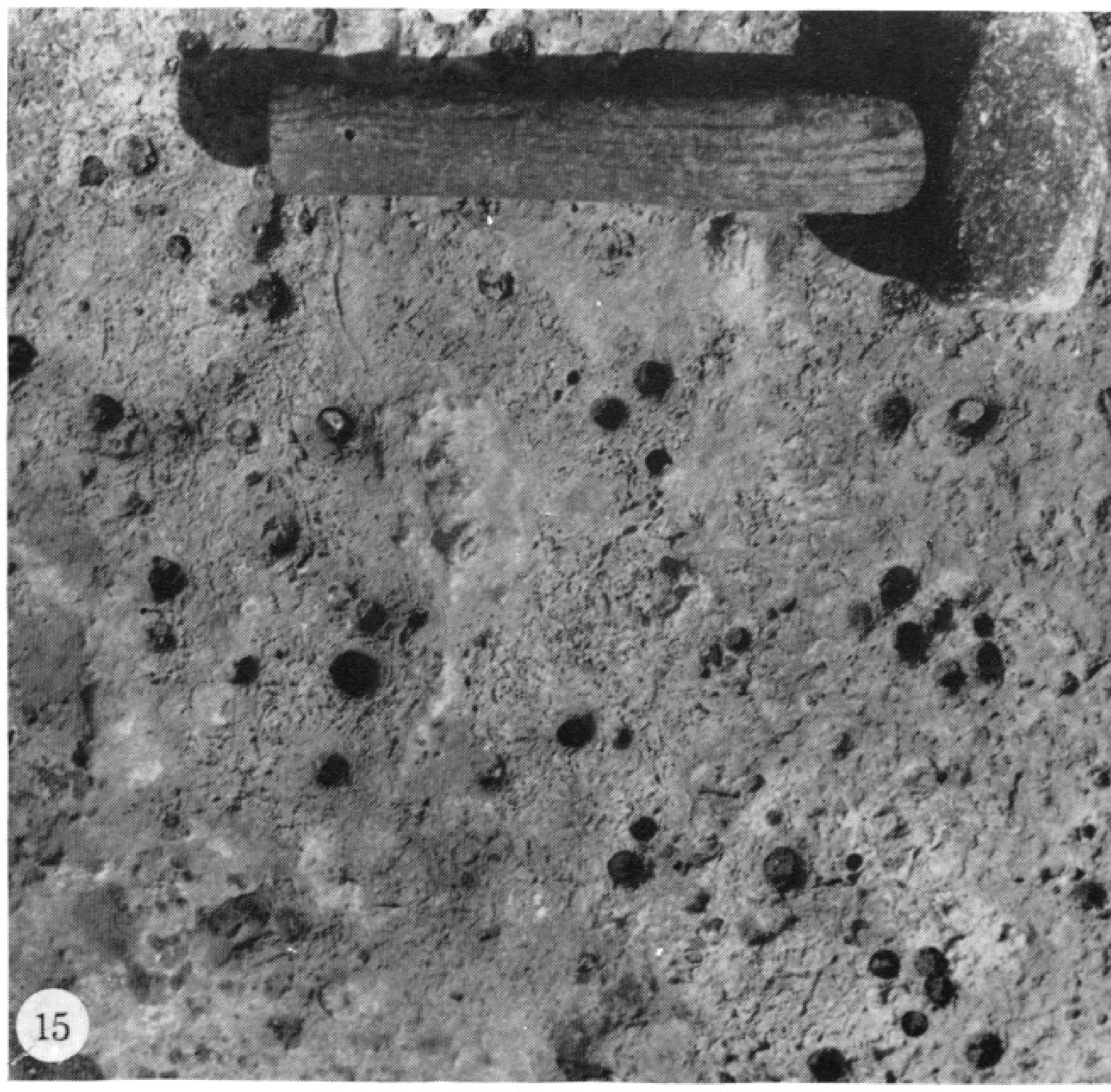
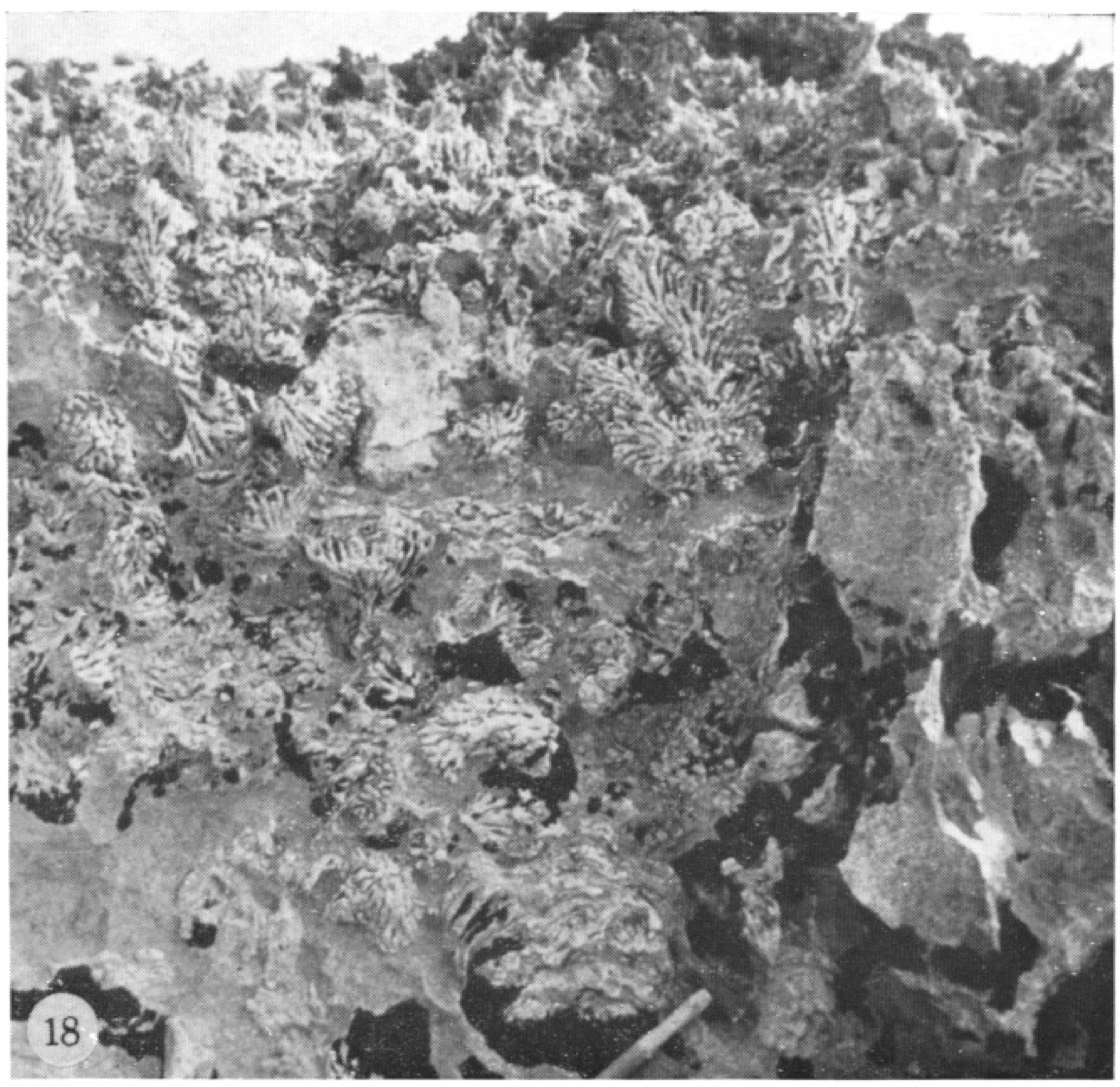


FIGURE 3. Geological map of Aldabra.

(Facing p. 310)

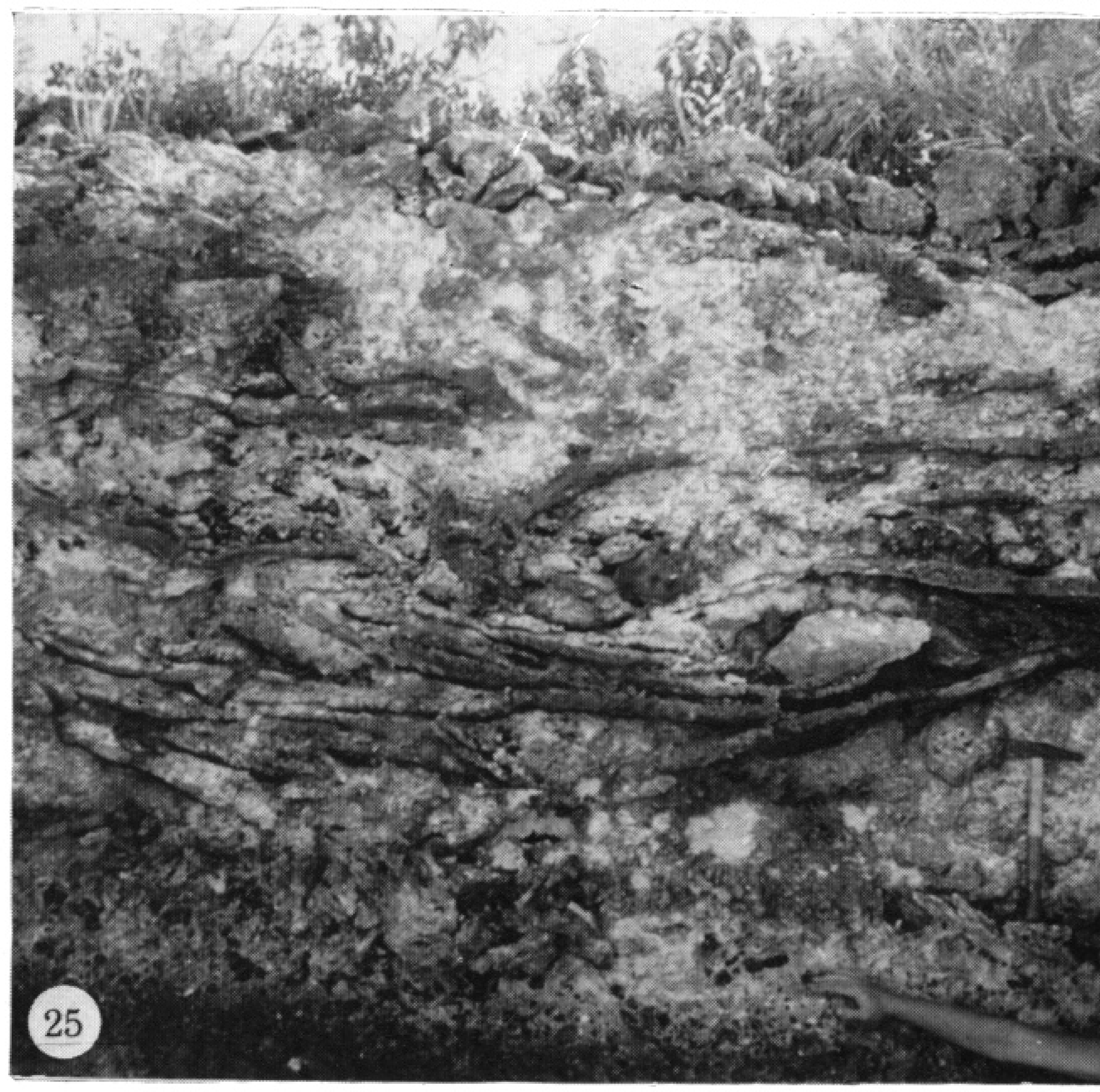
FIGURES 8–13. For legends see facing page.

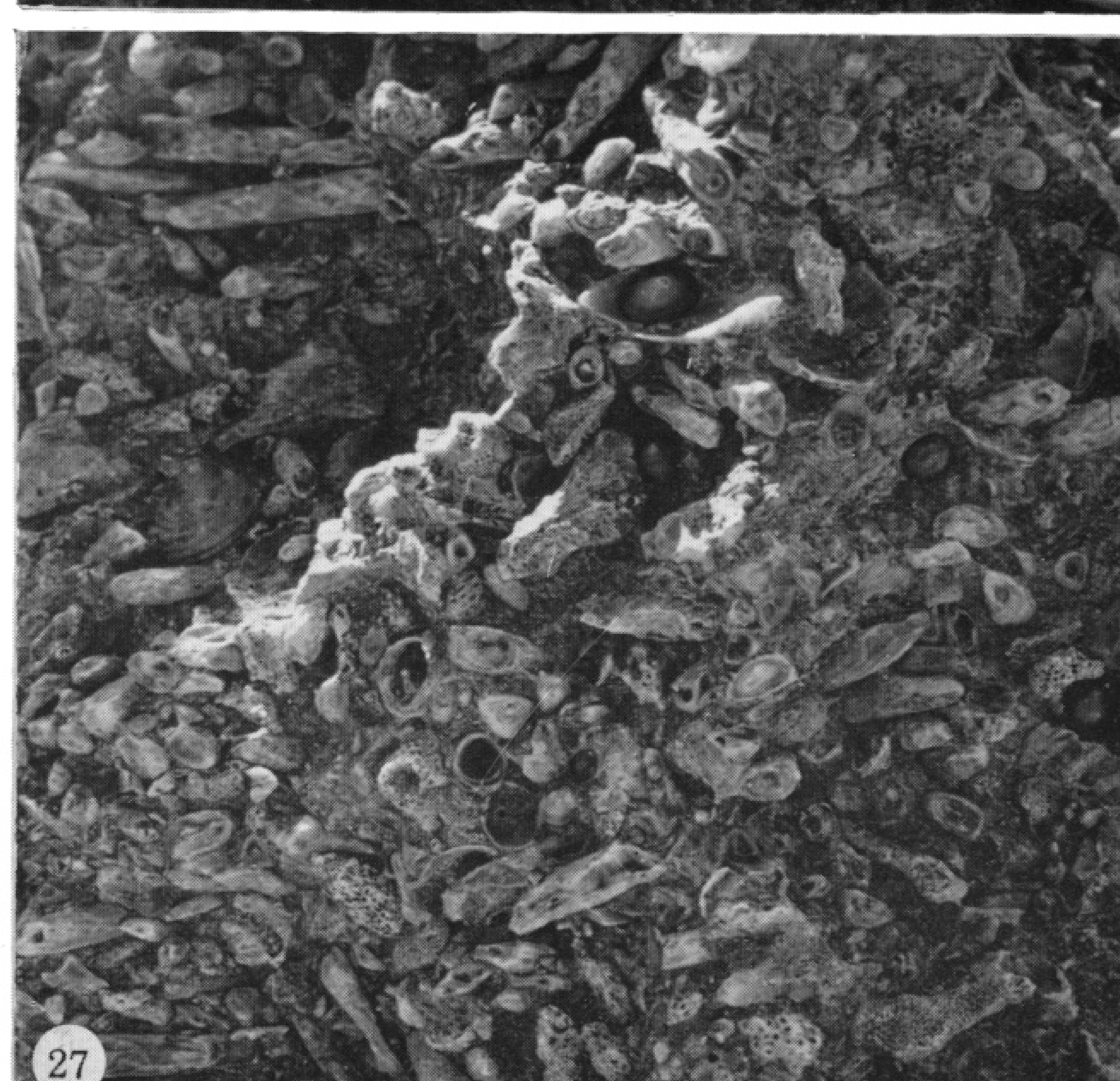




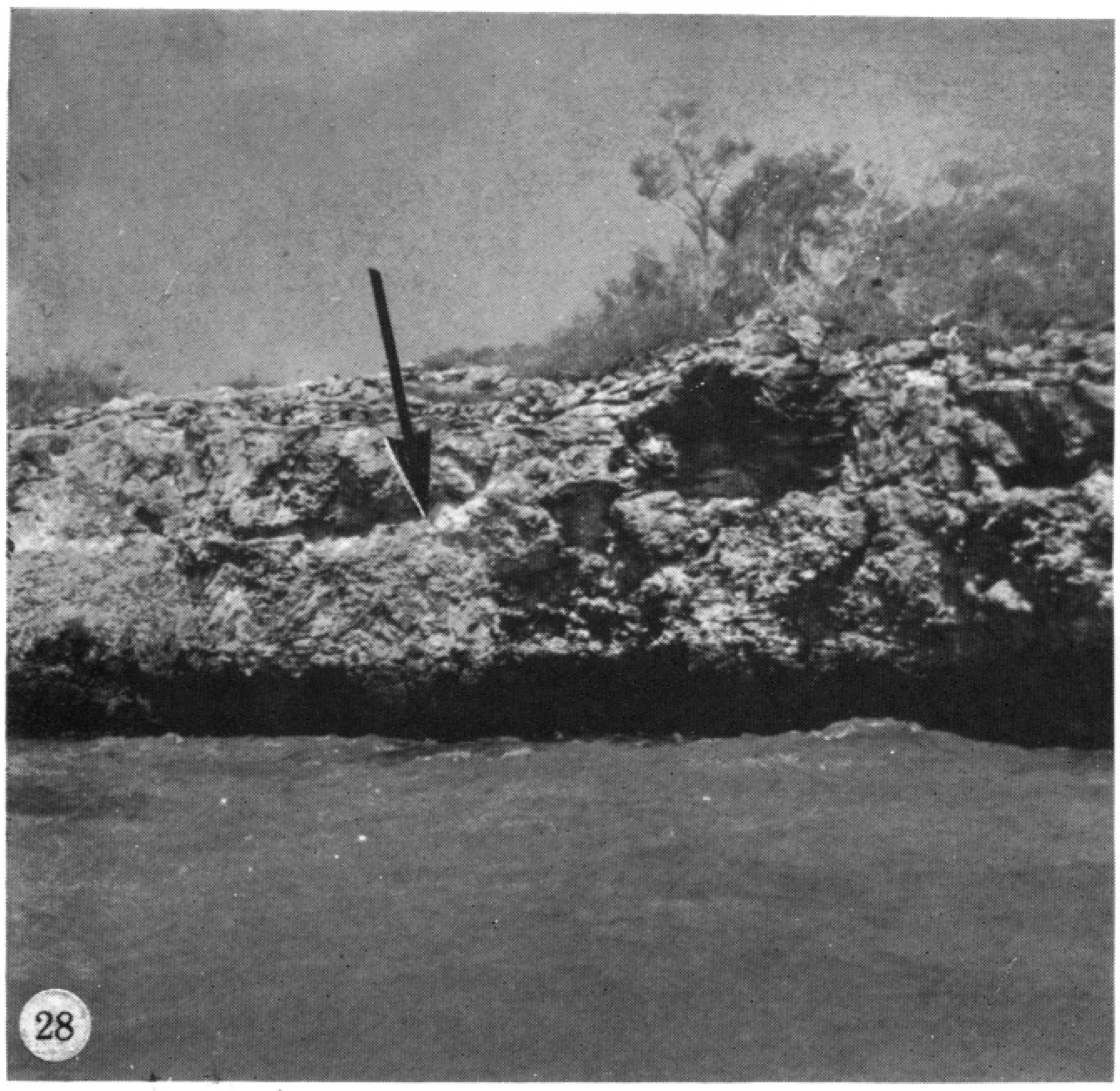
FIGURES 14–19. For legends see facing page.

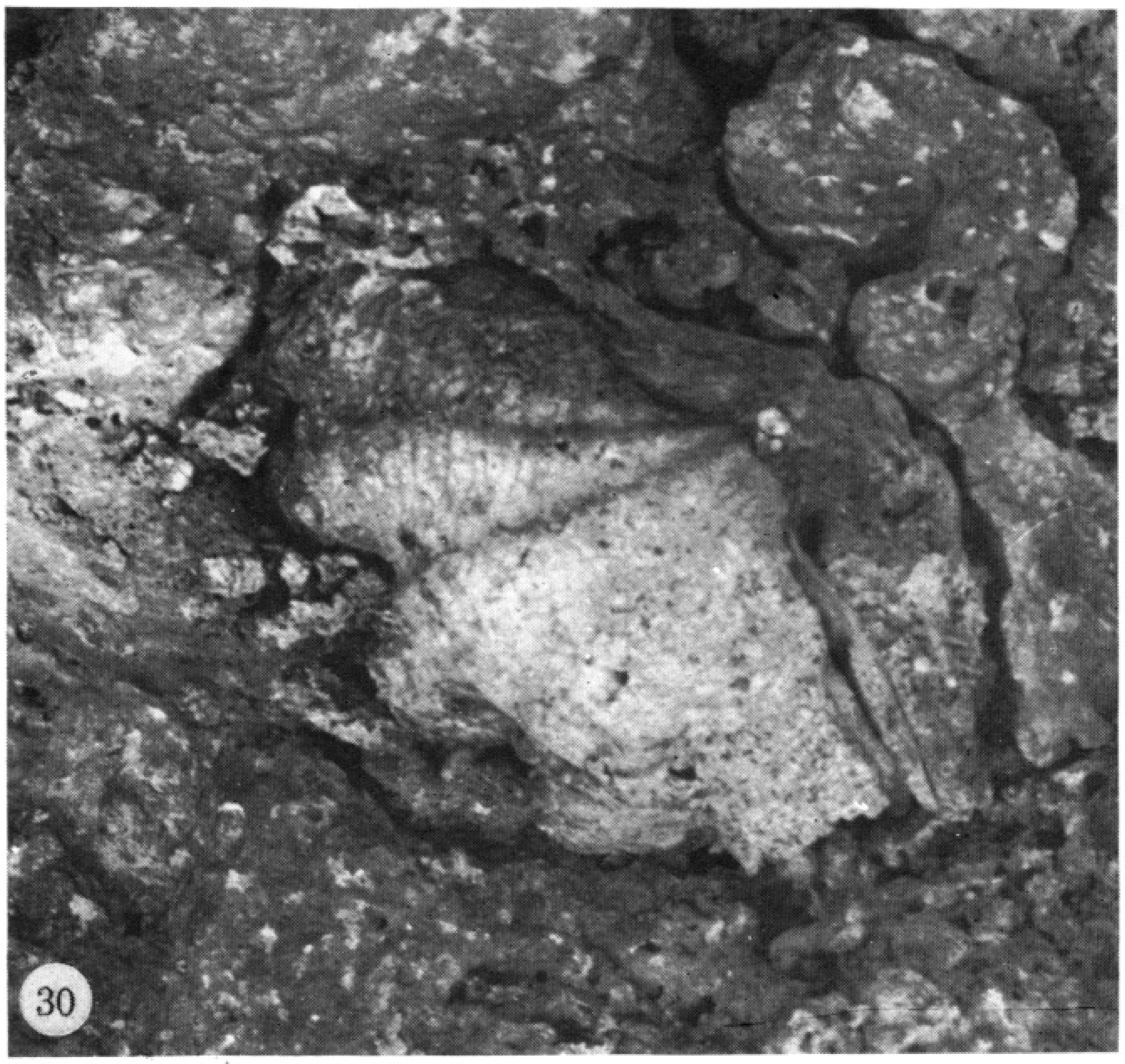


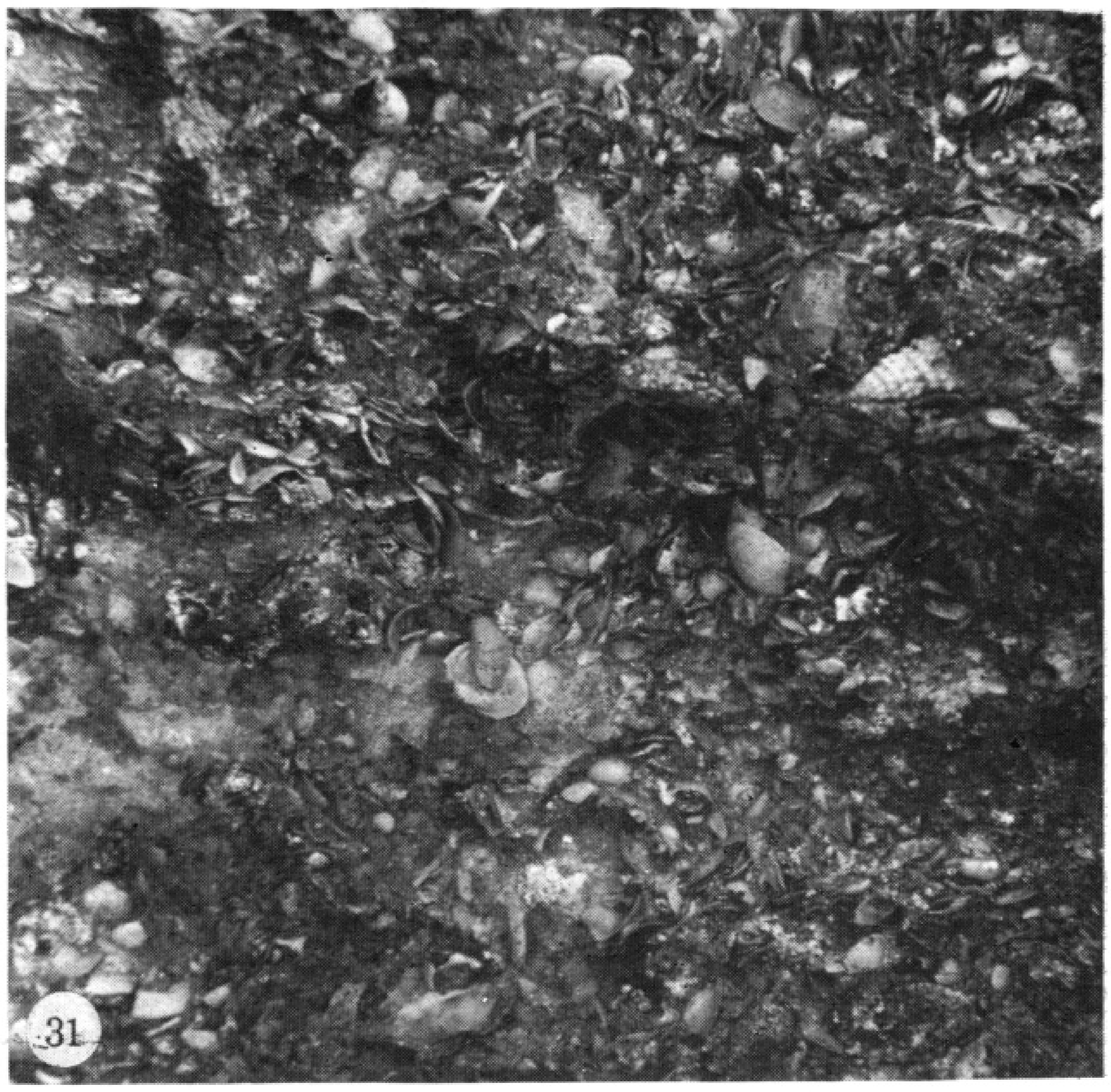



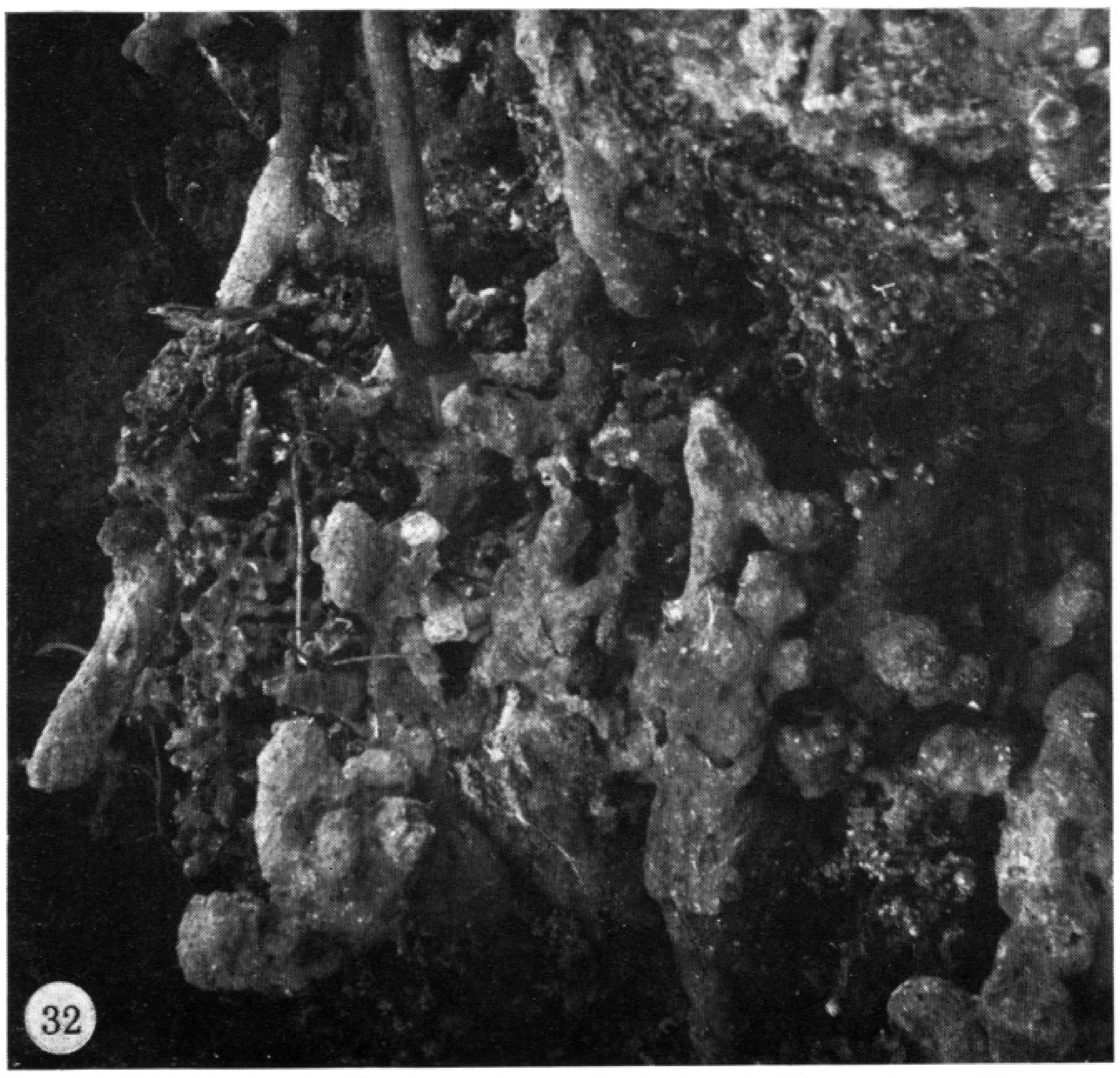


FIGURES 22–27. For legends see facing page.









FIGURES 28–33. For legends see facing page.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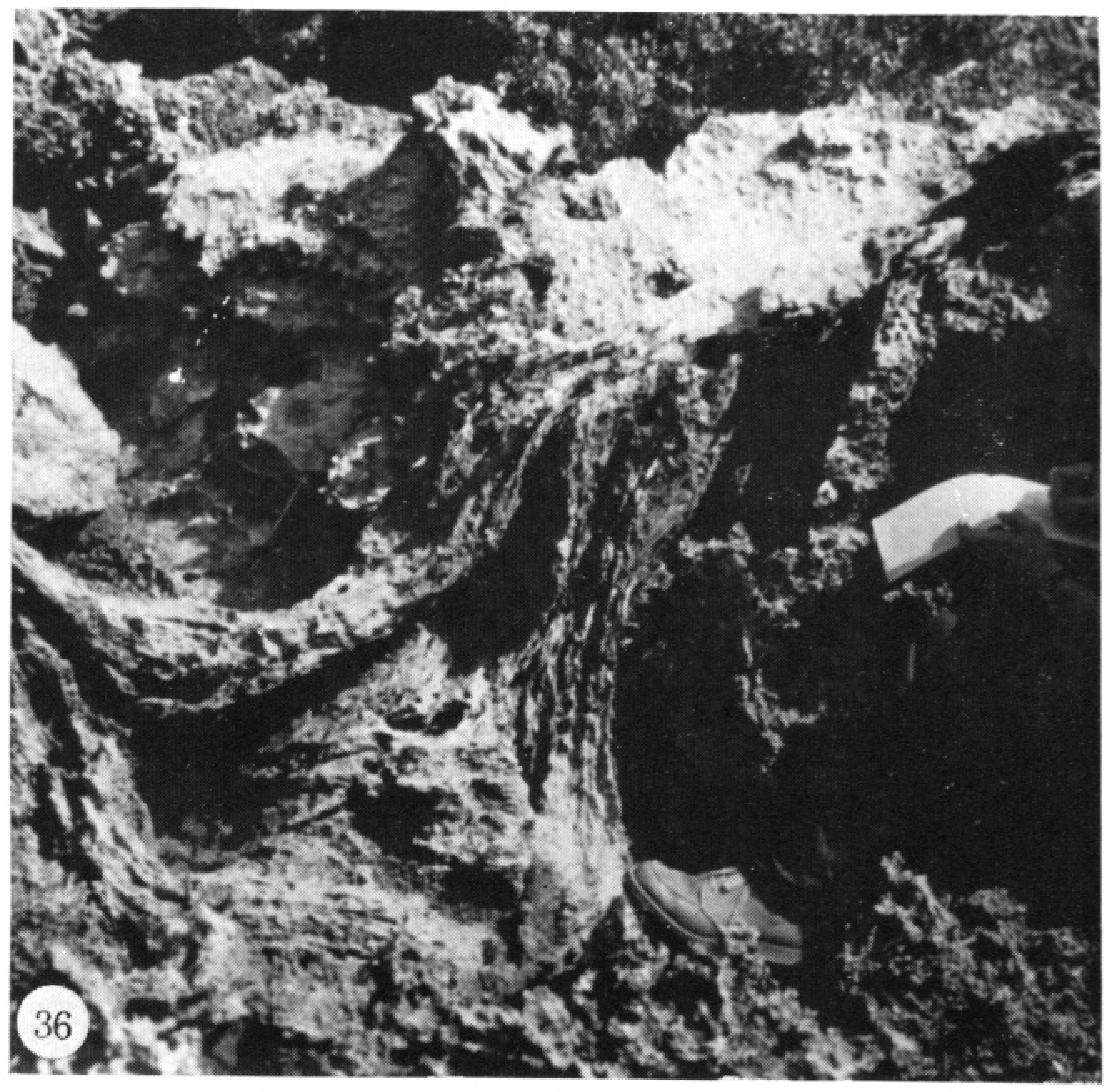
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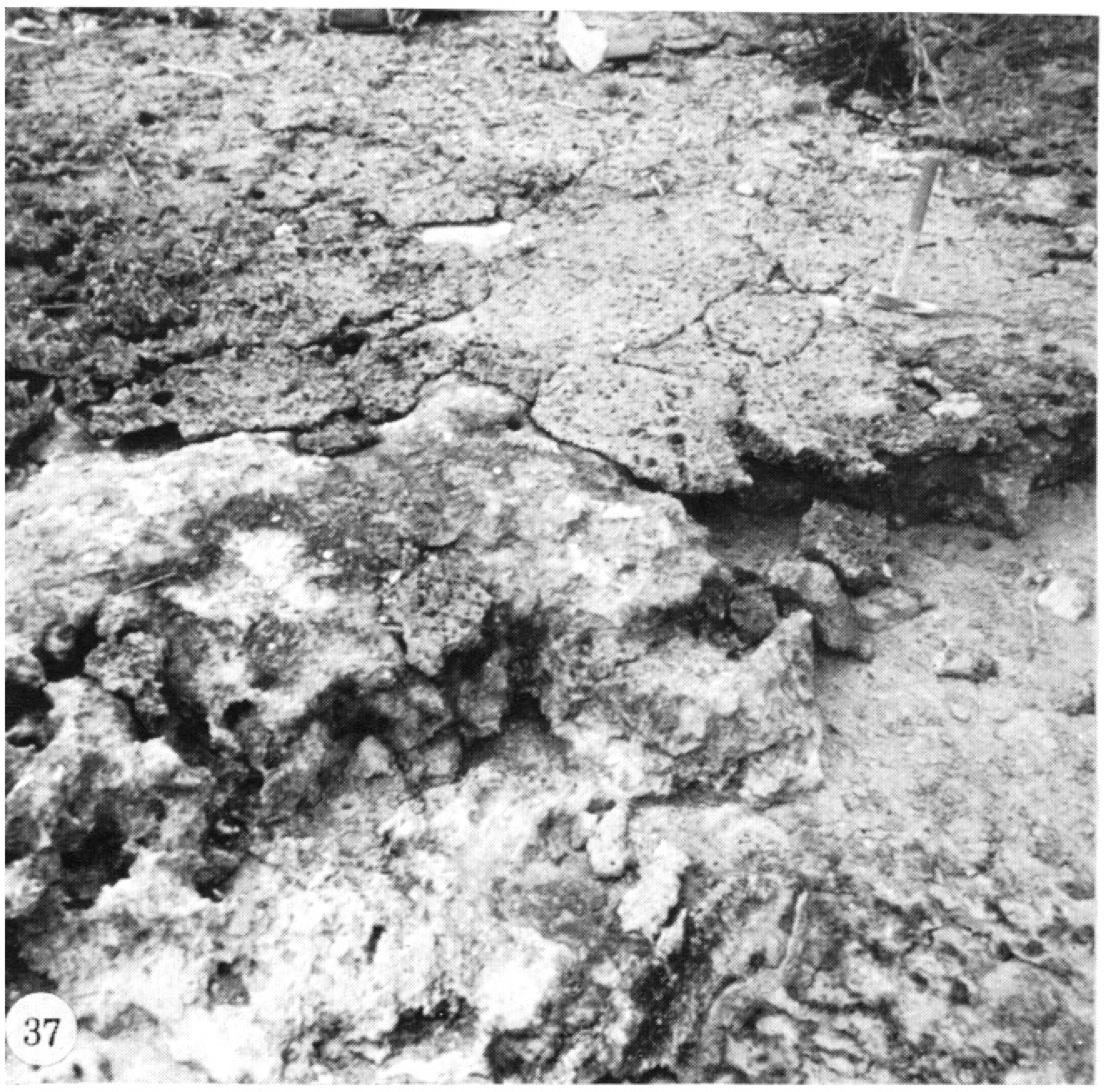
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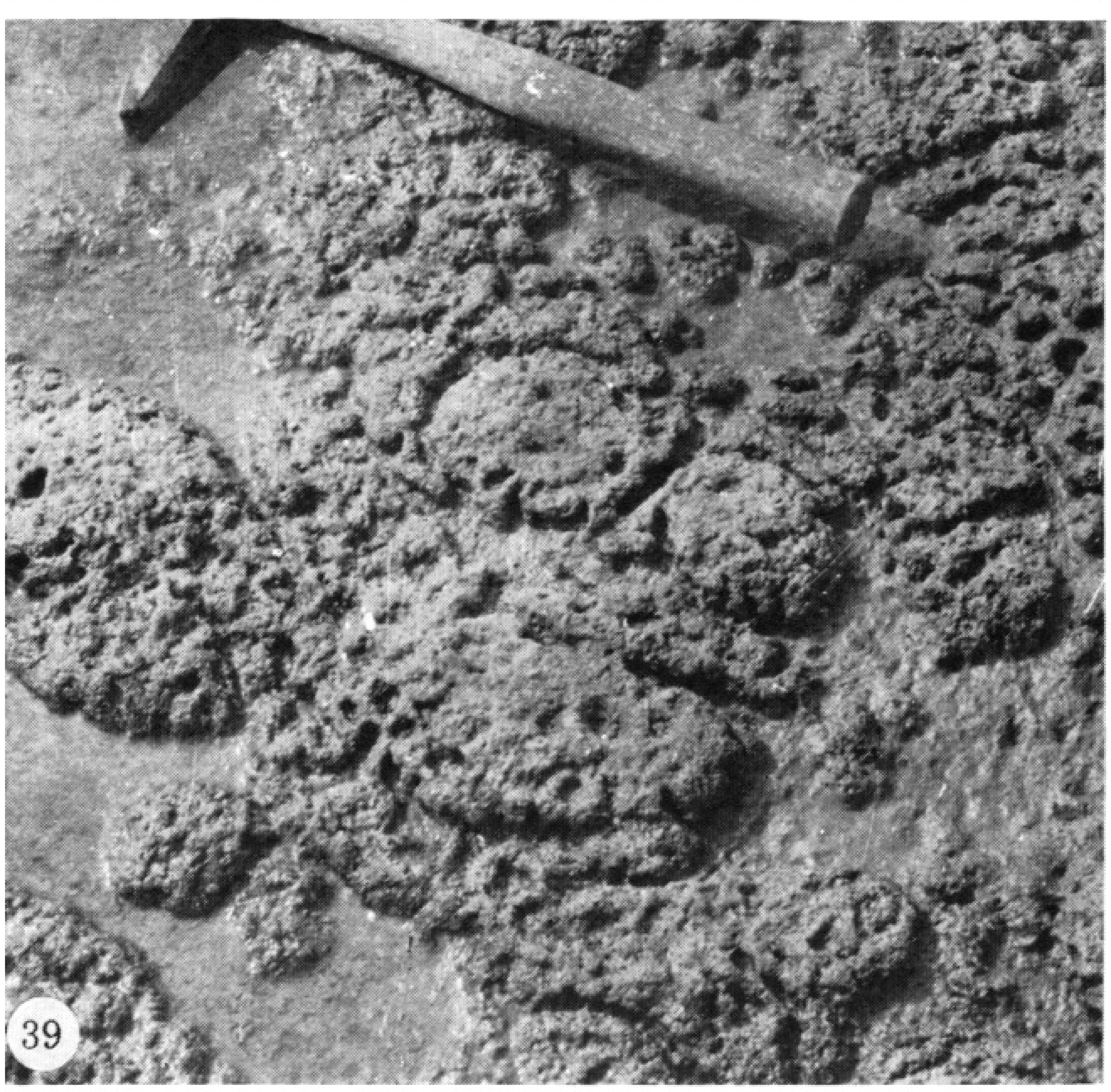
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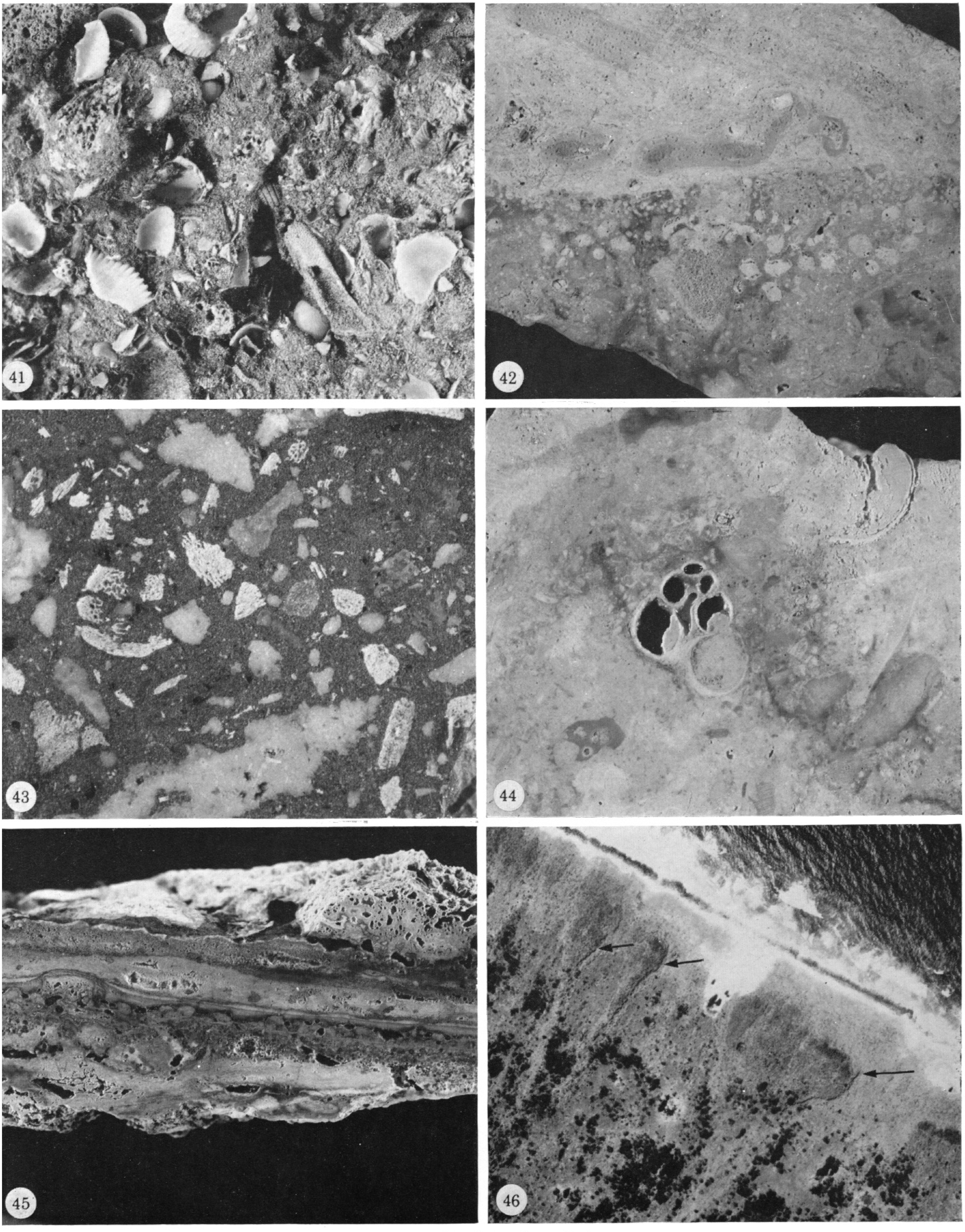
FIGURES 35–40. For legends see facing page.



FIGURES 41–46. For legends see facing page.