Lithology and Origin of Middle Ordovician Calcareous Mudmound at Meiklejohn Peak, Southern Nevada

GEOLOGICAL SURVEY PROFESSIONAL PAPER 871

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By REUBEN JAMES ROSS, JR., VALDAR JAANUSSON, *and* IRVING FRIEDMAN

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A description of the various carbonate sediments constituting the Stromatactis-*rich mound core and the basal "zebra limestone," isotopic analyses of contrasting components, and review of possible complex origins of components*

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LITHOLOGY AND ORIGIN OF MIDDLE ORDOVICIAN CALCAREOUS MUDMOUND AT MEIKLEJOHN PEAK, SOUTHERN NEVADA

By Reuben James Ross, Jr., Valdar Jaanusson[1], and Irving Friedman

ABSTRACT

The large dome-shaped (300 m wide by 80 m high) calcareous mudmound at Meiklejohn Peak is the largest and most accessible of three such Ordovician mudmounds in southern Nevada. It has been studied in hopes of deciphering the origin of zebra limestone which forms its base and of *Stromatactis* which is abundant in the main, virtually unstratified, core of the mound. The mudmound is completely enclosed within the Middle Ordovician Antelope Valley Limestone; it is underlain by calcarenite and poorly laminated limestone of the Paiute Ridge Member. Silty limestone of the Ranger Mountains Member intertongues with the lower third of the mound and abuts against and completely covers its higher parts.

Cyclic laminated zebra limestone that forms the lower part of the mudmound is characterized by repeated sequences of three, or two, distinctive calcilutites. Radiaxial fibrous calcite separates some cycles; in these the third calcilutite tends to be missing. The origin of zebra limestone may be variously attributed to formation of submarine hardgrounds, to parallel shear cracks, to displacive precipitation, or to the precipitation of radiaxial fibrous calcite in parallel cavities of incredible extent. Some radiaxial calcite may have filled cavities but most resulted from recrystallization or neomorphic aggradation of other preexisting metastable carbonate.

It seems likely that origin of the zebra limestone was linked to algal mats in light of geologic and geochemical evidence.

The core of the mound is composed of 40–60 percent calcareous mud, 20–60 percent sparry calcite, and 4–11 percent skeletal sand. *Stromatactis* is a prominent constituent of the sparry calcite. Regardless of the origin of *Stromatactis* as such, the radiaxial fibrous calcite crystals are the result of diagenetic change. The calcareous mud of the mound comprises at least two and possibly three generations. Within skeletal sand, echinoderms predominate; spicules, possibly of sponges, are second in abundance. Ostracodes outnumber trilobites. Neither bryozoans nor any other organism seems to have been present in numbers adequate to bind the mound sediments together.

Stromatactis seems to represent cavity fillings. The radiaxial mosaic of *Stromatactis* was fully developed before the mound had ceased to grow. This indicates an early lithification of the mound.

Examination of isotopes of oxygen and carbon indicates that calcilutites and radiaxial fibrous calcite formed in the same seawater. No evidence for fresh vadose water is present.

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INTRODUCTION

Three Middle Ordovician carbonate mudmounds are known in southern Nevada (localities shown in fig. 1, this report; Ross and Cornwall, 1961; Ross, 1972, fig. 1). These mounds resemble somewhat younger Ordovician features in the Siljan district, central Sweden (Thorslund, 1936; Thorslund and Jaanusson, 1960, p. 24-35), and Carboniferous "knoll reefs" of northwest and west-central Ireland (Schwarzacher, 1961; Lees, 1964). Development of sparry calcite in the main part of the biggest of the Nevada mudmounds may have some relation to structures called *Stromatactis*, well known in middle and upper Paleozoic mudmounds in Western Europe (Black, 1952; Bathurst, 1959; Schwarzacher, 1961; Lees, 1964; Jaanusson, 1975). In the basal part of the Nevada mound there is enigmatic, thinly interlayered calcilutite and sparry calcite which together resembles "sheet spar" described by Lees (1964, p. 523-524) and "zebra limestone" described by Fischer (1964, p. 115, figs. 15, 17, and 18).

At least three generations of sparry calcite are present. In the early phase of development there were two generations, one producing *Stromatactis* and the other producing the laminar sparry calcite near the base.

Limestone boulders, some of prodigious size, are known in southern Quebec (Mystic conglomerate) (Cooper, 1956, p. 14, 15, 31) and at Lower Head, western Newfoundland (Whittington, 1963, p. 7). Although no *Stromatactis* has been reported in them, some of these boulders are composed of limestone seemingly very similar to that in the main body of the Nevada mudmounds and the fossils obtained from them are so similar that their temporal correlation seems obvious (Cooper, 1956, p. 15, 31; Whittington, 1963; Ross, 1967, 1970, 1972). Fossils from beds surrounding these boulders in Newfoundland corroborate the correlation with beds covering the Nevada mudmounds.

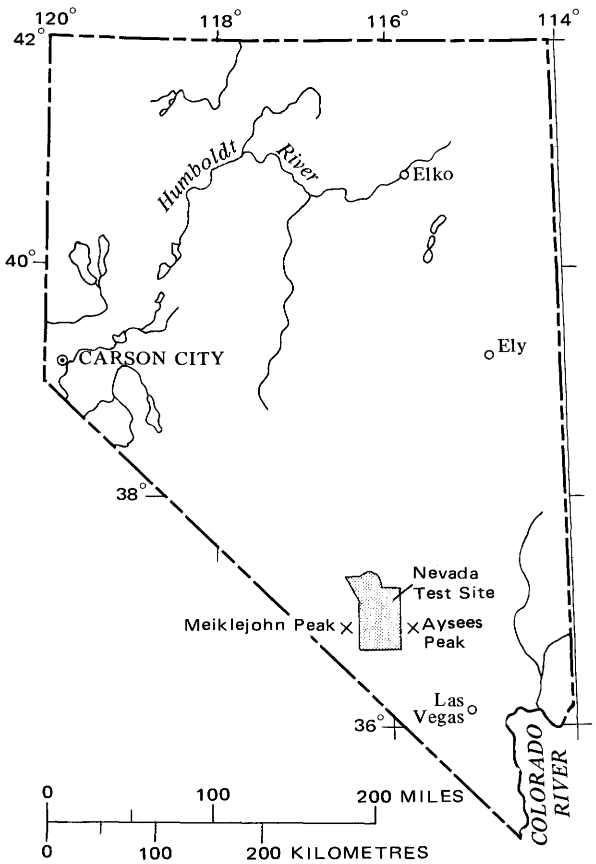


FIGURE 1. — Map of Nevada showing location of Nevada Test Site. Coevally formed Middle Ordovician mudmounds are known at Meiklejohn Peak and near Aysees Peak.

The largest and most readily accessible Nevada mudmound is on the west face of Meiklejohn Peak, Bare Mountain quadrangle, 6 miles east of the town of Beatty, Nev. (fig. 2; Ross, 1972, fig. 2).

Cephalopods from this mound have been studied by R. H. Flower; a stratigraphic resumé of the fossils of the mound and covering beds, as well as descriptions of brachiopods and trilobites, was presented by Ross (1967, 1972). Krause (1972) studied the inarticulate brachiopods of the mudmound and the covering beds; he concluded that infaunal lingulides preferred the covering beds, whereas abundant acrotretids probably were attached to algae on the mound. The numerous complete bivalved acrotretids indicate that the upper part of the mound was deposited in relatively quiet water. A Master's thesis by Elizabeth Stilphen Yancey (1971), mentioned this locality.

PURPOSE OF REPORT

It is our purpose to describe the calcareous mudmound at Meiklejohn Peak in more detail than has been attempted previously (Ross, 1972), to compare it with similar structures in Europe with which Jaanusson has the greater familiarity, and to describe and speculate about the origins of various kinds of sparry calcite and about origins of the mound itself.

The origin of the carbonate mudmound at Meiklejohn Peak has been enigmatic ever since the mound was first reported (Ross and Cornwall, 1961). Though it constitutes only a small part of the total volume, the origin of the basal zebra limestone facies has been particularly puzzling.

Most colleagues knowledgeable in the study of carbonates with whom we have discussed possible origins have urged us to consider the high proportion of radiaxial fibrous calcite as the filling of former cavities. But all those who have accompanied us to the mound have agreed that, geologically and mechanically, cavities amounting to 60 percent of the volume of the basal facies are unreasonable and that the spar must have preferentially replaced some other material.

It is our belief that the kinds of deformation shown by the laminated zebra limestone must have taken place prior to lithification and that many of these reflect earlier topography over which consecutive parallel laminae have been draped.

In the main body of the mound *Stromatactis* accounts for about 20 percent of the volume. Some of it may have filled cavities but at least part replaced preexisting carbonate mud.

ACKNOWLEDGMENTS

In examining the mudmound in the field, we had the assistance of N. F. Sohl in 1969, W. T. Dean and Ellis Yochelson in 1970, and A. J. Rowell and F. F. Krause in 1972, each of whom gave important suggestions about field observations and their interpretation. In particular, Rowell and Krause pointed out that mound sedimentation, whether along the base or above interfingerings of flank lithology high on the sides, is initiated by the laminated facies. Our conversations with J. L. Wray, Richard Rezak, L. A. Hardie, R. N. Ginsburg, P. R. Rose, and M. J. Brady have been concerned mainly with possible origins of the mudmound and expectable effect of algae on sedimentation. We are indebted to R. E. Wilcox for his petrographic examination of minerals in the insoluble residues from the laminated facies of the mudmound and to B. F. Leonard III and W. N. Sharp for X-ray diffraction identification of the same residues. Leonard and D. M. Pinckney have discussed replacement fabrics in carbonate rocks with us; O. B. Raup, R. J. Hite, and W. C. Culbertson called our attention to similarities in lamination of certain saline deposits and the basal facies of the mudmound. A. T. Myers made a spectrographic analysis of the laminated limestone on which R. C. Surdam of the University of Wyoming ran numerous X-ray microprobe traverses. Thin and polished sections were prepared by M. E. Johnson and L.

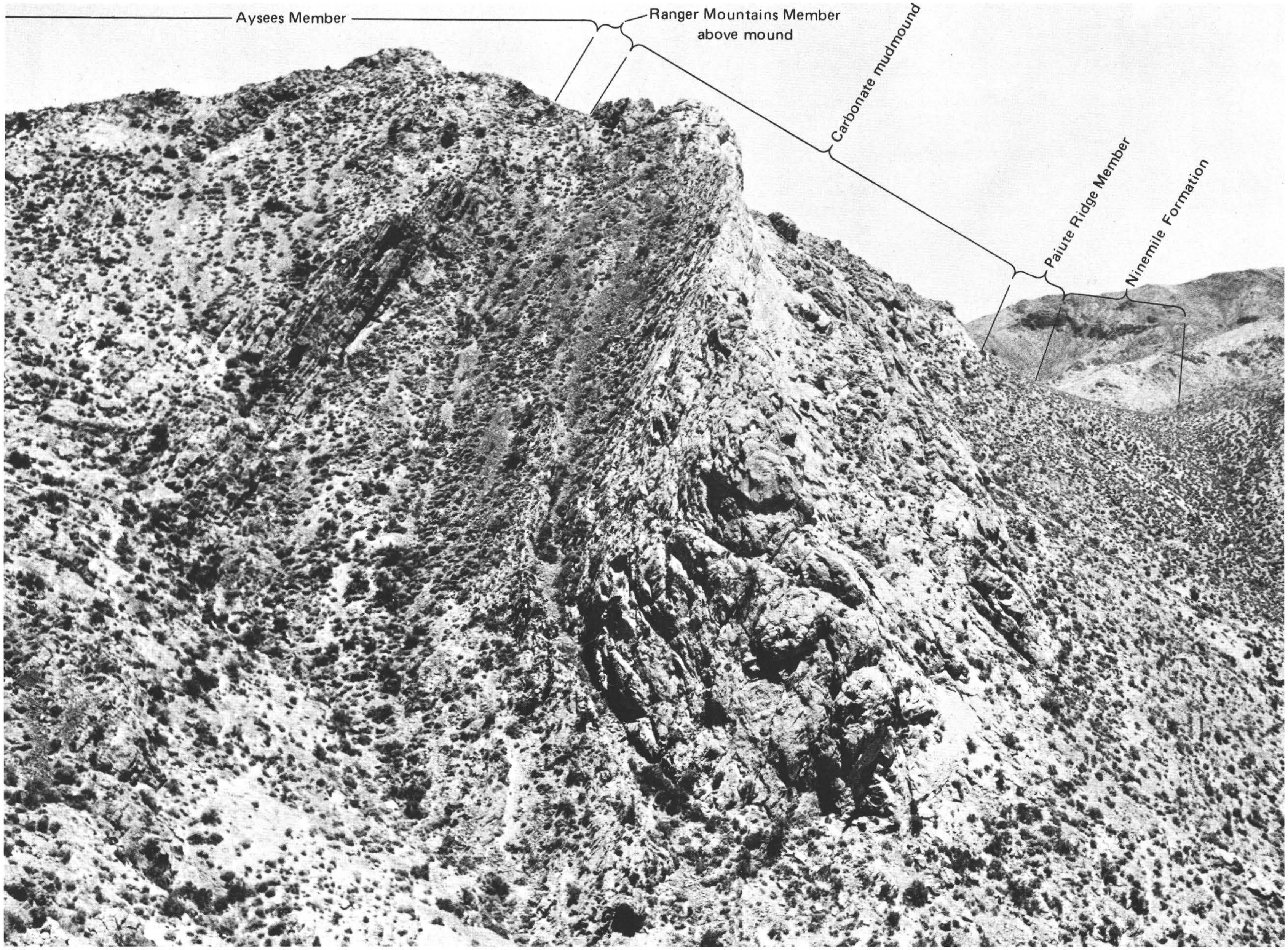


FIGURE 2. — The carbonate mudmound on the west side of Meiklejohn Peak as seen from the north. Stratigraphic units indicated are the Lower Ordovician Ninemile Formation and the Paiute Ridge, Ranger Mountains, and Aysees Members (Byers and others, 1961) of the Antelope Valley Limestone.

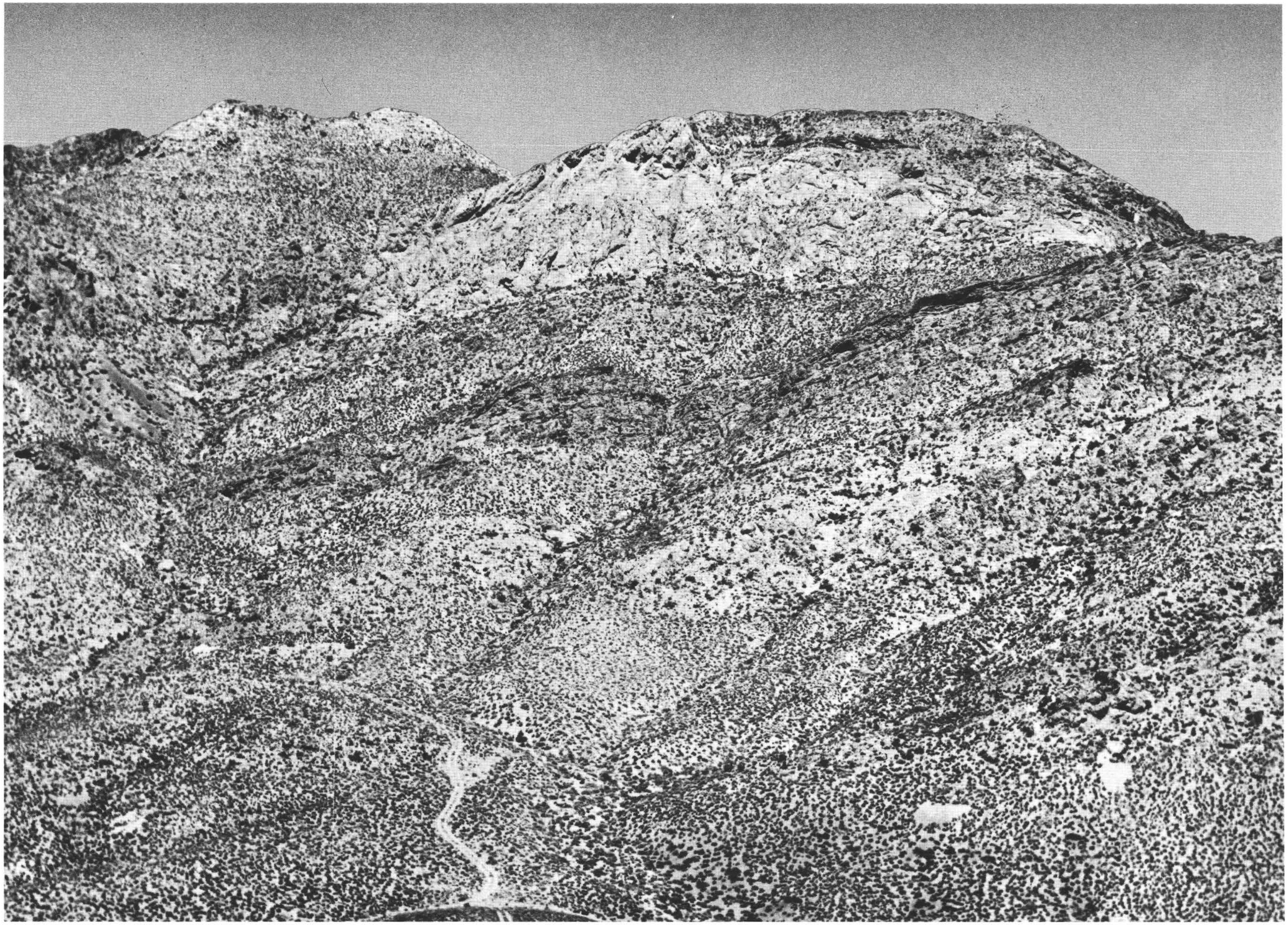


FIGURE 3. — Meiklejohn Peak and the mudmound as seen from relay station hill one-half mile to the west. Secret Pass lies in foreground (fig. 4). Mudmound is about 300 m (1,000 ft) wide and 80 m (270 ft) high.

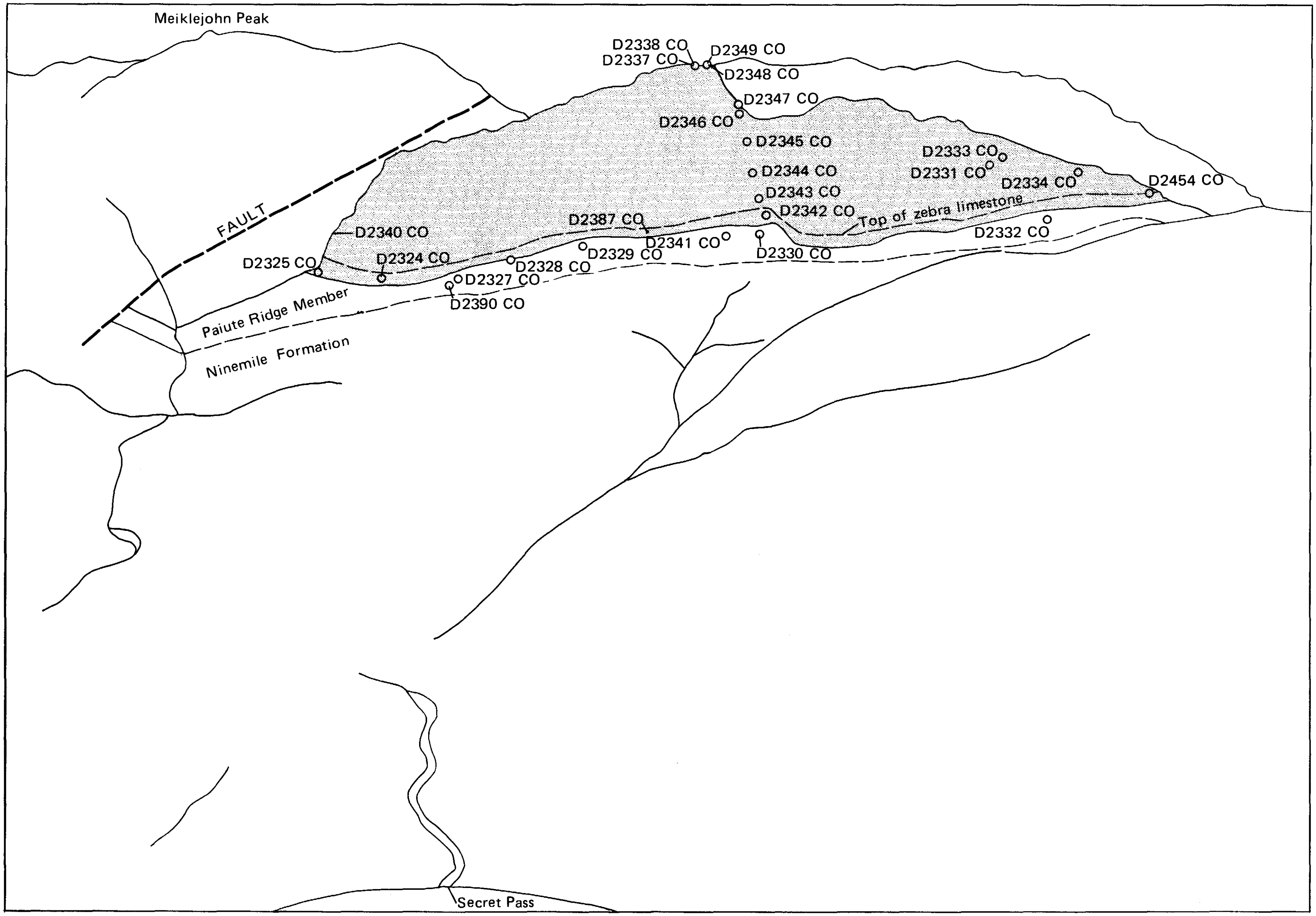


FIGURE 4. — Approximate positions of lithologic samples and selected fossil collections in the carbonate mudmound (stippled).

A. Wilson. R. E. Miller made a biochemical analysis of the laminated facies and established the presence of fatty acid and lipids.

At the 1971 annual meeting of the Geological Society of America (Washington, D.C.) and at the 1972 annual meeting of the American Association of Petroleum Geologists (Denver, Colo.), we discussed most features of the mound with many geologists, among them M. J. Brady, John Harper, James Lee Wilson, Graham Davies, P. N. Playford, Perry Roehl, H. Zankl, Richard Rezak, Robert Dunham, P. W. Choquette, and R. W. Beales.

Jaanusson and Ross were joined in an examination of the mound on August 2–3, 1972, by Nils Spjeldnaes, C. P. Hughes, R. A. Fortey, J. L. Henry, and L. R. M. Cocks. P. E. Cloud, Jr., joined Ross in a visit to the mound on April 14, 1973.

GENERAL DESCRIPTION AND GEOLOGIC SETTING OF THE MUDMOUND

As shown by Cornwall and Kleinhampl (1961) the geologic setting of the carbonate mudmound at Meiklejohn Peak is complex. The mound and surrounding strata are tilted tectonically with dips of 45° toward the east-northeast (fig. 2; Ross, 1972, fig. 4). The underlying calcarenitic limestone north of the mound has been displaced by a steep normal fault (Ross, 1972, fig. 3). The entire Ordovician section has overridden Devonian dolomite on a thrust fault.

All three known Ordovician carbonate mounds in southern Nevada lie above limestone of the Paiute Ridge Member and within the Ranger Mountains Member (Byers and others, 1961), both constituting the lower member of the Antelope Valley Limestone (Ross, 1967, pl. 11). Immediately covering each mound is thin-bedded, silty, nodular limestone. As shown by Ross (1972) the mounds lie within the *Orthidiella* zone; correlations by McKee, Norford, and Ross (1972) indicate that this zone is equivalent to the graptolite zones of *Isograptus caduceus* and *Paraglossograptus etheridgei*.

The exact geometry of the carbonate mudmound is not known. In fact, we do not know what part of the mound is exposed to view, how much may be buried by covering sediments, or how much may have been eroded away. The exposed section suggests that the bottom is nearly flat, and that the mound is thickest in its middle and thinnest at the sides. It is about 300 m (1,000 ft) across its greatest visible dimension and 80 m (270 ft) high (figs. 3, 4).

The laminated zebra limestone at the base of the mound is underlain by interbedded coarse calcarenite, dark-gray, silty, nodular limestone, and crudely laminated, partly stylolitic limestone; this underlying unit is about 9 m (30 ft) thick and can be followed approximately 0.9 km (0.6 mi) northward above the Ninemile Formation. This unit is equivalent to the Paiute Ridge Member of the Antelope Valley Limestone on the Nevada Test Site.

Although another mound is present at the same stratigraphic level east of the Nevada Test Site (Ross and Cornwall, 1961), its exposure is much smaller and it seems to lack the basal zebra limestone facies. We do not know whether that exposure represents a lateral tip of a large mound or the center of a small mound; the laminated facies may be present but hidden from view.

The mound at Meiklejohn Peak shows evidence of several generations of fracturing, the details of which have not been explored. Clearly a system of cavities opened after formation of radiaxial fibrous calcite in the core and in the basal laminated beds. In many places cavities are filled with brown-weathering material. The cavities resemble distal parts of postdepositional fissures which are known in most other carbonate mounds. Such fissures are particularly conspicuous in the mounds of the Siljan district, Sweden, because they are filled by black graptolite shale. Within the core of the Meiklejohn Peak mound one can find several patches of intraformational conglomeratic material; it is also common in similar carbonate mounds elsewhere.

The mound core is composed mainly of *Stromatactis*-bearing calcilutite which shows only slight evidence of bedding. Some channels or pockets are filled with shells of cephalopods, brachiopods (particularly *Idiostrophia*), trilobites, and gastropods. In the upper part of the core *Stromatactis* constitutes about 20 per cent of the volume of the rock.

The entire basal part of the core is laminated limestone composed of couplets of calcilutite (micrite) and radiaxial fibrous calcite. Each couplet is 6–10 mm thick. Following the example of Fischer (1964, p. 115), we call this basal facies zebra limestone. The aggregate thickness of the facies is highly variable, in some places being 20 cm and in others 9 m.

Covering the mound are thin beds of siliceously silty, highly fossiliferous, partly nodular, dark-gray limestone, whose silty parts weather grayish orange. Here and there in the lower third of the Ranger Mountains Member this lithology forms tongues into the mass of the mudmound. Two probable channels in the mound seem to have been filled by it. But the covering beds, particularly in the upper part of the mound, butt against the sloping sides of the mound and at the top cover it.

Lithology of the part of the Ranger Mountains Member that forms the mound cover (*Orthidiella* zone) was studied by Jaanusson in thin sections of a series of samples collected at the northern end of the mound. Jaanusson found that the covering limestone is preponderantly a sparitic calcarenite with the former voids between sand grains partially or completely filled with sparry calcite. Most of the limestone is a pelletal, sparitic calcarenite in which the majority of sand grains are cryptocrystalline pellets, mostly 0.08 to 0.2 mm in diameter. During deposition, the pellets were obviously indurated. The pelletal sand includes varying amounts of skeletal sand grains which dominate in some thin sections and form skeletal sparry calcarenite. The para-axial sparry calcite has to a large extent assimilated adjoining parts of skeletal grains making it difficult to determine the original grain boundaries. Therefore, it was impossible to apply modal analysis for quantitative determination of original sand constituents.

In some places, the matrix is micritic, the interstices between sand grains being filled with carbonate mud, but such rock (micritic calcarenite) seems to be quantitatively less important than sparitic calcarenite. Radiaxial calcite was not observed in any of the thin sections studied. The irregular, argillaceous intercalations between limestone beds abound in quartz silt grains, mostly 0.02 to 0.06 mm in diameter.

Jaanusson found that the limestone covering the mound is very different from that of the mound core. He concluded that a considerable winnowing of the sediment occurred and that deposition was in an environment with a much higher water energy than that during which the mound core was formed.

LITHOLOGY

Each lithologic facies of the mudmound was examined in thin section. Because its origin is highly controversial, the zebra limestone was subjected to other analyses. A semiquantitative spectrographic analysis was run by A. T. Myers. The laminae of calcilutite and radiaxial spar were analyzed for the isotopes of oxygen and carbon by Friedman. Insoluble residue was examined and identified by R. E. Wilcox and B. F. Leonard III. A sample was subjected to X-ray fluorescence and microprobe analysis by Ronald C. Surdam of the University of Wyoming.

Representative thin sections of samples from the core of the mudmound were examined in detail by V. Jaanusson.

LAMINATED LIMESTONE (ZEBRA LIMESTONE)

By Reuben James Ross, Jr.

GEOLOGIC RELATIONS

At the north end of the carbonate mound, about 30 feet (9 m) of the zebra limestone is strikingly exposed (fig. 5; Ross, 1972, fig. 6). Some individual laminar couplets may extend laterally for tens of feet (more than 3 m) without break, but others are of much shorter extent. Lateral terminations of couplets are sedimentary rather than tectonic and account for variations in thickness of the laminated facies along the bottom of the mound.

Although the laminated limestone forms the base of the mound core, it also occurs in restricted areas higher along the edges of the core. Wherever core mud has been deposited over channels or tongues of dark, silty limestone of the covering lithology the initial phase of mound deposition is laminated. An example was called to our attention by A. J. Rowell and F. F. Krause (Oct. 6, 1971) about 80 feet (25 m) above the base and 200 feet (61.5 m) from the south end of the mound (USGS colln. D2334 CO; fig. 6).

In one place near the middle of the base where the laminated rock totals about 35 cm (1.2 ft) in thickness, two flat segments are connected without interruption by a quasi-flexure as if a very thick carpet were draped over a single step, the riser of which is also about 35 cm (1.2 ft) high. No fracture or tectonic displacement accounts for the flexure.

Close to this place, about 3 m (10 ft) above the bottom of the mound, Professor Nils Spjeldnaes (Aug. 3, 1972) noted that the zebra limestone facies was interrupted by a cavity which itself was filled with shells of about 30 nautiloid cephalopods and three generations of carbonate mud and sparry calcite. The visible, lens-shaped cross section of the cavity was almost 1 foot (30 cm) in height and 2 feet (60 cm) in width. Cephalopods were not confined to the youngest part of the cavity although the majority were "nested" therein. This disparity indicates that the laminated zebra facies had already formed early in the depositional and diagenetic regime because the cephalopods are the same as those found in the zebra limestone about 60 m (200 ft) farther south (R. H. Flower, written commun., 1972).

CALCILUTITE LAYERS

The laminated limestone exemplified by USGS colln. D2325 CO is composed mostly of alternating layers of calcilutite and of radiaxial fibrous calcite (fig. 7). Any attempt to categorize the kinds of calcilutite present or its relations with the radiaxial mosaic runs into complexities that defy simple interpretations. Any description of this rock seemingly involves speculation about its origins.

In the simplest form, each layer of calcilutite consists of two parts (fig. 8):

1. A lower fossiliferous calcilutite (ca_1), the upper and lower surfaces of which are highly irregular. Fossil material is contributed by ostracoda, trilobita, and echinodermata. Attitudes of fossils parallel layers of calcilutite (fig 9) except where ca_1 is flexed or disrupted; there, fossils may rest at angles highly canted relative to the attitude of the laminae (fig. 10).
2. An upper pelletoid calcilutite (ca_2) in which the diameter of the pelletlike particles is about 0.05 mm. This material seems to fill depressions in the upper surface of the fossiliferous calcilutite. In

FIGURE 5. — Cyclically laminated zebra limestone. This lithology is exposed through a thickness of 20 cm to 9 m (1–30 ft) along the base of the mound.

many cases all depressions are filled and a flat surface results (figs. 7, 8).

In other places, a third, more homogeneous, unfossiliferous, equigranular calcilutite (ca_3) is present above the pelletoid mud (ca_2) and seems to hold the position of the radiaxial fibrous spar (fig. 11). This third calcilutite (ca_3) locally appears crossbedded with pelletoid material (fig. 12) or intergrading with pelletoid calcilutite. Its usual position is above the pelletoid material (ca_2) and below the next higher fossiliferous calcilutite (ca_1) (figs. 11, 13).

The zebra limestone is remarkable for its constant

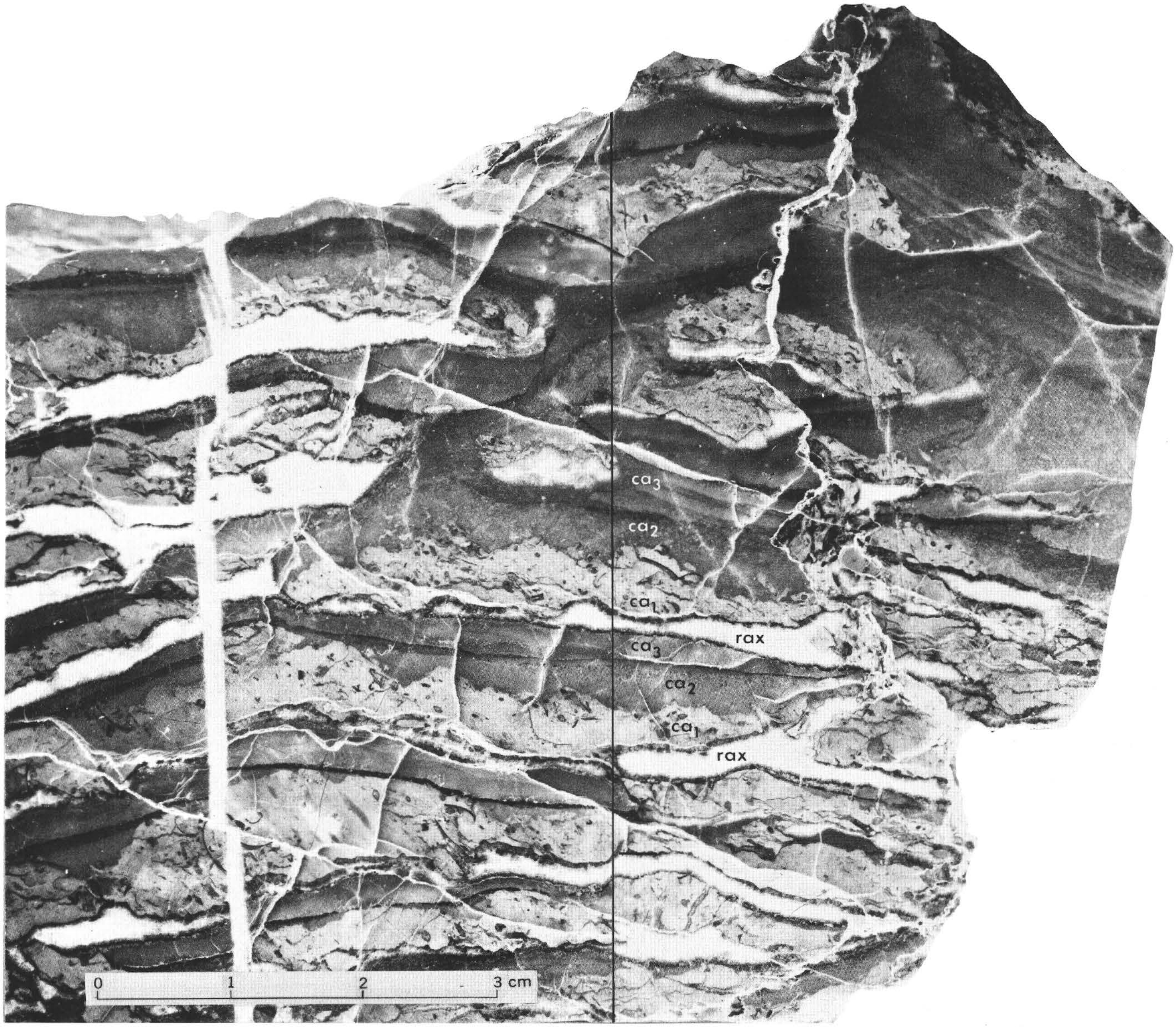


FIGURE 6. — Polished section of zebra limestone from south side of mound high on flank. All three calcilutites (ca_1, ca_2, and ca_3) are developed. Disruption and deformation took place while ca_2 and ca_3 were saturated with water and hence semifluid. ca_1 was more coherent, but not lithified. Radiaxial fibrous calcite (rax) formed only along bottom contact of ca_1. Section illustrated in figure 40 cut along indicated line. USGS colln. D2334 CO.

cyclicity whether at the bottom of the mound (figs. 7, 14) or above intertongued sediments higher on the sides of the mound (figs. 6, 11). I estimate that at the north end there are 900 cycles present within a thickness of 9 m.

It should further be noted that when present the radiaxial fibrous calcite discussed below invariably occurs at the bottom contact of calcilutite ca_1 further emphasizing the cyclic nature of the rock.

From the zebra limestone Jaanusson made a modal analysis of four separate layers of calcilutite ca_1 in thin section after visiting the mound in 1972. (For method see Jaanusson, 1972.) He found that the mean values of the main constituents are (1) matrix, 95 percent (range, 92–97 percent); (2) para-axial calcite, 2 percent (range, 0.1–3 percent); and (3) skeletal sand, 3 percent (range, 1–6 percent). Compared with the bulk of the limestone in the massive mound core (mean values for matrix, 56 percent; para-axial calcite, 21 percent; radiaxial calcite, 16 percent; and skeletal sand, 7 percent), the absence of radiaxial calcite and the low values of para-axial calcite in calcilutite ca_1 of the zebra limestone are particularly noteworthy. Qualitative examination of peels and thin sections—too thick for a reliable modal analysis—of other ca_1 layers suggests that these data are fairly representative.

The average amount of skeletal sand is less in

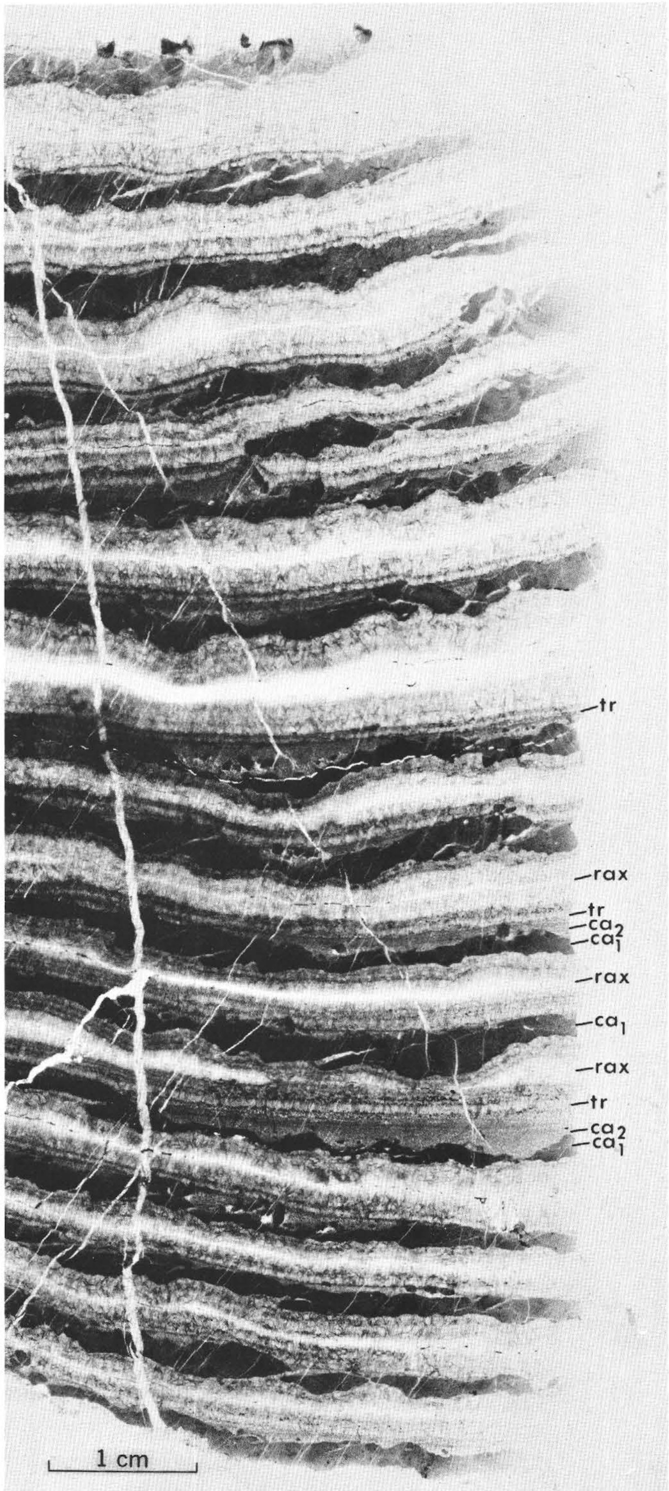


FIGURE 7. — Large section of laminated zebra limestone, showing cyclic nature. Calcilutite ca_1 is fossiliferous; ca_2 is pelletoid and fills hollows in top of ca_1. Radiaxial fibrous calcite (rax) in every example is immediately below calcilutite ca_1. In the bottom of rax, a thin tier of clear radiaxial calcite (tr) is common. Compare with figure 8. USGS colln. D2325 CO.

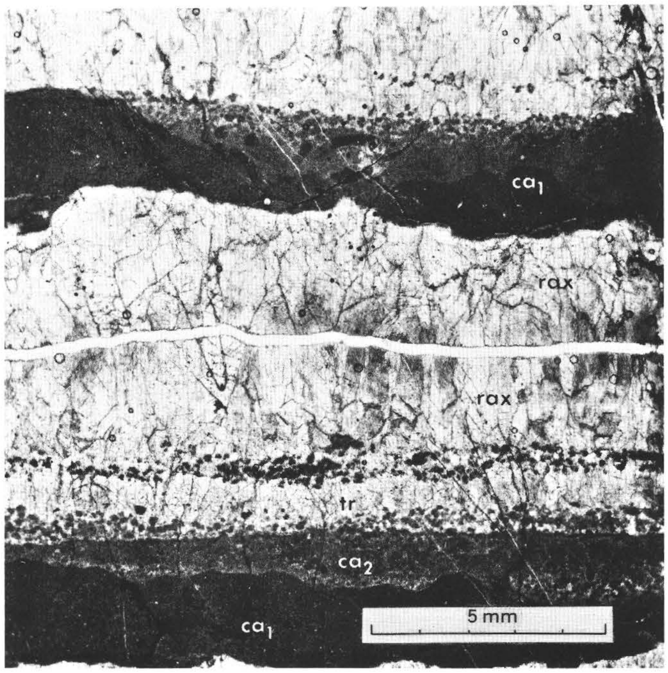


FIGURE 8. — Cyclic laminae. Depressions in upper surface of fossiliferous calcilutite (ca_1) are filled or covered by pelletoid calcilutite (ca_2). Space along median seam in radiaxial fibrous calcite (rax) opened during preparation of thin section. Lower tier (tr) of radiaxial calcite is well defined by micritic peloids along its top. USGS colln. D2325 CO.

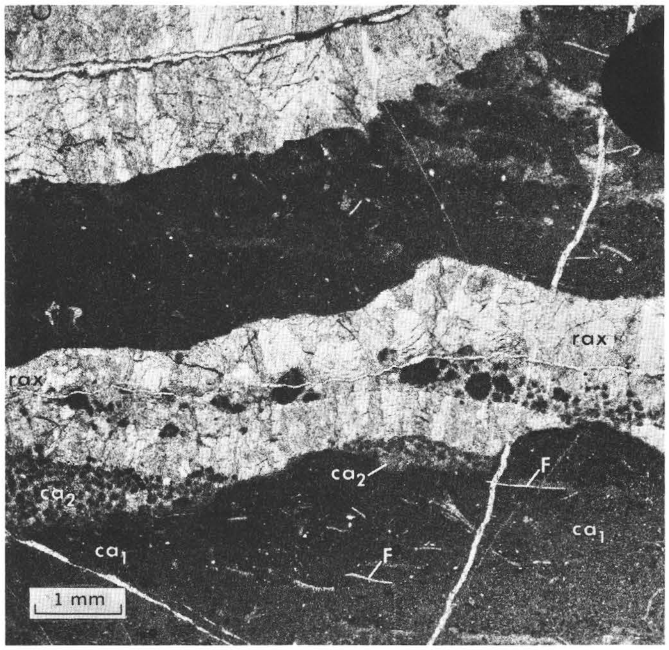


FIGURE 9. — Pelletoid material within radiaxial fibrous calcite (rax) is cut by median seam. Seam may be a secondary feature. Pelletoid material would not have been deposited unsupported in middle and upper half of cavity but could be relict calcilutite, partly converted by aggrading neomorphism. F, fossils. Thin section. USGS colln. D2325 CO.

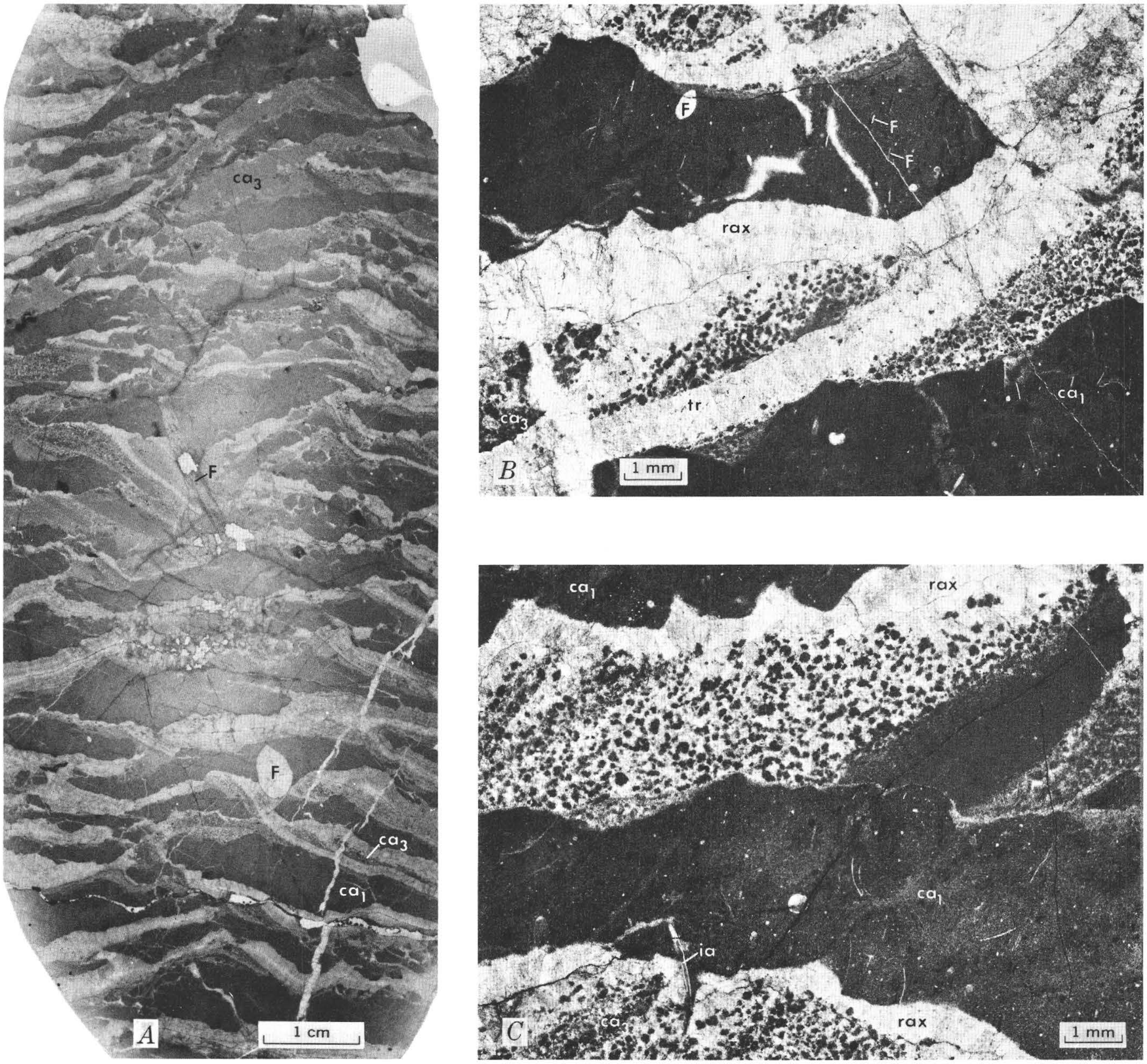


FIGURE 10. — Disrupted layers of zebra limestone contrast with those shown in figure 7, which are less than 60 cm distant. Orientation of fossils in disrupted layers of calcilutite ca_1 might be interpreted to indicate that calcilutite ca_1 was divided by vertical crevices. USGS colln. D2325 CO. *A*, Thick section illustrating fluid appearance of calcilutite (ca_3) between torn layers of ca_1. Orientation of large fossil fragment (F) in center of section agrees with that of small fossils in *B* and *C*. *B*, Small part of section near top of *A*. Cross sections of fossils (F) are oriented at high angles to enclosing layers of calcilutite ca_1, therein contrasting with fossils in figure 9. Radiaxial calcite (rax and tr) might be lining of partly filled cavity, but would imply a different orientation than fossils. Radiaxial calcite may also have resulted from neomorphic conversion of preexisting aragonitic calcilutite. *C*, Small part of section near top of *A* and close to *B*. Note cross section of inarticulate brachiopod (ia) projecting downward into calcilutite (ca_3) here made pelletoid. If boundaries of calcilutite ca_1 were fracture or shear surface, the fossil could not have survived. Despite attitude of seeming crossbeds of ca_3, radiaxial calcite (rax) is developed preferentially immediately beneath each layer of ca_1.

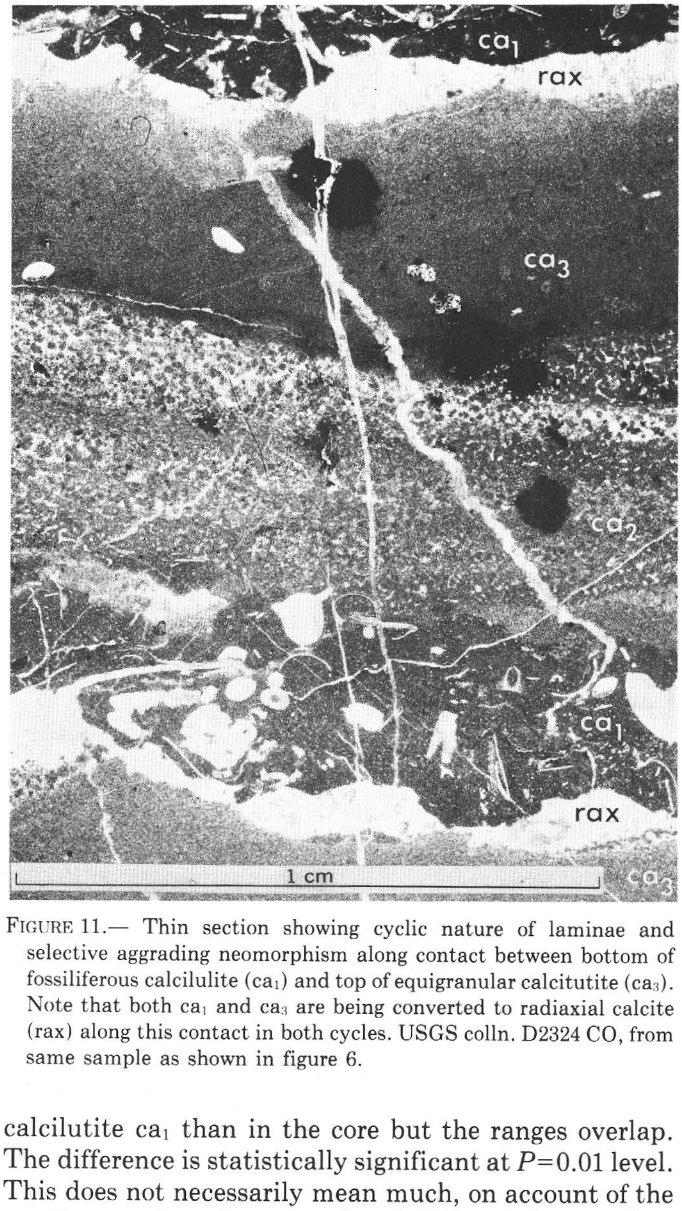


FIGURE 11.— Thin section showing cyclic nature of laminae and selective aggrading neomorphism along contact between bottom of fossiliferous calcilulite (ca_1) and top of equigranular calcitutite (ca_3). Note that both ca_1 and ca_3 are being converted to radiaxial calcite (rax) along this contact in both cycles. USGS colln. D2324 CO, from same sample as shown in figure 6.

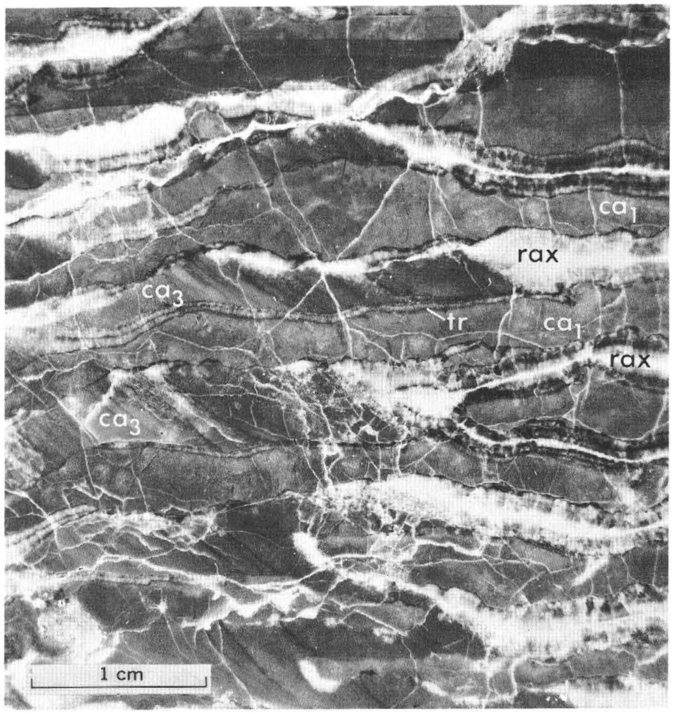


FIGURE 12. — In contorted or disrupted parts of zebra limestone cyclic succession of calcilutites may be disturbed. Here layers of calcilutite ca_1 are separated by seemingly crossbedded interlayering of pelletoid and equigranular calcilutite(ca_3). Radiaxial fibrous calcite (rax) is immediately below ca_1. In some cycles a tier (tr) of radiaxial calcite appears to underlie ca_3 and is analogous to tr in figure 8. Polished surface. USGS colln. D2325 CO.

calcilutite ca_1 than in the core but the ranges overlap. The difference is statistically significant at $P=0.01$ level. This does not necessarily mean much, on account of the small area of ca_1 layers analyzed. Nevertheless, it does indicate that the carbonate mud which formed ca_1 layers was finer grained than most of the carbonate mud in the core.

Owing to the small amount of skeletal sand present in the measured areas of ca_1 layers, composition of the skeletal sand was calculated for all four analyzed areas together. The data, in percent, are as follows:

	Percent
Echinodermata	52
Trilobita	14
Ostracoda	10
Brachiopoda	3
Mollusca	1
Indeterminable	20

Trilobites are more common than ostracodes, whereas in the core, the reverse is true; no "spiculae" were found.

Owing to the small area of ca_1 layers measured, the low content of skeletal sand present, and the relatively high amount of small indeterminable grains, these data may not be representative for ca_1 rock as a whole. But the analysis does suggest that the rock forming calcilutite ca_1 was somewhat finer grained than most calcilutite in the massive core; its small content of drusy calcite indicates a diagenetic history different from that of the core.

Jaanusson found that the pelletoid calcilutite (ca_2) was too recrystallized (with many indistinct grain boundaries) to yield reliable data by modal analysis.

RADIAXIAL FIBROUS CALCITE LAYERS

The coarse calcite in the zebra limestone exhibits the essential characteristics of Bathurst's (1959, p. 511–512; 1971, p. 426-427) radiaxial fibrous mosaic. In the simplest form, each radiaxial fibrous calcite layer is divided symmetrically into upper and lower halves by a median seam to which coarse crystals are roughly perpendicular. The seam is remarkably smooth despite the large side of the adjoining crystals (figs. 14, 15). Zoning in the coarse radiaxial calcite is disposed symmetrically above and below relative to the seam (fig. 14*A*); the zoning is not necessarily parallel to the top or bottom contact of the spar.

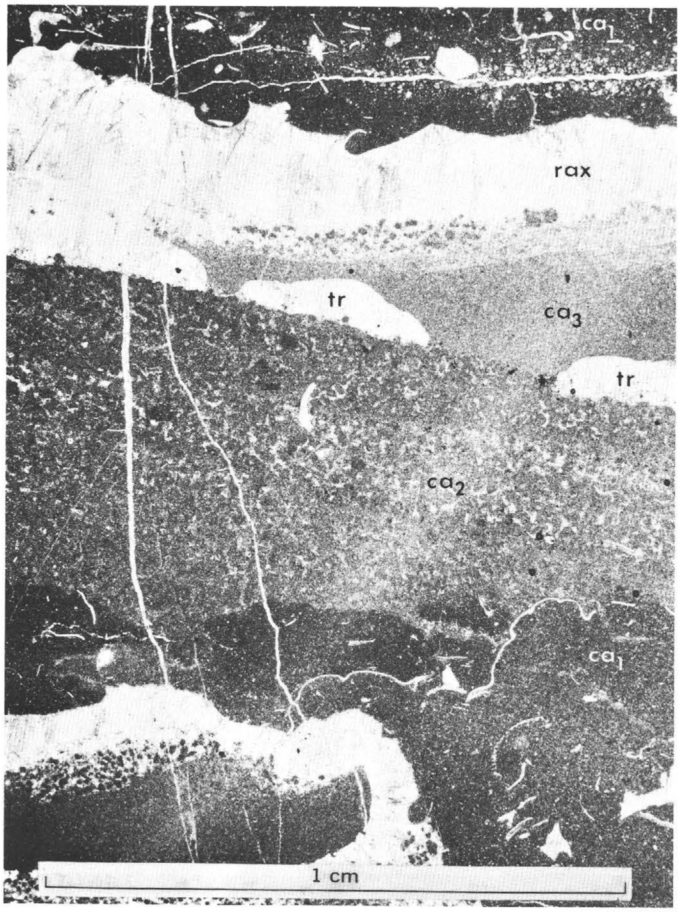


FIGURE 13. — Thin section cut normal to surface shown in figure 6 and parallel to surface shown in figure 40. Two cycles of fossiliferous calcilutite (ca_1) are shown. Pelletoid calcilutite (ca_2) and very fine equigranular calcilutite (ca_3) complete the sedimentary cycle. Aggrading neomorphism has resulted in partial conversion of ca_3 and bottom of overlying ca_1 to radiaxial calcite (rax). Calcilutite above ca_3 is not fragmental; if it were, it should also be spread to left on "floor" over ca_2. USGS colln. D2334 CO.

In many places the radiaxial calcite layer is somewhat more complex. Below the thick symmetrical calcite layer is one, very rarely more than one, thin tier of radiaxial calcite. This thin tier can be distinguished in plane-transmitted light with assistance of the pelletoid material incorporated in its bottom and in the bottom of the overlying radiaxial calcite (figs. 8, 14*A*, 14*B*). In polarized light, whether reflected or transmitted, the boundary between the upper thick symmetrical radiaxial calcite and the lower thin tier of radiaxial calcite is distinct only where peloids intervene; laterally the distinction between the two may disappear (fig. 14*B*). The tier is remarkably like the radiaxial calcite that occurs beneath seemingly crossbedded calcilutite in disrupted parts of the zebra limestone (figs. 10*B*, 16, 17).

The crystals of calcite in the thick, symmetrical calcite tend to be largest close to the median seam and smallest along contacts with calcilutite (figs. 14*C*, 18). Large crystals exhibit undulate extinction and intergrown boundaries (figs. 14*B*, 14*C*). Relict extinction suggests that many large crystals have grown at the expense of their neighbors, be it by "cannibalism," aggrading neomorphism, or some other means.

Pelletoid material and other bits of calcilutite are common within the radiaxial fibrous calcite. This material may be along the bottom of the thin lower radiaxial calcite tier or along the bottom of the lower half of the symmetrical thick radiaxial calcite (fig. 8). Although the pelletoid and calcilutitic material is usually below the median seam of the thick radiaxial calcite (fig. 15), it appears to be above or across the seam in some instances (fig. 9).

At the south end of the outcrop and less than 3 m (10 ft) above the base of the mudmound the zebra limestone overlies a tongue of dark-gray, nodular limestone of the covering facies (Ranger Mountains Member) and takes two forms.

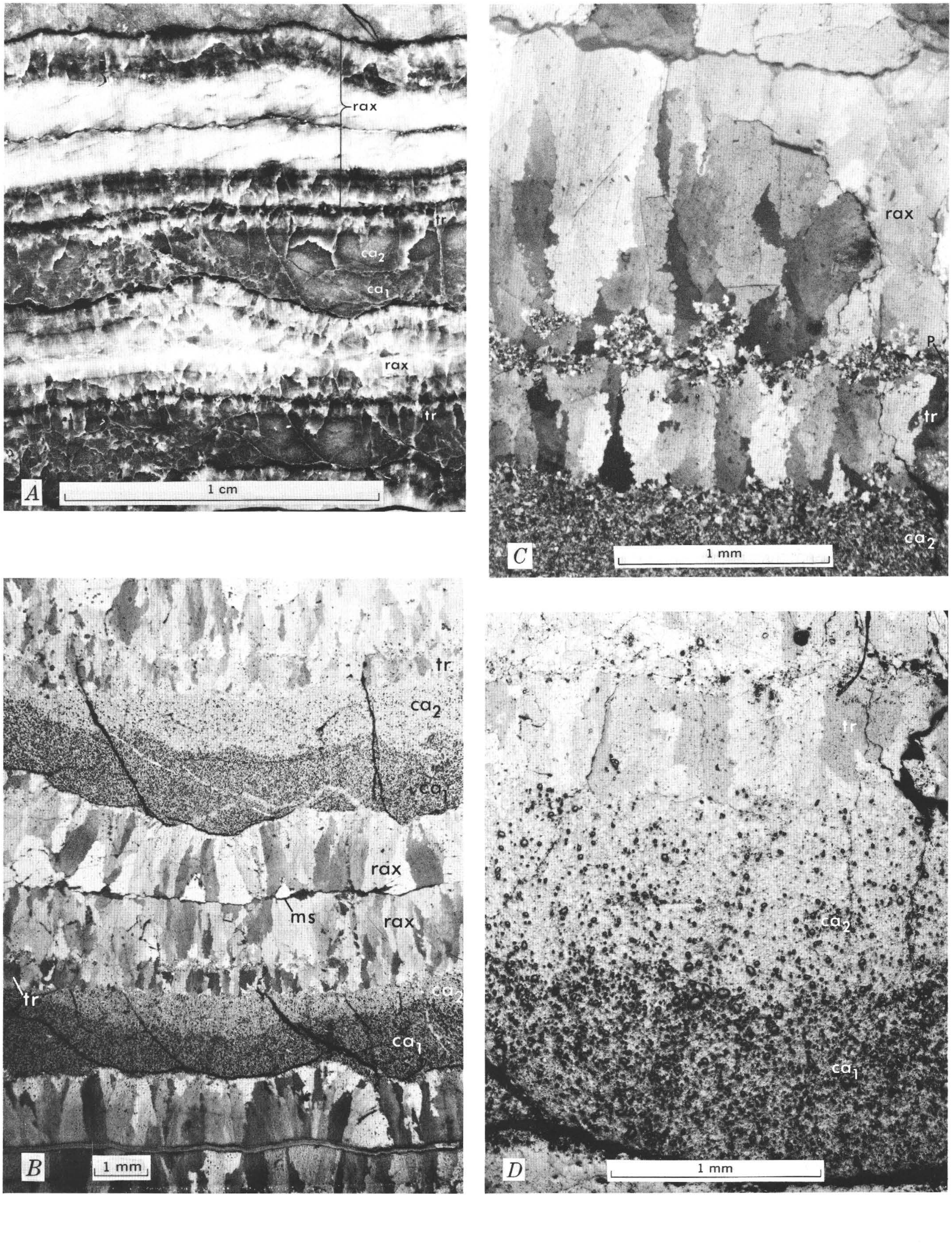
The first of the forms occurs immediately above the nodular limestone as irregular masses not more than 20 cm across and 10 cm high composed of very thin discontinuous laminae of calcilutite ca_1 and radiaxial sparry calcite (fig. 19). There is a suggestion that these laminar bodies grew as small heads on the upper surface of the nodular limestone. Laminae range from 0.25 to 2.0 mm in thickness.

The small finely laminated masses are reminiscent of a cross section through a head of cabbage. The thickness of radiaxial calcite between layers of calcilutite ca_1 is about equal to the thickness of the layers of ca_1. Although space taken up by radiaxial calcite may once have been occupied by calcilutite, it seems equally likely here that radiaxial calcite has filled spaces between thin crusts composed of calcilutite ca_1.

Covering not only the nodular limestone but also the more finely laminated "cabbageheads" is the zebra limestone in a second, more conventional form. Here (fig. 20), it is composed of alternations of calcilutite ca_1 and pelletoid calcilutite ca_2; in some couplets ca_2 may have been deposited in two generations. Along the contact between ca_2 and the next succeeding layer of ca_1, radiaxial calcite has formed irregularly.

Laterally, to the north, the layers of pelletoid calcilutite ca_2 are taken over by radiaxial fibrous calcite. The field evidence suggests that the pelletoid calcilutite has been selectively replaced by or recrystallized into radiaxial calcite. Just as elsewhere along the base of the mudmound, the lateral extent of the zebra limestone facies, the thinness and irregularity of calcilutite ca_1, and the even spacing of laminae argue against the mechanical possibility that the radiaxial calcite filled cavities.

Chambers of nautiloids are filled with both para-axial and radiaxial calcite (fig. 21). Most contain para-axial


rax
tr
ca_2
ca_1
rax
tr
A
1 cm
rax
P
tr
ca_2
C
1 mm
tr.
ca_2
ca_1
rax
ms
rax
tr
ca_2
ca_1
B
1 mm
tr
ca_2
ca_1
D
1 mm

calcite; para-axial calcite occurs only as filling of nautiloid chambers or as filling of fractures that cut all other lithologies. Radiaxial fibrous calcite surrounds all shells except where they are still imbedded in calcilutite; one nautiloid chamber shown slightly left of center of figure 21 is mostly filled with radiaxial calcite but also contains calcilutite. Only the para-axial mosaic is certainly a cavity filling. The radiaxial calcite may have resulted from the conversion of calcilutite surrounding and in some places partially filling shells.

TRACE-ELEMENT ANALYSIS

A semiquantitative six-step spectrographic analysis was run by A. T. Myers on both the calcilutite and the radiaxial fibrous calcite in order to determine whether a significant chemical difference existed between them. The results (Myers, written commun., Dec. 1, 1971) were as follows:

USGS colln. D2325 CO	*Calcilutite*	*Radiaxial calcite*
Fe (percent)	.01	.003
Mg	0.3	0.3
Ca	>10	>10
Ti	0.01	Detected
Si	2.0	.02
Al	0.15	0.01
Mn (ppm)	200	70
Ba	70	50
Cr	10	5
Cu	15	5
Mo	10	Not detected
Pb	20	15
Sr	500	500
V	20	20

FIGURE 14 (facing page). — Polished sections of zebra limestone. USGS colln. D2325 CO. *A*, Ordinary light; × 6. Two complete cycles of laminated sediment. Only part of zoning in radiaxial fibrous calcite (rax) is symmetrical about median seam. Lowest zonal band is lower tier of calcite (tr) as in figure 8. Calcilutites ca_1 and ca_2 are difficult to differentiate under ordinary light. *B*, Polarized light; part of view shown in *A*; × 9. Within radiaxial fibrous calcite (rax) crystal faces are intergrown; shadowy relicts of small crystals are visible within larger crystals; the smaller, younger crystals tend to be at the top and bottom margins. Median seam (ms) is relatively smooth. Quartz, K-feldspar, and goethite stand in relief and are most abundant in fossiliferous calcilutite (ca_1), less abundant in pelletoid calcilutite (ca_2), and rare in radiaxial calcite. Lower tier of calcite (tr) is clear at middle but fades to right, where peloids have already been recrystallized to spar. *C*, Polarized light; small area of lower half of middle radiaxial fibrous calcite (rax) in *B*; × 40. Peloids (P) are relict, not having been recrystallized; therefore, the top of the lower calcite tier (tr) is distinct, and this tier may be comparable to tiers beneath ca_3 in figure 16*B*. Pelletoid calcilutite (ca_2) under high magnification and polarized light appears crystalline intermediate between coarse radiaxial calcite and more finely crystalline ca_1. *D*, Polarized light; part of view shown in *B* and *C*. × 40. Quartz and K-feldspar stand in relief; they are most abundant in calcilutite ca_1, less abundant in ca_2, and very sparse in radiaxial calcite (tr and rax).

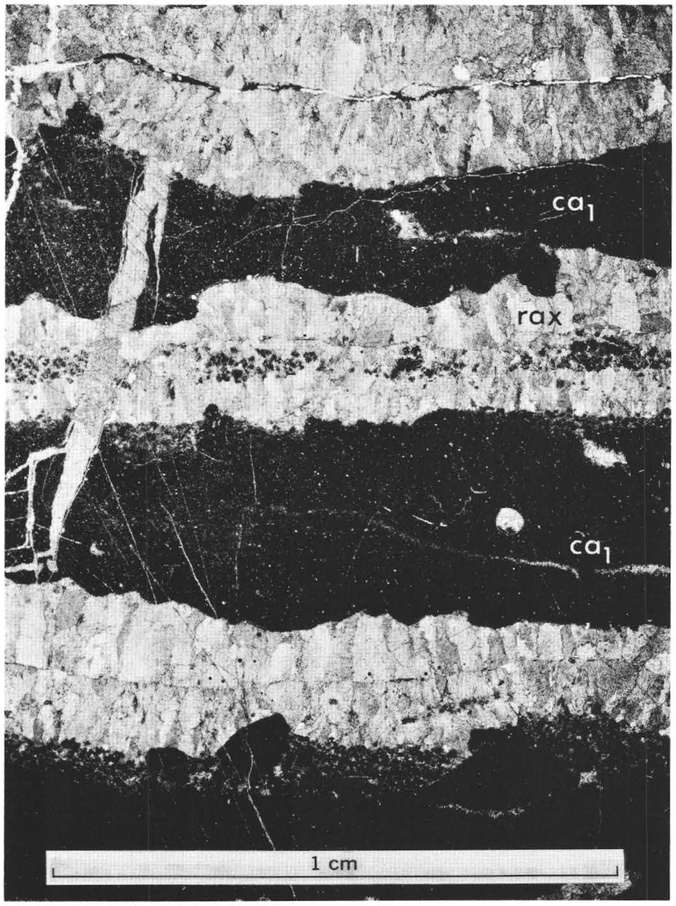


FIGURE 15. — Thin section of three cycles in zebra limestone. Bright points within fossiliferous calcilutite (ca_1) are crystals of quartz and K-feldspar. Relict peloids and small bodies of calcilutite in radiaxial calcite (rax) may be comparable to those above calcilutite ca_3 in figure 13. USGS colln. D2325 CO.

The calcilutite is consistently richer in trace elements than the radiaxial calcite, but the amounts concerned are not particularly unusual. The higher percentage of silicon in the calcilutite can be credited to the presence of quartz and feldspar.

INSOLUBLE RESIDUE

Photographs taken in polarized light of a polished surface of a sample from USGS collection D2325 CO (fig. 14*D*) indicate the presence of material that is harder than calcite, particularly in the fossiliferous calcilutite (ca_1). Microscope examination of thin sections suggests that particles of quartz and an opaque mineral are the more resistant minerals seen in relief on the polished surface.

Part of one sample from collection D2325 CO dissolved in dilute hydrochloric acid yielded 1.3 percent by weight insoluble residue. A second sample yielded 3.33 percent by weight insoluble residue. The particles of residue are almost entirely in the silt sizes; some particles are as large as very fine sand. By volume about 70 percent of

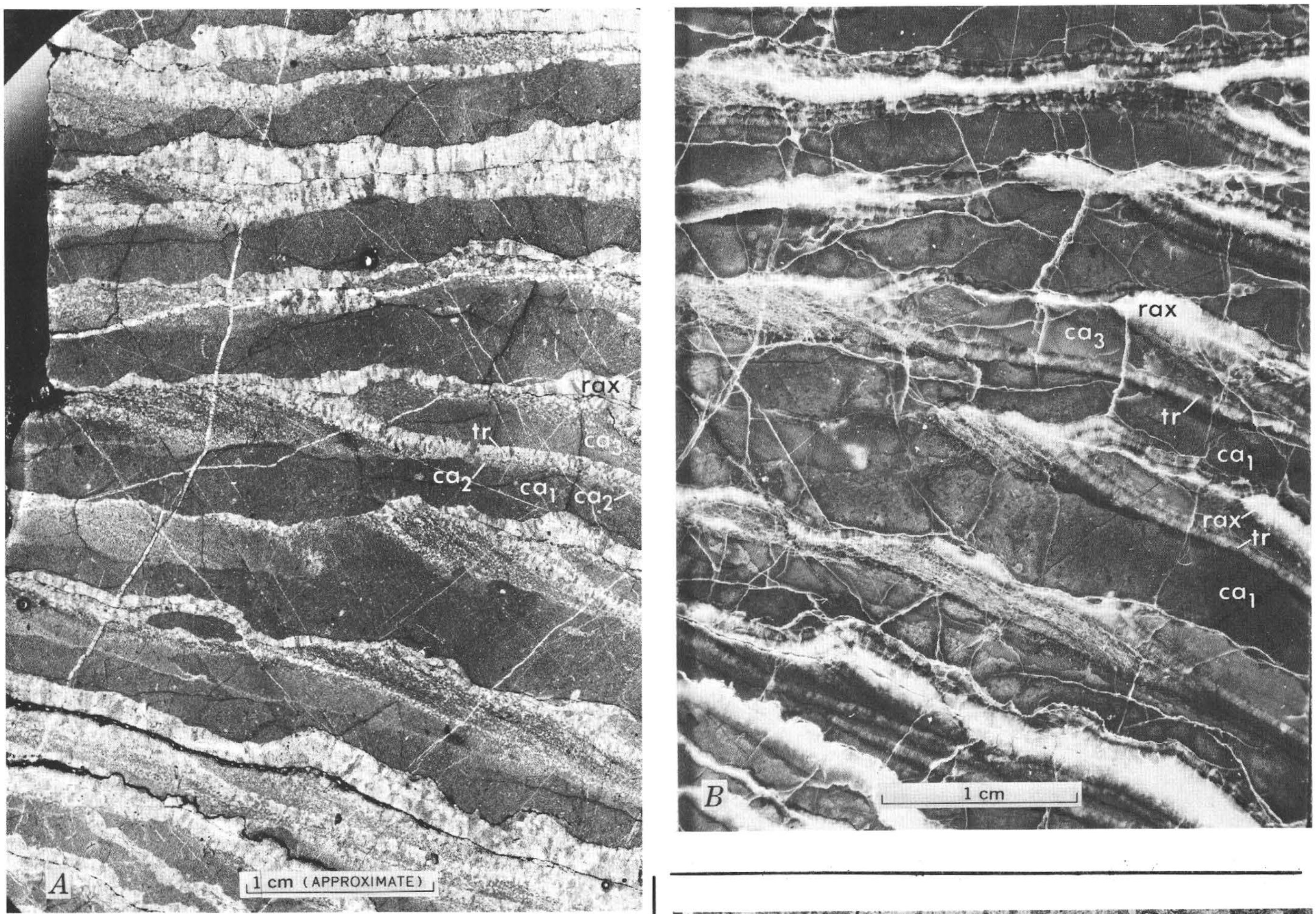


FIGURE 16. (above and upper right) — Layers of fossiliferous calcilutite (ca_1) separated partly by radiaxial calcite (rax) and partly by seemingly crossbedded pelletoid calcilutite (ca_3), which also grades into radiaxial calcite. Pockets of calcilutite ca_2 are overlain by a thin layer of radiaxial calcite (tr) just as in undisturbed parts of the zebra limestone. (See, for example, fig. 8.) Lower tier (tr) of radiaxial calcite may be analogous to that in figures 8, 13, 14*A*, and 14*C*. USGS colln. D2325 CO. *A*, Collodion peel. *B*, Polished surface.

these particles are quartz, slightly fewer than 25 percent are potassic-feldspar, and about 7 percent are opaque. According to R. E. Wilcox (written commun., Feb. 25, 1972), "Most of the particles of quartz and feldspar are made up of nuclei, probably detrital, about which have grown mantles of authigenic material to provide crude to well-developed euhedral crystal forms." According to B. F. Leonard III (written commun., Jan. 17, 1972), most of the opaque mineral is goethite.

Assuming that the typical distribution of these insoluble minerals is shown on the polished section (figs. 14*B*, 14*D*), we estimate that 70 percent are in the fossiliferous calcilutite (ca_1) and 25–30 percent are in the overlying pelletoid material (ca_2). A trace (1–5 percent) is present in the radiaxial calcite, which makes up more than half the total rock.

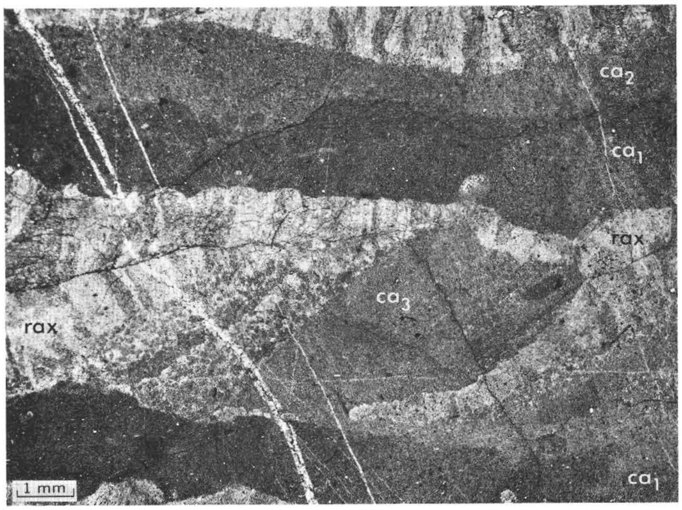
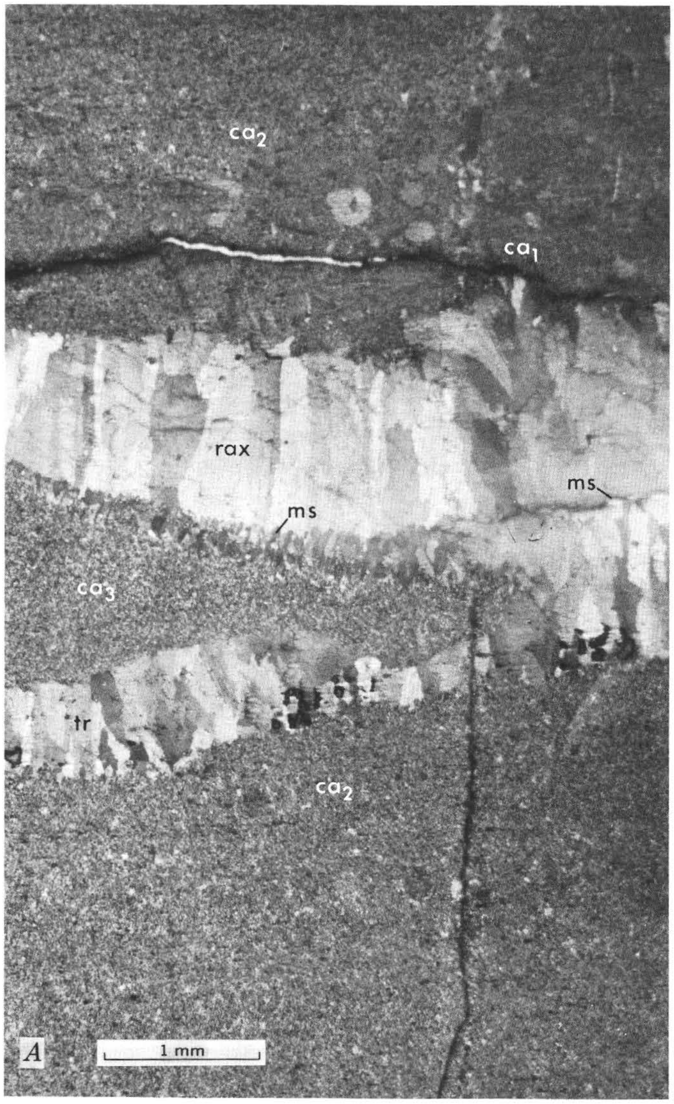


FIGURE 17. — Radiaxial fibrous calcite (rax) associated with seemingly pelletoid calcilutite between layers of calcilutite ca_1. Radiaxial calcite on right would not be discontinuous if it had lined a cavity prior to filling by calcilutite. Radiaxial calcite appears to have grown along more permeable sedimentary contacts. Pelletoid sediment may have provided permeable channel. Or pelletoid texture may be *structure grumeleuse*, resulting from aggrading neomorphism. As shown in figure 16, depressions above ca_1 may be filled by pelletoid calcilutite (ca_2); much of space between layers of ca_1 is filled by typically equigranular ca_3. Collodion peel. USGS colln. D2325 CO.



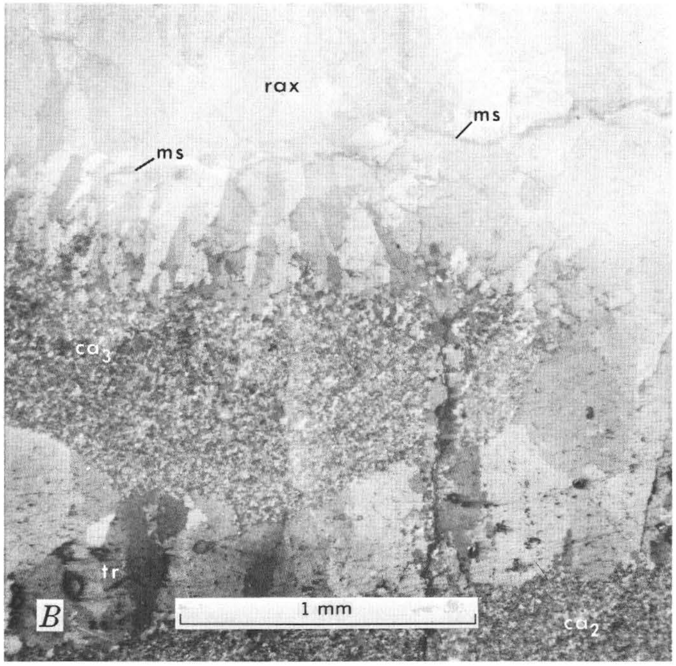


FIGURE 18. (left and above) — Polished sections showing radiaxial fibrous calcite (rax) divided by nearly flat median seam (ms). Seam above calcilutite ca_3 is jagged; terminations of crystals below seam in ca_3 also seem jagged. Top of calcilutite ca_3 partly converted to radiaxial calcite by aggrading neomorphism below seam. If conversion of ca_3 continued, the tier of calcite (tr) below ca_3 would correspond to lower tier (tr) in figures 8, 14*B*, and 14*C*. Polarized light. USGS colln. D2334 CO. *A*, $\approx\times$ 20. A part of the sample shown in figure 41, this surface parallels and is 7 mm distant from that in the samples illustrated on figures 13 and 40. *B*, Enlarged view of part of *A*, $\times$ 39.

In laminated sediments in Shark Bay, western Australia, quartz constitutes 1 percent of the sediment in the intertidal zone and 2–20 percent in the supratidal zone (Davies, 1970, table 1, p. 177). The small content of quartz in the laminated sediments at Meiklejohn Peak is therefore not unusual.

Concerning Shark Bay, Davies (1970, p. 186) further noted that "pyrite or a related iron sulphide" is present in laminated sediments from the intertidal zone and that "gypsum is absent." Both these conditions are also met by the laminated facies from Meiklejohn Peak. After an X-ray microprobe analysis of a sample of this Ordovician zebra limestone, R. C. Surdam (oral commun., Apr. 5, 1972) concluded that there is no difference in iron, calcium, or magnesium content between the calcilutite layers and the radiaxial fibrous calcite, and that the chemical suite present does not indicate deposition in a hypersaline or supratidal environment.

A sample (USGS colln. D2343 CO) from the unlaminated upper part of the mudmound, 28 m (86 ft) above the base yielded a residue which is 2.16 percent by weight of the original sample. X-ray analysis by W. N. Sharp indicated that quartz and mica, probably illite, are the prominent constituents of this residue, and that some hematite is present.

UNDERLYING LIMESTONE

Northward from the mudmound the underlying calcarenite is exposed in a deep gully beyond which it is displaced westward by a fault. This calcarenite was initially considered to be a detrital apron derived from the mound; however, its continuity north and south beneath the zebra limestone of the mound shows it to be a part of the limestone 9 m (30 ft) thick that lies stratigraphically below the mound and that extends over a wide area as the topmost part of the Paiute Ridge Member of the Antelope Valley Limestone. In the lower third of the 9-metre-thick limestone a crudely laminated interval (figs. 22, 23) resembles the zebra limestone but lacks the predominance of radiaxial calcite and the striking cyclic nature.

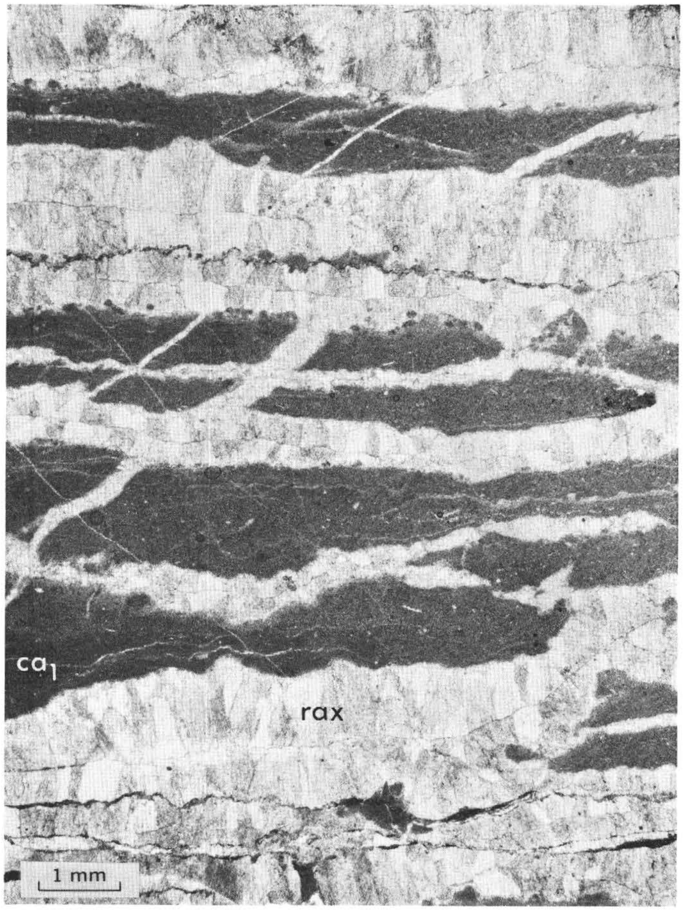


FIGURE 19. — Thin section from small, irregular "cabbagehead" mass composed of calcilutite ca_1 and radiaxial fibrous calcite (rax). About 10 feet (3 m) above base of mound at south end of outcrop. USGS colln. D2454a CO.

In the calcarenite (fig. 24) recrystallization has obliterated the boundaries of skeletal grains making planimetric measurements of the original composition of the rock impossible. Some echinodermal material is present and ostracodes appear to be abundant.

A collection (USGS colln. D2390 CO) was made at the bottom of the crudely laminated facies at a point where coarse sparry calcite is a minor constituent in the hope that the crude laminae might be analogous to the calcilutite layers of the overlying zebra limestone.

A greater proportion of the rock is composed of fossiliferous calcilutite (figs. 22, 23). Layers, possibly of pelletoid origin (figs. 23*B*, 25), about 3 mm thick are interbedded and seem to be equivalents of the radiaxial calcite layers in the overlying zebra limestone. Spicules are present in clumps within the fossiliferous calcilutite (figs. 26, 23*B*). No such spicular clumps have been found in the zebra limestone.

The poorly laminated limestone lacks the uniform cyclicity of the zebra limestone. The fossiliferous calcilutite ca_1 forms rather irregular layers 5–30 mm thick. Some of these layers have been bioturbated and locally the material has invaded lower layers in what appear to have been liquid protrusions from above; in other places there is as much evidence for upward flow of sediment as for downward flow. In still other places the sediment that appears to have been fluid in one spot has clearly been fractured a few millimetres away. Where fossils are abundant a considerable amount of pelletoid calcilutite is protected by "umbrellas" of larger shells.

Within the fossiliferous calcilutite ca_1 are numerous scattered dark-gray shapes in which spicules are prominent (figs. 23*B*, 26). Associated with the spicules is a fine anastomosing network of clear sparry calcite. After examining samples of the spicules and network, Robert Finks reported (oral commun., Nov. 9, 1972) that the straight spicules are probably root tufts of a lithistid sponge for which there is no other immediate evidence. He also thought that the anastomosing network of calcite was too irregular and devoid of overall geometry and spicular shape to belong to any sponge now known in the lower Paleozoic. In his opinion, this fine network might best be explained as the matrix in an original pel-

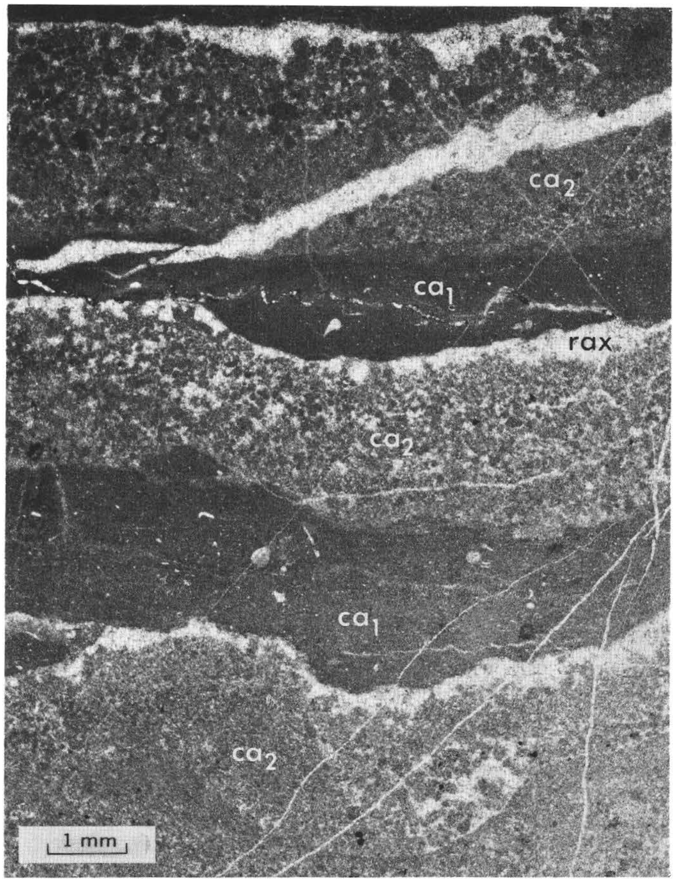


FIGURE 20. — Thin section from zebra limestone facies adjacent to "cabbagehead" mass shown in figure 19. Laminae composed of alternating calcilutite ca_1 and pelletoid calcilutite (ca_2). Radiaxial calcite (rax) is incipient below ca_1. Laterally layer ca_2 becomes radiaxial fibrous calcite. At bottom of section note scour-and-fill(?) in ca_2. USGS colln. D2454b CO.

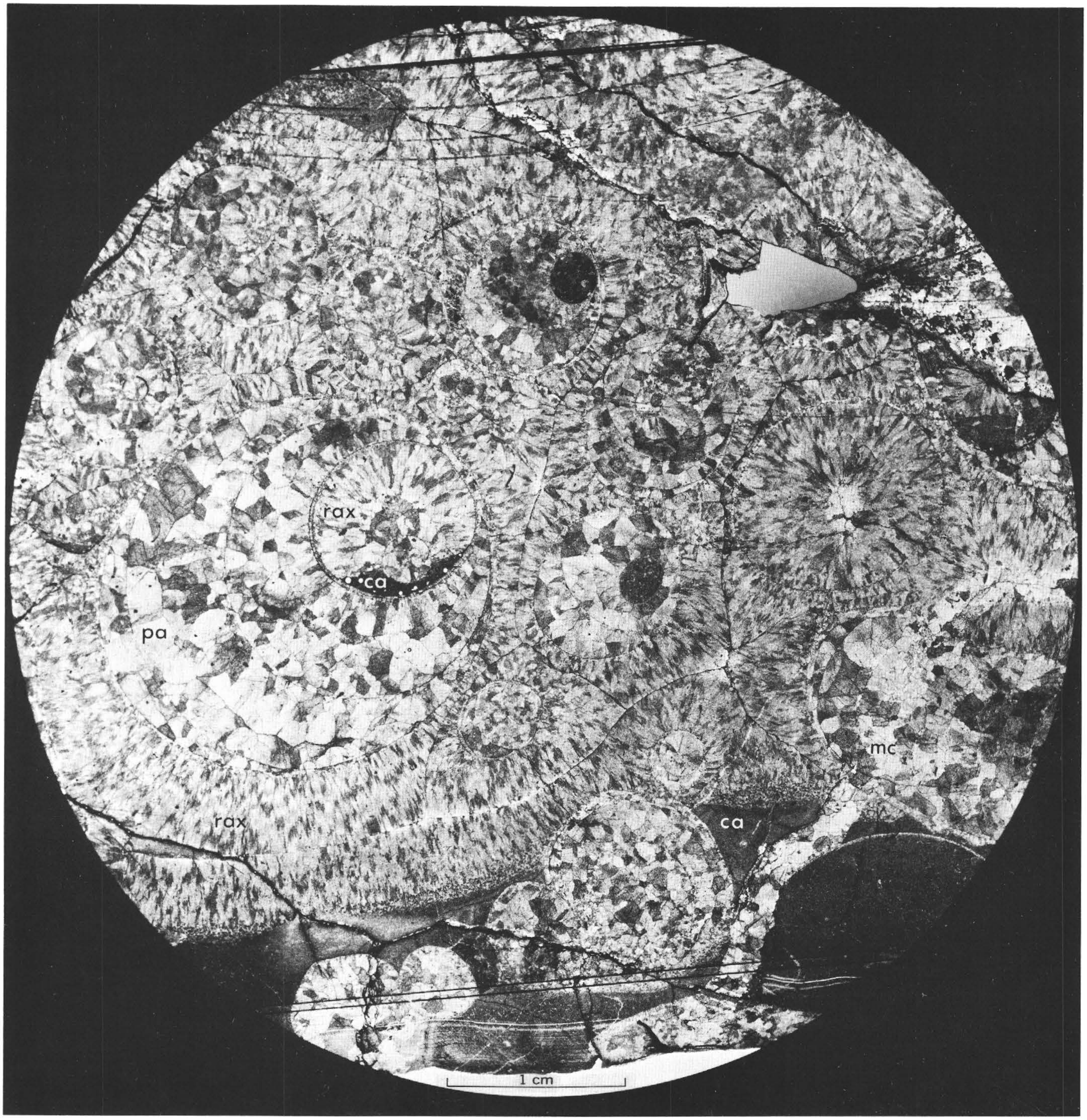


FIGURE 21. — A small part of a vertical section of a pocket or "nest" filled with shells of nautiloid cephalopods. All the space surrounding shells not now occupied by calcilutite (ca) is radiaxial fibrous calcite (rax). Almost all chambers are filled with blocky para-axial calcite mosaic (mc). A few chambers are filled with radiaxial calcite (rax). One chamber slightly left of center is filled partly with calcilutite and partly with radiaxial calcite. Presence of calcilutite may have been essential to formation of radiaxial fibrous calcite. Para-axial calcite (pa) occurs outside chambers only in fractures which cut all other lithologies. Collodion peel, photographed by transmitted light with one polarizer. USGS colln. D2389 CO.

letoid calcilutite (Beales, 1958, pl. 1, figs. 1–3); Ross here considers this interpretation less likely for the network associated with spicules than for the somewhat similar texture found in the thin (2–5 mm thick) layers that are interstratified with the fossiliferous calcilutite (figs. 23*A*, 25*A*, 25*B*). Both textures are shown in figure 23*B*.

FIGURE 22. — Polished section of poorly laminated limestone below mudmound. Dark-gray shapes contain spicular roots (sr) of sponges. Thin layers are pelletoid. Some thin layers and sparry calcite are fillings of internal cavities. USGS colln. D2390 CO.

In texture the thin interlayer shown in figure 27 somewhat resembles the late Paleozoic hydrozoan *Palaeoaplysina* described by Davies (1971, fig. 4 B, E). Dr. Davies kindly examined the sample illustrated and expressed the opinion (written commun., Nov. 3, 1972) that it was more readily interpreted as a pelletoid calcilutite with sparry matrix; however, he also suggested that the texture might be interpreted as a clastic biomicrite with algal(?) borings.

Some of the thin layers in this crudely laminated facies contain sparry calcite and may have a different origin. These tend to be discontinuous and to cut across the fossiliferous calcilutite ca_1. Many, but not all, appear to have been open fractures in the calcilutite, some cutting steeply across beds and some running nearly parallel. These presumed fractures are partly filled with geopetal sediment much of which was pelletoid. Most of the calcite bodies are entirely sparry para-axial mosaic; a few have radiaxial calcite enveloping the para-axial mosaic. The spar seems to have been formed in small discontinuous cavities. However, surrounding many of these calcite bodies is a halo of goethite at the contact with the calcilutite; such halos are common in replacement textures and it is difficult to explain the concentration of goethite within floor, walls, and ceiling of a cavity.

MASSIVE CORE FACIES OF THE CARBONATE MUDMOUND

By VALDAR JAANUSSON

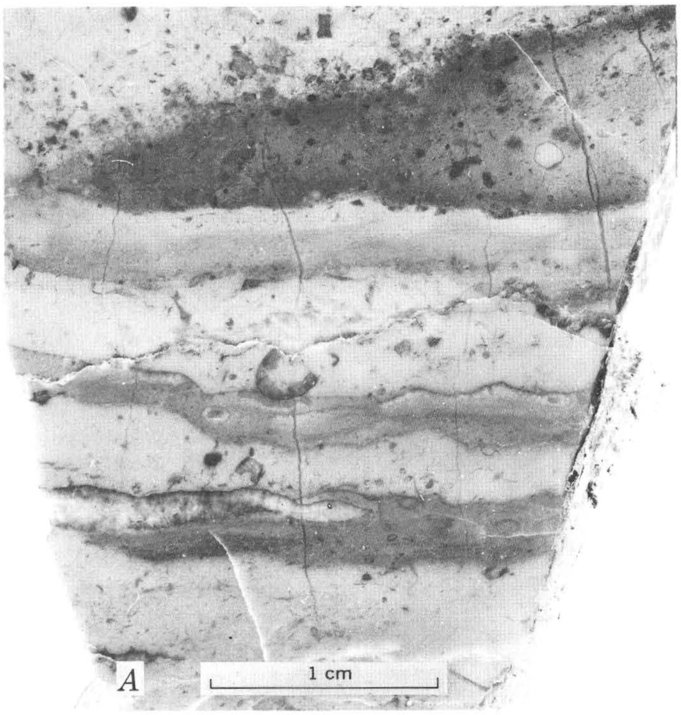
MACROSCOPIC CONSTITUENTS

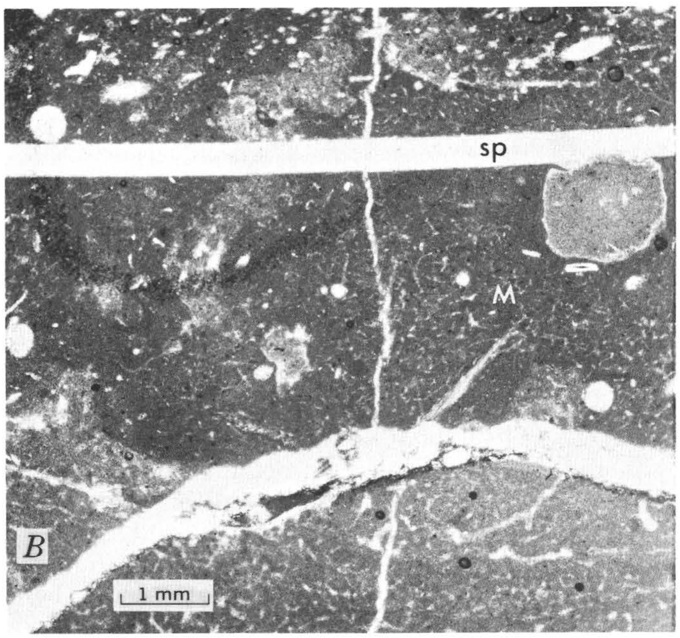
In the massive limestone forming the core of the mound, three main macroscopic constituents (here defined as structures larger than about 0.5 cm) can be distinguished: (1) sparry calcite bodies (*Stromatactis*), (2) skeletal particles, and (3) the rest of the rock, macroscopically mostly of fine-grained appearance.

STROMATACTIS

The sparry calcite bodies are elongated in cross section and distributed throughout the core facies with the long axis approximately parallel to the former depositional surface. Their thickness rarely exceeds 2 cm. The floor in most examples is fairly even, whereas the roof varies from even to digitate. Examination of these structures is made difficult by the sparsity of natural plane surfaces that are perpendicular to the depositional surface. Only a few such surfaces of sufficent size were found in the outcrop area of the mound core. Point counting in the field on three surfaces, each approximately 0.25 m^2 and all located in the uppermost part of the mound, showed that the macroscopic sparry calcite bodies form about 15, 17, and 18 percent of the volume of the rock, respectively. Examination of thin sections revealed that the sparry calcite bodies are composed of radial calcite (Bathurst, 1959) — that is, radiaxial fibrous calcite with undulose extinction, irregular, often highly digitate intercrystal boundaries, and numerous subgrains.

The mode of occurrence, general shape, and microstructure of the sparry calcite bodies resemble those in what is generally known as *Stromatactis*, and the same term is used here for the structures from the





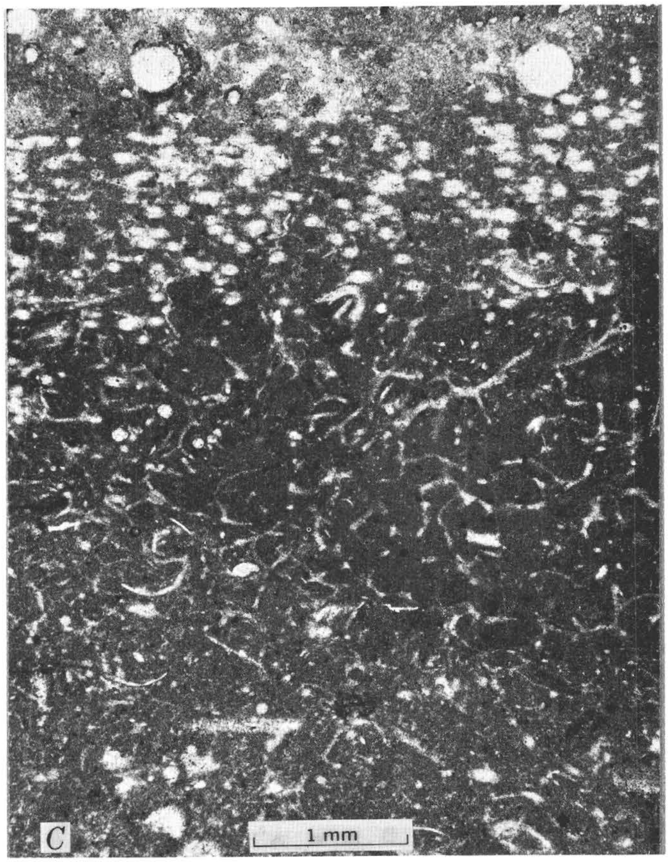


FIGURE 23 (left and above). — Polished and thin sections of sample of poorly laminated facies. USGS colln. D2390 CO. *A*, Polished section showing fossiliferous calcilutite (ca) separated by thin layers perforated by anastomosing tubes (tu). Tubes now filled with calcite mosaic, which may be matrix around pellets. Large dark-gray mass was produced by sponge and contains spicules (sp) of *Pyritonema*(?) and meshwork (M) of uncertain origin shown enlarged in *B* and *C*. *B*, Brachiopod(?) attached to long spicule (sp) paralleling plane of section appears as round spot in dark spicular mass in *A*. Discontinuous meshwork (M) below spicule may be sponge or calcite matrix around pellets of calcilutite. Abundant small white circles near top of photomicrograph are cross sections of spicules. Texture at bottom may be sparry calcite matrix around pellets or *structure grumeleuse*. Thin section. *C*, Thin section parallels *B* but does not cut brachiopod or large spicule. Large white circles are cross sections of *Pyritonema*(?) spicules. Peculiar discontinuous meshwork in center of view also appears below brachiopod in *B*.

core of the Meiklejohn Peak mound. The *Stromatactis* in the core differs from the sparry calcite layers in the zebra limestone by the much more irregular shape of the individual bodies, by their seemingly irregular distribution, and by their smaller size. The maximum observed length of a cross section of *Stromatactis* in the core of the mound is 24 cm; most are considerably shorter. The microstructure of *Stromatactis* and the sparry calcite layers in the zebra limestone, on the other hand, is very similar. The radiaxial crystals or mosaic of crystals from the floor and roof normally meet in a distinct seam (fig. 28).

None of the *Stromatactis* examined in the core of the mound exhibited a central, "residual" cavity or a well-defined central filling with para-axial (Bathurst, 1964) calcite. The absence of such structures may depend on the relatively small dimensions of *Stromatactis* in the Meiklejohn Peak mound or on their sparsity.

The origin of *Stromatactis* has been, and still is, very much disputed and numerous different explanations have been proposed. Comparison of *Stromatactis* from the core of the Meiklejohn Peak mound with similar

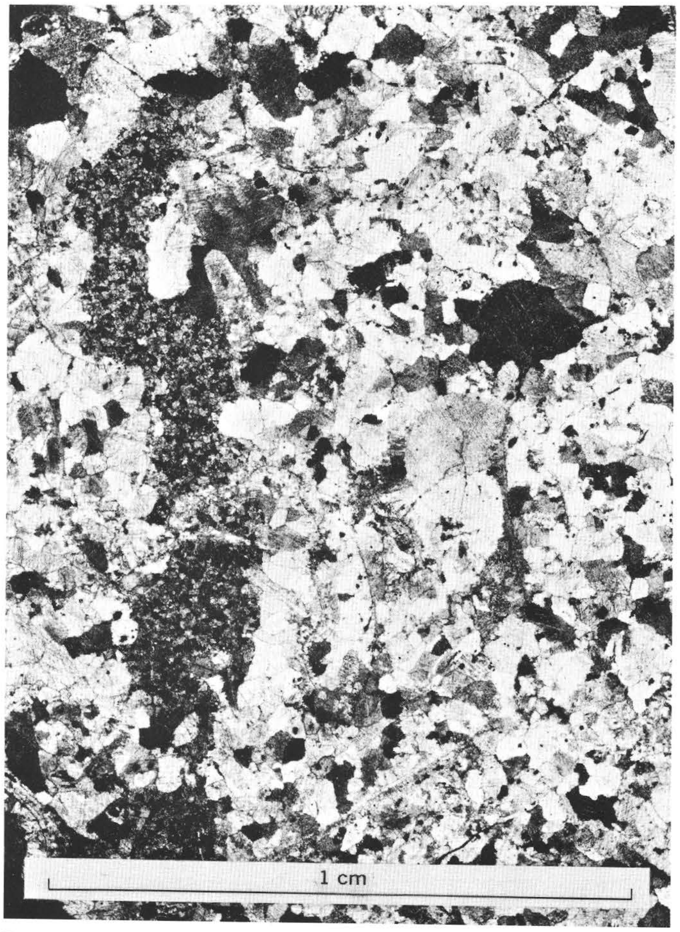


FIGURE 24. – Coarse calcarenite below mudmound, about 60 m (200 ft) from the south end of outcrop. USGS colln. D2332 CO.

structures from various other Paleozoic carbonate mounds suggests that the main factor in the origin is common to all. The material available for comparison includes *Stromatactis* from the Devonian of the Dinant Basin in Belgium (including samples from the quarries around Philippeville, the type area for *Stromatactis* Dupont, 1881), from the Ordovician of Sweden, and from the Carboniferous of England and Ireland. The material from the Meiklejohn Peak mound alone is too limited for forming a satisfactory basis of an extensive discussion of the whole problem of *Stromatactis*. Some observations presented here are deemed to be pertinent for understanding the origin of the structures.

Several observations indicate that, irrespective of what the origin of *Stromatactis* may be, the shape and size of the radiaxial crystals, and possibly the whole radiaxial mosaic as such, is not original but a result of diagenetic processes. The radiaxial mosaic has demonstrably incorporated skeletal particles (Black, 1952; Orme and Brown, 1963; Jaanusson, 1975) and grown at their expense. The material from the core of the Meiklejohn Peak mound shows numerous examples of this phenomenon (figs. 29, 30). A particularly interesting example (fig. 31) shows carapaces of ostracodes that occur in various stages of incorporation into radiaxial mosaic within a *Stromatactis*. Some of the carapaces are situated at the median seam of the radiaxial mosaic. The radiaxial mosaic has probably also assimilated fine-grained matrix, although this cannot be proved.

A mosaic which is very similar to the radiaxial mosaic can be shown to result from recrystallization (increase in the size of crystals) of finely fibrous normal calcite mosaic and, possibly, when aragonite is transformed into calcite in situ in closed space. Probably one of these processes was operative in the formation of radiaxial mosaic on *Stromatactis*. Subsequently, the mosaic grew by incorporating adjoining grains or extending into voids. The core of the Meiklejohn Peak mound contains numerous narrow veins filled with calcite. Some of the fissures probably formed early during the diagenetic history of the mound. The normal vein filling of these fissures is para-axial sparry calcite but where narrow veins cut a *Stromatactis* the calcite in the vein filling is generally radiaxial and in optical continuity with the crystals in adjoining radiaxial mosaic (fig. 15). This phenomenon has been observed in almost all carbonate mounds with *Stromatactis* from which material has been available. Orme and Brown (1963) suggested that this proves the mosaic of *Stromatactis* to postdate the formation of fissures, but in my opinion, a more plausible explanation is precipitation in a fissure with the crystal structure controlled by that of the wall. There are examples in the core of the Meiklejohn Peak mound where a vein cuts an echinoderm grain and the filling of the vein at that place is calcite in optical continuity with both halves of the echinoderm grain.

Thus the present radiaxial mosaic of *Stromatactis* is most likely secondary. Determining the primary structure is difficult. This type of mosaic occurs in what demonstrably have been cavities in sediment (for example, in closed shells of brachiopods), but it is also known to replace original organic structures (stromatoporid coenosteums and stromatolitelike organic structures in the Upper Ordovician carbonate mounds of Sweden). The presence of a distinct median seam might indicate filling of a cavity, because such seams have not been observed to be associated with recrystallization into a radiaxial mosaic.

MACROSCOPIC SKELETAL PARTICLES

Macroscopic skeletal particles are scarce in most of the core of the Meiklejohn Peak mound. The point-counted surfaces mentioned previously (p. 20) did not include any skeletal particle of macroscopic size. Macrofossils tend in the core facies to be assembled into pockets or channellike structures but their importance relative to the total volume of the core of the mound is small.

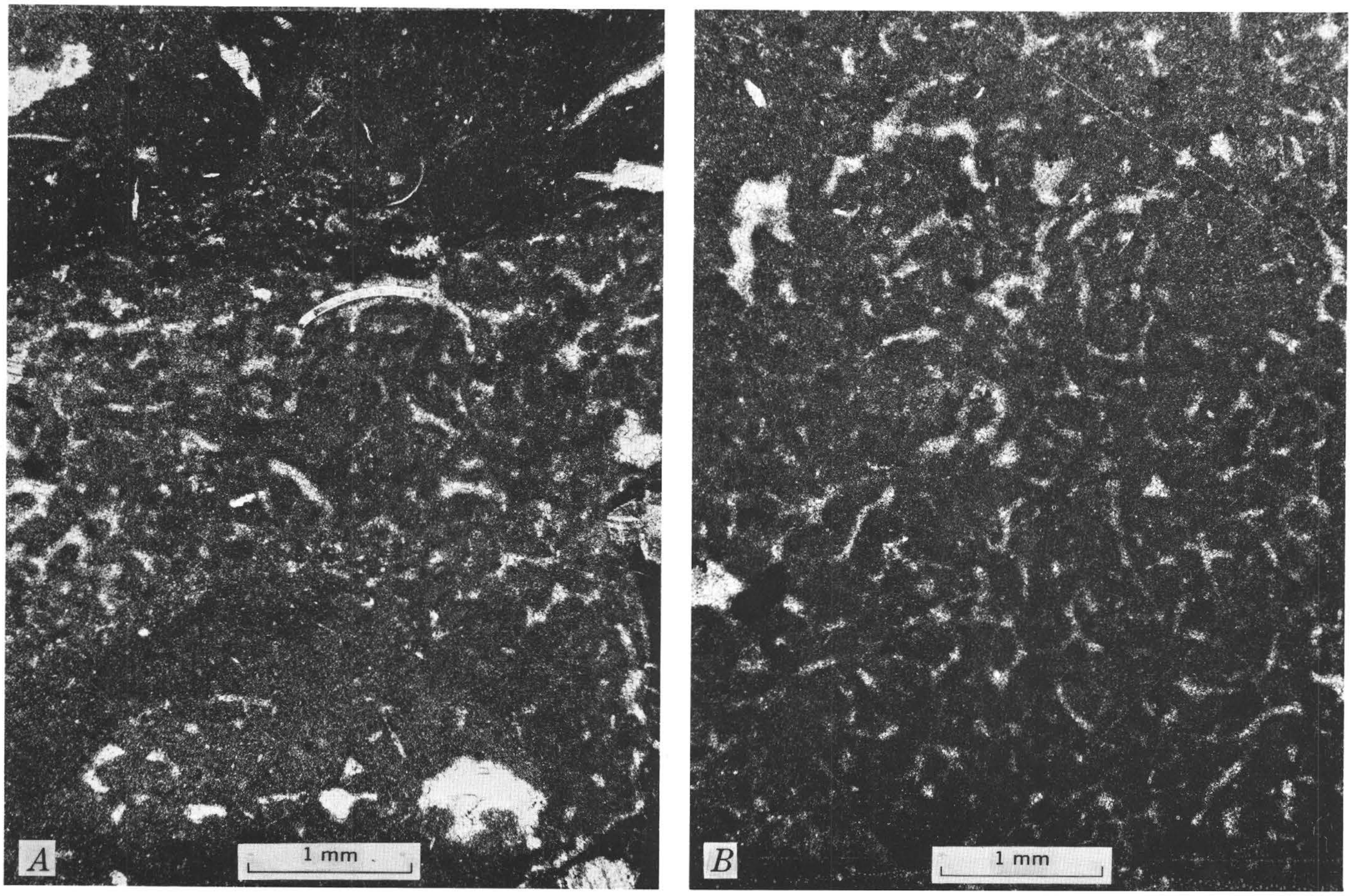


FIGURE 25. — Pelletoid(?) texture in thin light-gray layer similar to that below dark spicular mass in figure 23*A* and to that at bottom of figure 23*B*. Thin sections of poorly laminated facies below mudmound. USGS colln. D2390 CO. *A*, Vertical section. *B*, Horizontal section.

FINE-GRAINED LIMESTONE

In some of the samples several generations of fine-grained limestone can be distinguished; other samples are more homogeneous and contain possibly only one generation of micrite. The various generations differ mainly by microstructure and contact relations. Differences in color are so slight that recognizing the generations in the field is difficult, unless the rock surface is etched or stained, or both.

The seemingly earliest generation of the fine-grained limestone (*Li 1*) is the commonest and resembles layer ca_1 in the zebra limestone. It normally consists of cryptocrystalline micrite with varying amounts of skeletal grains (fig. 32). The skeletal grains of sand size are mostly more abundant than in ca_1, and so the sediment is coarser grained than the limestone of the ca_1 layers.

What probably is the next generation (*Li 2*) has a more varied composition. Micrite similar to that of *Li 1* is common, but the limestone also contains layers or patches of peloid limestone similar to that in ca_2 of the zebra limestone recrystallized portions, and spar, radiaxial as well as para-axial (fig. 32).

Where typically developed, the boundaries between *Li 1* and *Li 2* are well defined (fig. 32). The complex distribution pattern of both generations suggests a system of burrows or borings in *Li 1* filled with *Li 2*. With the material at hand, it is difficult to prove whether burrowing or boring was responsible for the pattern—whether the cavities had been formed in soft sediment or in a rock. Some observations, such as shells protruding from *Li 1* into *Li 2*, suggest burrows, but the evidence is inconclusive.

The succession of the generations *Li 1* and *Li 2* is not always clear, and further studies may reveal a more complicated pattern of relations.

In the available samples it is difficult to see any clear spatial relation between the two generations of fine-grained limestone and individual bodies of *Stromatactis*, comparable to that between the layers of spar and ca_2 layers of calcilutite in the zebra limestone or between *Stromatactis* and layers considered as internal sediment described from English and Irish Carboniferous carbonate mounds (Bathurst, 1959; Schwarzacher, 1961; Lees, 1964). In this respect further studies are necessary.

The third generation of fine-grained limestone (*Li 3*) is relatively rare but distinctive. It mostly consists of a

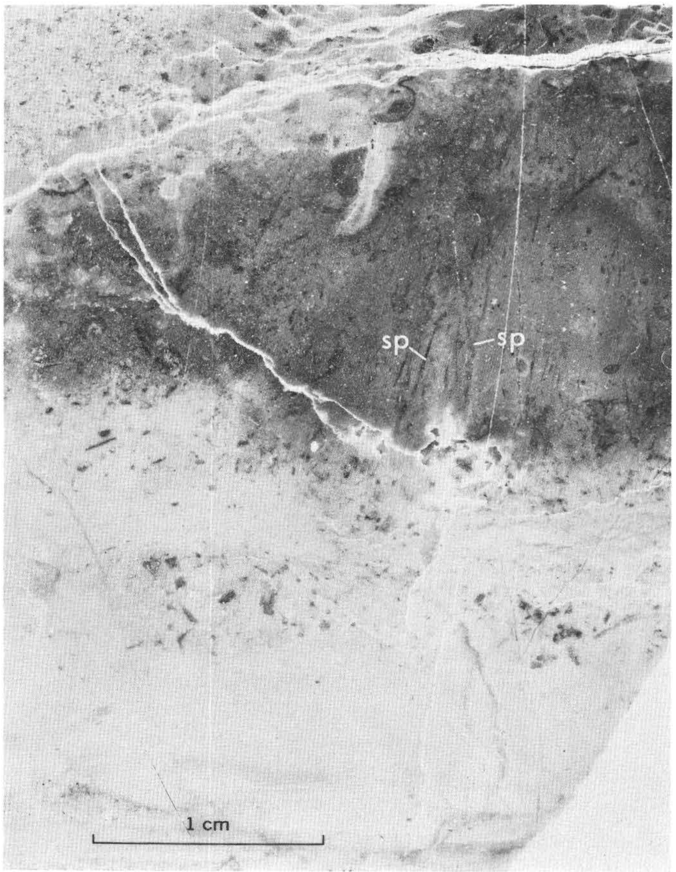


FIGURE 26. — Polished section showing one of the dark masses illustrated in figure 22 (sr) where large spicules (sp) are particularly abundant and probably constituted roots of a sponge. USGS colln. D2390 CO.

relatively homogeneous, fine-grained microspar with few skeletal grains. It generally occurs as a layer or fissure-filling at a steep angle or perpendicular to the former depositional surface. The boundaries against *Li 1* and *Li 2* are sharp and accentuated by a thin layer of sparry, para-axial calcite, 0.07–0.15 mm thick.

The relation of *Li 3* to *Stromatactis* is illustrated in figure 33. There a small *Stromatactis* is faulted into four pieces, only three of which are visible in the photomicrograph (the fourth piece was just outside the right field of view). The almost straight margin of the *Stromatactis* to the right is formed by the fault which separates the third and fourth pieces. It cuts through a normally developed radiaxial mosaic in the same way as the first and second faults do. Faulting at the right formed a fissure, 2.6 to 2.9 mm wide, which is now filled with the limestone of the generation *Li 3*. The faulting also caused a vertical displacement of about 2.5 mm. This example shows conclusively that *Li 3* postdates the formation of *Stromatactis* and that the general structural pattern of the radiaxial mosaic must have been fully developed before the deposition of *Li 3*. The sediment above and below the *Stromatactis* may still have been somewhat friable when faulting took place, as judged from the smooth curvature of the margin of the fault at some places (fig. 33). At other places, particularly where the wall is coated with spar, the wall of the fissure is straight.

In parts of the mound the core is transected by macroscopically distinguishable, locally irregular fissures of varying width filled with brown-weathering limestone. This limestone obviously is still later than *Li 3*.

MICROSCOPIC CONSTITUENTS

The microscopic composition of the limestone in the core of the Meiklejohn Peak mound was studied by modal analysis in a series of thin sections. The samples from which thin sections were prepared were intentionally taken from the macroscopically fine-grained parts of the core. Thus, the quantitative data apply only to this macroscopic component, comprising 80–85 per-

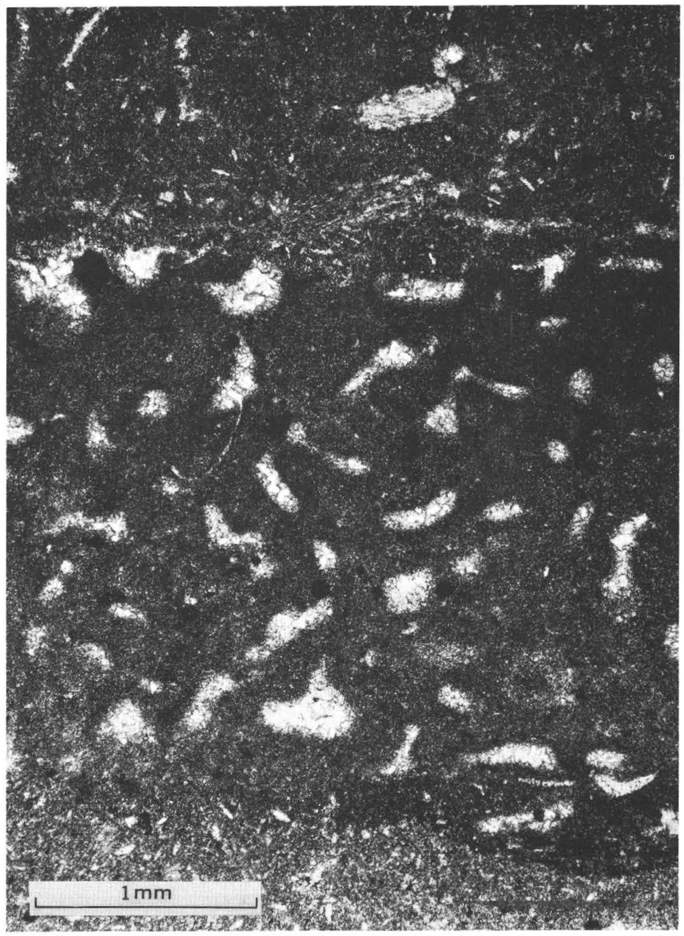


FIGURE 27. — Vertical section across thin layer of calcilutite perforated by irregular calcite-filled tubes, similar to those shown in figure 25. These may be sparry matrix around indistinct pellets or algal borings in calcilutite. USGS colln. D2390 CO.

cent of the volume of the core. The general objectives of the study of microscopic carbonate constituents, as well as the methods, were reviewed and discussed by Jaanusson (1972).

The series of samples for constituent analysis was collected by Ross in 1970 along a section through the middle part of the core of the mound (samples D2341 CO to D2349 CO; fig. 4). In two thin sections (from D2341 CO and D2346 CO) recrystallization has nearly obliterated original grain boundaries; these thin sections were not measured. One thin section, from the sample D2349 CO, showed two clearly different rock types (calcilutite and calcarenite) separated by a sharp boundary; the areas of both types were measured separately. Patches of rock within almost all thin sections showed various degrees of aggrading neomorphism, and measurements involved more subjective judgments than is usual for such modal analysis. Still, qualitative study of peels from additional samples collected by Jaanusson in 1972 seems to indicate that the quantitative data are reasonably representative for the fine-grained limestone of the mound core.

Owing to difficulties in distinguishing the generations *Li 1* and *Li 2* in most thin sections, these limestones are not discussed separately. The limestone of the generation *Li 3* was not included in the measured area.

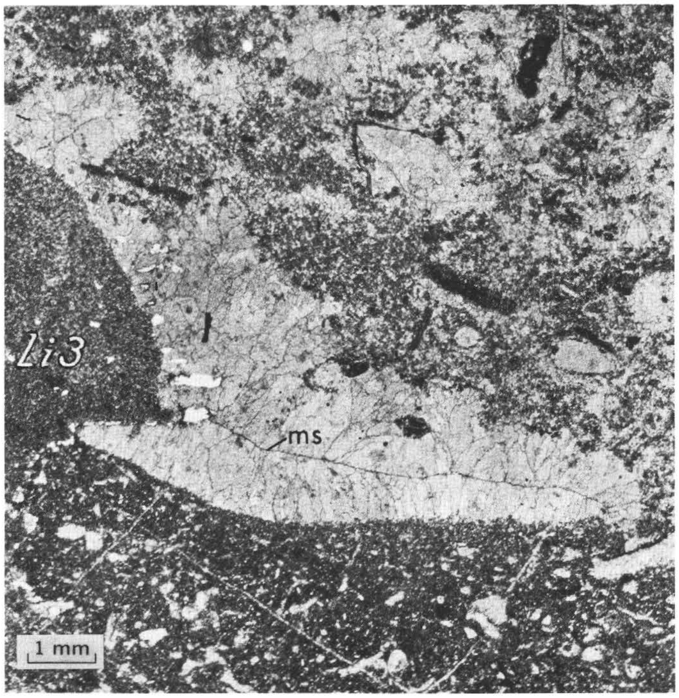


FIGURE 28. — Thin section of a "microstromatactis" (ms) from the core of the mound. The surrounding limestone is either first *(Li1)* or second *(Li 2)* generation, except to the left, where a third generation of limestone *(Li 3)* is in contact with the radiaxial calcite. USGS colln. D2345 CO. Photograph by U. Samuelson of Naturhistoriska Riksmuseet. Lithologic sequence explained on p. 23.

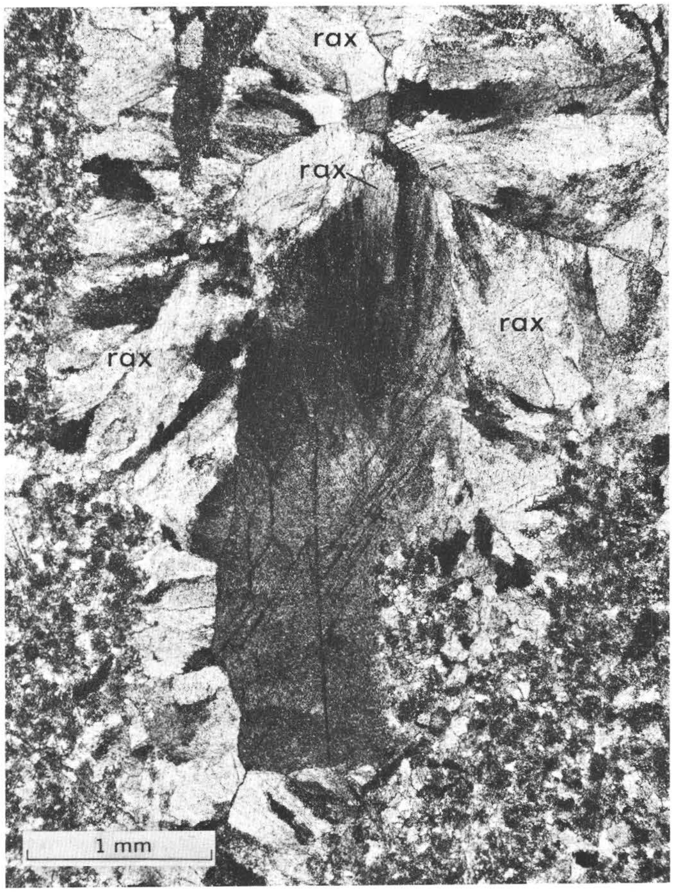


FIGURE 29. — Plate of an otherwise unidentified echinoderm partly converted to radiaxial fibrous calcite (rax). Thin section. USGS colln. D2345 CO.

MAIN MICROSCOPIC CONSTITUENTS

In the core of the Meiklejohn Peak carbonate mound, the main microscopic constituents (table 1) of the limestone are (1) sparry calcite, (2) skeletal sand, and (3) matrix. Sparry calcite was considered as a separate constituent only when a well-defined mosaic of calcite crystals was 0.1 mm long or larger. Skeletal sand is defined as those skeletal particles 0.1 mm long or larger in thin section (Jaanusson, 1952, 1972). The matrix — the rest of the rock — consists of material of various origin, such as skeletal grains smaller than 0.1 mm, carbonate mud, terrigenous mud, and probably at least 40 percent calcium carbonate cement. Much of the matrix is recrystallized into an ultramicroscopic mosaic of calcite crystals whose original constituents are no longer recognizable.

Some thin sections contain dark, cryptocrystalline, pelletlike spots, almost completely surrounded by spar. In places they seem to represent indurated pellets, in others, it is difficult to prove whether they are depositional features (represent pelletlike sedimentary grains) or are phenomena developed during recrystallization (*structure grumeleuse)*. Many of the spots are shorter than 0.1 mm and have indistinct boundaries. In the thin section D2343 CO, the peloids 0.1 mm long or larger comprise 8 percent of the measured area; in all other thin sections, they are much rarer or are absent. The peloids are tabulated as matrix.

Modal analyses show that the fine-grained parts of the rock consist, in average, of 37 percent sparry calcite, 7 percent skeletal grains, and 56 percent matrix.

SPARRY CALCITE

About 44 percent of the microscopic sparry calcite is radiaxial and the rest is para-axial. The microscopic bodies of radiaxial sparry calcite (fig. 28; Ross, 1972, fig. 7) resemble *Stromatactis* in microstructure and general shape. For convenience they are termed here

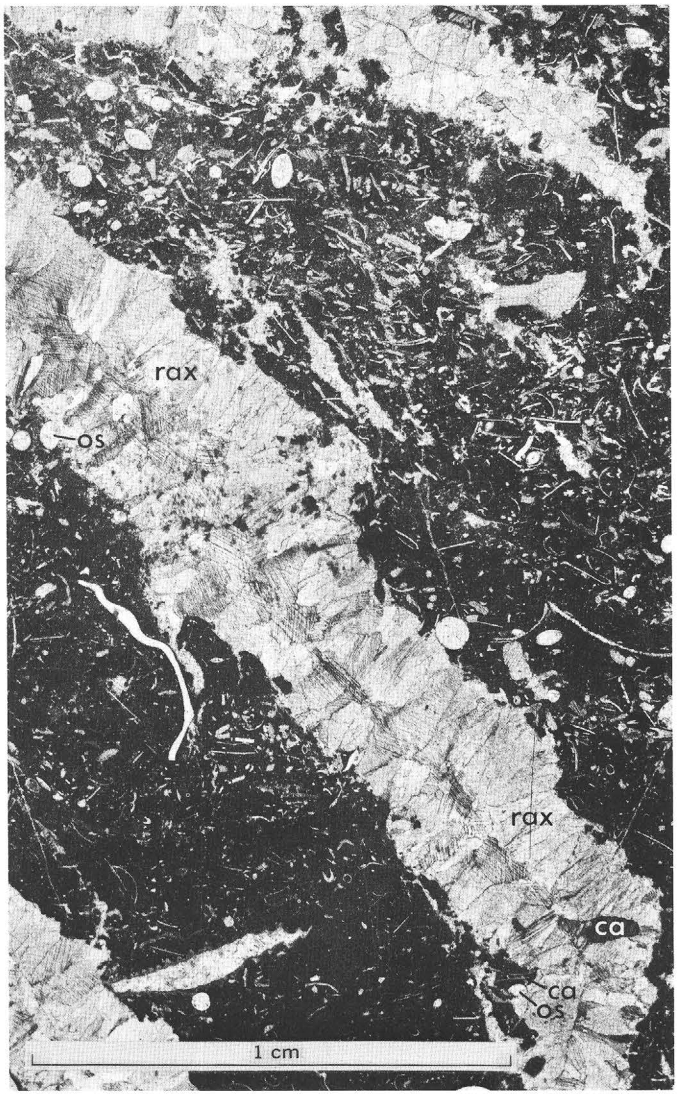


FIGURE 30. — Thin section from USGS colln. D2342 CO showing fossil ostracodes (os) and pieces of calcilutite (ca) relict in radiaxial fibrous calcite (rax).

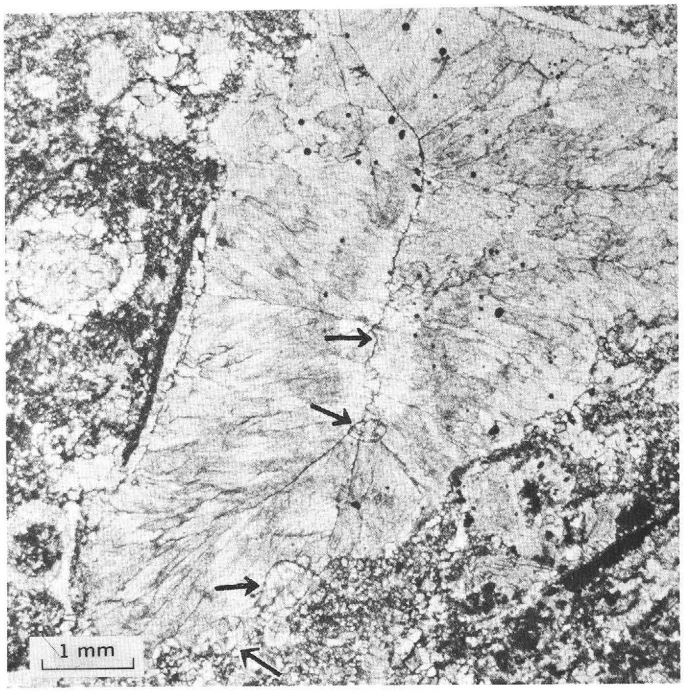


FIGURE 31. — Thin section of a "microstromatactis" with incorporated ostracode carapaces (arrows) in various degrees of recrystallization into radiaxial calcite. USGS colln. D2344 CO. Photograph by U. Samuelson, Naturhistoriska Riksmuseet.

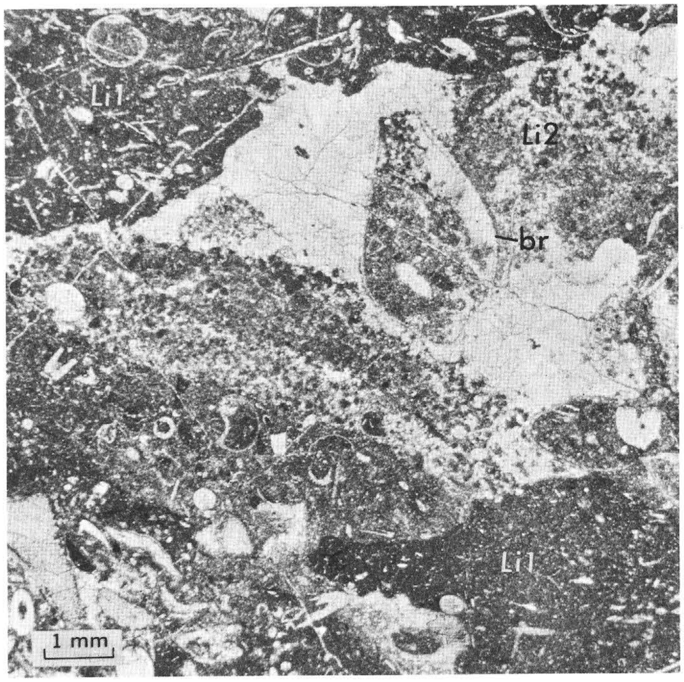


FIGURE 32. — Thin section from the core of the mound showing distribution of two generations of limestone (*Li 1* and *Li 2*). The large sparry calcite mosaic in *Li 2* is radiaxial, as is the spar inside a partially closed brachiopod shell (br) which is mostly filled with micrite. USGS colln. D2343 CO. Photograph by U. Samuelson, Naturhistoriska Riksmuseet.

"microstromatactis." There are all gradations in size from microstromatactis (with a thickness less than 1 mm) to *Stromatactis* of macroscopic dimensions. Other microscopic mosaics of radiaxial calcite have less regular outlines and lack a clear median seam. The nature of such mosaics is not always clear. Some represent peripheral cuts of microstromatactis; others suggest formation by aggrading neomorphism.

Where former original cavities can be demonstrated, such as within closed carapaces of ostracodes and closed shells of brachiopods, the cement is mostly radiaxial calcite. Some such intragranular cavities contain a central filling of para-axial calcite which is later than the radiaxial calcite.

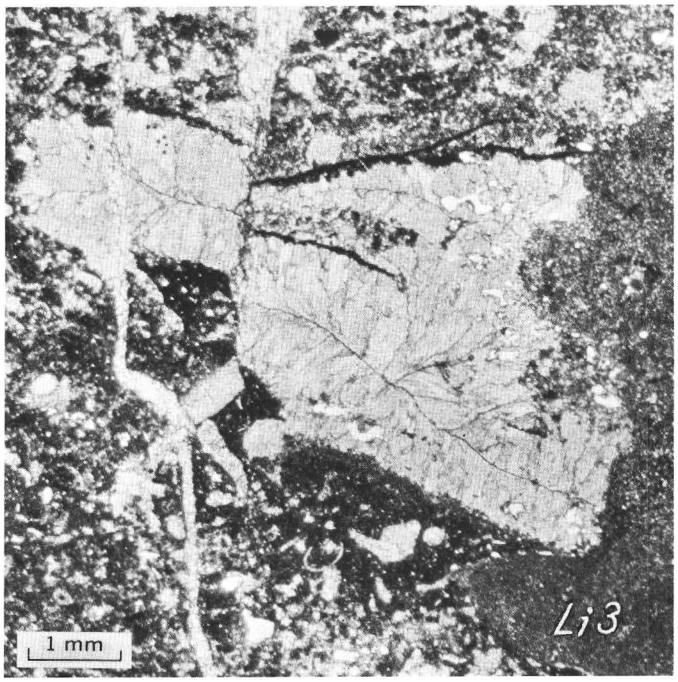


FIGURE 33 (right). — Thin section of a "microstromatactis" which is faulted into four pieces (the fourth piece is to the right just outside the lower right corner of the photograph). The fissure at the right is filled with limestone of the generation *Li 3.* USGS colln. D2343 CO. Photograph by U. Samuelson, Naturhistoriska Riksmuseet.

TABLE 1. — *Relative proportions of microscopic constituents for six collections taken stratigraphically through center of the carbonate mudmound at Meiklejohn Peak*

[Positions of collections indicated in fig. 4. Collection D2349 CO from nodular limestone immediately covering mound]

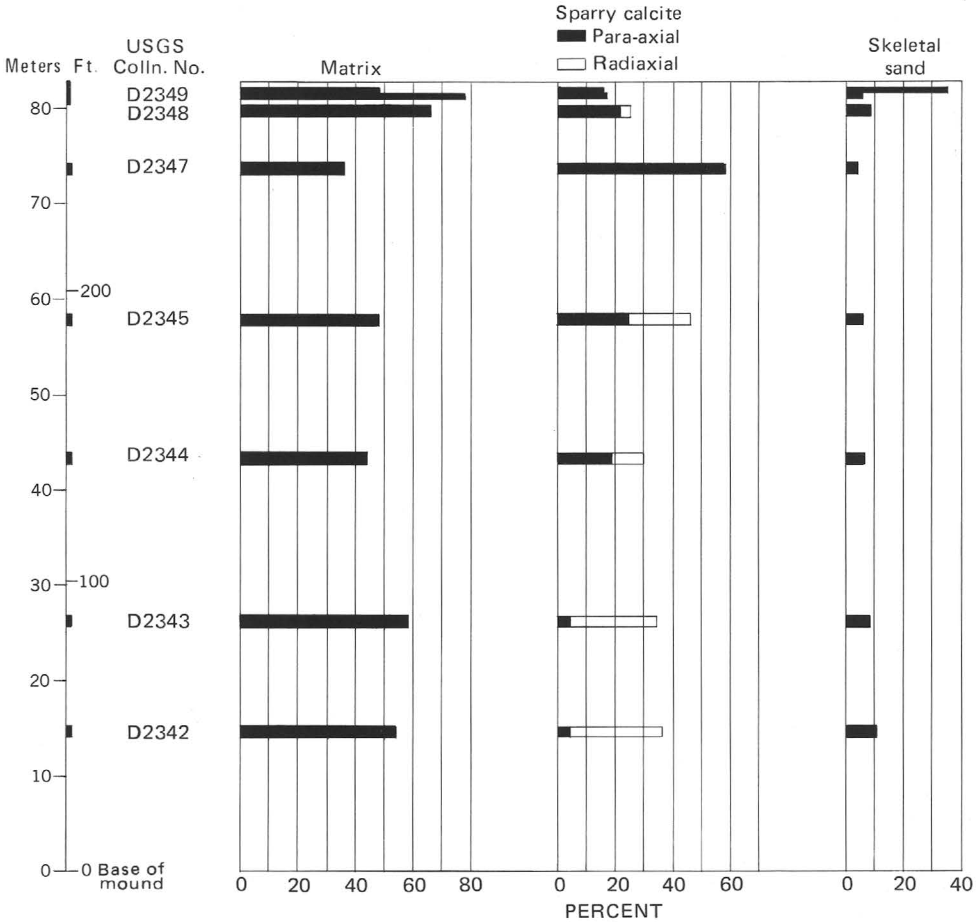
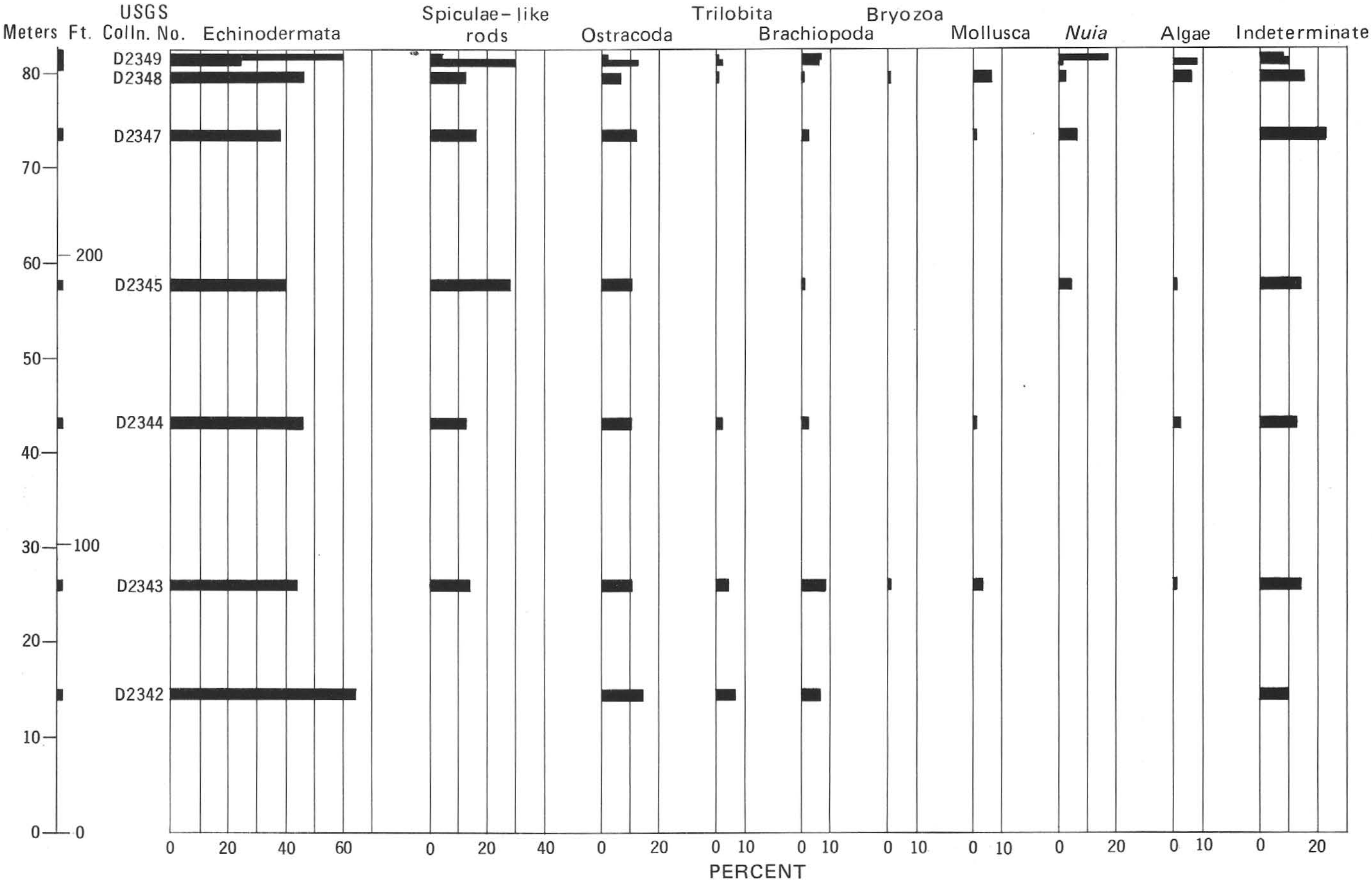


TABLE 2. — *Relative proportions of organic components of the skeletal sand fraction shown in table 1, for six collections taken stratigraphically through center of the carbonate mound*

[Positions of collections indicated in figure 4. Collection D2349 CO from nodular limestone immediately covering mound]



Para-axial calcite frequently forms relatively coarse mosaics similar in size and shape to microstromatactis except that the outline tends to be much more irregular and a median seam is seldom present. Such para-axial mosaics may belong to a generation different from that of radiaxial calcite but this could not be proved. Where both types of sparry calcite mosaics are in contact, the boundary between the mosaics is generally transitional. However, this may be a phenomenon of the same nature as the development of radiaxial calcite in those parts of narrow veins that cut a radiaxial mosaic; the structure of the crystals acting as seeds may have become propagated beyond the original boundary of a mosaic.

Radiaxial and para-axial sparry calcites tend frequently to be concentrated in different patches — in different samples or in different parts of a thin section. This affects, then, not only the relatively large mosaics but also intragranular and intergranular cement. Near the top of the mound para-axial sparry calcite predominates, whereas in the lower and middle parts of the mound radiaxial calcite predominates. The implication of these differences in distribution is not clear.

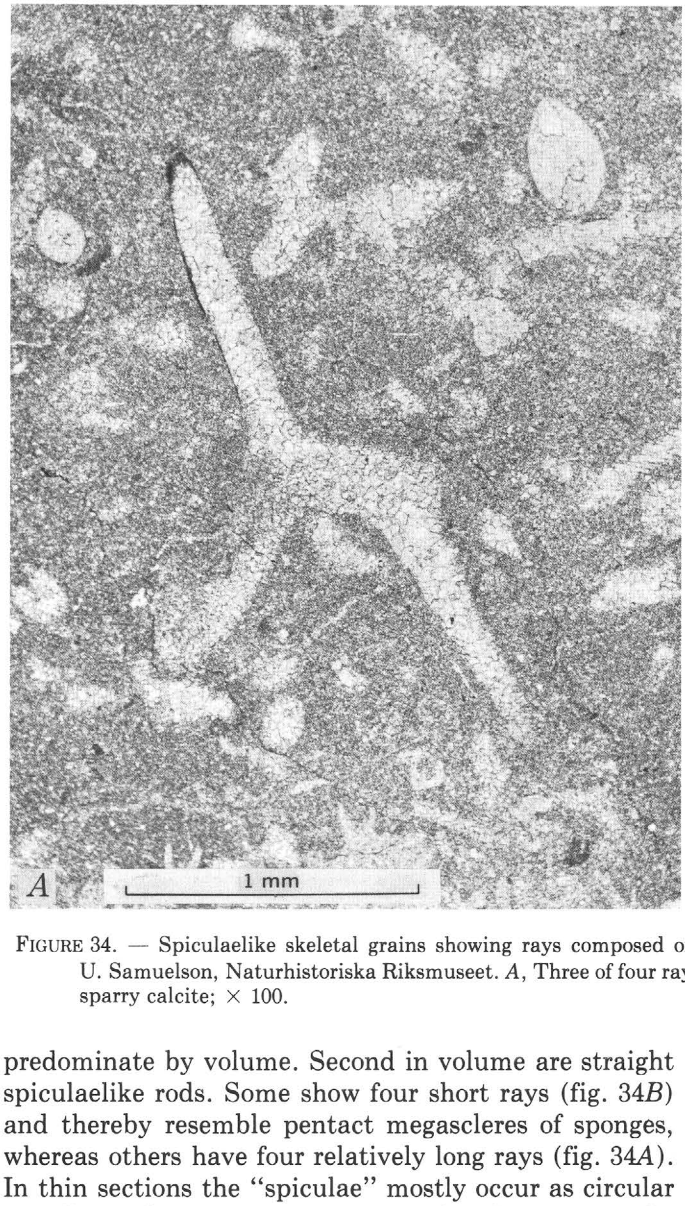
Skeletons which were originally aragonitic (here regarded as part of the skeletal sand) have mostly been replaced by a para-axial sparry calcite even in areas where radiaxial calcite dominates. This might suggest that the transformation of aragonite to calcite was later than the formation of intragranular radiaxial spar. However, there are exceptions and further studies are needed.

Much of the microscopic para-axial sparry calcite forms irregular patches of relatively fine-grained mosaic which obviously formed by aggrading neomorphism, as defined by Bathurst (1971, p. 481).

COMPOSITION OF SKELETAL SAND

In the thin sections studied the amount of skeletal sand varies between 4 and 11 percent (table 1), and thus the rock can be characterized as a calcilutite. Calcarenitic areas do occur, particularly in pockets abounding in skeletal remains, but they are quantitatively unimportant. The sediment was mud-supported.

Within the skeletal sand (table 2) echinoderms



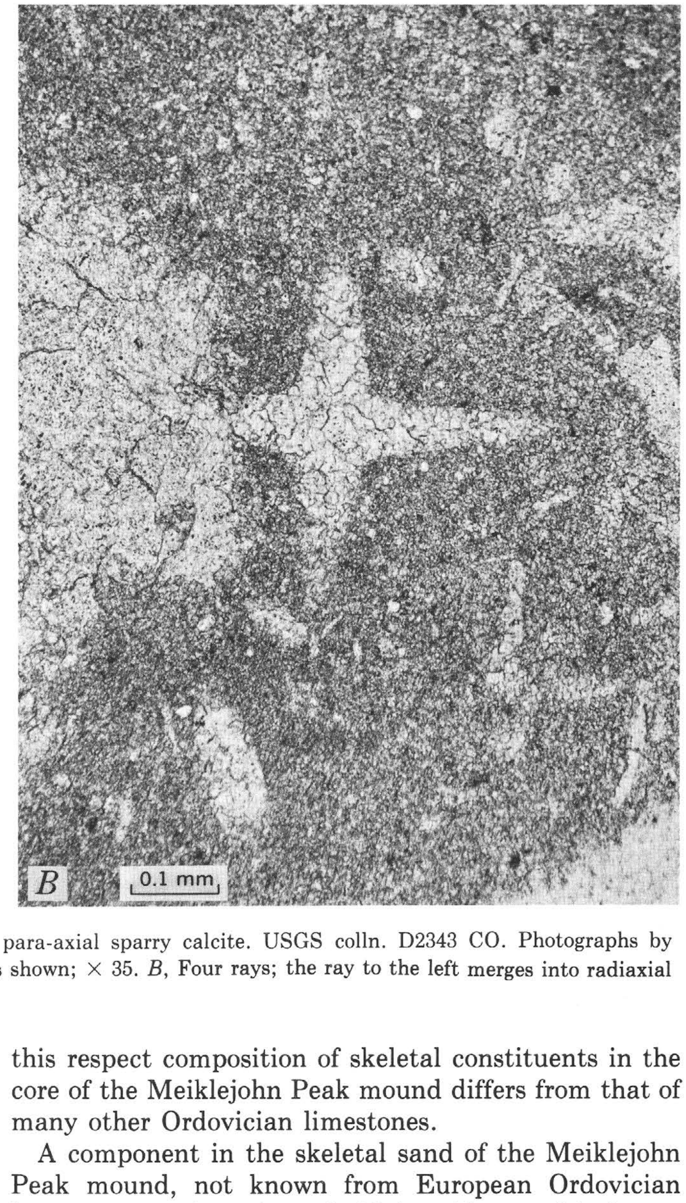


FIGURE 34. — Spiculaelike skeletal grains showing rays composed of para-axial sparry calcite. USGS colln. D2343 CO. Photographs by U. Samuelson, Naturhistoriska Riksmuseet. *A*, Three of four rays shown; × 35. *B*, Four rays; the ray to the left merges into radiaxial sparry calcite; × 100.

predominate by volume. Second in volume are straight spiculaelike rods. Some show four short rays (fig. 34*B*) and thereby resemble pentact megascleres of sponges, whereas others have four relatively long rays (fig. 34*A*). In thin sections the "spiculae" mostly occur as circular to elliptical cross sections of rods. Some may be *Pyritonema,* which is similar in microstructure and general dimensions. The original composition of the skeleton was probably aragonite because the "spiculae" are now a relatively coarse para-axial mosaic of sparry calcite. This often hampers recognition of the spiculaelike skeletal grains; some spiculae either have not been distinguished from sparry calcite or have been confused with other groups which originally had aragonitic skeleton, such as mollusks or an enigmatic tubelike microfossil with a very thin wall. Many tubes are filled with sparry calcite and then the wall is difficult to recognize. Aragonite as a skeletal mineral is, to the best of our knowledge, not reported among sponges and the attribution of the spiculaelike skeletal grains is at present uncertain.

By volume ostracodes predominate over trilobites. In this respect composition of skeletal constituents in the core of the Meiklejohn Peak mound differs from that of many other Ordovician limestones.

A component in the skeletal sand of the Meiklejohn Peak mound, not known from European Ordovician limestones, is the enigmatic *Nuia*, widespread in Lower and Middle Ordovician limestones of North America (Toomey and Klement, 1966; Johnson, 1966; Toomey, 1967). Originally the skeleton of this possible alga probably was calcite.

COMPARISON WITH SELECTED OTHER PALEOZOIC CARBONATE MOUNDS

In several respects the Meiklejohn Peak mound resembles certain other Paleozoic carbonate mounds, such as the Ordovician Kullsberg and Boda Limestones of the Siljan district of Sweden and the Carboniferous "reef knolls" of the British Isles and Belgium. In all these mounds, as well as in several others, *Stromatactis* is an important macroscopic constituent. In the Kullsberg Limestone *Stromatactis* forms about half the volume of the rock and in northwestern European Carboniferous mounds the importance of *Stromatactis* seems to be closely comparable. The Meiklejohn Peak mound differs in its smaller content (15–20 percent) of the sparry calcite bodies.

In all these carbonate mounds microscopic sparry calcite is abundant, radiaxial as well as para-axial. In the Kullsberg Limestone it forms, in average, about a third of the volume of what macroscopically is fine-grained limestone (Jaanusson, 1975). Microscopic sparry calcite is abundant also in thin sections examined from the northwestern European Carboniferous mounds. In the Meiklejohn Peak mound the macroscopically fine-grained limestone of the core abounds in sparry calcite, averaging about a third of the volume of the rock. A part of the sparry calcite may have been precipitated as cement but a part is demonstrably formed by aggrading neomorphism, that is, by recrystallization of sedimentary particles and carbonate cement into sparry calcite mosaic after aragonite had either dissolved or been transformed into calcite. The carbonate mounds in Sweden, Belgium, and the British Isles consist of limestones of high purity (97–99 percent $CaCO_3$; in the core of the Meiklejohn Peak mound the amount of insoluble residue is about 2–3 percent). A contributing factor to the extensive recrystallization of such limestones may be the low content of terrigenous material, particularly clay minerals (Zankl, 1969) and other impurities which can hinder crystal growth.

The skeletal constituents of the Meiklejohn Peak mound (table 2) differ markedly from those of the Ordovician mounds of the Siljan district, Sweden; (Jaanusson, 1975), the Devonian Upper Koneprusy mounds in Bohemia (Jaanusson, 1975), and the Carboniferous "reef knolls" of the British Isles and Belgium. In all those carbonate mounds fenestrate bryozoans (phylloporinids in the Ordovician mounds and fenestellids in the Devonian and Carboniferous mounds) are abundant and commonly are the predominant component of the skeletal sand. Abundance of fenestrate bryozoans has been reported also from several other carbonate mounds (Pray, 1958; Cotter, 1965; and others). The abundant fronds of fenestrate bryozoans formed grain-supported sediment; not all the extensive intergranular voids became filled with sediment; some voids persisted and sparry calcite cement was subsequently precipitated therein. The fenestrate bryozoans may also have acted as sediment traps and contributed to the growth of the carbonate mounds.

In the Meiklejohn Peak mound bryozoans are very rare and no fenestrate form has been found. Bryozoans are much more common in the upper member of the Antelope Valley Limestone well above the mound but do not form an important constituent of the skeletal sand therein.

Many Paleozoic carbonate mounds show evidence of an early lithification. That a mound was lithified prior to deposition of the covering beds can be demonstrated in numerous examples. During final settling of a mound, broad dilatational crevices were formed in the then-lithified rock and subsequently filled with sediment from above. (See Isberg, 1917, 1918, and others for the Ordovician carbonate mounds of the Siljan district, Sweden; Chlupáč, 1955, for Devonian Upper Koneprusy "reefs" of Bohemia; Philcox, 1963, for Carboniferous "reef knolls" of Ireland; Pray, 1965, for "banks" of Waulsortion type in the Sacramento Mountains, New Mexico; Cotter, 1965, for Mississippian "banks" of central Montana.) In the Ordovician carbonate mounds of the Siljan district, Sweden, it can be shown that not only was the mound lithified before formation of the crevices but the main features of the radiaxial mosaic in *Stromatactis* were already fully developed (Jaanusson, 1975). This proves that *Stromatactis* formed before development of the crevices. This relation sets an upper limit for the time of formation of the radiaxial mosaic in *Stromatactis* and the lithification of the mound.

The Meiklejohn Peak mound apparently had no major postdepositional crevices comparable to those in other mounds. However, fissures are known which were obviously formed in a lithified sediment before the growth of the mound had ceased. The main features of the radiaxial mosaic of *Stromatactis* can be shown to have been developed when the mound was still growing. This agrees with the suggestions by Lecompte (1936, 1937), Schwarzacher (1961), and Lees (1964) as to the very early formation of the spar in *Stromatactis*.

ISOTOPIC INTERPRETATIONS

By Irving Friedman

The contrasting components of the zebra limestone, the beds covering the mudmound, and cement from breccias and fractures that cut both the mound and covering beds were analyzed for the isotopes C^{13} and O^{18} (tables 3, 4).

All isotopic data are given in per mil. The δC^{13} values are in respect to PDB (Peedee belemnite), and the δO^{18} is given in respect to SMOW (standard mean ocean water). The isotopic data are given in per mil and are precise to ± 0.1 percent.

The δC^{13} of the samples is plotted on a frequency composition diagram, figure 35. The δC^{13} compositions of the calcilutite and coarse radiaxial and para-axial calcite are very similar and equal to the δC^{13} of modern marine carbonate. The small spread in δC^{13} values indicates that they formed from a well-mixed carbon reservoir and that carbon from organic matter was an unimportant component. Organic carbon has a δC^{13} of -8 to -26 per mil, compared to present-day ocean water bicarbonate of -2 per mil. The covering beds, by contrast, show great variability in δC^{13}, and about half the samples have a

δC^{13} that is much lighter than any of the calcilutite or coarse calcite samples. This enrichment in C^{12} and the variability of δC^{13} can be accounted for if the covering beds formed in an environment in which CO_2 from organic matter formed an important but varying part of the CO_2 reservoir, in addition to the normal atmosphere-derived ocean water bicarbonate.

Keith and Parker (1965) found that the δC^{13} of mollusk shells growing in marginal marine environments was dependent upon the accessibility of continental (land plant-derived) carbon, and that the δC^{13} values of the samples approached the marine values as the sampling sites progressed from estuarine to marginal bays. The samples from marginal bays also show a variable δC^{13}, which Keith and Parker (1965, p. 127) attribute to "variable effects due to locally-produced CO_2 from decompositon of organic detritus, both continental and marine (Landegren, 1954) and from respiration of aquatic plants. Development of a local C^{13} deficiency by aquatic plants in waters with restricted circulation is consistent with observations by Wickman (1952)."

That the covering beds contained organic matter is shown by the rich fauna (trilobites and particularly brachiopods). The decomposition of the soft parts probably contributed light CO_2 to the pore water. Restricted circulation resulted in some of this CO_2 being incorporated into the shells of organisms living in this environment.

In the mudmound the similarity of δC^{13} between the calcilutite and the coarse calcite indicates either that both formed from the same well-mixed, large carbon reservoir, or that one formed from this reservoir and the other formed by recrystallization of the first-formed material without a significant admixture of carbon from decomposing organic matter.

The cause of this recrystallization can be found in the greater solubility of the fine particles as compared to the coarse spar crystals. The large surface area of the calcilutite particles results in greater surface energy and therefore less stability for those grains than for the large calcite crystals. The process of solution of the finest grains and growth of the coarse calcite would have been aided by small temperature oscillations, which would have occurred before deep burial of the mound. The process probably almost stopped when burial was deep enough to damp out diurnal and seasonal temperature fluctuations, and this may account for the persistence of some calcilutite.

Possibly, the recrystallization was facilitated because some of the original calcilutite was not calcite but a form of calcium carbonate (aragonite or vaterite) which is thermodynamically less stable than calcite.

The isotopic data for the cement of the dolomite fault breccia show that this material is similar in δO^{18} values to the calcilutite and spar, and probably formed in Ordovician time. If it formed from fresh water, a lower δO^{18} value would be expected, and if it formed from seawater in later times, its δO^{18} value should be heavier.

Figure 36 is a frequency δO^{18} diagram. The samples from covering beds and calcilutite have similar ranges of composition, from+20.3 to +22.5. The coarse calcite covers a slightly larger range, from +20.3 to +23.2, with a clustering of values between +21.8 and +23.2. The radiaxial fibrous calcite therefore has about the same δO^{18} value as do covering beds and calcilutite, but appears to be slightly enriched by about 0.5 per mil in O^{18}.

One explanation for the rather small spread of δO^{18} values is that the carbonate formed under marine conditions with little influence from fresh water. Another explanation is that all the samples have been altered and their δO^{18} content modified. However, if alteration had occurred with water of different δO^{18} than the original seawater, we would expect either that the fine submicron calcilutite would have exchanged more than the very coarse millimetre-sized radiaxial calcite grains, or that they both would have exchanged completely. This latter case would have resulted in a very uniform δO^{18} content rather than the range of δO^{18} values found. The first case would have resulted in the calcilutite having much lighter δO^{18} values than the coarse calcite. The similarity

TABLE 3. — *Isotopic analysis of beds of Antelope Valley Limestone around mudmound, shown in fig. 4*

[All values are given in per mil]

Sample No.	Description	δC^{13}	δO^{18}
3376-30	Middle, thick-bedded Aysees Member about 50 ft above highest point of mudmound. D2335 CO. Dolomitized	−1.0	+21.4 (20.6)
29	Dolomite fracture filling in D2335 CO	−1.6	+19.2
47	Covering beds of Ranger Mountains Member abutting bioherm, approx. 200 ft above base of mound. D2340 CO. Calcilutite fraction	−2.5	+20.6
48	do	−3.8	+20.6
13	Covering beds of Ranger Mountains Member abutting bioherm, about 195 ft above base of mound. D1970 CO	−1.6	+21.8
49	Covering beds of Ranger Mountains Member, about 5 ft below D1994 CO, about 108 ft above base of mound D2326 CO. Dark-gray fine-grained limestone	−1.4	+21.5
50	Covering beds of Ranger Mountains Member, about 5 ft below D1994 CO, about 108 ft above base of mound D2326 CO. Grayish-orange-weathering calcarenite	−1.2	+21.5
32	Covering beds, close to mound on south side, about 150 ft above base. Worm tubes. 40 ft south of D2334 CO. (71/30)	−0.5	+21.7

TABLE 4. — *Isotopic analysis of limestone from main core of mudmound and from zebra limestone*

["Spar" refers to radiaxial fibrous calcite in this table. Samples are listed stratigraphically from top to bottom. All values are given in per mil]

Sample No.	Description	Sparry calcite δC^{13}	Sparry calcite δO^{18}	Calcilutite δC^{13}	Calcilutite δO^{18}
3376-52	Nodular limestone capping mound. USGS colln. D2338 CO.	---	---	−1.1	+21.8
52	Para-axial calcite in "birdseye" D2338 CO.	−0.9	+22.5	---	---
53	Topmost outcrop of mudmound (71/2). D2337 CO.	---	---	−0.5	+22.1
51	Topmost outcropp of mudmound (71/2). D2348 CO.	---	---	−0.3	+19.6
32	Cephalopod, chamber filling, 170 ft above base of mound (71/27). D2331 CO. Inner part	−0.5	+21.4	---	---
32	Cephalopod, chamber filling 170 ft above base of mound (71/27). D2331 CO. Outer part	+0.3	+21.5	---	---
35	Lens of covering bed lithology, 30 ft south of D2331 CO. D2333 CO.	---	---	+0.1	+22.3
27	Laminated limestone, 143 ft above base of mound. D2344 CO.	0.0	+21.7	+0.4	+21.6
28	Random sample, zebra limestone, less than 40 ft above base of mound.				
	Spar	−0.2	+21.5	---	---
	Calcilutite, fossiliferous	---	---	−0.2	+21.3
	Spar	−0.1	+20.5	---	---
	Calcilutite, fossiliferous	---	---	−0.2	+20.4
	do	---	---	−0.2	+20.6
	Calcite vein, crosscutting	−1.8	+13.6	---	---
43	Calcilutite, fossiliferous[1]	---	---	−0.6	+21.3
42	Spar, in upper dark zone[1]	−0.4	+21.9	---	---
36	Spar, below median seam[1]	−0.1	+21.8	---	---
37	Spar, lower dark zone[1]	−0.3	+21.8	---	---
38	Calcilutite, fossiliferous[1]	---	---	−0.5	+21.0
44	Spar[1]	0.0	+22.4	---	---
45	Calcilutite, fossiliferous[1]	---	---	−0.1	+20.9
46	Spar[1]	−0.2	+21.4	---	---
41	Calcilutite, fossiliferous[1]	---	---	−0.5	+20.9
40	Spar, two dark zones above seam[1]	−0.3	+22.0	---	---
39	Spar, above median seam[1]	−0.1	−22.4	---	---
18	Spar and calcilutite lamina[2]	−0.1	+22.4	−1.0	+20.4
		−0.1	+22.4	−1.0	+20.4
		0.0	+22.7	−0.4	+20.3
		+0.3	+22.6	0.0	+20.7
24	Spar, upper half[2]	+0.1	+22.4	---	---
23	Spar, lower half[2]	−0.1	+22.4	---	---
22	Calcilutite, fossiliferrous[2]	---	---	−0.2	+20.7
21	Spar, upper half[2]	+0.2	+22.4	---	---
20	Spar, lower half[2]	+0.1	+22.1	---	---
19	Calcilutite, fossiliferous[2]	---	---	−0.4	+20.9
3379- 8	Calcilutite, fine, light gray, wackestone[3]	---	---	+0.2	+22.3
9	Spar, filling gastropod shell[3]	0.0	+22.2	---	---
10	Spar, lining channel (?)[3]	+0.2	+23.2	---	---
7	Calcilutite, fossiliferous adjacent to spar above seam[4]	---	---	+0.4	+21.3
6	Spar, outer zone, above seam[4]	+0.1	+22.4	---	---
5	Spar, at center, above seam[4]	+0.2	+20.3	---	---
1	Spar, at center, below seam[4]	−0.1	+22.0	---	---
2	Spar, outer zone, below seam[4]	+0.3	+22.2	---	---
3	Calcilutite, pelletoid[4]	---	---	−0.1	+21.1
4	Calcilutite, fossiliferous[4]	---	---	−0.1	+21.3
3376-54	Calcarenite, 15 ft below base of mound near center. D2330 CO.	---	---	+0.3	+22.2
3376-55	Para-axial calcite in fracture or seam cutting calcarenite	−0.7	+20.4	---	---
3379-19	Black calcilutite, fine[1]	---	---	−0.7	+20.5
20	Black calcilutite, coarse[1]	---	---	+0.4	+20.6
21	Brown calcilutite[1]	---	---	−0.1	+20.5
22	Black pelletoid calcilutite[1]	---	---	−0.2	+22.1
23	Spar[1]	−1.1	+21.0	---	---
24	Brown calcilutite[1]	---	---	0.0	+20.6
25	Spar[1]	+0.2	+22.8	---	---

[1]Zebra limestone, approx. 60 ft above base of mound. D2325 CO. This sample taken from a huge block, which lies askew to surrounding rock. A. J. Rowell (oral commun., 1971) proposes that this block may have tumbled from a part of the mound long since removed by erosion, perhaps in Ordovician time. This possibility needs consideration.

[2]Random samples, zebra limestone above base of mound at south end.

[3]Channel fill, near base of mound. D2324 CO.

[4]Below basal bed of mudmound, poorly laminated limestone (no calcarenite present). D2327 CO.

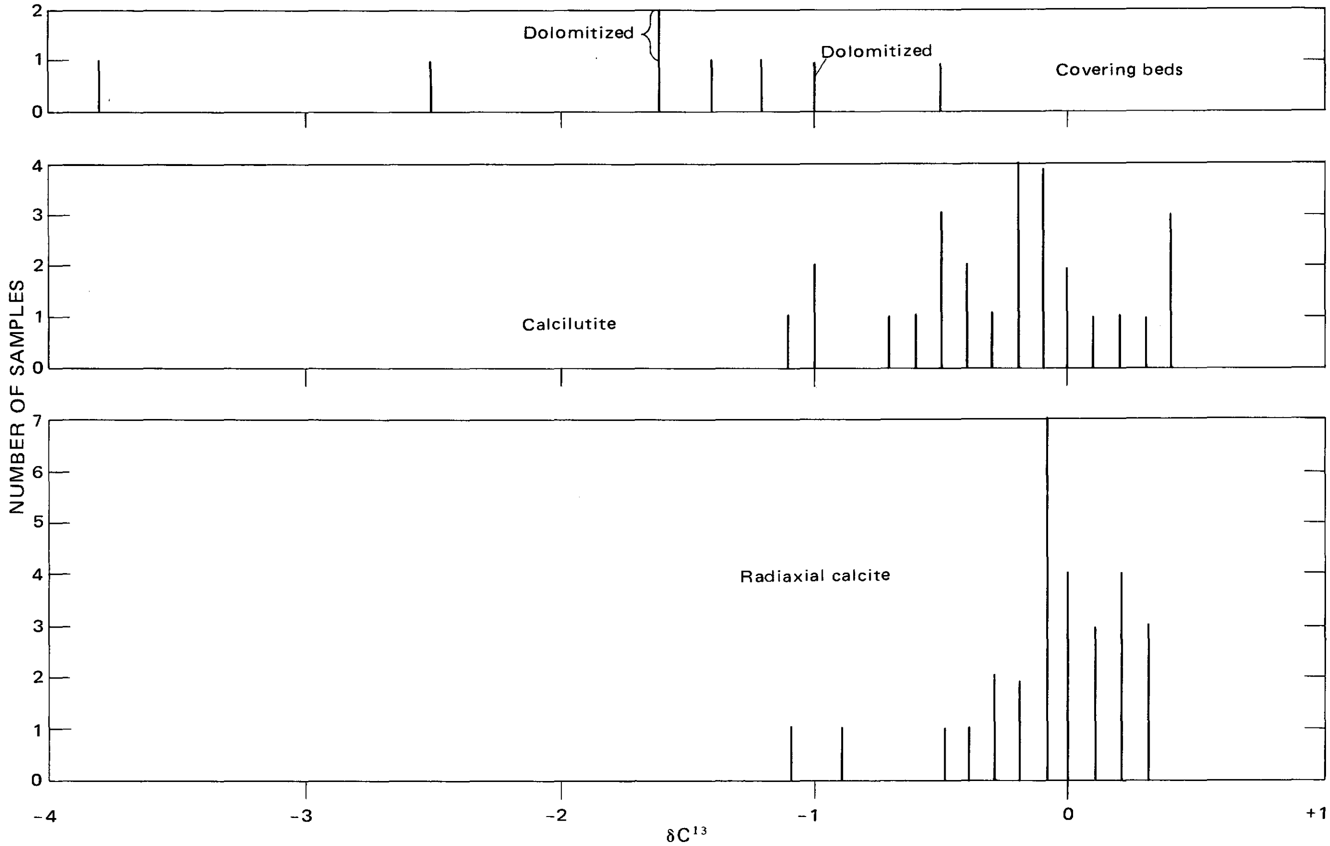


FIGURE 35. — Frequency composition diagram for δC^{13} in samples of calcilutite and radiaxial calcite from zebra limestone, from mound core, and from limestone of covering beds.

in δO^{18} values between the two precludes any important amount of recrystallization in fresh (light δO^{18}) water.

The isotopic evidence from δC^{13} and δO^{18} is consistent with the spar's having formed by recrystallization of the fine-grained calcilutite. Further, this recrystallization must have taken place in water of the same isotopic composition as that in which the calcilutite originally formed and at a temperature, in general, the same as or 5°–10°C cooler than the temperature of formation of the fine lime mud.

From evidence already presented we have concluded that later alteration of the calcite by fresh water was unimportant, and that the calcite (or aragonite) has the same δO^{18} content as it originally had. Shell material forming in the present marine environment has a δO^{18} value of +30 to +32 (Epstein and others, 1951). Forming carbonate of +21.5 per mil from water of 0 per mil (present-day ocean) requires a temperature of about 65°C. An alternate explanation for the +21.5 per mil is that the entire Ordovician ocean—or the part of it which formed the mudmound—had a δO^{18} value of −10 per mil. This hypothesis is consistent with the O^{18} data of Perry and Tan (1972) on marine chert. Perry and Tan postulate a change in the oceans of 15 per mil from early Precambrian to Holocene. Lowenstam (1961) presented evidence for the relative constancy in O^{18} content of the oceans from late Mississippian to Holocene. Our data suggest that most of the O^{18} change in the oceans since early Precambrian took place in the Ordovician-Mississippian interval.

ORIGIN OF THE MUDMOUND

ORIGIN OF THE ZEBRA LIMESTONE

By REUBEN JAMES ROSS, JR.

Because the laminated zebra limestone forms the base of much of the mudmound one must attempt to understand its origin in order to understand the reasons for the mound's existence. Grossly, the striking feature of the laminated facies is the seeming alternation of calcilutite and radiaxial fibrous calcite (figs. 5, 7). The formation of similar calcite layers elsewhere has had widely differing interpretations (Bathurst, 1959, p. 511–512; Schwarzacher, 1961, p. 1494–1495; Lees, 1964, p. 518, 523–524; Fischer, 1964, p. 114–116, figs. 15, 16F, 17, 18; Ross, 1972, p. 6–8; Kendall and Tucker, 1973; Jaanusson, 1974). In the search for a modern analog of this varvelike sediment, we may fail if we look for a modern zebra limestone instead of an alternation of two kinds of calcilutites, one of which under conditions extant in the Ordovician ocean might have changed into radiaxial calcite selectively.

The origin of the zebra limestone is complex. No simple explanation satisfies all the evidence, much of which is contradictory. Any theory of the origin of this striking rock must at least take into account:

1. The great lateral extent and the aggregate thickness of the zebra limestone couplets.
2. The cyclic nature of the laminated rock, involving a repetitive stratigraphic sequence of three calcilutites, designated ca_1, ca_2, and ca_3.
3. The determination of whether radiaxial fibrous calcite is a cavity filling or a product of neomorphic recrystallization.
4. The position of radiaxial fibrous calcite when present always immediately below calcilutite ca_1.
5. The disposition of geopetal sediment, particularly peloids, relative to radiaxial fibrous calcite.
6. Disposition and orientation of fossils within calcilutite ca_1, sometimes parallel to and sometimes normal to the stratification.
7. Occurrence of calcilutite ca_3 (possibly also ca_2) as seemingly crossbedded "internal sediment" where the layers of calcilutite ca_1 are disturbed or disrupted.
8. The drape of zebra limestone without attenuation over a "step and riser" in preexisting topography and similar physical relationships.
9. The results of isotopic and other analyses.

In attempting to explain the origin of the zebra limestone, we have considered the above evidence although not necessarily in the order listed.

GEOCHEMICAL EVIDENCE

Various analyses were made not only of the laminated limestone but also of the more massive part of the mound core. We found (1) that all but a trace of insoluble component is in calcilutites ca_1 and ca_2 rather than the radiaxial calcite mosaic, (2) that trace elements are somewhat more abundant in the calcilutite than in the radiaxial calcite, and (3) that X-ray microprobe analysis showed no significant difference between the calcilutite and radiaxial calcite in regard to Fe, Mg, and Ca. According to R. C. Surdam, there is no geochemical evidence for a hypersaline or supratidal environment for either component.

The isotopic data suggest that the radiaxial calcite was deposited in higher salinities or lower temperature than the calcilutite in the lowest part of the zebra limestone, but both were deposited under the same conditions higher in the mound. This evidence is important in eliminating the possibility that origin of the radiaxial calcite is allied to percolation of meteoric water as Dunham (1969, p. 160–163) proposed for the Permian Townsend Mound in New Mexico. It further requires that genesis and diagenesis of both radiaxial calcite and

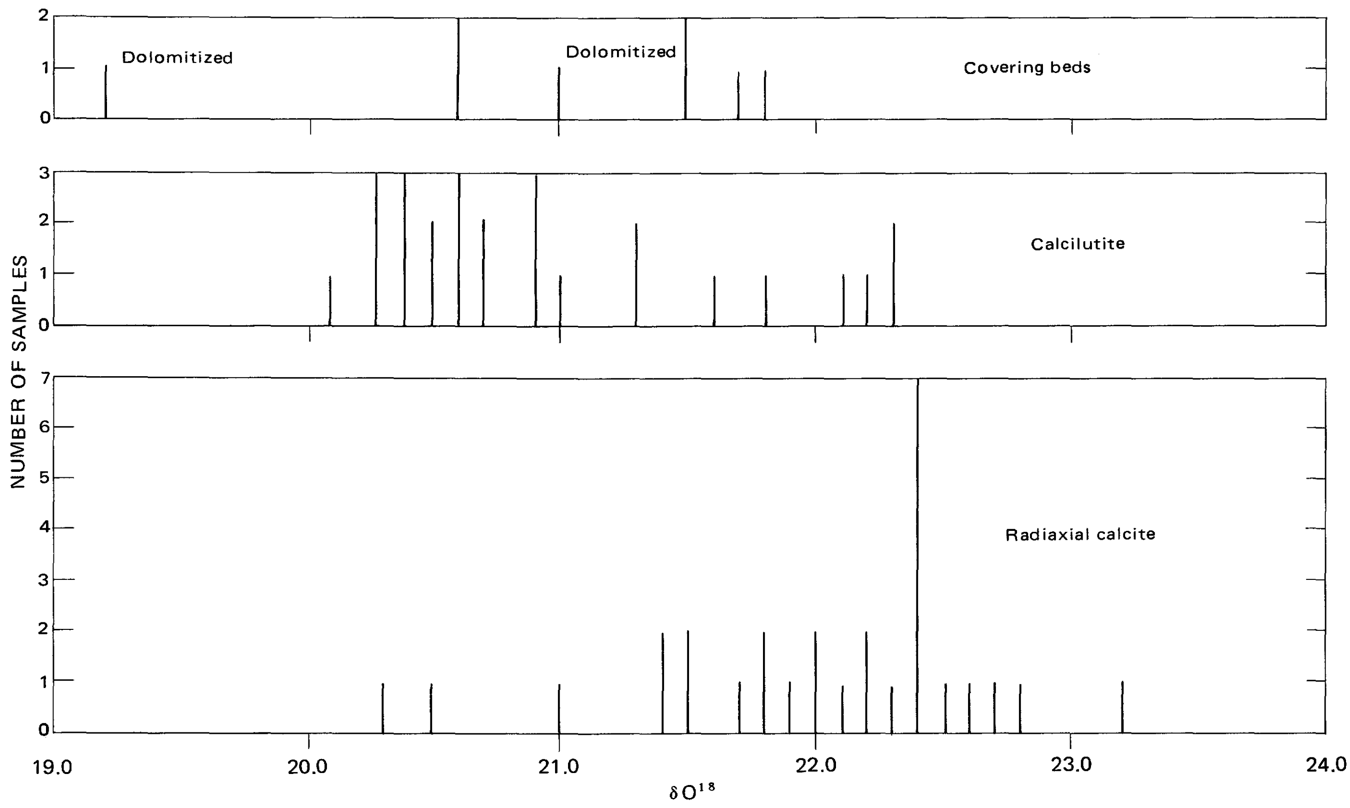


FIGURE 36.— Frequency composition diagram for δO^{18} in samples from calcilutite and radiaxial spar of zebra limestone, from mound core, and from limestone of covering beds.

calcilutite have been affected by essentially the same factors.

The analytical evidence therefore favors a totally marine origin for the zebra limestone.

PHYSICAL EVIDENCE

Most geologists knowledgeable in carbonate sedimentology who have examined hand specimens and thin sections of the zebra limestone from Meiklejohn Peak have insisted that the radiaxial fibrous calcite was the primary filling of former cavities. Such an interpretation would agree with the original inference of Bathurst (1959, p. 511; 1971, p. 426–427) concerning the habit of radiaxial fibrous calcite.

However, it has been my belief, based on field evidence, that the radiaxial fibrous calcite must have replaced some other substance. The distinction between the two interpretations could be significant in regard to the depth of water in which the zebra limestone was deposited. Therefore the evidence is here reviewed.

More than half the total volume of the zebra limestone is composed of radiaxial fibrous calcite (fig. 14). As shown in figure 5 (and Ross, 1972, fig. 6) the laminae may extend several metres (tens of feet) laterally and are present through a stratigraphic thickness of 1–10 m (3–30 ft). It seems mechanically impossible to maintain more than half the volume of the rock as simultaneously open galleries in which radiaxial fibrous calcite eventually grew.

Even if such open galleries could have existed simultaneously the stratigraphic evidence calls for deposition of calcilutite ca_2 in depressions above every layer of ca_1, followed by growth of a thin tier of radiaxial fibrous calcite in virtually every gallery. Water level in each gallery would have been very shallow; if it had filled the galleries the fibrous calcite would have grown from the ceiling as well as from the floor. Above each tier peloids of micrite would have been scattered; only then could the galleries have been filled with water to their ceilings so that radiaxial fibrous calcite could grow downward as well as upward.

The circumstances required to control such water levels and sedimentation within a stack of galleries would try the ingenuity of a wizard, let alone a hydrologic engineer. That the radiaxial fibrous calcite now occupies space which was previously simultaneously open galleries is here considered impossible. The possibility that such galleries could have been maintained open even one at a time is unlikely but conceivable.

The steplike flexure of the zebra limestone mentioned previously would have been structurally beyond belief if composed of parallel shells of calcilutite ca_1 separated by parallel layers of water of thickness equal to that of the calcilutite. Some substance must have intervened between layers of calcilutite ca_1 to maintain spacing between them.

To the left of the hammer in figure 5 there appears to be a lump of calcilutite that has depressed the surrounding laminae. Actually this may be the filling of some sort of depression in the laminated sediment but that makes little difference. What is important is the fact that the seeming lump is completely surrounded by radiaxial calcite.

A similar lump was isolated from a more accessible part of the outcrop and sectioned. It was found to be suspended in radiaxial calcite in three dimensions. It is unlikely that a lump of calcilutite could be suspended so that it was completely surrounded by a cavity and that the cavity was subsequently filled by radiaxial calcite or acicular aragonite.

I therefore conclude that radiaxial fibrous calcite must have replaced some other substance which may have been mineral, or vegetable, or partly both.

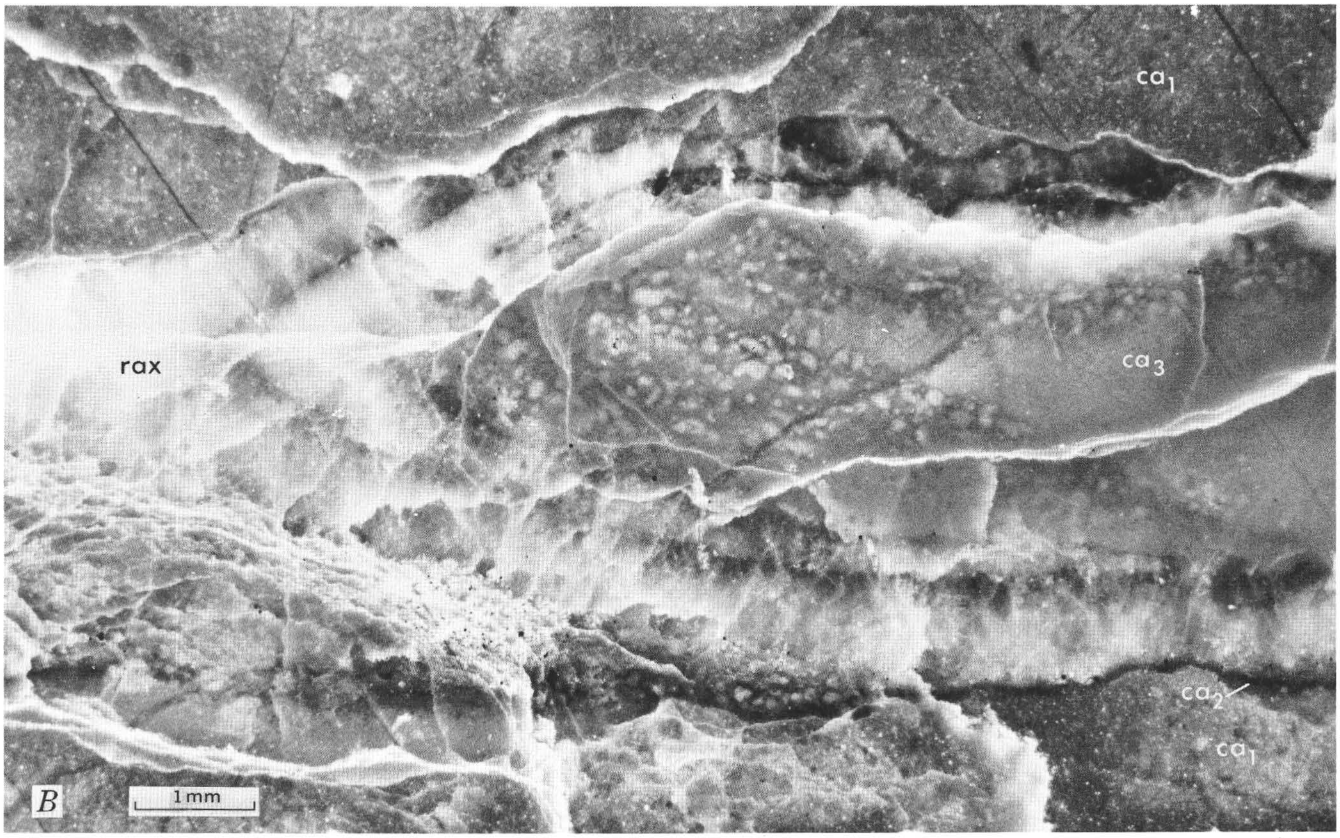
Typical cavities filled with alternating generations of sparry calcite lining and geopetal sediments are illustrated by Sander (1951, p. 183, fig. 28; p. 184, fig. 29) in limestones of the Austrian Alps. Coarse calcite lines not only the floor but also the walls and ceiling of the cavities. We know of no way to explain precipitation of sparry or radiaxial fibrous calcite at selected disconnected spots along the floor, walls, or ceiling of a totally submerged cavity. Nor can we explain deposition of calcite on the walls or ceiling without deposition on the floor of a partially submerged cavity. Yet both circumstances are exemplified at Meiklejohn Peak.

The large block of laminated limestone from which the section shown in figure 7 was taken was variously cut and polished to reveal that the radiaxial fibrous calcite pinches laterally (figs. 16B, 37) and yet the fossiliferous calcilutite layers ca_1 maintain their same vertical spacing. Where the sparry calcite is lacking, the space is filled by a layer of very fine, mostly equigranular calcilutite, much of which seemingly exhibits very regular foreset bedding. This very fine calcilutite is an original layer of sediment in a cyclic sequence (figs. 7, 11). As shown in figures 16A, 17, 37*A*, 37*B*, and 38, parts of the very fine calcilutite (ca_3) and the bottom of the fossiliferous calcilutite (ca_1) seem to be partly converted into radiaxial fibrous calcite.

In discussing Irish Waulsortian mounds, Lees (1964, p. 523–524) attributed the origin of "sheet spars" to the filling of extensive nearly horizontal cracks caused by shear failure, but he met with difficulties in explaining how roofs of such extensive cavities could be supported. Indeed, he questioned how such cavities could even open in wet calcareous mud and he appealed to localization of layered organic matter to hold the cavities open.

Commenting on supposed cavities in which the sparry calcite of *Stromatactis* grew, Bathurst (1959, p. 514) stated, "the labyrinthine cavity system, supported now by such a small volume of intervening siltstone, could never have existed in an empty state all at once; it would


rax
ca3
tr
ca2
ca1
A
1 mm


ca1
rax
ca3
ca2
ca1
B
1mm

have collapsed." After thoroughly discussing possible explanations, Bathurst (1959, p. 520) concluded that "for the maintenance of cavity roofs and steep slopes a sediment binder was necessary" and like Lees he considered the possibility "that the cavities are, at least in part, molds of a buried organism which decayed."

The position in which we now find radiaxial fibrous calcite in many examples is occupied laterally by calcilutite ca_3 (figs. 10*B*, 12, 16, 39, 40). Much of this calcilutite appears to be crossbedded. In some instances the radiaxial calcite appears to be interbedded within the crossbeds (figs. 10*B*, 16, 37*A*, 38, 39). One might be tempted to attribute these relationships to alternating calcite lining of the walls of a cavity and internal sedimentation, like that clearly illustrated by Bathurst (1971, fig. 311). The superficial resemblance to Bathurst's example requires discussion.

In Bathurst's illustrated example, an unfilled residual cavity still exists and the calcite crystals are terminated with "dogteeth" pointing into the cavity. Equally important, every layer (or lining) of calcite buried on the floor and wall has a continuous counterpart on the ceiling. As Bathurst's photograph clearly shows, terminations of calcite crystals are preserved even where buried.

In contrast, no examples of similar-looking calcite from the zebra limestone at Meiklejohn Peak had pointed terminations (figs. 17, 37*A*, 37*B*, 38); we have found no open cavities. There are more layers of radiaxial calcite on conjectural floors and walls than on ceilings (figs. 10*B*, 16). There may be a layer of radiaxial calcite on a supposed ceiling but not on the corresponding floor, and vice versa (figs. 17, 39). Calcite layers within and paralleling crossbeds are associated with and grade into pelletoid calcilutite; some such layers terminate without completely following the contact between crossbeds (fig. 17). Evidently these examples from the Nevada Ordovician differ significantly from Bathurst's (1971, fig. 311) and the radiaxial calcite may be the result of neomorphic processes (Folk, 1965, p. 23; Bathurst, 1971, p. 481–503) rather than the lining of a cavity.

We do not suggest that the mudmound of Meiklejohn Peak is or was devoid of cavities that became filled by spar. On the contrary, we can demonstrate the presence, in the upper part of the mound, of "birdseye" and similar structures which are conceded to be cavity fillings. But we insist that, within the zebra limestone,

FIGURE 37. (facing page) — Polished section showing detailed views of the same small part of sample illustrated in figure 16*B*. USGS colln. D2325 CO. *A*, The inner surfaces of the coarse radiaxial calcite (rax) lack crystal terminations; such terminations would have been expected if calcite lined the inside of a cavity prior to filling by calcilutite ca_3; photographed in polarized light. *B*, Equigranular calcilutite (ca_3) appears to have been partly converted to pelletoid calcilutite (ca_2) as first step toward conversion to radiaxial fibrous calcite (rax); photographed in ordinary light.

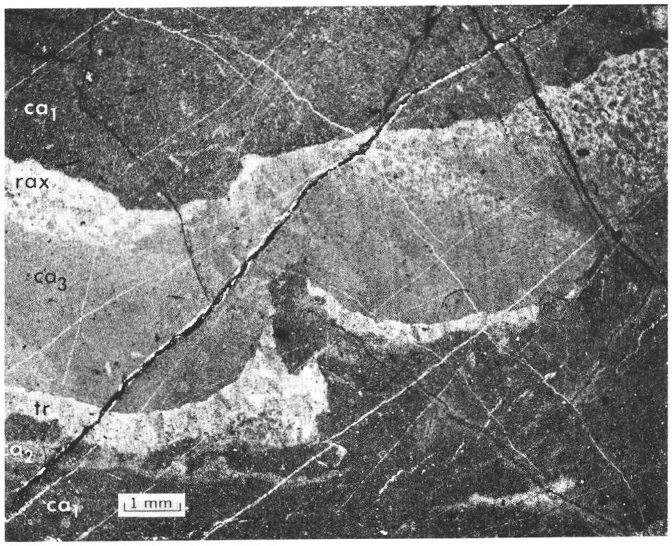


FIGURE 38. — Coarse calcite along contact at bottom of calcilutite ca_1 is discontinuous and could not have formed lining of a submerged cavity prior to filling by seemingly crossbedded calcilutite (ca_3). Pelletoid layers, fractures, and contacts may have provided permeable channels along which aggrading neomorphism produced radiaxial calcite (rax). Note lack of crystal terminations on upper side of lower calcite layer (tr). USGS colln. D2325 CO. Collodion peel.

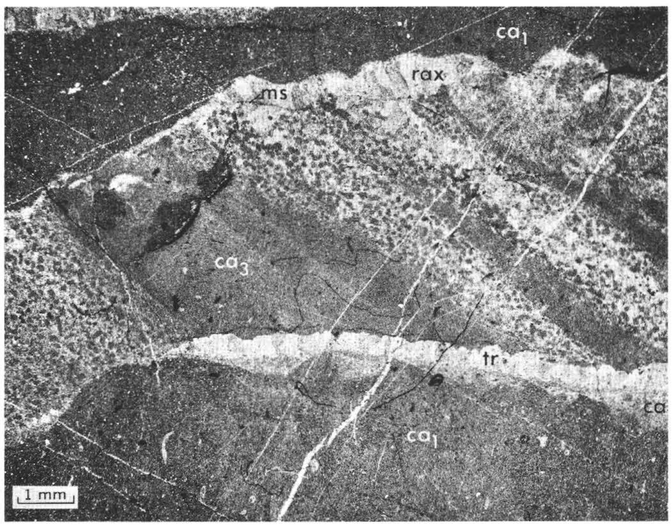


FIGURE 39. — Coarse calcite (tr) at bottom of crossbedded calcilutite ca_3 is discontinuous; it resembles lower tier (tr) in radiaxial calcite (rax) of figure 14*B*. Radiaxial calcite (rax) above crossbeds is continuous with coarse calcite in pelletoid layers, but is not continuous with lower calcite (tr). Therefore, rax, tr, and coarse calcite within pelletoid layers did not form the lining of a cavity prior to deposition of crossbedded calcilutite ca_3. Median seam (ms) is comparable to same feature in figures 7, 8, 9, 14*B*, and 15, and has no relation to middle of a preexisting cavity. Presence of calcilutite ca_2 filling depressions in the upper surface of ca_1 indicates that calcilutite ca_1 was essentially horizontal prior to deposition of crossbedded calcilutite ca_3. Radiaxial fibrous calcite may have resulted from neomorphic conversion of calcilutite ca_3 selectively along pelletoid layers. Collodion peel. USGS colln. D2325 CO.

cavity filling played a minor role unless such filling took place layer by layer accompanied by almost immediate lithification of preceding layers.

ZEBRA LIMESTONE ABOVE BASE OF MOUND

The previous discussion applies to the zebra limestone at the base of the mudmound. That occurrence is not unique. High on the south side of the mound a tongue of covering rock extends into the mound. As noted previously, the mound lithology is re-initiated above this tongue by deposition of zebra limestone. As shown in figures 6 and 40, the laminae are generally less regular and more deformed than in the basal part of the mound. Nonetheless the same four lithologic elements are present, listed stratigraphically:

4. Radiaxial fibrous calcite (rax). Particularly along the contact below ca_1 and above ca_2.
3. Very fine equigranular calcilutite (ca_3) deposited above the pelletoid calcilutite. Locally crossbedded. Overlain by another fossiliferous calcilutite ca_1.
2. Pelletoid calcilutite (ca_2), filling depressions and other irregularities in the top of the fossiliferous calcilutite ca_1. Perhaps somewhat plastic.
1. Fossiliferous calcilutite (ca_1), in places much disrupted. Most of the insoluble residue—authigenic quartz and potassium feldspar—concentrated in this unit.

The block shown in figure 6 was cut at right angles along the line indicated and polished; the resulting surface is shown in figure 40. The fourth and fifth laminae from the bottom in figure 40 are of particular interest, because seeming conversion of the calcilutite to radiaxial fibrous mosaic is incomplete; it can be seen in greater detail in figure 13.

In the thin section (fig. 13) two layers of fossiliferous calcilutite ca_1 are shown. The lower is overlain by evenly bedded pelletoid calcilutite (ca_2), and that in turn is overlain by very fine equigranular calcilutite (ca_3). However, unit ca_3 has been changed partly to radiaxial calcite, as has the bottom of the overlying fossiliferous calcilutite ca_1 in the next cycle. No neomorphism has affected the pelletoid layer. Neomorphism seems to have taken place extensively along the upper contact of the equigranular calcilutite ca_3 and above the median seam of the radiaxial calcite (rax). Above the unconverted calcilutite ca_3 is considerable fragmental material, which might be interpreted as fragments loosened from the ceiling and fallen to rest on the floor of a cavity. Such an interpretation is untenable here; it fails to explain the lack of similar material all along the supposed floor to the left in this view. Calcilutite ca_3 appears to be virtually in place and only partly converted into radiaxial fibrous calcite.

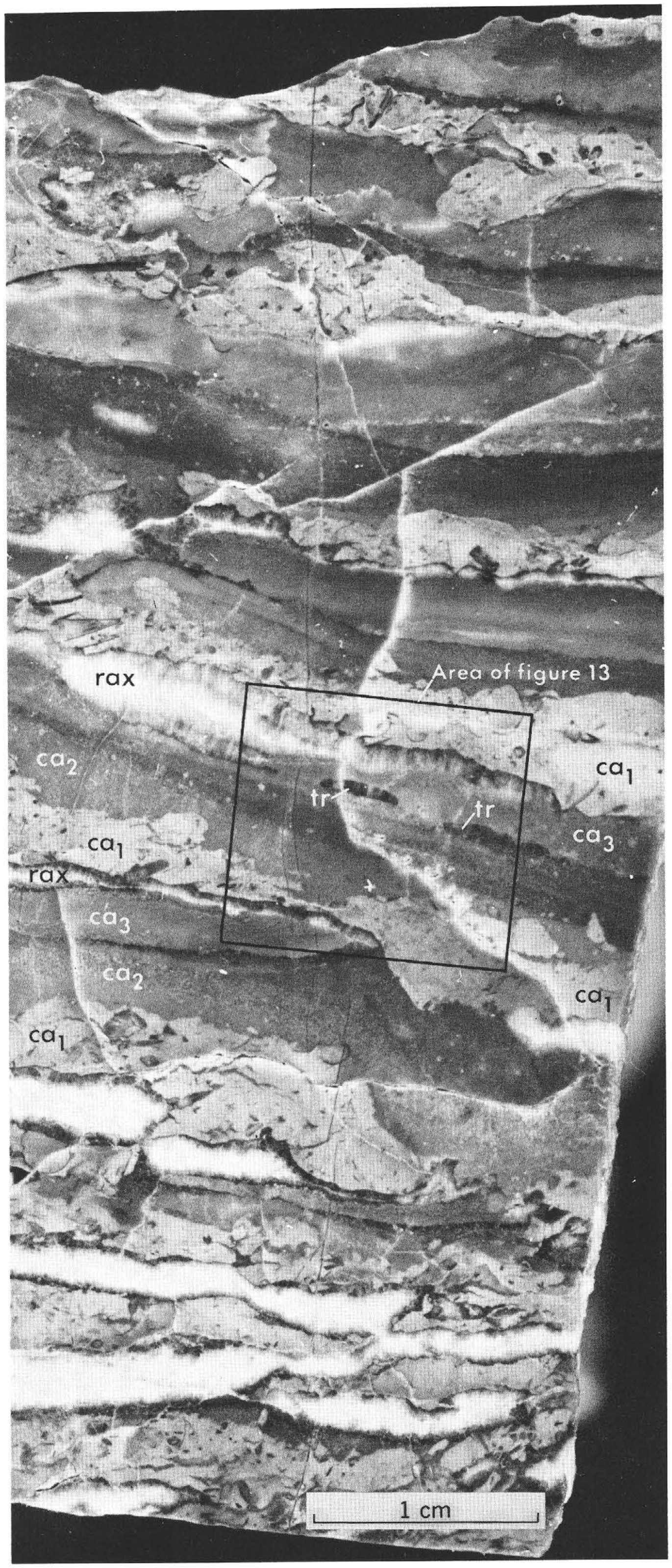


FIGURE 40. — Cyclic calcilutites ca_1, ca_2, and ca_3 in polished surface normal to surface shown in figure 6. In fourth and fifth cycles from bottom, calcilutite ca_3 is incompletely replaced by radiaxial fibrous calcite (rax). Thin section illustrated in figure 13 was cut from this surface. USGS colln. D2334 CO.

Figure 41, another polished section, shows lithologic relations 7 mm from the surface shown in figure 40. The same features are present except that in figure 41 the two patches of coarse calcite (tr) in the lower part of the very fine equigranular calcilutite have coalesced. Two enlarged views in polarized light of this polished mirror image are instructive. Figure 18*A* shows the full thickness of equigranular calcilutite ca_3 completely converted to radiaxial calcite (rax) on the right and divided into upper and lower halves by the smooth median seam. To the left the median seam is above the unconverted calcilutite; in this sector the crystals of spar are large above the seam and only very small below. This sector magnified still further is shown in figure 18*B*.

Figure 18*B* presents an informative puzzle. If we assume that the radiaxial calcite is filling a cavity, the median seam should be the surface along which crystals growing from floor and ceiling met. As discussed previously, we may also assume that dogtooth calcite crystals face the inside of a cavity. The radiaxial calcite above ca_3 seems to have such teeth pointing downward into the calcilutite; we therefore might suppose that calcilutite ca_3 filled a cavity of which the radiaxial calcite immediately above formed the ceiling. But this same calcite, we have already noted, should have been growing upward to close a cavity at the median seam. How radiaxial calcite crystals could have remained suspended in space to grow both upward and downward to form the floor of one cavity and the ceiling of another is difficult to comprehend.

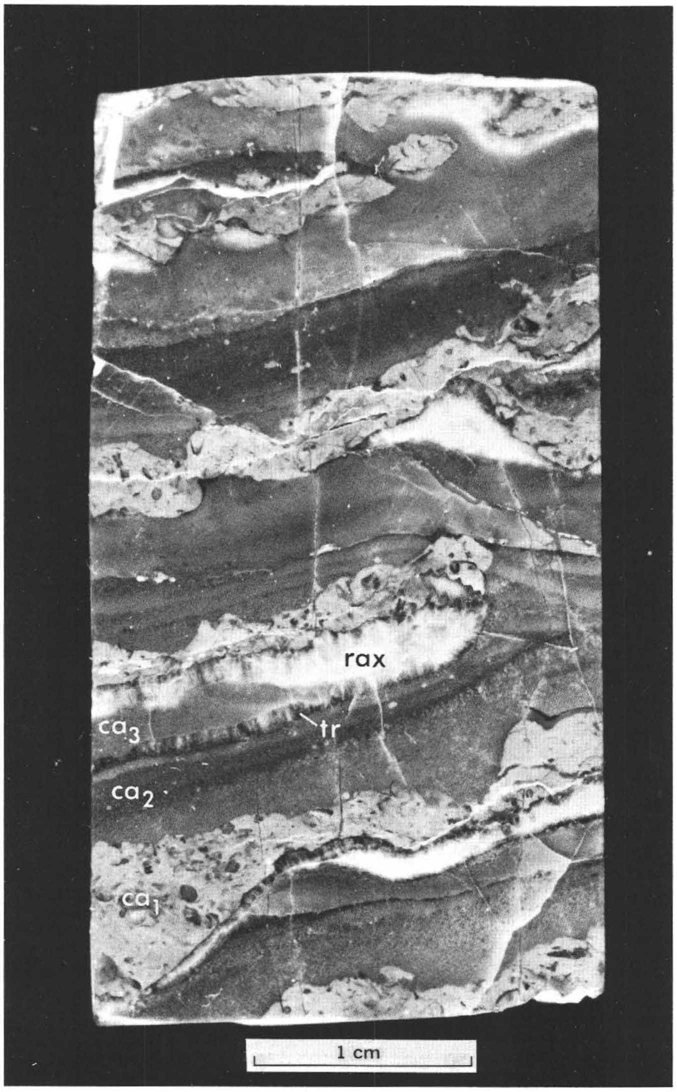


FIGURE 41. — Two patches of the same radiaxial calcite as shown in figure 13 and figure 40 have coalesced below calcilutite ca_3 in a distance of 7 mm. Polished surface, facing that shown in figure 40 at a distance of 7 mm. USGS colln. D2334 CO.

Therefore, I suggest that the equigrains of calcilutite ca_3 began to aggrade to form increasingly larger crystals upward toward the median seam. This was no cavity floor. The median seam is jagged here; it would have become smooth when crystals above and below grew to the same size. Calcilutite ca_3 was being selectively converted to radiaxial fibrous calcite.

PELLETOID CALCILUTITE

Beales (1958, p. 1867–1871) reviewed the occurrence of "Bahaman type" limestone characterized by its pelletoid texture and he favored a nonskeletal aggregation of finely crystalline aragonite or calcite in agitated and possibly supersaturated water to form such sediments. Whether the pelletoid material within the Meiklejohn Peak zebra limestone was derived from fecal pellets or from mechanically aggregated microcrystalline carbonate or is a result of *structure grumeleuse* (Cayeux, 1935, p. 271–272) is uncertain, but a case could be made for each of these origins. The correct interpretation bears on the origin of radiaxial fibrous calcite.

In figure 39, two layers of calcilutite ca_1 are separated by what appears to be crossbedded pelletoid calcilutite and homogeneous calcilutite. A tier of calcite (tr) separates the bottom of the crossbedded calcilutite from ca_1 but pinches out to the left; scattered small depressions in the top of ca_1 are filled with another calcilutite (ca_2) beneath the tier of calcite. Above the crossbedded calcilutite is a small body of radiaxial fibrous calcite which grades downward into two of the crossbeds; these two crossbeds are pelletoid, but they are so impregnated with radiaxial calcite that there is no clear boundary between the calcite and the pelletoid calcilutite.

The radiaxial calcite at the bottom is not the same as that on top; if it were, both would grade into the crossbeds. The lower one clearly does not. Therefore, there was no submerged cavity between the two layers ca_1 at the time the lower radiaxial calcite was formed or it would have formed continuously and simultaneously along the floor and on the ceiling.

If the pelletoid layers were originally pelletoid their high permeability may have permitted easy flow of supersaturated water, in the same manner as contacts between the layer. Increased permeability may have stimulated the formation of radiaxial fibrous calcite in selected parts of the sediment.

On the other hand, some unknown factor, perhaps increased permeability along sedimentary contacts, may have enhance the conversion of homogeneous calcilutite to *grumeleuse* calcilutite as an intermediate step in the change to radiaxial fibrous calcite.

In figure 17, radiaxial fibrous calcite is somehow intimately related to pelletoid material. And in figure 38 there is a suggestion that pieces of calcilutite considerably larger than pellet-size are in the process of being surrounded by or perhaps converted to calcite.

Two even more detailed views, figures 10*B* and 10*C*, also could be interpreted to show that radiaxial calcite is formed with the assistance of or at the expense of pelletoid material. These two photomicrographs show parts of the thick section shown in figure 10*A*.

Shinn (1969, p. 133, figs. 21, 22) observed that the pelletoid texture of a modern carbonate mud may be accentuated by inward replacement or recrystallization of the periphery of each original peloid. This observation suggests to us that a similar mechanism could modify any calcilutite which had been divided into pellet-sized particles or aggregates.

AGGRADING NEOMORPHISM: OTHER VIEWS

As early as 1904 Cullis concluded that aragonitic mud and fossil shells had been converted to calcite spar at Funafuti atoll, Ellice Islands; this evidence has been reviewed by Bathurst (1971, p. 350–355). Bathurst (1971, p. 489–490) also recorded the discovery that aragonite shells may be replaced by fibrous sparry aragonite.

Kendall and Tucker (1973) carefully reviewed the evidence on the formation of radiaxial fibrous calcite and concluded that it is a product of replacement of acicular metastable carbonate and that replacement took place by a process of solution-precipitation and by "migration of a fluid film through the acicular host." According to this theory the acicular carbonate filled voids prior to replacement.

Ross, Friedman, and Jaanusson (1971) considered that radiaxial fibrous calcite could be a product of selective recrystallization of carbonate mud in a totally marine environment. The process they envisaged was similar to that of Kendall and Tucker but was independent of a preexisting acicular cement.

EVIDENCE OF RUPTURE STRUCTURES

Although the spacing of laminae is remarkably uniform there are evidences of minor deformation, rupture of layers, and flexures irregularly throughout the facies (fig. 5). To examine an example of such disruption the block of limestone shown in figure 10 was cut serially, sectioned, polished, and etched for collodion peels. As already noted, there are striking differences from as well as strong similarities to, the section shown in figure 7. (The two sections occurred within 60 cm of each other.) One section of the disrupted rock (fig. 10*C*) is particularly enigmatic.

In most of the subparallel laminae of the zebra limestone, fragments of fossils which characterize the calcilutite ca_1 are oriented randomly or roughly parallel to the laminations (figs. 9, 11) as might be expected. However, where the the calcilutite ca_1 is deformed into flexures and(or) ruptured, the layering in calcilutites ca_2 and ca_3 appears crossbedded and the fossil fragments in calcilutite layers ca_1 may be oriented at angles as high as 90° to the lamination (figs. 10*B*, 10*C*, 12). It seems patently impossible to devise a mechanism by which these laminae could have been deposited on edge as the orientation of fossils seems to require. Strangely, these discordant orientations are not limited to the small areas of deformed laminaė and are independent of the seeming crossbedding of ca_2 and ca_3.

Moreover, a shell of an inarticulate brachiopod still partly enclosed in calcilutite (fig. 10*C*) projects into a combination of radiaxial fibrous calcite and pelletoid crossbeds. How could this fossil have survived any mechanical separation of layers of calcilutite ca_1?

We may suppose that the layers of calcilutite ca_1 were all part of a single body, that it was cut by subparallel tensional fractures which resulted in cavities, and that these cavities were filled by semifluid, partly pelletoid calcilutite. But if there were any component of shear, as suggested by Lees (1964, p. 523–524), the fossil should have been broken. Indeed, one wonders how the fossil could have avoided breaking unless the intervening pelletoid material acted truly as a fluid of low viscosity.

On the other hand we may be dealing with cyclically deposited sedimentary layers one of which (ca_2 and(or) ca_3) has been partly and preferentially replaced by or recrystallized into radiaxial fibrous calcite in each cycle. Originally, this layer may have behaved much like a fluid because of high water content, while calcilutite ca_1 was more cohesive and coherent because of its organic content.

Philip N. Playford kindly examined examples of the zebra limestone and pointed out (oral commun., April 1972) that the accordance in attitude of the supposed crossbeds (figs. 10*C*, 12) might indicate that spaces between many layers of calcilutite ca_1 were open at the same time, canted at a steep angle to the horizontal, and filled by a succession of nearly horizontal pelletoid and equigranular calcilutite layers; he further suggested that key layers found in a succession of spaces could confirm this interpretation. Key horizons cannot be traced precisely from one set of "crossbeds" to the next and there is no simple sedimentary explanation for the three divergent contradictory orientations of (1) layers of calcilutite ca_1, (2) positions of fossils within yet normal to layers of ca_1, and (3) crossbedded calcilutite ca_3.

We have considered the possibility that layers of calcilutite ca_1 might have become indurated and buckled in a manner similar to that deduced from Ordovician limestone in the Baltic area by Lindström (1963, p. 252–256) or similar to the cemented layers forming today in the Persian Gulf (Shinn, 1969, p. 112–119, 122, 128). Buckling of such layers involves shear and we have already discounted any explanation involv ing shear.

Although we do not know how the sediment was deposited, we propose that the calcilutites ca_2 and ca_3 might have behaved thixotropically because of high water content. Perhaps hydraulic pressure contributed locally to the rupture of calcilutite ca_1 and more broadly to its support. Distortion and rupturing of layers, as illustrated in figures 6, 10, and 40, may have occurred in such a fluid environment, wherein unconsolidated thixotropic calcareous muds (ca_2 and ca_3) flowed through ruptures in more competent ca_1 to mix with other unconsolidated mud in younger or older cycles.

This theory eliminates the necessity for mechanically impossible open galleries equaling 60 percent of the final volume of the rock. It provides for local disruption of some layers and the undisturbed nature of others. It accounts for flowage of internal sediment, permitting as much upward as downward movement.

Accordingly, each layer of fossiliferous calcilutite ca_1 may be considered as the more competent layer in a repeated cycle and may represent a time of slow sedimentation and of partial winnowing of the calcilutite to concentrate fossil remains. Layers of pelletoid and homogeneous calcilutite (ca_2 and ca_3) may have been deposited over a much shorter time and in more turbulent water. The unconsolidated and saturated mud (ca_2 and ca_3) could have provided the permeable avenues wherein aggradational neomorphism eventually converted the calcilutite to radiaxial fibrous calcite. This conversion may have taken place selectively along certain sedimentary contacts. Whether pelletoid muds contributed to permeability and easier access of $CaCO_3$-bearing water or were the result of neomorphic production of *structure grumeleuse* is uncertain. In either process, rapid crystallization, probably of aragonite, within the saturated, unconsolidated carbonate mud was necessary to preserve the cyclic nature of the zebra limestone.

RAPID SUBMARINE LITHIFICATION

Alternatively, one may speculate that rapid cementation or aggrading neomorphism contributed to the production of successive hard, lithified sedimentary crusts a few millimetres thick and that each crust expanded laterally as it lithified, according to Shinn's (1969, p. 128, fig. 17) observations in the Persian Gulf. As a result, each new crust may have had the strength necessary to hold itself off the underlying crust with a few points of contact. In the resulting slim cavities calcite or aragonite may have crystallized from saturated seawater, or pelletoid and fine homogeneous carbonate mud may have been introduced from the overlying sea bottom.

DERIVATION FROM ALGAL MATS

In describing Alpine Triassic zebra limestone, very similar to the Ordovician laminated limestone from Meiklejohn Peak, Fischer (1964, p. 127) noted their close resemblance to modern algal mat deposition. Such mat deposits come most readily to mind when we seek a modern laminated analog.

Direct evidence of algae within the carbonate mound is scarce. Algae are present but those few that are preserved could hardly have acted as the binder for the entire mound. *Sphaerocodium* (fig. 42) is present in collections D2349 CO, D2348 CO, D2343 CO (fig. 4) as scattered filaments. Nowhere does it form the closely packed structures reported in Devonian reefs of Australia (Wray, 1967, p. 35–40) and Canada (Wray and Playford, 1970, p. 547-552, pl. 2, figs. 1–4).

The problematic micro-organism *Nuia* is found in the calcarenite parts below and in the mound in collections D2341 CO (echinodermal lime packstone), D2345 CO, D2346 CO, D2347 CO, D2348 CO, and D2349 CO (fig. 4). This form was reported by Toomey (1970, p. 1325, fig. 12a) and by Toomey and Klement (1966) in Lower Ordovician carbonate mounds of the El Paso Limestone, west Texas. At Meiklejohn Peak *Nuia* is a minor constituent and seems to occur in fragmental deposits within the mound. In fact *Nuia* could not have been significant in binding the mound together.

Rowell and Krause (1972, 1973) inferred that plants, presumably algae, were present on the mound, because two genera of inarticulate brachiopods were adapted for attachment to "cylindrical objects."

Although we have no direct evidence that algae were abundant enough to form extensive mats, we must not completely exclude the possible former existence of green or blue-green algae, all remains of which have disappeared.

G. M. Friedman and others (1973) showed that carbonate laminites may have been deposited within algal mats in the geologic past, and they suggested a mechanism for the formation of calcite cement in layers within the mats themselves. Their observations support the belief that algae not only may trap and hold sedimentary particles but also may be directly responsible for the "precipitation of carbonate laminites which preserve the morphology of the mats even after the organic matter has become degraded and has disappeared" (Friedman and others, 1973, p. 552).

Such a process, if cyclic, could result in formation of zebra limestone one lamina at a time without requiring any voids. Furthermore, irregularities in the bottom configuration would be duplicated by the mats; damage to mats would result in depressed features like those shown in figure 5. Local upward disruption of laminae could have resulted in structures shown in figures 6 and 10. The trapping of small fossils on edge (fig. 10*C*) within an algal mat is conceivable. Without such a mat it is nearly impossible to explain why such fossils are not parallel to the stratification.

Otte and Parks (1963, p. 394) concluded that radiaxial fibrous calcite forming *Stromatactis*-like masses in Upper Pennsylvanian and Lower Permian limestone in New Mexico had taken the place of a firm-bodied organism capable of supporting mud layers but incapable of secreting a calcareous skeleton. Some modern blue-green algae have the consistency of tough rubber. Layers of such a rubbery organic material might have supported

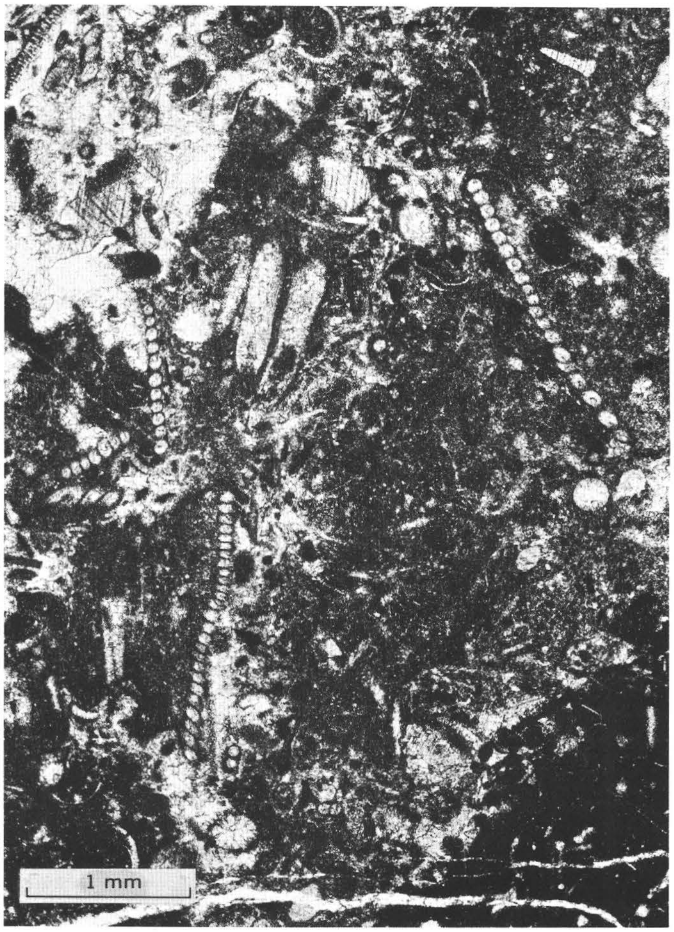


FIGURE 42. — Filaments of *Sphaerocodium* found in main core of mudmound, particularly at top. Thin section. USGS colln. D2348 CO.

layers of calcilutite and later been replaced by sparry aragonite. Perhaps, one need no longer speculate on this sort of origin for the radiaxial calcite, inasmuch as G. M. Friedman and coauthors (1973) have observed a reasonable analog.

The zebra limestone might have formed on a tidal flat but Hardie and Ginsburg (1971) found that cyclic laminae on Bahaman tidal flats are formed during periods of major storms, not as the result of diurnal tides. They further noted that persistent winds, over 30 km/hr, "are needed to suspend pelleted lime mud * * * and flood the tidal flats with sediment-charged seawater. Deposition from these floodwaters produces either a thin mud lamina (made by the flypaper-like trapping action of algal mats) or a couplet consisting of a basal mud layer overlain by a sorted layer of fine sand peloids."

Like the couplets observed by Hardie and Ginsburg on Andros Island, Bahama Islands, the laminae at Meiklejohn Peak are composed of a basal mud (ca_1) (rich in ostracodes and other fossils) and a layer of well-sorted pelletoid mud (ca_2). But a third layer of calcilutite is present in the cycle; where laminae lie flat, this third calcilutite (ca_3) is equigranular, but where laminae are disrupted or deformed, calcilutite ca_3 appears pelletoid and crossbedded (fig. 38, 39).

In Shark Bay, Western Australia, well-laminated sediments are, according to Davies (1970, p. 183–186), only found with smooth algal mats and they occur in two environments—in the outer intertidal zone and in the landward parts along the floors of tidal channels. Neither dolomite nor gypsum is present in sediments in the intertidal zone, but both are present, in varying amounts, in the supratidal zone (Davies, 1970, p. 177, table 1).

The laminated rock at Meiklejohn Peak lacks any evident dolomite, magnesian calcite, or gypsum. Therefore, deposition in the intertidal, rather than the supratidal, zone is favored.

The small "cabbagehead" masses mentioned previously (p. 13) (fig. 19) may have resulted from deformed growth of algal mat over preexisting topographic irregularities (compare with Davies, 1970, figs. 12 B, C). Similarly, deformation of calcilutite ca_1 as shown in figure 10 may have been caused by breaching of such a "cabbagehead," by upward movement of fluid mud or of gas (Davies, 1970, p. 191–192), or by bioturbation.

EFFECT OF ORGANIC SUBSTANCES

Recently, Meyers and Quinn (1971, p. 992) showed that fatty acids and other lipids are absorbed by calcite in seawater and may provide a coating that prevents the solution of calcite in seawater which is undersaturated for calcite. The coating may also prevent the precipitation of calcite in supersaturated seawater. It therefore seems to us possible that the presence or absence of such organic substances within some of the components of the laminae at Meiklejohn Peak could have influenced the formation of sparry calcite, although identifying that influence now may be virtually impossible.

The important influence of blue-green algae, other organisms, and organically derived chemicals in the formation of modern laminated carbonate sediments in the Gulf of Aqaba has been demonstrated by Friedman and others (1973, p. 553–556). These same authors (p. 552, figs. 9, 14) showed not only that the algal mat encloses great amounts of particulate carbonate but also that the laminites may consist of alternating layers of "cryptocrystalline high magnesian calcite and fibrous aragonite." Such alternations are suggestive of the cyclic calcilutites and radiaxial fibrous calcite of the zebra limestone.

Bathurst (1967) called attention to a "subtidal gelatinous mat" which acts to stabilize the calcareous sands of the Great Bahamas Bank. This mat is widespread. The mat seems to be partly algal but it is inhabited by and is the food source for such a multitude of minute animals that its precise origin is a mystery. According to Bathurst, such a mat could leave no direct evidence in the geologic record, for it disappears as soon as buried. And yet if this mat were suddenly buried without disruption by very fine sediment, we believe an organic film would surely be trapped.

Zangerl (1971) reviewed the effect of decaying animal matter in the formation of concretions, involving the rapid crystallization of calcium or other carbonates.

There should be little doubt that organic substances may exert influences on the deposition of carbonate sediments, influences so complex and so little understood that current conventional thinking about the origin of limestone is inadequate.

THEORY OF LIFTING BY CRYSTAL GROWTH

Several of our colleagues suggested that the sparry and radiaxial calcite may have grown in place, "shouldering" its way along the contact between couplets; they proposed that the growth of the calcite, like the growth of gypsum and trona in the Pennsylvanian Paradox Member of the Hermosa Formation and in the Eocene Green River Formation (Deardorff and Mannion, 1971, p. 35; O. B. Raup, R. J. Hite, and W. C. Culbertson, oral commun., 1972) might have lifted the overlying layers as it grew—the displacive precipitation theory of Folk (1965, p. 24). In many of the Ordovician laminae there are pelletoid bodies within the lower layers of the radiaxial fibrous spar (fig. 8); these bodies might be compared with fragments of the underlying shale which have been lifted during crystal growth into the coarsely crystalline gypsum or trona of the Pennsylvanian and Eocene deposits. However, at Meiklejohn Peak where the radiaxial fibrous calcite layer is incompletely formed (fig. 7), the calcilutite couplets obviously were not mechanically disturbed by formation of the calcite. In such places the radiaxial calcite appears to have grown at the selective expense of one or more of the calcilutites.

CONCLUSIONS

The original sediment of the zebra limestone was probably an alternation of partly or wholly cemented fossiliferous calcilutite with unconsolidated saturated carbonate mud. Much of the latter was pelleted. Whether pelleted muds were produced as fecal pellets or whether they were in some way related to algal mats is unknown. No direct evidence for such algal origin was found. In either circumstance pelleted texture would have produced high permeability, thereby aiding the diffusion of seawater saturated with $CaCO_3$.

The depth of water is uncertain. If the formation of the laminae was related to algal mats one might expect very shallow, even supratidal, conditions to have been possible. Isotopic analysis indicates that all components of the mound were formed under the same conditions, precluding vadose water as an agent of diagenesis and making unlikely a supratidal environment for formation of the radiaxial fibrous calcite in the zebra limestone.

Inasmuch as the main core of the carbonate mound rests upon the zebra limestone, growth of the mound may have started in depths not exceeding 30 m.

Shinn (1969, p. 110, 112–117) showed that submarine cementation can take place in depths of 30 m in the Persian Gulf although examples in which he found multiple crusts of relatively close vertical spacing were at depths of less than 3 m. He also found that submarine cementation took place in areas of low sedimentary accumulation such as the windward side of offshore highs. Presumably the essential factors of low sediment accumulation, saturated seawater, and permeable sediment could be found at considerable depths.

We do not know what, if any, influence algae, sponges, or other organisms had in protecting the depositional surface, in binding the sediment, or in controlling crystallization of $CaCO_3$. Although Meiklejohn Peak must have been scores of miles from the shore, it surely was not subjected to wave action sufficiently destructive to tear apart the laminated zebra limestone.

The fact that cephalopod shells are most common in the laminated facies, particularly in pockets, suggests that their empty shells, weighted down by cameral deposits and waterlogged, were swashed into shallow depressions and cemented into the surrounding rock.

Ginsburg and James (1973, p. 24) have discovered off the coast of British Honduras that lithification of limestone has taken place at depths not less than 20 m in completely submarine conditions; one specimen was found to be less than 2,500 years old. They have found that the cement is aragonite and high-magnesium calcite, both of which are unstable minerals. The cement, according to Ginsburg and others (1973, p. 781), "almost obliterates many primary depositional fabrics." If such is the case in the Neogene off British Honduras we can speculate that the inversion of the cements to calcite will unavoidably result in further recrystallization and obliteration of original sedimentary fabric.

Ginsburg and James' discovery of cavities filled or lined with "dense, radiating fibrous growths of aragonite" provides a lithology which could readily invert to the radiaxial fibrous calcite of the zebra limestone and the *Stromatactis*-like bodies of the main mudmound at Meiklejohn Peak.

Despite our lack of positive evidence for algal mats, the observations of G. M. Friedman and others (1973) suggest that the origin of the zebra limestone should be attributed to mats. Most fossils in calcilutite ca_1 are oriented parallel to laminations where layers are undisturbed but the shells lie at angles as high as 90° to laminations, particularly where layers are disturbed; each lamina was deposited initially as a layer draped over various irregular surfaces where fossils settled and were trapped in the cohesive "flypaper" of algal filaments.

By no analogy other than to algal mats can we as easily explain the great lateral extent of laminae in the zebra limestone, the complete isolation of lumps of calcilutite, and the steplike flexure of laminae. Seasonal climatic fluctuations—whether producing storms, changes in water chemistry, or alternations of algal growth—could have accounted for the varvelike cyclic nature of the calcilutites ca_1, ca_2, and ca_3. The radiaxial fibrous calcite may have been a product of selective recrystallization of aragonite needles within the algal mat, or of micritic metastable carbonate within or below the mat, or both.

One of the calcilutites, possibly ca_1, may represent the micritic material within the algal mat itself and therefore may appear to have been the most competent layer in the cycle. Locally, ca_1 was deformed just as we might expect an algal mat to be where ruptured by bioturbation, wave action, or the upward pressure of gas or contained fluid.

Locally, there must have been a briefly fluid, possibly thixotropic, pelletoid calcilutite ca_2 and calcilutite ca_3 between layers of ca_1; whether the resulting carbonate slurry filled cavities from above or was deposited as a layer in a repeated cycle and was locally squeezed hydraulically into flow structures cannot be proved.

The zebra limestone seems to indicate that intertidal or extremely shallow infratidal deposition initiated the building of the carbonate mudmound and Meiklejohn Peak. However, the depth to which algal mats may extend depends largely on the abundance and voracity of browsing marine fauna.

The occurrence of minor amounts of zebra limestone above tongues of cover beds, approximately 25 m above the bottom of the mound, proves that for the first third of its growth the mound was only slightly above the surrounding bottom. We must therefore conclude that the covering silty limestone of the *Orthidiella* zone was likewise deposited in shallow water in the vicinity of present-day Meiklejohn Peak.

Although some radiaxial fibrous calcite may occupy former cavities it may also have resulted from recrystallization and neomorphic aggradation of other metastable carbonate. Whether triggered by organic substances, by the instability of aragonite, or by greater permeability, this neomorphism was highly selective.

Further, it must have taken place very early in the diagenetic process, perhaps as rapidly as the algae decomposed.

These conclusions free us from the necessity of postulating the prior existence of cement-filled cavities wherever radiaxial fibrous calcite is encountered. We need not pursue an ontological speculation on the critical size of a cavity.

If, as Kendall and Tucker (1973) believe, radiaxial fibrous calcite is derived by recrystallization from acicular aragonite, why should it not be derived even more readily from micritic aragonite or high-magnesian calcite? If such a fine-grained aragonite were converted by aggrading neomorphism to coarse radiaxial spar the oldest crystals — those that increased most by incorporating their neighbors — should be the largest (figs. 14*C*, 18*B*). Bathurst (1958, p. 15, 20; 1959, p. 509) showed that grain (crystal) size of calcite increases with growth away from the wall of the cavity; that is, the older crystals are the smaller. I do not dispute this finding, but I question the belief that direction of increase in grain size always indicates the center of a former cavity. The direction of neomorphic conversion of micrite would be from coarse (old) to fine (young) crystals, a very different conclusion involving no cavity at all. Neomorphic conversion can be demonstrated at Meiklejohn Peak; the conversion of an echinodermal plate to radiaxial calcite is shown in figure 29. Calcite and fossils left relict in radiaxial fibrous calcite are illustrated in figures 30 and 31.

I suggest that the median seam, which is virtually ubiquitous in such calcite, does not represent the surface along which crystals grown from opposing ceiling and floor have met. The seam may be entirely related to recrystallization, being some sort of surface of equal pressure between two tiers of large aggrading crystals.

ORIGIN OF THE CORE OF THE MUDMOUND

By Valdar Jaanusson

The Meiklejohn Peak mound had no skeletal frame. Constituents of the skeletal sand do not indicate the presence of organisms that could have acted as important sediment traps. Sponges are a possible exception, provided that the spiculaelike skeletal particles belong to this group. Nevertheless, the "spiculae" do not seem sufficiently numerous, and macroscopic skeletons of sponges are very rare. The prolific occurrence of sponges (and *Pyritonema*) in the so-called sponge beds of the Ikes Canyon section, Toquima Range, Nevada, is not associated with a mound. Whatever organisms did control the growth of the mound must have lacked preservable hard parts.

M. J. Brady (oral commun., Nov. 1971; written commun., April 3, 1972) found that low banks of lime mud in lagoons of Yucatan are not dependent on any framework organisms. The buildup of mud is related to hydrologic conditions — to changing currents, to bottom configuration, to wind direction, and to tidal currents. As soon as the mudbanks "became prominences on the lagoon floor" they seemingly grow, because they disrupted sediment-laden currents.

Understanding the original nature of the carbonate mound requires interpretation of how *Stromatactis* formed. These structures may occupy 50 percent or more of the volume of a carbonate mound. Even at the Meiklejohn Peak mound they form 15–20 percent of the volume. Bathurst (1959) suggested that *Stromatactis* represents cavity-fillings — a proposal accepted by most subsequent writers who investigated such structures. This suggestion implies that during growth or diagenetic history of a mound a considerable volume was occupied by cavities of macroscopic size. That *Stromatactis* in fact is cement precipitated into cavities can be proved in many instances but this does not necessarily mean that all *Stromatactis*-like calcite bodies have the same origin. Such calcite bodies can originate through recrystallization although bodies so formed lack a median seam. Moreover, radiaxial mosaic forming *Stromatactis* can demonstrably grow at the expense of included sedimentary grains and surrounding sediment. The quantitative importance of the latter process, though not always evident, seems to be small in comparison with the volume of a *Stromatactis*. The evidence from the Meiklejohn Peak mound is not conclusive but if the median seam of radiaxial mosaic does indicate cavity-filling, then most of the *Stromatactis* in the mound has been formed as cement precipitated into cavities.

Interpretation of the growth of the mound depends on that of the diagenesis in the early generations of limestone. If in the Meiklejohn Peak mound the generation *Li 1* (fig. 32) was bored by organisms—if it was lithified prior to the deposition of *Li 2* —lithification of parts of the mound took place early enough for formation of hardgrounds. In that case, the mound probably represented a lithoherm (as defined by Neumann and others, 1972) and not a mound of carbonate mud. In fact, much of what now looks like a lithified carbonate mud would possibly not have been soft sediment at all but a rock largely formed by calcium carbonate micrite precipitated from the seawater. Recent limestone, formed largely by precipitation of high-magnesian calcite, has been described from the Mediterranean (Alexandersson, 1969). Some of the rock from the lithoherms of the Straits of Florida (Neumann and others, 1972) is closely similar to the mound at Meiklejohn Peak in appearance (my observations on the material exhibited by A. C. Neumann at the AAPG meeting in Denver, April 1972) as well as composition. This type of rock is termed here "thalassic limestone." Particles of sediment were trapped and encrusting organisms were incorporated therein, but it formed mainly by precipitation of calcium carbonate from seawater. The growth of thalassic limestone tends to be irregular. Cavities of various shape and size can be enclosed within the rock and filled by trapped sediment or drusy cement, or both. The organisms associated with modern thalassic limestones are mainly those that bore into the rock or attach themselves upon the surface of the rock, that is, boring endofauna and sedentary epifauna. Such rock tends to be intensely bored by various organisms (Alexandersson, 1969).

If the Meiklejohn Peak mound and similar carbonate mounds were once lithoherms, how the large volume of cavities could be formed in the mound and could exist without collapsing would be easily explained. The early formation of spar in *Stromatactis* would also be easy to understand. More difficult to explain would be the locally distinct lineation parallel to the depositional surface of the former cavities within the mound.

During field examination of the Meiklejohn Peak mound we considered the possibility that the mound represented a lithoherm. However, no structures could be recognized that would indicate the former presence of hardgrounds. No bored surfaces were found, or even any unmistakable traces of boring activities. The presence of several generations of limestone was discovered later, during laboratory examination, in some samples. Skeletal remains of encrusting organisms are rare in the macrofauna of the mound. However, on Ordovician hardgrounds (discontinuity surfaces) an encrusting epifauna is generally notoriously poorly represented (Jaanusson, 1961). It is also important to note that when the growth of a *Stromatactis* carbonate mound had ceased, the mound was demonstrably lithified and formed a hardground before covering beds were deposited. This cannot be proved with respect to the Meiklejohn Peak mound, but it is true for numerous other Paleozoic carbonate mounds. At least in the Ordovician carbonate mounds of Sweden, the mounds' upper surfaces show no evidence of borings; environmental conditions obviously were not suitable for boring organisms. An epifauna encrusting the surface has not been observed.

If the Meiklejohn Peak mound was not a lithoherm, it presumably was soft carbonate mud which lithified early but not at the interface between sediment and seawater. If the mound had emerged before deposition of the covering beds, the cavities could have formed as a result of differential shrinkage within the mound during subaerial exposure. Emersion and shrinkage could have been followed by internal sedimentation, lithification, and cementation in the cavities (Dunham, 1969). However, contact relations between the mound and the covering beds do not suggest a phase of emersion between these two periods of deposition. Moreover, the data on δO^{18} indicate that the spar and calcilutite have the same isotopic composition and that precipitation of the spar from fresh water is very unlikely (p. 31).

It is difficult to find a suitable actuogeological model for the Meiklejohn Peak mound if formation of the extensive cavities and early lithification took place within the carbonate mud in constantly submarine conditions, as postulated by many writers for similar carbonate mounds (Bathurst, 1959; Schwarzacher, 1961; Lees, 1964; Heckel, 1972, and others). The origin of the cavities has been variously explained: space left after decay of soft organisms (Bathurst, 1959; Lees, 1964), differential settling and shear failure (Schwarzacher, 1961), solution (Textoris and Carozzi, 1964), burrows made by animals (Shinn, 1968), and differential compaction (Heckel, 1972). Some of the explanations (solution, burrows) are very unlikely for the Meiklejohn Peak mound and for other mounds herein mentioned. There is no positive or negative evidence for the former existence of abundant soft organisms whose decay could have left the cavities after the enclosing carbonate mud had become firm (see also Heckel, 1972). Shear failure alone cannot be an important factor in forming the cavities, because it implies that the mound was originally much larger. Differential settling and differential compaction, or a combination of both, are possible agencies in formation of cavities within a soft sediment but our knowledge is scanty about what really happens when a mound consisting of carbonate mud settles and compacts. Small cavities of the general shape of microstromatactis have been experimentally produced by settling Holocene carbonate mud (Cloud, 1960, 1962). However, whether the same or a similar process can produce macroscopic cavities aggregating as much as 50 percent of the total volume of a carbonate mud is not known. Differential settlement of a mound has demonstrably caused transverse fissures and crevices but formation of a considerable volume of horizontal cavities is not readily explained from the standpoint of soil mechanics. Thus, if the Meiklejohn Peak mound was once a mound of soft carbonate mud continuously in a submarine environment, there is much in the diagenetic history of the mound that we do not understand.

The depth of water during formation of the Meiklejohn Peak mound is difficult to determine. The presence of calcareous algae suggests deposition within the general limits of the photic zone. The bedded limestone covering the mound abounds in what probably have been indurated pellets. In modern seas such pellets are not known to be formed below the upper photic zone, and they may indicate similar shallow-water conditions during the deposition of the covering beds. Regardless of whether the Meiklejohn Peak mound was or was not a lithoherm, the calcarenitic covering beds give the impression of having been deposited in an environment with a higher average water energy level than that which prevailed during deposition of the soft carbonate mud of the mound. The significance of this difference is not clear; in carbonate sediments estimating the water energy level from the grain size distribution is usually difficult mainly because of the trapping and binding action of plants (Ginsburg and Lowenstam, 1958; Baars, 1963; Lynts, 1966; Scoffin, 1970) and the local occurrence of gelatinous mats on the surface of the sediment (Bathurst, 1967). The aspects related to depth of deposition can be discussed with greater confidence when the carbonate lithology of contemporaneous beds has been studied in a regional scale.

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