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# 34. CEMENT STRATIGRAPHY AND THE DEMISE OF THE EARLY–MIDDLE MIOCENE CARBONATE PLATFORM ON THE MARION PLATEAU[1]

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## ABSTRACT

The Marion Plateau is a major carbonate province in northeastern Australia. This plateau has several shallow-water platforms, most of which have been drowned so that they now lie in more than 400 m of water and have been buried by a thin cover of hemipelagic sediments. The oldest of these drowned platforms was drilled during Leg 133, and here we report the diagenetic history of this platform and use cement stratigraphy to examine the cause and timing of its demise. The diagenetic history of the early to middle Miocene age platform shows an initial shallow-marine phreatic phase of cementation, followed by meteoric diagenesis, which in turn is followed by dolomitization and/or a deep marine phase of cementation. Cavity-filling, datable hemipelagic sediments enable us to place the cement stratigraphy in an absolute time frame. The demise of the platform was caused by exposure for up to 7 m.y. because of a relative decrease in sea level during the late middle to late late Miocene.


## INTRODUCTION

The Marion Plateau (Fig. 1) is one of several major carbonate provinces in northeastern Australia and consists of several major shallow-water carbonate platforms that were deposited during the Miocene to Holocene (Davies et al., 1989). The plateau is located to the east of the central Great Barrier Reef and forms a deep-water extension of the shelf. Water depths range from 100 m adjacent to the Great Barrier Reef to 500 m around the northern and eastern edges of the plateau (Fig. 1). During Leg 133, three sites were occupied in the northwestern corner of the plateau (Figs. 1 and 2). Before this drilling, little was known of the age, facies, and diagenetic history of the platforms that make up the plateau. A gross outline of the distribution and age of the major platform phases had been assembled from a few dredge samples and from seismic data. This had shown that there were two major phases of platform growth in the Neogene: an older, probably early to middle Miocene age platform in the northern part of the plateau (M1), and a younger, probably late Miocene phase in the southeast (M2) that had been initiated in lowstand position relative to M1 (Davies et al., 1989; Pigram et al., 1992). The upper surface of M1 is a prominent unconformity (Figs. 2A and 2B). Both platforms had also been drowned and were now in more than 400 m of water and had been buried or partly buried by what were assumed to be hemipelagic sediments.

The three sites drilled on the northwestern margin of the Marion Plateau during Leg 133 were designed to obtain samples with which to address the problems of the age of the older platform (M1), its facies association, the age and nature of the bounding unconformity, and the cause or causes of its demise and drowning. The three sites form a north-south transect across the edge of M1 (Fig. 2). Site 815 intersected late Miocene to Pleistocene hemipelagic sediments (Units I-IV), overlying late Miocene (Zone N17) shallow-water packstone (Unit V) that rests unconformably on late middle Miocene (Zone N12) shallow-water wackestone and rudstone (Shipboard Scientific Party, 1991a; Pigram, 1993). The M1 time-equivalent slope facies were not intersected at this site. Site 816 intersected Pliocene–Pleistocene hemipelagic sediments (Unit I) overlying early Pliocene shallow-water transgressive carbonate sand (Unit II). Unit II rests unconformably on middle Miocene shallow-water limestone (Shipboard Scientific Party, 1991b; Chaproniere and Betzler, this volume). Site 826 intersected Pliocene–Pleistocene hemipelagic sediments resting unconformably on middle Miocene (N10?) shallow-water limestone (Shipboard Scientific Party, 1991c; Chaproniere and Betzler, this volume). Biostratigraphic data from the ODP cores (Chaproniere and Betzler, this volume) and from dredge samples collected from M further to the east (Figs. 1 and 2C) (Chaproniere and Pigram, in press) show M1 to range in age from at least late early to middle Miocene (planktonic foraminifer Zones N7 to N10/12). The complete age range for M1 could not be determined because the drill holes did not penetrate the entire platform thickness.

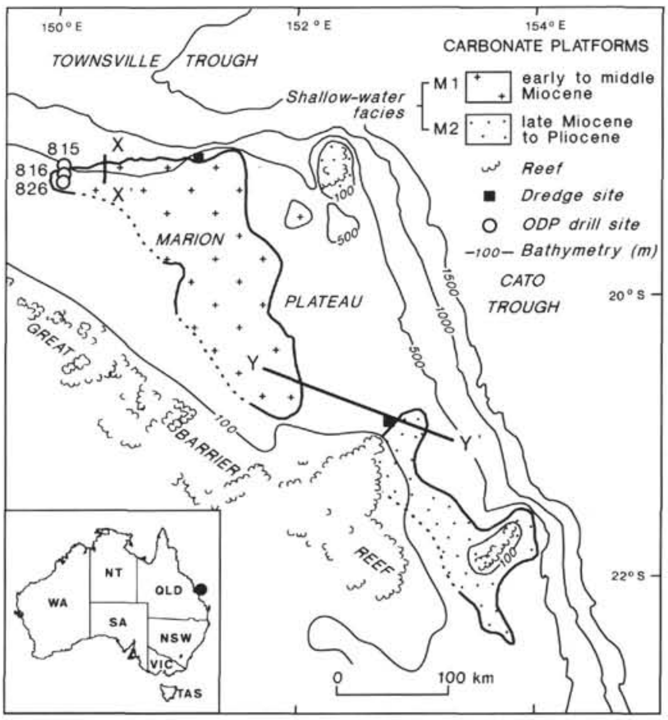


Figure 1. Locality map showing the Marion Plateau in northeastern Australia, the location of the major carbonate platforms on the plateau, and the position of ODP and dredge sites. XX' and YY' give the location of the cross section shown in Figure 2A.

The unconformity separating the shallow-water limestone and the hemipelagic sediments extended from middle Miocene to early Plio-

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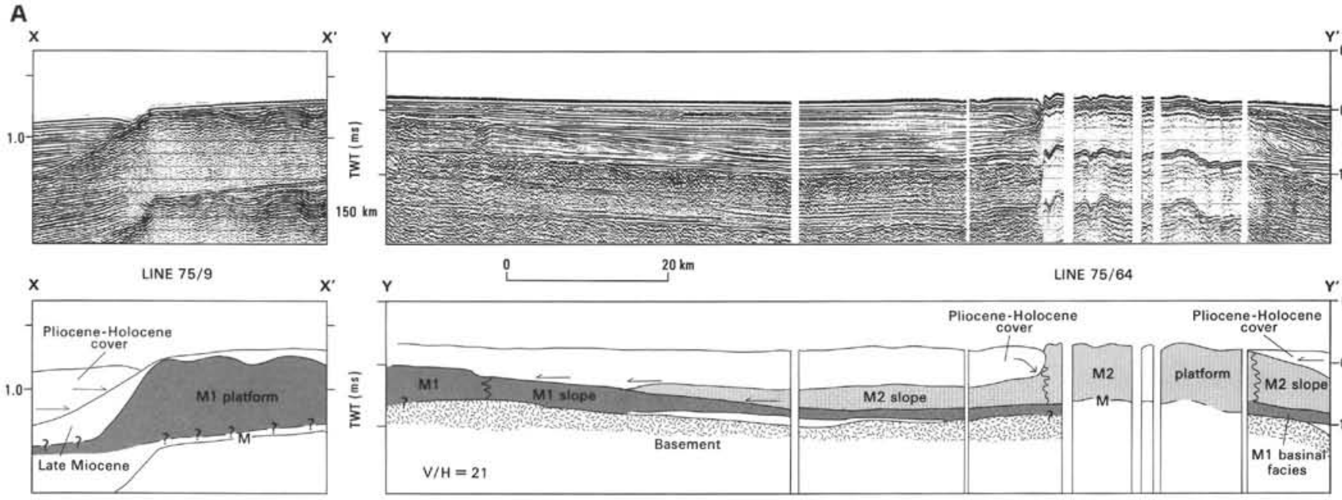



Figure 2. **A.** A section across the Marion Plateau showing the Neogene carbonate platforms M1 and M2 and illustrating their relationship. The location of XX' and YY' is shown in Figure 1. **B.** Seismic section through Sites 815, 816, and 826 showing them in relation to the edge of the M1 carbonate platform. **C.** Seismic section across the dredge site along the northern edge of the early to middle Miocene age carbonate platform (M1).

cene (from Zones N10/12 to N19/20 or CN11). During this period, the plateau was either starved of sediment, in which case the upper surface of M1 should be a marine hardground, or subaerially exposed, in which case the limestone should show evidence of meteoric diagenesis. An analysis of the Neogene sea-level record preserved on the Marion Plateau (Pigram et al., 1990; Pigram et al., 1992) suggests that subaerial exposure, caused by a major fall in sea level, led to the demise and erosion of the older platform.

The purpose of this paper is to report the results of an analysis of the diagenetic history of the shallow-water limestone samples obtained by drilling at Sites 816 and 826 and by dredging the M1 platform. The aim of this analysis was to establish the cement stratigraphy of the platform so as to examine the timing and cause or causes of the platform's demise.

## METHODS

Of the 270 thin sections examined, approximately half were stained to determine their mineralogy. Initially, the samples were stained with Feigl's solution (to identify aragonite), then with Clayton's Yellow (to determine the high magnesium calcite [HMC] components), and finally with alizarin red S (to distinguish calcite from dolomite) (Freidman, 1959; Dickson, 1966; Lewis, 1984). Several of the dolomitized samples were tested for cathodoluminescence but were found to be nonluminescent.

Some of the bioclasts, and very rarely some of the cements, retained their original mineralogy, but most were partially or completely dolomitized. Many of the dredge and some of the drill samples retained their original textures with remarkable fidelity despite the dolomitization. In other cases, the fabrics were almost completely destroyed.

The cement stratigraphy in these samples was readily established from the relationships preserved in the samples. It also was possible to establish the broad timing of each of the phases of cement precipitation because of the deposition of planktonic-foraminifer-rich mud in crosscutting dissolution cavities, borings and fractures in many of the dredge samples. The interpretation of the environments of precipitation for each phase of cementation is based largely on morphology as described by numerous authors but summarized by Bricker (1971), Bathurst (1975), Longman (1980), James and Choquette (1983a and 1983b, 1984), Choquette and James (1987), and Moore (1989). Oxygen isotope analysis of the cements was not attempted, as it was assumed that the dolomitization of the cements would have significantly altered their original isotope signature, thereby rendering that signal useless for the interpretation of the environments of precipitation of the cements. Sr isotope analysis of dolomites from many Leg 133 sites, including four from Site 816, was undertaken to establish the timing of dolomitization (McKenzie, Isern, et al., this volume). The results of Sr isotope analysis of the samples from Site 816 are discussed in the section on the timing of the dolomitization.

## LOWER TO MIDDLE MIOCENE SHALLOW-WATER LIMESTONES, CEMENTS, AND OTHER DIAGENETIC PROCESSES

The lower to middle Miocene shallow-water limestones are generally dolomitized floatstone and minor rudstone (Pigram, 1993). The floatstone consists of bioclasts (including rhodoliths) in a matrix of peloidal micrite. In some samples the sediment is clast supported; therefore the samples are rudstones. The major bioclasts consist of larger foraminifers, coralline algae (nodules as well as those forming rhodoliths), articulate red algae (including ?*Arthrocardia*), and *Halimeda*. The minor bioclasts include echinoderm, gastropods, bryozoan, coral, and brachiopod fragments.

The cement types and the effects of other diagenetic processes, such as neomorphism and dolomitization, are briefly described below and are illustrated in Figures 2 through 7 and summarized in Figure 9. Other processes, such as boring and fracturing that crosscut cement phases and thereby assist in dating events, are briefly described also.

### Botryoidal Aragonite

This cement consists of radiating clusters of needle-shaped aragonite crystals (determined by staining with Feigl's solution) that form botryoids in the conceptacles and intraskeletal cavities of coralline algae (Fig. 3A), occasionally filling the zooecia of bryozoa and, rarely, the chambers of foraminifer. The needles are up to 10 μm across and 100 μm long. Similar clusters with the same morphology and occurring in the same locations but having either a low magnesium calcite (LMC) or dolomite mineralogy are common. Because of their habit and morphology, these cements are interpreted to be of the same origin, but as having undergone neomorphism from aragonite to LMC or dolomite. The original habit of the clusters is generally well preserved despite neomorphism.

### Isopachous Fibrous Rim Cement

Isopachous fibrous rims form cements up to 50 μm thick (Figs. 3B and 3C). They tend to occur on grains separated by large interparticle

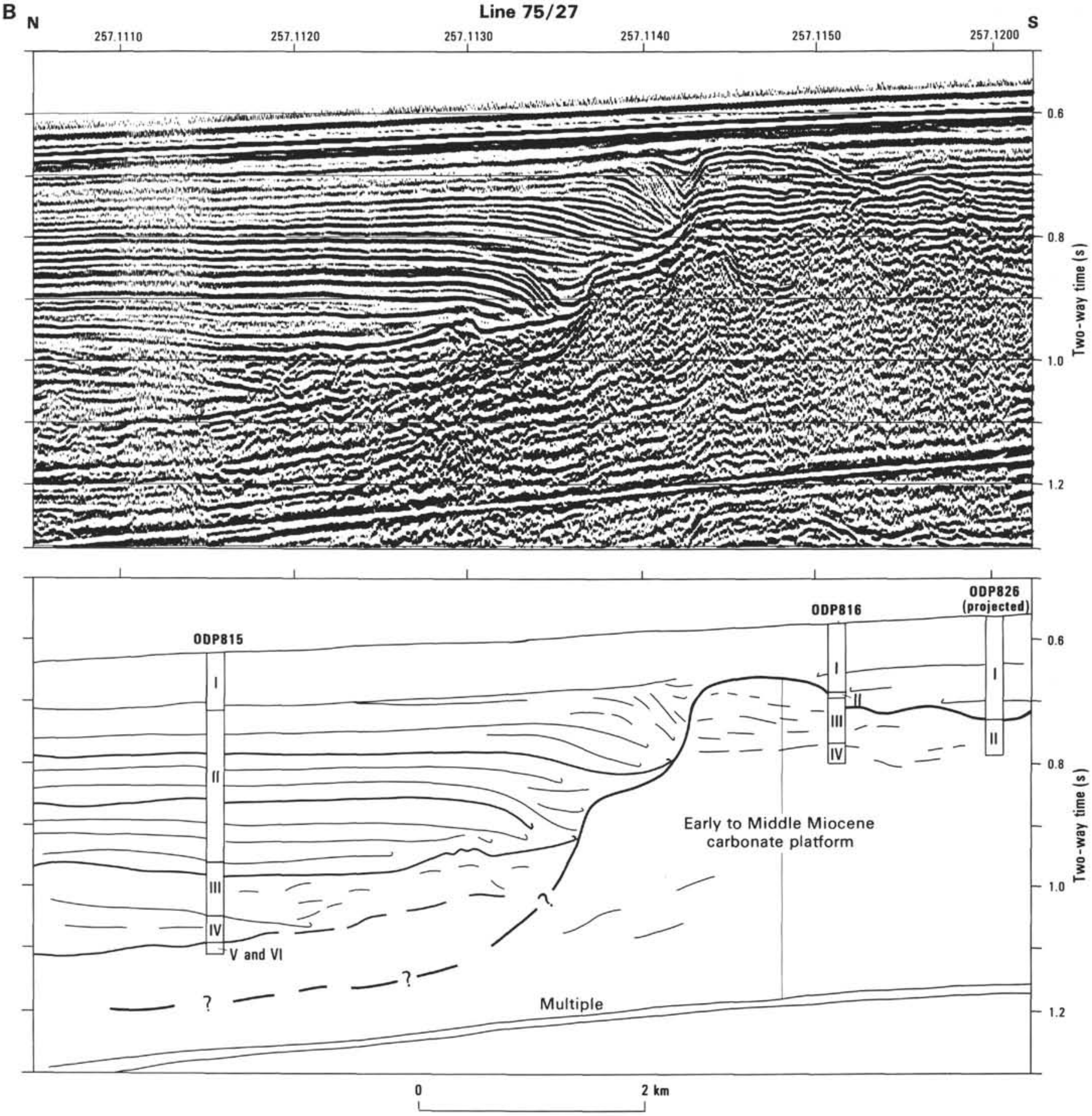



Figure 2 (continued).

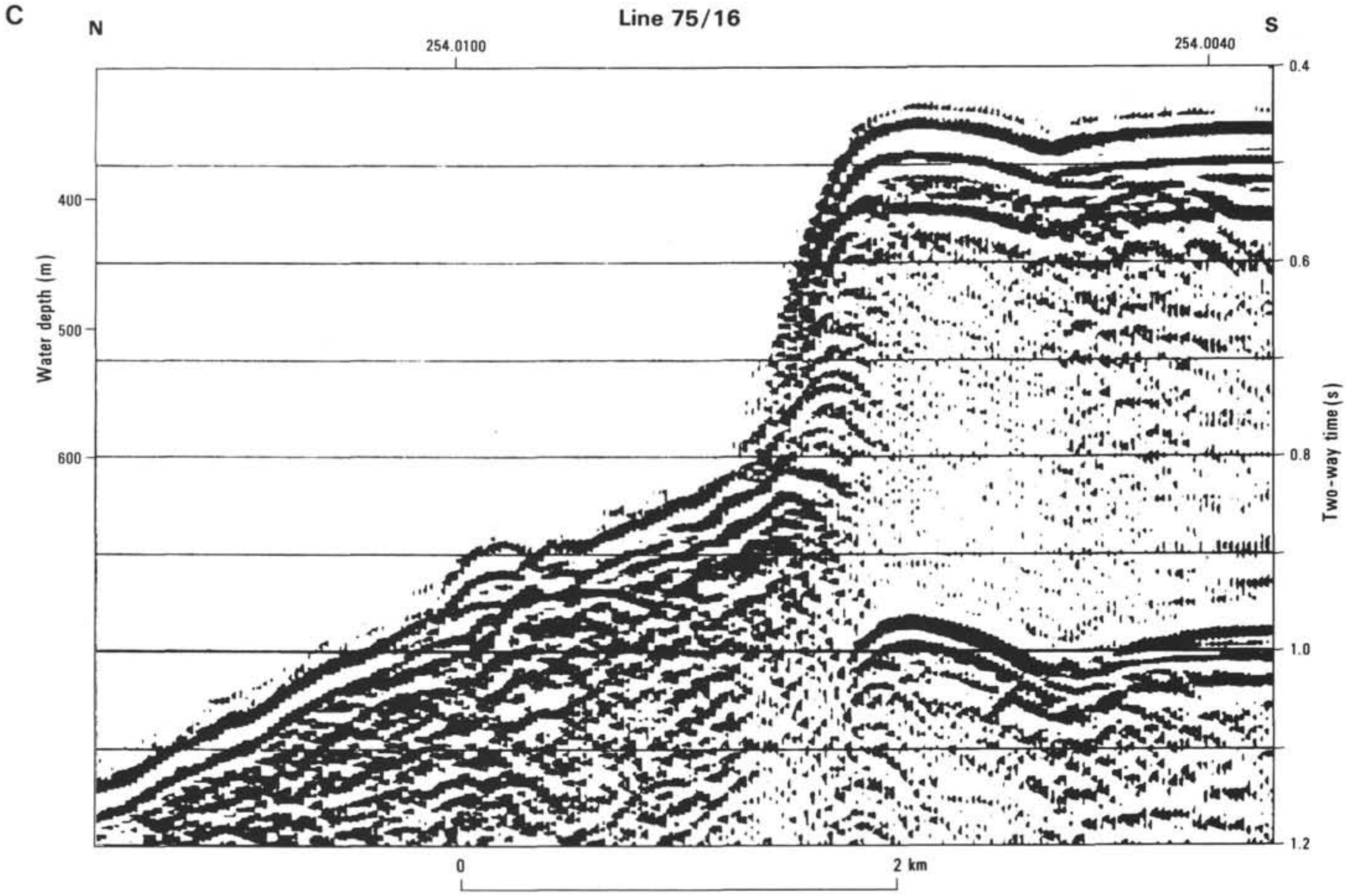
pores; they are, therefore, comparatively rare. As this cement lines cavities filled with peloidal micrite and micrite, it is interpreted as the first cement precipitated in these sediments. Staining shows these fibrous isopachous pore-lining cements to consist entirely of LMC or dolomite. No relic aragonite or high magnesium calcite (HMC) is preserved.

## Syntaxial Overgrowths

Syntaxial overgrowths on echinoid fragments and spines are a common, but volumetrically insignificant, cement type (Fig. 4A). These overgrowths originally were LMC but have been mimically replaced by dolomite. LMC relics (identified by staining with alizarin red S) within the dolomite attest to the original composition of the overgrowths. The syntaxial cements vary widely in dimension but characteristically out-compete the isopachous calcite pore-lining cement for the available pore space.

## Bladed to Granular Pore-Lining Cements

Bladed to granular pore-lining cements up to 300 µm thick are common throughout the lower to middle Miocene sediments (Figs.

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4B and 4C). The morphology of individual crystals within these cements is most commonly bladed, but granular and irregular forms also occur (Fig. 4D). These cements are now mostly dolomite, but rare relic LMC occurs within the dolomite and shows with staining (alizarin red S). Dolomitization has occurred by mimic replacement and has preserved the original textures to a high degree.

## Granular or Blocky Cement

Blocky to granular, pore-filling, clear cement up to 0.3 mm wide is the most common cement in these rocks (Figs. 3C and 4C). This spar typically becomes coarser toward the center of the pore. This cement is now dolomitized, but relics of LMC identified by staining with alizarin red S suggest that it was originally calcitic.

## Apatite Crusts

The borings are often lined with multiple generations of apatite crusts (Figs. 5C and 5E). Those borings lined with apatite crusts crosscut hemipelagic sediments of late Miocene and early Pliocene age and are, in turn, filled with hemipelagic sediments of latest Pliocene age. These relationships suggest that the apatite crusts were precipitated in mid-Pliocene time (Pigram, 1993).

## Coarse Equant Spar

The last phase of cement in these sediments consists of a coarse, equant, calcite spar containing numerous inclusions (Figs. 5D and 5E). As this cement post-dates the apatite crusts that were deposited during the mid-Pliocene, it was precipitated during the late Pliocene to Holocene. Individual crystals are up to 300 μm wide. The spar either fills or partially fills the cavities, some of which are lined with apatite or manganese crusts.

## Dolomitization

All the lower to middle Miocene samples have been dolomitized to some degree. The nature and, where possible, the timing of the dolomitization is described in the following section. Here the dolomites are described using the nomenclature and classification of Sibley and Gregg (1987).

### *Dredge Samples*

The limestones recovered by dredging are only partially dolomitized and, because the dolomitization is not fabric destructive, they have a more complete stratigraphic history preserved. This good state of preservation of the cements in the dredge samples, when combined with age information from the cavity-filling hemipelagic sediments, enables us to place some constraints on the timing of some of the phases of dolomitization. The Sr dating of some of the samples from Site 816 (McKenzie, Isern, et al., this volume) dates the dolomites from that part of the platform in which there are no cavity-filling hemipelagic sediments and, hence, no constraints on the age of the dolomitization.

Dolomitization in these rocks is selective and tends to be fabric retentive. Dolomite has mimically replaced all cements that have

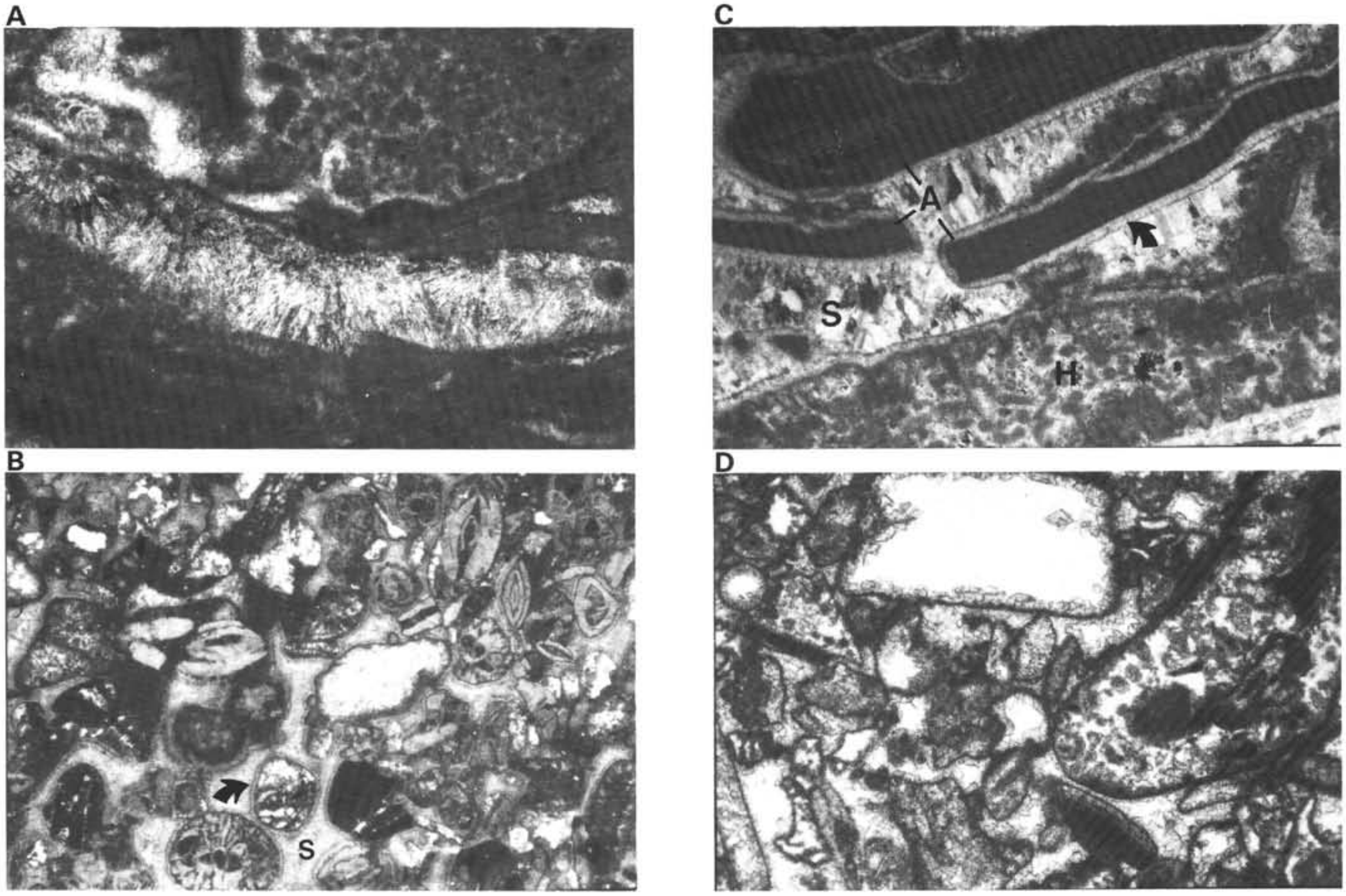


Figure 3. **A.** Radiating clusters of needle-shaped crystals in an intraskeletal cavity of a coralline algae. These clusters, which form botryoids, also occur in other locations, such as the conceptacles of coralline algae, in the zooecia of bryozoa, and rarely in the chambers of foraminifers. Although most clusters now consist of low magnesium calcite (LMC) or dolomite, some retain an aragonitic mineralogy (as determined by staining with Feigl's solution). Field of view, 1 mm, plane light, (dredge Sample 75DR03/I/8). **B.** Middle Miocene rudstone with isopachous fibrous cement (arrow) on most bioclasts. In the center of the photograph, the isopachous cement and the micrite envelope are all that is left of the bioclast. The pores have been largely filled with bladed and blocky spar cements (S). All the cements are now dolomite. The slide has been etched. Field of view, 8 mm, plane light (Sample 133-826A-9R-1, 1–3 cm). **C.** Isopachous fibrous cements (arrow) on coralline algae fragments (A) and *Halimeda* (H). The isopachous cement pre-dates the peloidal mud (to the right). The pore space has been filled by blocky calcite cement (S). All the cements have been selectively dolomitized. The coralline algae is still calcitic, whereas the *Halimeda* has been dolomitized. Field of view, 2.5 mm, crossed polars (dredge Sample 75DR03/I/7). **D.** Micrite envelopes lined with planar-S dolomite. Plane light, field of view, 4.5 mm (Sample 133-816C-6R-1, 26–27 cm).

either LMC relics or are interpreted to be LMC based on their morphology. However, most calcitic bioclasts, such as larger benthic foraminifers, coralline algae, and bryozoans, were not dolomitized. Similarly, much of the micrite remains LMC. Some of the micrite has been partially replaced and has, in places, dolomite rhombs scattered through it (Fig. 6D). The mimic replacement of the calcitic cements by dolomite has occurred with great fidelity, and the cements generally retain their original morphology (Figs. 3 and 4). Only the dolomite in some of the *Halimeda* and within the micrite shows planar crystal structures (Fig. 6C).

### *Upper Miocene–Pliocene Floatstone*

During the dredging of the M1 platform, upper Miocene to Pliocene floatstones consisting of lower middle Miocene lithoclasts in a matrix of foraminifer-rich hemipelagic sediment were recovered (Fig. 7C). The diagenetic history of these rocks is described briefly here because it provides clues about the timing and nature of some of the dolomitization that has occurred. The lithoclasts contain all the cements that were precipitated before the deposition of the hemipelagic sediments that, in these rocks, form the matrix. Some of the clasts have been dolomitized, suggesting that they were dolomitized before being eroded. The rock also has been fractured and bored. Both types of voids have a complex fill that consists of apatite crusts and scattered manganese crusts, with interlayered planktonic-foraminifer-rich hemipelagic sediment and late-stage equant spar cement.

## ODP Sites

The middle Miocene samples recovered from M1 at Sites 816 and 826 have the same cements that dredge samples have, except for the apatite crusts and late-stage equant spar. Although the samples contain many cavities of various origins, none of the cavities is filled with hemipelagic sediment. Consequently, the age control on the development of the various phases of diagenesis is more difficult to establish. In these rocks dolomitization is the most pervasive diagenetic process.

### *Site 816*

Middle Miocene floatstones from the top 10 m of the shallow platform (top of Unit II in the descriptions of Site 816 in Davies, McKenzie, Palmer-Julson, et al., 1991) have been partially dolomi-

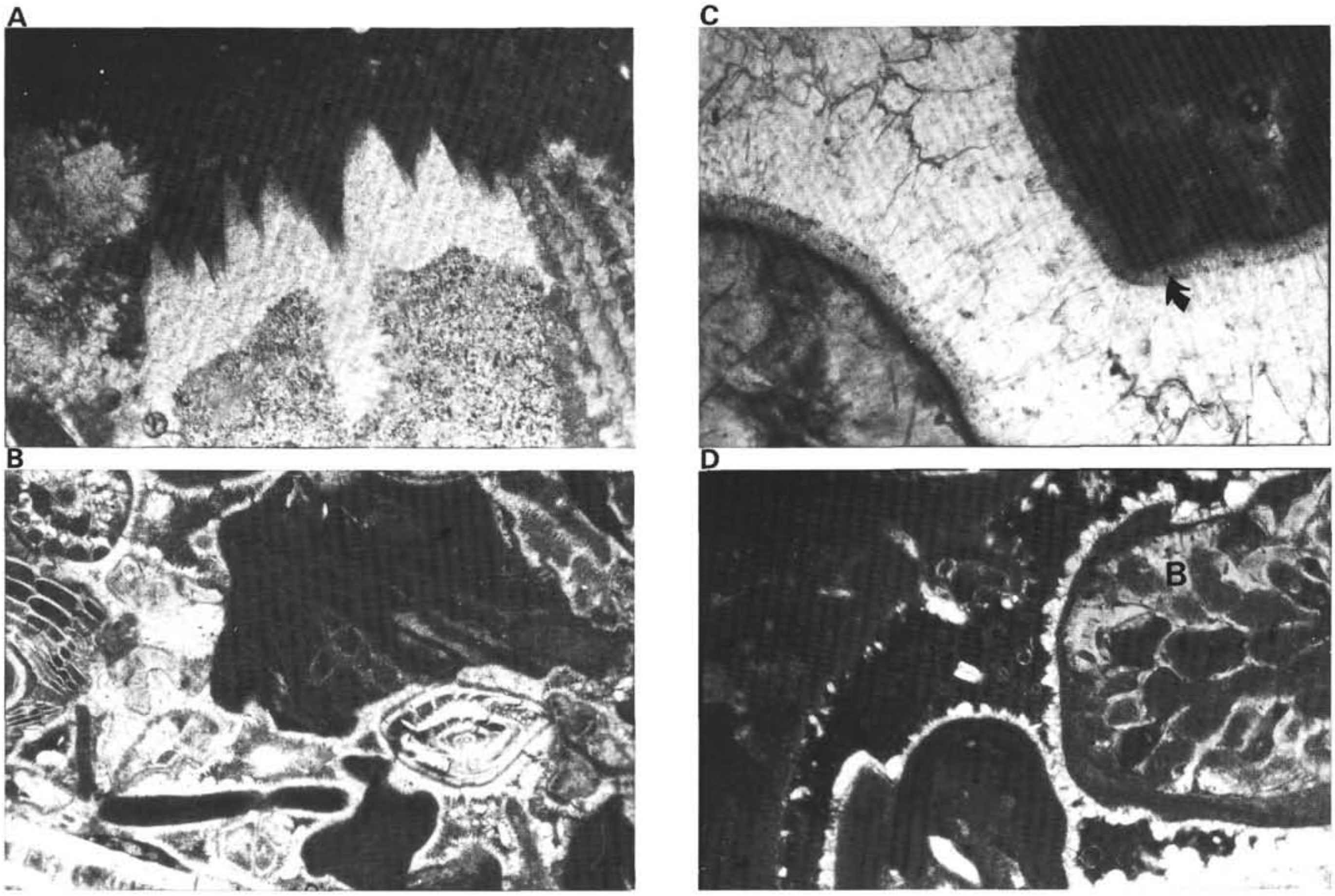


Figure 4. **A.** Syntaxial overgrowth on an echinoderm fragment. The overgrowths have been mimically dolomitized. Field of view, 1 mm, plane light (dredge Sample 75DR03/II/3). **B.** An overview of dolomitized, bladed to granular pore-lining cements. Field of view, 4.5 mm, plane light (dredge Sample 75DR03/5-B2-1). **C.** Closer view of bladed cement. Note that it has developed on top of an isopachous fibrous cement (arrow) and that blocky cement fills the space between the bladed cement in the top left of the photomicrograph. Field of view, 1 mm, crossed polars (dredge Sample 75DR3/I/7). **D.** Pore-lining cements showing the variation in crystal morphology that this phase of cement may exhibit around a single pore space. The cement is poorly developed along the left side of the pore, where the substrate is micrite. It has a blocky or granular form on the algae at lower left but becomes bladed to the right on the same grain. It has a mixture of forms on the coralline algae that encrusts the bryozoan (B) to the right of the photo. The pore space was later filled by hemipelagic sediment. Field of view, 2.5 mm, plane light (dredge Sample 75DR03/I/6).

tized. This dolomitization was selective and generally fabric retentive. Bioclasts have been selectively dolomitized. All former aragonitic bioclasts have been dolomitized, whereas original calcitic bioclasts (such as larger benthic foraminifers, coralline algae and bryozoans) are unaltered. The micrite matrix is not dolomitic. The dolomite that now occurs in bioclasts that were originally aragonitic (such as *Halimeda*) is fabric destructive and consists of a planar-s mosaic. Former calcitic cements have been mimically replaced, and some voids are lined with a rim of planar-s dolomite (Figs. 6A and 6B). The remainder of Unit II and all of Unit III are totally dolomitized with increasing fabric destruction downhole. The matrix in these rocks is completely replaced and consists of polymodal planar-s dolomite (Fig. 7A). Bioclast preservation varies both within an individual sample and downhole. In Unit II, many of the original bioclasts simply have been mimically replaced; however, deeper in the section this dolomite replacement has progressively destroyed the fabric of the bioclasts until now the rock consists of angular fragments of coralline algae in a polymodal planar-s matrix (Fig. 7A).

The dolomitization process appears to have created considerable new porosity. In some samples, this porosity has been measured at up to 40% (Fig. 7B). In the above descriptions, we have assumed that the highly dolomitized rocks had the same diagenetic history as the samples from higher up in the section, although this assumption cannot be proved for many of the samples because their original fabric has been destroyed. However, some samples retain the relic cement textures that suggest that this assumption is valid.

### *Site 826*

Samples recovered from Site 826 are generally less dolomitized. Fabrics are usually preserved and the dolomitization is selective. In most rocks, some relics of the original cements have been preserved. The bioclasts have been selectively and mimically replaced. All the former aragonitic bioclasts have been dolomitized, whereas the original calcitic bioclasts have remained unaltered, although some have been partially replaced. The micrite matrix has been only partially replaced. This pattern of dolomitization is identical to that in the top part of the platform at Site 816. Some samples have been completely dolomitized and have textures similar to those described above for the deeper parts of the platform at Site 816.

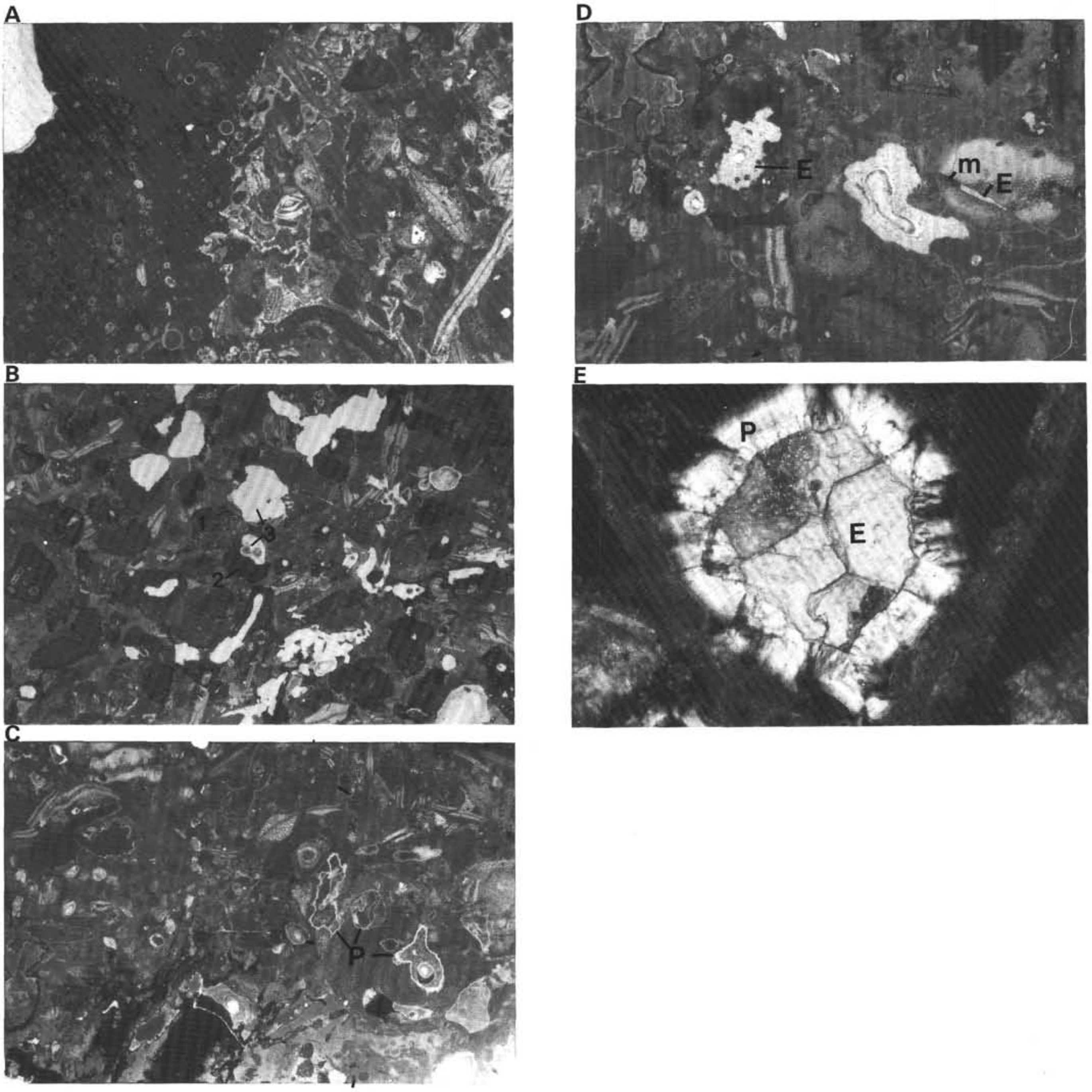


Figure 5. **A.** Middle Miocene (Zone N8–N9) rudstone (right-hand side) showing part of a large dissolution cavity filled with upper Miocene (Zone N17) hemipelagic sediment (left-hand side). The calcitic pore-lining cements of the rudstone were selectively dolomitized before or during the deposition of the hemipelagic sediment. Field of view, 2 cm, plane light (dredge Sample 75DR03/5-B2-1). **B.** Extensively bored rudstone. At least three phases of borings exist (labelled 1, 2, and 3 in the center of the photo, where crosscutting relationships are clear). Many of the cavities are filled with hemipelagic sediment. The irregular shape of the unfilled cavities suggests that they may have been enlarged by dissolution that must have occurred in a deep water environment after the plateau was drowned. Field of view, 2 cm, plane light (dredge Sample 76DR02/5). **C.** As for (B), but some cavities are lined with apatite crusts (P = narrow bright rims). Field of view, 2.5 cm, crossed polars (dredge Sample 76DR02/1). **D.** Coarse granular spar. Lower middle Miocene floatstone that had numerous cavities formed by boring, dissolution, and, perhaps, fracturing. Some of these cavities have been lined with apatite (upper left–narrow bright rims) or manganese oxides (upper right–black rims). Many of the cavities are filled or partly filled with micrite. The residual porosity in these cavities has been filled or partially filled by equant calcite spar (E). Note also that the fracture within the larger foraminifer on the right is filled with manganese oxides (m) and equant spar (E). Field of view, 2.5 cm, plane light (dredge Sample 76DR02-1). **E.** Equant spar (E) filling a small cavity lined with multiple layers of apatite (P). Field of view, 1 mm, plane light (dredge Sample 76DR02/1).

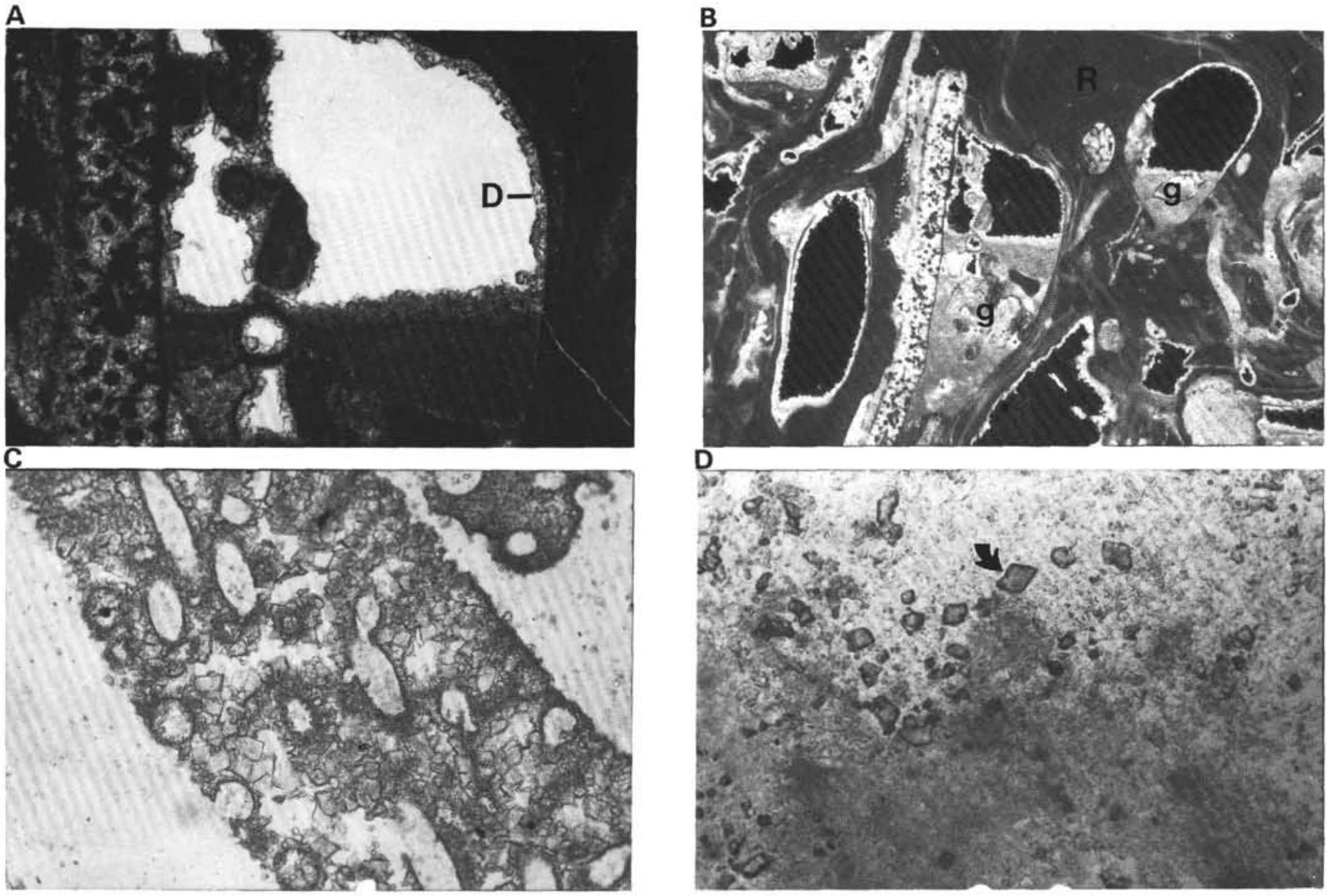


Figure 6. **A.** Pore-lining dolomite (D) rims. Field of view, 5 mm, plane light. **B.** Overview of a large rhodolith (R) with several cavities (black), some of which have geopetal fillings (g) and all of which are lined with dolomite (narrow bright white lining) (see Fig. 5A for close-up). Field of view, 1 cm, crossed polars (Sample 133-816A-14X-1, 50–51 cm). **C.** Planar-euhedral dolomite rhombs in *Halimeda*. Etched and stained with alizarin red S. Field of view, 1.0 mm, plane light (dredge Sample 75DR03/I/6). **D.** Dolomite rhombs in the matrix of a partially dolomitized middle Miocene floatstone. Etched and stained with alizarin red S. Field of view, 1.0 mm, plane light (dredge Sample 75DR03/I/6).

## OTHER PROCESSES

### Micrite Envelopes

The development of micrite envelopes is comparatively rare. Where they occur, they have formed on *Halimeda*, brachiopod, and gastropod fragments (Fig. 3D). The original material in most of these bioclasts either has undergone dissolution, and the mold has been filled with blocky spar, or has neomorphosed to calcite or been replaced by dolomite.

### Formation of Molds

Moldic porosity is common, having formed as a consequence of the dissolution of the aragonitic skeletons of corals, gastropods, and bivalve fragments.

### Cavities

#### *Dissolution Cavities*

One of the dredge samples contains a cavity approximately 10 cm across. The edge of the cavity is highly variable; some of the bioclasts are preserved and protrude into the space, whereas others are truncated. The wall of the cavity is lined with a dolomitic bladed cement. The cavity, part of which is shown in Figure 5A, has been filled with hemipelagic sediment of late Miocene (Zone N17) age. The cavity, interpreted as a dissolution cavity, formed during the early late Miocene as a consequence of subaerial exposure.

#### *Borings*

In some of the dredge samples, there are at least three generations of crosscutting borings: two have been filled with foraminifer-rich hemipelagic sediment, whereas the third and youngest is unfilled (Fig. 5B). The cavity-filling wackestones are late Miocene (N17, N17B), early Pliocene (N18, N19/20), late Pliocene (N19/20–N21), and post N19/20–N21 in age. Some of the cavities appear to have been modified by dissolution processes, because they are somewhat irregular in shape (Fig. 5B) and the walls are not smooth.

#### *Fractures*

Some of the dredge samples also have fractures that have been healed or filled, usually with a mixture of hemipelagic sediment, apatite crusts, manganese oxide crusts, and equant spar (Fig. 7C).

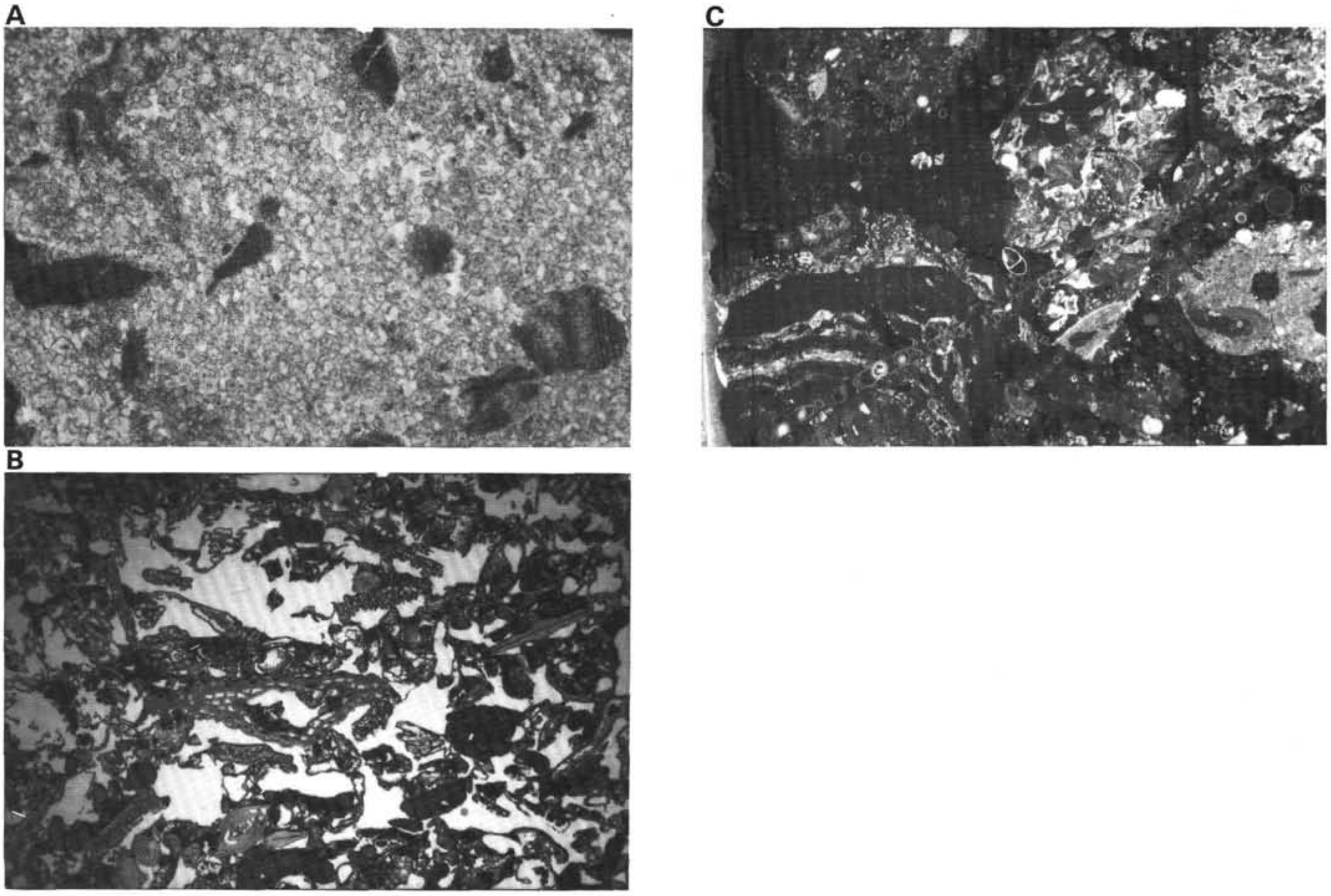

Figure 7. **A.** Fragments of coralline algae preserved in a matrix of planar-e dolomite. Field of view, 4.5 mm, plane light (Sample 133-816C-5R-1, 85–90 cm). **B.** Overview of dolomitized middle Miocene rudstone in which the bioclasts and the matrix have been mimically replaced. Extensive dissolution has produced vuggy, interparticle, intraparticle, and moldic porosities. Field of view, 2 cm, plane light (Sample 133-826A-4R-1, 16–18 cm). **C.** Middle Miocene lithoclasts of dolomitized rudstone and a rhodolith (lower left) in a matrix of early Pliocene hemipelagic sediment. A fracture extending from the lower left to the upper right of the photomicrograph is filled with younger, late Pliocene hemipelagic sediment, apatite crusts (narrow, bright white linings), and coarse granular spar (bright white spots in lower left part of fracture). Field of view, 2 cm, plane light (dredge Sample 75DR02/III/4).

## CEMENT STRATIGRAPHY AND INTERPRETATION

The interpretation of the cements described above is based on their morphology, their relationship to each other, and to the crosscutting events.

Botryoidal aragonite (Fig. 3A) and isopachous fibrous rim cement (Figs. 3B and 3C) are both characteristic of warm-water shallow marine phreatic diagenetic environments (Bathurst, 1975; Bricker, 1971; Longman, 1980; James and Choquette, 1983b; J.F. Marshall, pers. comm., 1989). Micrite envelopes also are thought to form in this environment. The precipitation of the isopachous fibrous cement before the deposition of peloidal micrite matrix (Fig. 3C) is further evidence for its marine origin. The precipitation of these cements occurs soon after, if not contemporaneously with, deposition of the bioclasts; therefore, we can assume that these cements were precipitated during the late early to middle Miocene.

The LMC-bladed pore linings and granular to blocky cements (Figs. 4B, 4C, 4D), along with the development of dissolution cavities and moldic porosity, are considered to be indicative of meteoric processes (Bathurst, 1975; Longman, 1980; James and Choquette, 1984). The calcitic cements have been interpreted as having formed in a freshwater phreatic environment, because they are generally bladed, pore lining, and exhibit neither the meniscus nor the gravitational textures that characterize the freshwater vadose environment. Many of the syntaxial overgrowths (Fig. 4A) on echinoid fragments may have developed in the meteoric environment also.

Alternatively, it could be argued on textural grounds alone that these cements precipitated in a bathyal cold-water environment below the thermocline. Schlager and James (1978) pointed out that diagenesis in this environment follows a path similar to that of freshwater diagenesis. However, there are several reasons for rejecting this interpretation. These cements were deposited during the late Miocene when other evidence, such as the age of the unconformity at the top of M1, the deposition of neritic sediments on the slope during late middle Miocene time (Shipboard Scientific Party, 1991a, 1991b, 1991c), and the development of M2 in lowstand position, suggests that M1 was subaerially exposed as a result of a relative fall in sea level (Pigram et al., 1992). The top of the plateau was not reflooded until early Pliocene time. The presence of neritic late Miocene (N17) sediments overlain by bathyal late Miocene (N17) to Pleistocene sediments at Site 815, when combined with the Pliocene age for the oldest bathyal sediments at Sites 816 and 826 on top of the plateau, suggests that the M1 platform was progressively transgressed during the late Miocene and early Pliocene.

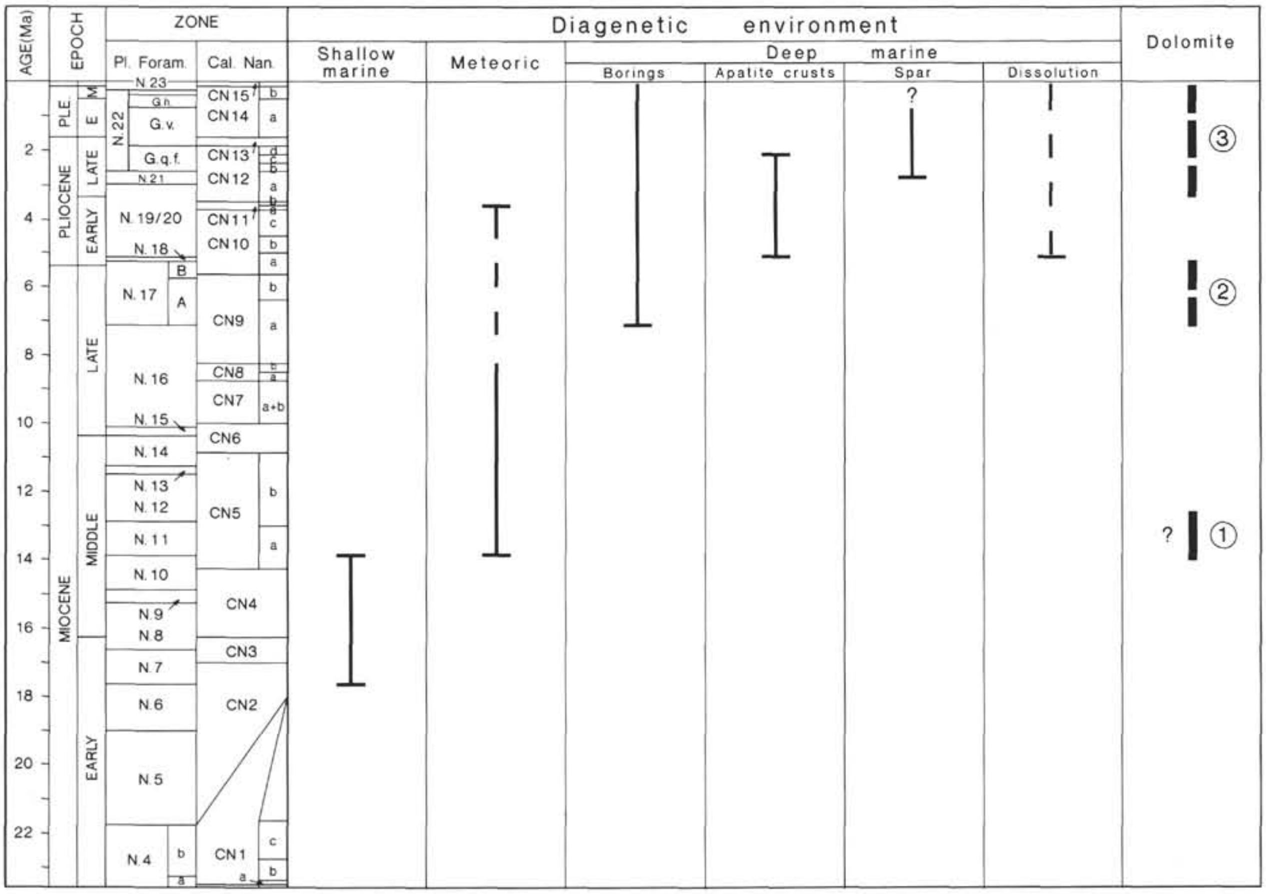


Figure 8. Summary of the timing of the major diagenetic events that have affected the early to middle Miocene age carbonate platform (M1) of the Marion Plateau.

This evidence supports the interpretation of the second phase of cementation and the formation of molds and dissolution cavities as products of meteoric diagenesis.

The last phase of cementation involved the precipitation of apatite and manganese oxide crusts and equant calcite spar. The apatite and manganese crusts are indicative of sediment-starved marine environments. The late-stage equant spar cement that occurs in these rocks could be interpreted as either a meteoric cement or as an upper bathyal, cool-water cement.

The samples containing this cement were recovered from water depths of more than 500 m, and the cement always postdates deposition of some of the Pliocene hemipelagic sediment and the apatite and manganese crusts. The cement was precipitated after M1 was drowned and, therefore, these samples have been in bathyal water depths since the early Pliocene. Its association with marine crusts and the timing of its precipitation strongly suggest that this cement was precipitated in an upper bathyal, cool-water environment. Freeman-Lynde et al. (1986) and McClain et al. (1988) have reported an equant spar cement from Cretaceous limestones of the Bahamas that they attribute to precipitation from cold marine waters. Their interpretation is supported by isotopic data.

The equant spar in the upper Miocene–Pliocene limestones resembles, petrographically, the cold-water marine spar described by Freeman-Lynde et al. (1986) and McClain et al. (1988). Furthermore, the interpretation of this cement as a product of meteoric processes requires the platform to have been exposed during the Pliocene–Pleistocene, whereas all other evidence suggests the top of the plateau was at upper bathyal depths beyond the influence of sea-level fluctuations during this period. The subsidence and flooding history of the plateau as deduced from the stratigraphy encountered in the drill holes would appear to preclude a meteoric origin for this equant spar cement.

In the absence of isotopic data, our interpretation of this cement as having formed as a precipitate from cool marine waters is more consistent with the observation that it is a very late-stage cement occupying pore space that already was lined with apatite or manganese crusts, and in sediments that were most likely in bathyal water depths throughout the Pliocene–Pleistocene. Furthermore, James and Choquette (1983b) argued that arrested sedimentation and prolonged exposure to seawater may be prime requisites for the precipitation of calcite spar in the cool, deep-marine environment. The presence of apatite crusts' separating thin layers of deep-water micrite and the nature of the scarp from which these samples were dredged suggest that this part of the northern margin of the plateau was sediment-starved at the time of precipitation of the equant spar, thereby supporting the argument for a deep-marine origin for this cement.

## TIMING OF DOLOMITIZATION

The timing of the dolomitization can be determined from cement stratigraphy because these sediments have a sequence of late Miocene age and younger hemipelagic sediments filling crosscutting cavities and the residual porosity. Three phases of dolomitization appear to exist in the samples dredged from the northern margin of the Marion Plateau:

1. A floatstone dredged from the northern flank of the plateau consists of dolomitized lower to middle Miocene lithoclasts in a

planktonic-foraminifer-rich, upper Miocene matrix (Fig. 7C). This relationship suggests that the lithoclasts were dolomitized before burial and possibly before they were eroded.

2. All of the cements that line cavities that have been filled by hemipelagic sediments are dolomitized. This relationship suggests a second phase of dolomitization occurred during the late Miocene to early Pliocene after the precipitation of the freshwater cements and either before or during the reflooding of the plateau that led to the infilling of the residual porosity with uppermost Miocene and Pliocene hemipelagic sediments.

The results of Sr isotope age dating of dolomitized samples from Site 816 appear to support the interpretation of dolomitization as the platform was reflooded. Three samples from the top 200 m of M1 give ages of 5.1, 5.17, and 5.42 m.y., and a fourth has a range of 8.0–5.5 m.y. (McKenzie, Isern, et al., this volume). The ages that cluster around 5 m.y. are little older than the oldest sediments deposited during the transgression of the plateau at this site. The 8.0–5.5 m.y. range is consistent with the time range of the transgression as implied from the stratigraphy at Site 815, as well as from the age range of the hemipelagic sediments that fill cavities in the dredge samples.

3. The final phase of dolomitization occurred during or after the late Pliocene, because most of the bioclasts in the hemipelagic sediments that were dredged from the northern slope of the platform are mimically dolomitized. This suggests that this phase of dolomitization occurred in a cool-water upper bathyal environment.

In summary, at least three major phases of dolomitization appear to be preserved in the samples dredged from the northern slope of the Marion Plateau: a middle Miocene phase; a latest Miocene phase (apparently related to reflooding of the plateau); and a Pliocene phase, which has occurred in a cool-water environment (Fig. 8).

## SUMMARY OF THE CEMENT STRATIGRAPHY

The diagenetic history of the sediments recovered from the Marion Plateau shows that the lithification of the sediments was achieved through a complex series of processes, summarized in Figure 9.

The lower middle Miocene shallow-water sediments passed from a shallow marine environment to a meteoric environment, where they were exposed for at least 7 m.y., and then back into a marine environment, which quickly became a deep-marine environment with upper bathyal paleowater depths (Shipboard Scientific Party, 1991a, 1991b, 1991c).

The initial sediment is assumed to have consisted of bioclasts having a grainstone or rudstone texture (Fig. 9A). In the shallow marine setting, these sediments were cemented by isopachous rim cements, and some cavities were filled by botryoidal aragonite (Fig. 9B). A peloidal micrite and micrite matrix also was deposited. Micrite envelopes were formed (Fig. 9B). The sediments were exposed to meteoric diagenesis during the late middle Miocene and late Miocene or Pliocene (Zones N10–12 to N17 or N19/20), depending on their position within the platform. This led to the neomorphism of most of the aragonite and HMC to calcite and the development of moldic porosity by dissolution of aragonitic bioclasts, such as gastropods (Fig. 9C); then followed the precipitation of calcitic cement, including syntaxial overgrowths, bladed to granular pore-lining spar, and pore-filling blocky or equant spar (Fig. 9D). These last two phases were probably contemporaneous and should not be separated in time. During the period when the plateau was exposed, vuggy porosity developed, and the platform eroded. As the platform was reflooded beginning during the late Miocene, several different processes were active, depending on the location of the rocks within the platform. On the outer edge of the platform, the calcitic cements were mimically replaced by dolomite (Fig. 9E). This was followed by, or occurred concurrently with, the deposition of wackestone in most of the residual pore space (Fig. 9F). This wackestone subsequently was dolomitized, probably during the (?)Pliocene (Fig. 9I). During the latest Miocene and Pliocene, these rocks were bored (Fig. 9G). At least three generations of borings can be seen. The two oldest phases of borings commonly are lined with multiple generations of apatite crust that separated phases of wackestone deposition (Fig. 9G). In the late Pliocene or Pleistocene, the residual porosity was filled or partly filled with equant spar of cool marine-water origin (Fig. 9J).

The sediments of the platform at Sites 816 and 826 were dolomitized after the formation of the meteoric cements during the late middle or early late Miocene. This dolomitization ranged from fabric-retentive, selective dolomitization to fabric-destructive dolomitization that led to almost complete replacement and recrystallization (Figs. 9K and 9L). The dolomitization process in these sediments also created new porosities in the form of vugs and intercrystalline voids.

## DEMISE OF THE PLATFORM

The diagenetic history of both the shallow-water carbonate sediments recovered from below this unconformity and similar aged sediments recovered by dredging shows that the M1 platform was exposed and subjected to meteoric processes and diagenesis for up to 7 m.y. This exposure, brought about by a relative fall in sea level, caused the demise of the platform.

The presence of extensive calcitic cements (both the pore-lining and pore-filling blocky spar), neomorphism, syntaxial overgrowths, and vuggy and moldic porosities provides evidence for the hypothesis that the M1 platform was subjected to meteoric diagenetic processes. The cement stratigraphy of the dredge samples shows that the meteoric diagenetic processes occurred after the deposition of marine phreatic cements during the early and early middle Miocene, and before the deposition of upper Miocene and Pliocene hemipelagic sediment in the residual pore spaces and across the plateau. The cement stratigraphy, therefore, suggests that the platform was exposed from the late middle Miocene to the latest Miocene (N10/12 to N17). This period is similar to, though shorter than, that represented by the unconformity intersected by the ODP holes on top of the platform. Two reasons are likely for this difference between the age of the unconformity in the dredge samples and that at the top of the platform:

1. The dredge samples were recovered from the slope of the platform, where they were drowned before the top of the platform, or
2. The dredge samples are not in situ and may have been transported down the slope into a marine environment, while the top of the platform remained exposed.

Both the diagenetic history and cement stratigraphy show that the M1 platform was exposed from the late middle Miocene until the early Pliocene as a result of a relative fall in sea level that produced a sea-level lowstand of 7–10 m.y. relative to the top of the M1 platform. This exposure, which caused the demise of the platform, produced an erosional unconformity that separated the platform from the overlying hemipelagic sediments.

The subsequent drowning of the plateau during the Pliocene appears to be a complex event related to several factors, including: 1) a major pulse of subsidence, 2) the influx of terrigenous detritus to the plateau (which may have caused a deterioration in water clarity), and 3) an influx of cooler nutrient-rich waters, all of which inhibited the re-establishment of a warm-water carbonate platform (Davies, McKenzie, Palmer-Julson, et al., 1991; Pigram, 1993; Isern et al., this volume; and Gartner, Wei, and Shyu, this volume).

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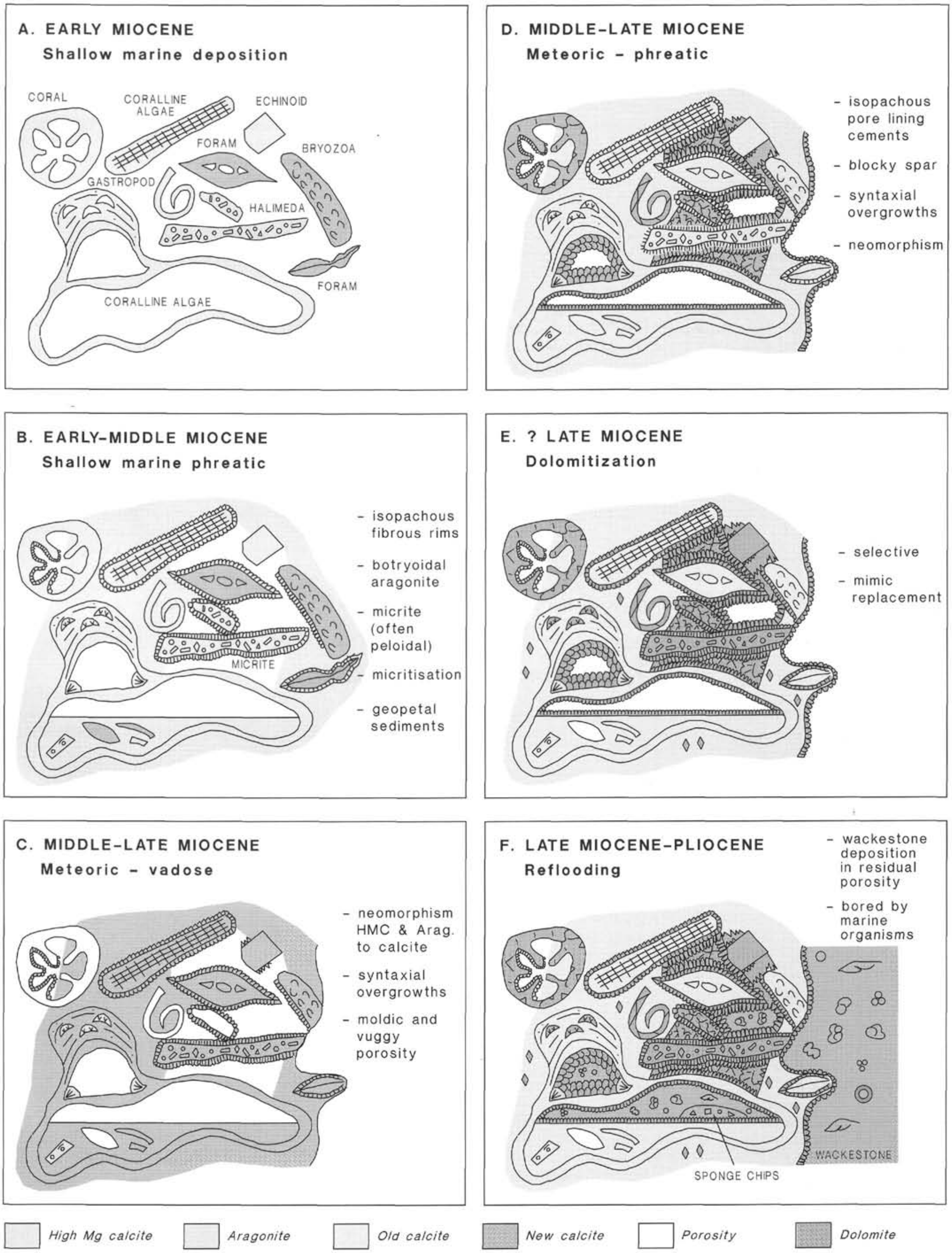


Figure 9. (See page 512 for figure caption.)

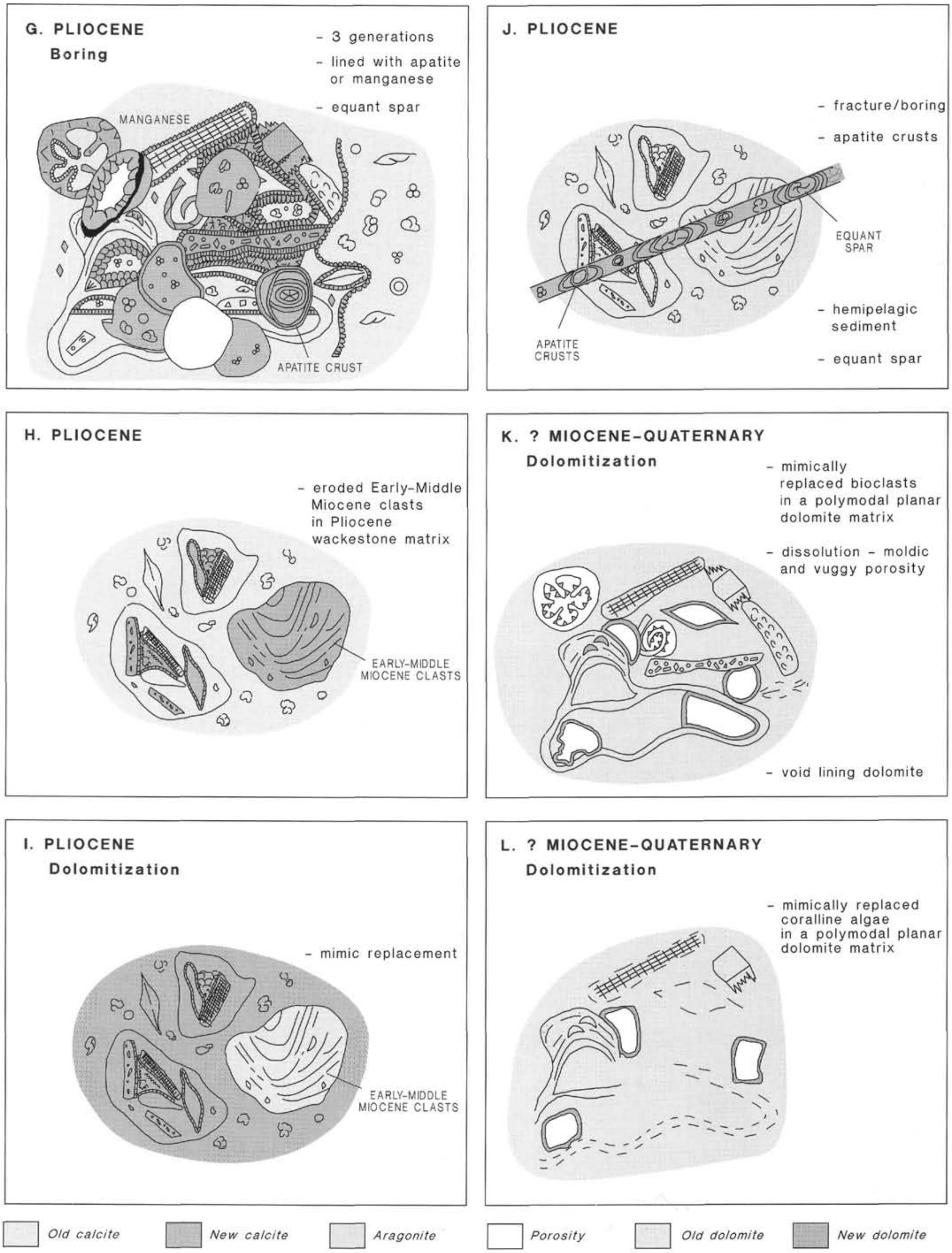


Figure 9 (continued).

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* Abbreviations for names of organizations and publications in ODP reference lists follow the style given in *Chemical Abstracts Service Source Index* (published by American Chemical Society).


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Figure 9 (see pages 510–511). Summary diagram of the diagenetic history of the lower to middle Miocene shallow-water carbonate sediments of the Marion Plateau. **A.** Initial sediment with a packstone or rudstone texture and consisting of bioclasts having differing mineralogy. **B.** Shallow marine phreatic cements precipitated, including isopachous fibrous aragonitic or HMC rims, botryoidal aragonite in intraskeletal cavities, or the conceptacles of coralline algae. Micrite, including peloidal micrite, also was deposited. Many grains also developed micrite envelopes at this time. **C.** Subaerial exposure. In the vadose zone, most of the aragonite and HMC converted to calcite, although some botryoidal aragonite survived. Syntaxial overgrowths developed on echinoid fragments, and moldic and vuggy porosity formed. **D.** Meteoric phreatic zone. Precipitation of calcitic isopachous pore-lining and pore-filling cements, ?further syntaxial overgrowths, and neomorphism. By the end of this phase, the sediment was almost entirely calcite. Erosion of the platform occurred at this time, also, and clasts of the limestone were deposited in front of the platform along its northern edge (see section H). Some dolomitization may have occurred during exposure of the platform. **E.** A phase of selective dolomitization occurred in which all the LMC cements were mimically replaced before or during the deposition of the wackestone in the residual pore space (see section F). The calcitic micritic matrix and the originally calcitic bioclasts (such as larger foraminifers) were unaltered at this stage of dolomitization. See text for discussion. **F.** Plateau reflooding. A relative rise in sea level during the late Miocene eventually led to the reflooding of the plateau during the early Pliocene. As a consequence, most of the residual porosity of the sediments along the northern slope of the plateau was filled with hemipelagic sediment. **G.** During the Pliocene, these rocks were subjected to multiple phases of boring. At least three generations of excavations can be recognized from crosscutting relationships and the age of the wackestone fill. Some of these excavations are lined with apatite or manganese crusts and, subsequently, filled with blocky calcitic spar that has been interpreted as a deep-marine phreatic precipitate. **H.** Clasts of partially dolomitized lower to middle Miocene rudstone were buried by Pliocene wackestone to form Pliocene floatstone. **I.** The floatstone was mimically dolomitized. **J.** Some of the Pliocene dolomitized floatstones were fractured or bored and their cavities subsequently filled with a mixture of hemipelagic sediments, apatite, and equant calcite spar. **K.** and **L.** The sediments of the platform drilled by ODP have the same early to early late Miocene history as the dredge samples, but then have a different late Miocene to Holocene diagenetic history. Instead, they show the effects of complete dolomitization with varying degrees of fabric preservation. **L.** In the dolostone with the least fabric preservation, only red algae fragments (along with ghosts of other bioclasts) survive in a polymodal planar dolomite matrix.