11. BURIAL DIAGENESIS OF CENOZOIC CARBONATE OOZES, LEG 79[1]

Johnnie N. Moore, Department of Geology, University of Montana[2]

ABSTRACT

Cenozoic and Cretaceous sediment recovered from Leg 79 shows distinct diagenetic zonation independent of age and composition. Cementation follows from compaction and growth of interstitial calcite and clay. Textures and diagenetic features result from burial and changes in pore water chemistry arising from the proximity of Mesozoic salt deposits. Ooze changes to chalk at approximately 200 m in normal sequences when diagenetic clay combines with calcite to form cement. Where sediment overlies salt, cementation occurs at much shallower depths.

INTRODUCTION

Drilling at four Leg 79 sites recovered cores of Tertiary and Cretaceous sediments of varying lithologies and depositional histories. Sites 544 and 546 were drilled through relatively thin sequences (104 and 147 m, respectively) of Cenozoic nannofossil ooze and Sites 545 and 547 were drilled through thicker sequences (253 and 422 m, respectively). Sites 544 and 546 were drilled on bathymetric and structural highs west of the Mazagan Plateau (see site chapter, this volume). However, the seismic basement underlying these two sites is significantly different. At Site 544, a thin sequence of Mesozoic limestone and continental terrigenous sediment underlie the Cenozoic ooze. The Mesozoic, in turn, rests unconformably on gneissic basement (see Site 544 chapter, this volume). At Site 546, a thin stratigraphic mixture of Jurassic, Cretaceous, and Miocene sediments separate the ooze from salt that is probably equivalent to salt seen in offshore Canada (see Site 546 chapter, this volume).

Cenozoic ooze at Site 544 was deposited in two separate and continuous sequences. Sediment accumulated at a rate of approximately 8 m/m.y. from the late Miocene to the Pleistocene forming approximately one-half of the sequence. A late/middle Miocene unconformity separates the upper part of the sequence from sediment below that also accumulated at approximately 8 m/m.y. during the middle and early Miocene (Site 544 chapter, Fig. 12). At Site 546, ooze accumulated at an average rate of 22 m/m.y. from late/Miocene to Recent (Site 546 chapter, Fig. 18). Middle Miocene sediments below the late/middle Miocene unconformity at Site 546 accumulated at a rate of approximately 25 m/m.y. These different rates at the two sites indicate that sediment accumulated at Site 546 at a rate approximately 3 times that of Site 544 (see site chapters, this volume).

The much thicker Cenozoic sections at Sites 545 and 547 accumulated at extremely high rates in the Pleistocene and Recent (approximately 100 to 240) with a rate of approximately 10–24 m/m.y. during the Miocene (see site chapters, this volume). Although the sedimentation rates at all four sites are somewhat different, and different ages of sediment are represented, all of the sites have similar downhole physical properties through the Cenozoic sections (Fig. 1), except for Site 546 where porosity decreases more rapidly downhole than at the other sites. The two thicker sections (Sites 545 and 547) contain a transition from ooze to chalk. Sediment textural changes downhole in each of these sites correspond to physical property changes.

The purpose of this paper is to describe the diagenetic changes at each site and the physical changes in clayey nannofossil sediments due to burial diagenesis. These changes and the associated stratigraphy are shown in Figure 2.

METHODS

To determine textural changes, samples of cores were taken for study by scanning electron microscopy (SEM). Subsamples of the porosity-water content samples were used for SEM study whenever possible to facilitate correlation with the physical properties data. Small chips of the water content samples were exposed to a stream of air to remove loose fragments and then glued on aluminum studs with colloidal silver liquid cement. The stud and sample were kept in a desiccator for one to two days and then coated with 250 to 300 Å of gold in an SPI Sputter. The samples were studied and photographed with a Leitz Novoscan SEM (Model 20) in the University of Montana Microbiology Electron Microscopy Laboratory. All mineralogic and compositional determinations were made by morphologic comparisons to published photographs because of the lack of analytical accessories on the Novascan.

All other data (porosity, sonic velocity, sedimentation rates, sediment descriptions, and pore water chemistry) are taken from the appropriate chapters of this volume. These data are not repeated in this paper except where replotted or tabulated to address a particular point.

DOWNHOLE TRENDS

Site 544

At Site 544, 104 m of Cenozoic, clayey, foraminiferal–nannofossil ooze was drilled. Carbonate content of this ooze ranged from 41 to 71% with all but one sample containing less than 50% carbonate (Fig. 1), and all but four containing more than 60% carbonate.

Samples from the upper 50 m show loosely packed nannofossils and clay with no diagenetic modification. At 12.2 m, individual coccoliths, fragments of nannofos-

[1] Hinz, K., Winterer, E. L., et al., *Init. Repts. DSDP*, 79: Washington (U.S. Govt. Printing Office).
[2] Address: Department of Geology, University of Montana, Missoula, MT 59812.

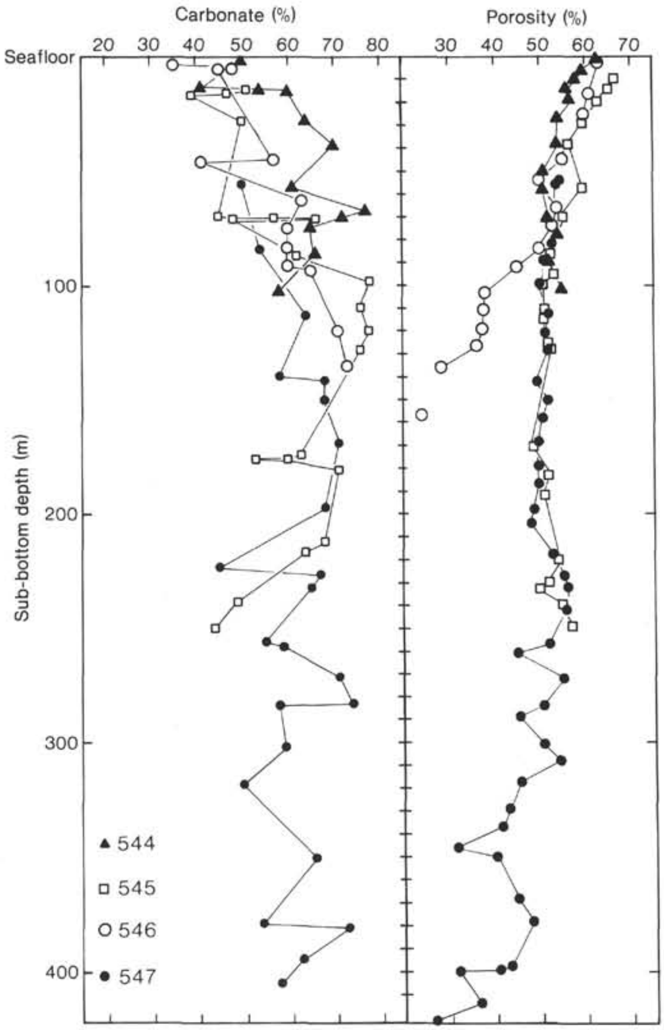

Figure 1. Downhole trends of porosity and carbonate content (data from site chapters, this volume).

sils, and detrital clay are mixed in a relatively uncompacted framework (Pl. 1, Fig. 1). This texture changes very little in the upper 50 m (Pl. 1, Fig. 2) and complete coccospheres are preserved at 37.6 m (Pl. 1, Fig. 3). Porosity of the sediment decreases rapidly from 63% at the surface to 50% at approximately 50 m (the level of the late/middle Miocene unconformity).

Below the unconformity, at 57.2 m, calcite crystals form localized overgrowths on coccoliths. Minor amounts of clay accompany the calcite but generally both calcite and clay are insignificant as cement. At 90.1 m calcite overgrowths occur throughout the sediment (Pl. 1, Figs. 4, 5) and dolomite crystals are present locally. In conjuction with this calcite cementation, the nannofossil structure has been degraded by dissolution and recrystallization. A fairly constant porosity of 50 to 55% characterizes the loosely packed sediment in the interval from 50 to 100 m.

Below 100 m, calcite and clay overgrowths become more extensive than above but, at 102.3 m, the sediment still maintains an open framework even though small amounts of clay and calcite fill pore space locally (Pl. 1, Fig. 6). The porosity remains at 54% in this basal part of the sequence.

In summary, Site 544 sediments are divisible into two distinct diagenetic zones, one of which contains two subzones.

Zone I: 0 to 50 m (approximate). This zone is characterized by decreasing porosity due to physical compaction of the sediment. Only slight calcite overgrowths modify the texture which becomes slightly more compact with depth. Compaction by physical rearrangement of grains is the dominant process affecting texture.

Zone II: 50 to 104 m. Calcite overgrowths characterize this zone. Calcite overgrowth increases with depth as does recrystallization of nannofossils. Diagenetic clay overgrowths become apparent near the base. Porosity remains constant with depth throughout the zone.

Subzone IIA: 50 to 100 m. Calcite overgrowths and recrystallization of coccoliths dominate throughout this subzone. Minor clay overgrowths occur locally.

Subzone IIB: 100 to 104 m. Sediment in this subzone contains more extensive clay and calcite overgrowths than in the sediment above. Pore spaces appear to be more completely filled even though the porosity remains similar to the sediment above.

Site 545

At Site 545, 252 m of clayey, foraminiferal-nannofossil ooze and chalk record Cenozoic sedimentation. Within this sequence transitions from ooze to firm ooze (at 86 m) and from firm ooze to chalk (at 180 m) offer opportunities to decipher diagenetic processes. Carbonate content ranges from 40 to 78% (Fig. 1) with an initial increase and, then, a decrease with depth. The upper 70 m of sediment contains 40 to 50% carbonate. Below 70 m to a depth of 220 m, carbonate content ranges from 60 to 78%, but below 220 m to the base of the sequence the carbonate content decreases to between 44 and 50%.

The upper 50 m drilled at Site 545 contains loosely packed sediment (Pl. 2, Fig. 1). Coccoliths and other biogenic grains show minor dissolution and overgrowths are absent. The porosity of these sediments decreases steadily from 67% at the top to 56% below 40 m (Fig. 1) as the texture becomes slightly more compact. At 56.7 m overgrowths of calcite occur on isolated coccoliths and by 69.7 m recrystallized nannofossils commonly contain heavy calcite overgrowths. Below 70 m, overgrowths are extensive but the texture remains somewhat open as the porosity continues to decrease with depth to the ooze-to-firm ooze boundary at approximately 90 m. At a depth of 99.8 m extensive calcite overgrowths continue to fill pore space and dissolution has isolated individual segments of coccolith shields (Pl. 2, Fig. 2). The porosity remains fairly constant at 50% from 90 m to a depth of 212 m. Calcite cementation generally increases with depth within this uniform porosity zone (Pl. 2, Figs. 3, 4). Minor clay overgrowths first appear at 181.5 m and clay becomes more abundant and joins calcite as a cement at 220.1 m. By a depth of 233.3 m, clay overgrowth is extensive and recrystallization obscures the detail of the coccoliths. This cementation and recrystallization continues downhole so that, at 249.8 m, clay and

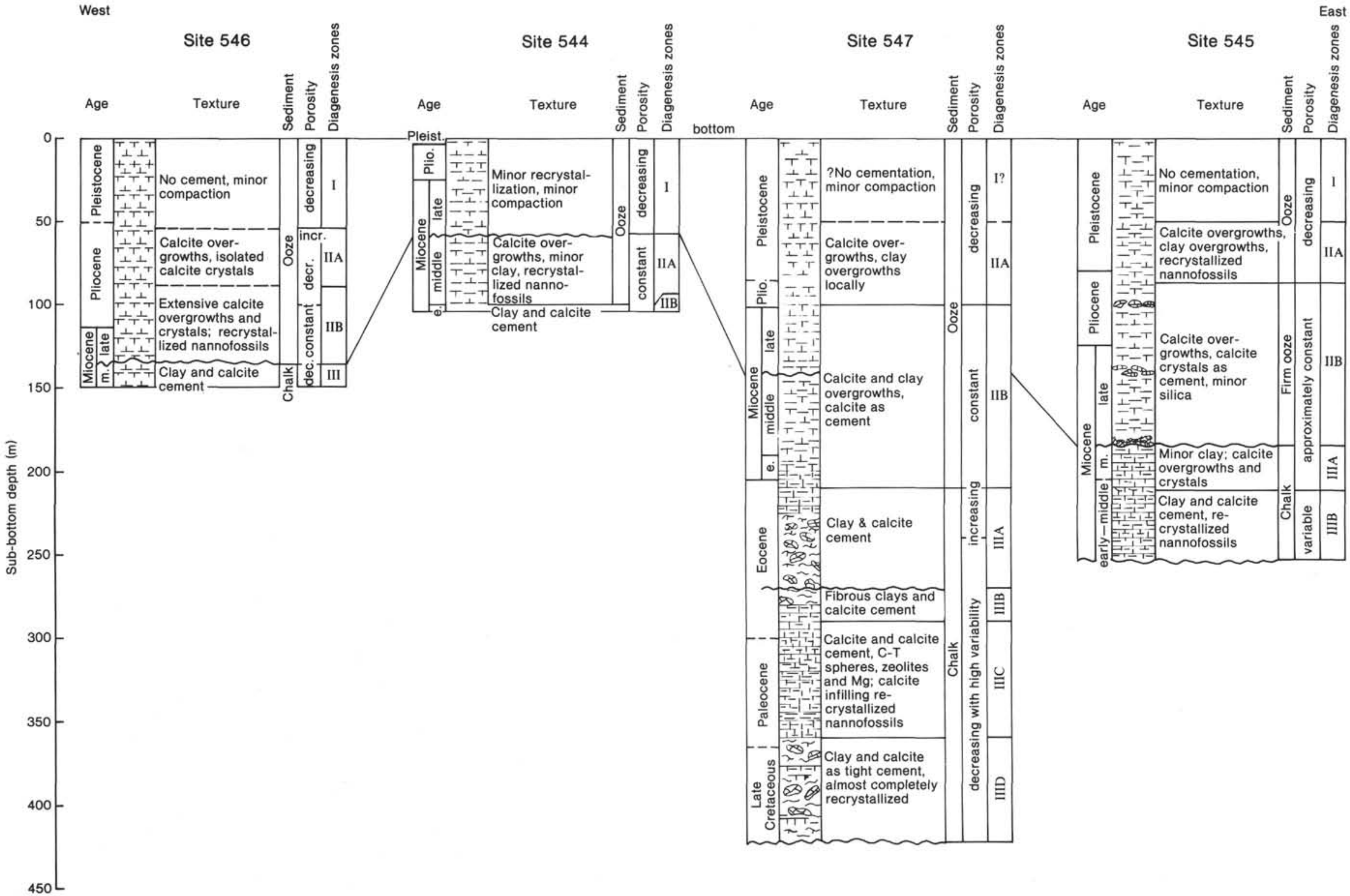

Figure 2. Sediment characteristics and diagenetic zones of Leg 79 sediment (data from this report; site chapters, this volume).

calcite extend throughout the pore space and most coccoliths show very little detailed morphology (Pl. 2, Fig. 6). In this deepest interval, below 212 m, the porosity varies slightly more than that above (Fig. 1), ranging between 50 and 53%.

The Cenozoic sequence drilled at Site 545 can be divided into three diagenetic zones, one of which contains three subzones:

Zone I: 0 to 50 m (approximate). This zone is characterized by linearly decreasing porosity with depth. The sediment is loosely packed with a slight increase in packing downward.

Zone II: 50 to 212 m. Calcite overgrowth and cementation characterize this zone with minor clay overgrowths. Porosity decreases rapidly in the upper 40 m but remains fairly constant below. This zone encompasses the ooze-to-chalk transition.

Subzone IIA: 50 to 90 m. This subzone is characterized by continued decreasing porosity with depth but at a lower rate than in Zone I. Calcite overgrowths occur locally, increasing downward. Diagenetic clay is rare.

Subzone IIB: 90 to 180 m. Nannofossils within the firm ooze of this subzone contain considerable calcite overgrowth and calcite also fills pore space as patches of crystals. Near the bottom of the subzone amorphous silica (?) and clay overgrowths occur locally. Porosity remains nearly constant with depth.

Subzone IIC: 180 to 212 m. As in Subzone IIB, this sequence is also characterized by constant porosity, calcite overgrowth, and cementation but is composed of chalk. However, clay joins calcite as a cement in this interval.

Zone III: 212 to 253 m. Cementation by clay and calcite is extensive in this zone and cementation as recrystallization of nannofossils increases downward. The porosity is somewhat variable when compared to the zone above. This sequence is composed of chalk.

Site 546

At Site 546, 147 m of clayey nannofossil ooze and calcareous mud was drilled above the salt and associated capping deposits. Carbonate content of the ooze is quite variable ranging from 35% at the top of the sequence to 73% at the base. Variable carbonate contents in the upper 50 m of the hole and more consistent values in the lower sequence modify the general downhole increase (Fig. 1). In general, the upper 50 m contains less than 50% carbonate, the 60 to 100 m interval, 60%, and the lower 47 m, more than 70%. This variation falls within the range of values of sediment at the other three sites and follows their general downhole trend (Fig. 1). However, the porosity of sediments at Site 546 deviates significantly from trends in all the other holes. Porosity decreased much more rapidly with depth at Site 546 and, at 100 m, the sediment had a porosity equivalent to those found only below 340 m at Site 547 (Fig. 1).

The upper 55 m of sediment drilled at Site 546 is loosely packed (Pl. 3, Fig. 1) with minor overgrowths of calcite first appearing at 25.4 m (Pl. 3, Fig. 2). The porosity in this interval decreases rapidly from 63% at the top to 50% at 55 m. Textures in the sediment become slightly more compact with depth and the porosity decrease appears to result only from compaction, with a minor addition from calcite overgrowths below 25 m. Calcite overgrowth increases significantly downward in the hole and, by 56.4 m, calcite fills pore space locally (Pl. 3, Fig. 3) and covers coccoliths. At 66.3 and 72.6 m (Pl. 3, Fig. 4), calcite overgrowths extend throughout the pore space and nannofossils show extensive recrystallization. Coccoliths begin to interpenetrate one another by 83.5 m, and their detailed structure disappears because of calcite recrystallization. Extensive coccolith dissolution and calcite cementation as overgrowths continues to below 126.2 m (Pl. 3, Fig. 5). Below 136.1 m, very extensive calcite overgrowth and cementation is joined by diagenetic clays to tightly fill pore space (Pl. 3, Fig. 6). Coccoliths are nearly totally recrystallized and very difficult to identify.

In summary, the Cenozoic sequence at Site 546 contains sediment divisible into three diagenetic zones, one of which is further subdivided into two subzones:

Zone I: 0 to 55 m. This zone is composed of sediment with a carbonate content of mostly less than 50% and characterized by a rapid porosity decrease with depth. Sediment is loosely packed; increased compaction and minor calcite overgrowths in the lower 30 m of the zone account for the porosity decrease.

Zone II: 55 to 130 m. Sediment in this zone contains calcite overgrowths and cement. Cementation and recrystallization increase with depth resulting in decreased porosity.

Subzone IIA: 55 to 88 m. This subzone is characterized by a rapid decrease in porosity with depth from 54 to 38%, after an initial porosity increase of 4%. Calcite overgrowth is common and isolated crystals occur among nannofossils near the base of the zone.

Subzone IIB: 88 to 130 m. Pore space of sediments within this subzone is filled by extensive calcite overgrowth and cementation. Coccoliths show very little detailed morphology because of recrystallization. Porosity is low and decreases only slightly with depth from 38% at the top to 36% at the base of the sequence.

Zone III: 130 to 147 m. This zone is characterized by extensive recrystallization and combined clay and calcite cementation. Porosity decreases to 24% at the base of the drilled sequence and is less than 30% throughout this zone.

Site 547

The thickest section of Cenozoic sediment was drilled at Site 547. The upper 205 m of the total 422 m thick sequence is composed of foraminiferal-nannofossil ooze and nannofossil ooze. The ooze-to-chalk transition was recovered at 210 m in a sequence of siliceous, clayey-nannofossil chalk. The remainder of the Cenozoic sediments is clayey nannofossil chalk. The carbonate content of these sediments ranges from 50 to 74%. Carbonate content generally increases from 50% at the top of the sequence (Fig. 1; the highest sample stratigraphically is at 53 m sub-bottom depth due to washing to a depth of 50+ m during drilling, see Site 547 chapter, this volume) to 74% at 200 m. Below 200 m carbonate content is variable ranging between 45 and 75%.

The uppermost sediment at Site 547 contains grains with calcite overgrowths and dissolved and recrystallized nannofossils. Many of the coccoliths are reworked from older deposits (see Site 547 chapter, this volume) which may account for some of the recrystallization. The sediment is loosely packed (Pl. 4, Fig. 1). Calcite overgrowth increases downward in the hole with isolated clay overgrowths and at 99.3 m, calcite crystals occur as isolated patches within pore space. At 121.4 and 128.3 m (Pl. 4, Fig. 2), clay and calcite both begin to fill pore space. At 178.9 m calcite becomes the dominant cement and fills pore space with isolated patches of crystals and extensive overgrowth (Pl. 4, Fig. 3). This extensive calcite cementation continues downward to approximately 225 m; the sediment changes from ooze to chalk at 210 m.

Porosity decreases slightly between 53 and 100 m, then remains fairly constant from approximately 100 to 210 m. Below the ooze-to-chalk transition at 210 m, porosity becomes slightly more variable but continues to decrease with increasing depth.

At 218.2 m, just below the ooze-to-chalk transition, clay and calcite overgrowths and isolated calcite crystals continue to fill pore space as nannofossils dissolve and lose detail (Pl. 4, Fig. 4). A slight increase in porosity (Fig. 1). is associated with this dissolution and recrystallization. In samples from 232.3 and 256.6 m, clay and calcite form a tight cement (Pl. 4, Figs. 5, 6). Porosity decreases in conjunction with extensive diagenetic clay. Fibrous clay (illite or palygorskite?) grows throughout the pore space in the sample from 284.2 m (Pl. 4, Fig. 6) and clay and opal C-T lepospheres join calcite as an extensive cement at 308.2 and 238.7 m (Pl. 5, Figs. 1, 2). The interiors of some of the remaining foraminifer tests are filled with zeolites (heulandite?) and magnesium calcite (Pl. 5, Fig. 3). Clays and calcite continue to fill pore space and recrystallization and cementation increases downward (Pl. 5, Fig. 5) until nearly complete recrystallization has obliterated nannofossil form and detailed morphology (Pl. 5, Fig. 6). Porosity varies significantly but continues decreasing downhole (Fig. 1).

In summary, sediments at Site 547 are divided into three zones (one speculative) and six subzones:

Zone I: 0 to 50 m. Although not sampled because of washing during drilling, the upper 50 m (approximately) of sediment is probably analogous to the sediment in the upper 50 m of the other three sites. This unsampled interval is most likely loosely consolidated sediment with only minor overgrowths as seen at all other sites.

Zone II: 50 to 210 m (approximately). This zone is characterized by calcite overgrowth and cementation with subordinate clay overgrowth. Cementation increases downward. Porosity decreases in the upper 50 m but remains fairly uniform in the lower 110 m.

Subzone IIA: 50 to 100 m. This sequence contains sediments with calcite overgrowths and minor clay overgrowths. Calcite forms isolated patches of crystals near the base. Porosity within this subzone decreases steadily with depth.

Subzone IIB: 100 to 210 m. This subzone is characterized by sediment with a nearly uniform porosity. Calcite overgrowths and isolated calcite crystals fill pore space and nannofossils are recrystallized near the base. Calcite overgrowth increases downward and the base is defined by the ooze-to-chalk transition.

Zone III: 210 to 422 m. Clay and calcite cement are extensive and increase downward within this zone. The porosity is variable but generally decreases downhole.

Subzone IIIA: 210 to 260 m. This subzone contains sediment cemented by extensive calcite and clay overgrowth and pore fillings.

Subzone IIIB: 260 to 290 m. Fibrous clays and calcite cement sediment in this zone. Porosity associated with this clay-cemented sediment is quite variable.

Subzone IIIC: 290 to 360 m. This subzone also contains sediments with variable porosity. Opal C-T lepospheres and zeolites fill foraminifer tests and along with calcite act as cement. Calcite crystals occur extensively throughout the pore space.

Subzone IIID: 360 to 422 m. Clays and calcite cement pore space tightly in this subzone and nannofossils are highly recrystallized. All detailed nannofossil morphology is lost near the base as sediment becomes almost totally recrystallized.

DIAGENETIC ZONATION

The diagenetic changes that transform deep sea ooze to chalk have been studied at many deep sea drilling sites (Matter, 1972; Davies and Supko, 1973; Schlanger et al., 1973; Schlanger and Douglas, 1974). The processes affecting this change have also been generally discussed by many authors and illustrated with specific examples (Bathurst, 1971; Adelseck et al., 1973; Davies and Supko, 1973; Berger and Winterer, 1974; Neugebauer, 1974). These studies have taken into account initial biotic content, fossil preservation, and relative percentages of different taxa (especially foraminifers versus nannofossils). Most of these studies present models of change that depend on original composition, depth of burial, age of sediment, and cementation resulting from selective dissolution of biogenic grains and subsequent filling of pore space. The result of this cementation is a downhole decrease in porosity and an increase in sonic velocity reported for nearly every DSDP site that penetrated carbonate ooze and chalk. This general trend is interrupted by inversions (Matter, 1972) but is applicable to carbonate sequences found throughout the world's oceans.

Although the diagenesis of pelitic sediments has received as much or more attention than carbonate sediments, few authors have discussed the diagenesis of clayey oozes, instead concentrating mostly on either clay or carbonate end-members. The oozes, calcareous muds, calcareous mudstone, and chalks drilled on Leg 79 include a significant percentage of detrital clay with nannofossils as the dominant biogenic component. The diagenesis of these sediments depends on the cementation by carbonate and clay. Also, the diagenetic changes occur at much shallower depths than those reported in completely biogenic deposits. In general, Leg 79 Cenozoic sequences show that significant diagenesis can occur in the upper 200 m of clayey carbonate sequences and that the transition from ooze to chalk can be controlled by clay formation as well as carbonate cementation. The details of downhole textural changes at all four sites of Leg 79 establish distinct zones of diagenesis. Although each site has differing sedimentation rates and sediment composition, diagenetic changes correspond exceedingly well (Fig. 2) and zones based on texture and porosity can be established. The upper 50 m (approximately) of each sequence is composed of sediment with no cement and little compaction (Zone I). Sediment that contains less carbonate (more detrital clay) appears to compact more readily in Zone I, so that samples from Sites 545 and 546 have slightly lower porosities than those from Site 544 (Fig. 1). This difference is minor and the upper 50 m of sediment is characterized by decreasing porosity with depth resulting from compaction. This compaction is apparently related to sediment thickness with subordinate control by age or carbonate content. However, at Site 544 the upper 50 m of sediment lies above the late/middle Miocene unconformity, whereas at Site 546, the unconformity lies at nearly 135 m and the upper 50 m is composed of Pleistocene sediment. At Sites 545 and 547, the upper 50 m of sediment is also Pleistocene in age and the late-middle Miocene unconformity lies at approximately 180 and 140 m, respectively. The slightly more compact texture and calcite overgrowth in the upper 50 m at Site 544 probably results from the older age and slightly higher carbonate content of the sediment. Because of this slight difference between Site 544 and the other sites, it seems very unlikely that a thick Pleistocene sequence once existed above the present section and was later removed by erosion. Instead, the Pleistocene must have been very thin or not deposited at all at Site 544.

Below Zone I, calcite overgrowths and cement modify the texture of sediment at all four sites. The top of this carbonate cementation zone (Zone II) occurs at approximately 50 m in all the sites but the bottom varies significantly. At Site 544, the base of the Cenozoic sequence at 104 m lies within this zone, but at Site 546, the base of the calcite cementation zone corresponds to the late/middle Miocene unconformity at 135 m. At both Sites 545 and 547, the transition from ooze to chalk marks the base of the zone of calcite cementation. Within this zone at Sites 544, 545, and 547, the porosity either remains nearly constant or decreases in the upper part to a uniform value in the lower part (fig. 2). The porosity of the sediment within Zone II at Sites 545 and 547 first decreases with depth and then reaches a fairly uniform value throughout the rest of the section. At Site 544 the porosity remains nearly constant throughout Zone II. These differences probably arise from the different age of the sediment at Site 544 because of the late/middle Miocene unconformity. When this difference is accounted for the calcite cementation zone at Site 544 is approximately equivalent to the lower part of the zone at Site 547 (Fig. 2). Because the sediment at Site 545 is younger than that in Zone II at Site 544 and also has a constant porosity, the main factor controlling cementation must be the depth of burial, not age of sediment. This, then, suggests that some amount of sediment was removed by erosion at the unconformity at Site 544, probably on the order of 40 to 50 m when compared to Sites 545 and 547.

Below Zone II in the two deep holes (Sites 545 and 547), changes in texture and porosity result from combined calcite and clay cementation. The base of Zone II corresponds to the transition from ooze to chalk. Cementation and porosity increase downward in the upper portion of Zone III and then porosity decreases with considerable variability throughout the lower part of the zone. Age of sediment and rock type between the two sites are very different. Sediment in Hole 545 contains a thin sequence of early and middle Miocene chalk. The equivalent section at Site 547 is a much thicker section of Paleogene–Upper Cretaceous chalks and claystones with a large component of debris flow deposits and reworked clasts. In spite of the differences in clay and carbonate content, the transition from ooze to chalk and the top of Zone III occur at nearly the same depth, 180 vs. 210 m at Sites 545 and 547, respectively. The correlation of diagenetic zones, even though sediments are dissimilar in age and type, indicates that diagenesis is controlled mainly by depth of burial.

Sediments in Hole 546, at depths of 130 to 147 m, have characteristics corresponding to much deeper depths in the other holes. The porosity of sediments at Site 546 decreases very rapidly and does not match the much slower decreasing trends at the other sites (Fig. 1) but instead is more like the sediment below 300 m at Site 547. The thin sequence at Site 546 lies directly below the late/middle Miocene unconformity and just a few meters above Jurassic salt (see Site 546 chapter, this volume). Pore water samples from this sequence have very high salinities. The first pore water sample taken at a depth of only 4 m had a salinity of 40 ppt and salinity increased to 180 ppt at the base of the Tertiary section. Salinities of pore water from all the other sites were much lower and reached a maximum of only 46 ppt at Site 547 at a depth of 964 m. The tightly cemented and highly recrystallized sediment at the base of Hole 546 may result from the extremely high salinity pore water, even though the sediment is relatively young and has not been buried deeply. This anomaly presumably results from the proximity of the salt and the effects of high salinity pore water on cementation in the sediment above. The increased salinity certainly has affected the Ca and Mg concentrations of the pore water because they also follow the trends of those from Site 547 at a much greater depth. At Site 547, Ca concentration decreases downhole as Mg concentration increases. The two concentrations cross at approximately 30 mm/L at a depth of 575 m. The same trends occur in Hole 546 but the changes are compressed into 150 m (see inorganic geochemistry section, respective site chapters, this volume). In the other two sequences (Sites 544 and 545), Ca and Mg concentrations increase and decrease respectively to constant values and do not follow the patterns at Sites 547 and 546.

The change from ooze to chalk in the Cenozoic sediments drilled on Leg 79 is controlled by depth of burial. Downward in the sequence porosity of the ooze is modified first by compaction. At depths of burial greater than approximately 50 m, nannofossils start to recrystallize and calcite forms overgrowths on coccoliths and detrital grains. Calcite cementation increases with depth and begins to fill pore space, but calcite does not act as the main agent in transforming ooze to chalk as described in purely carbonate oozes. (These changes are roughly equivalent to the "shallow burial realm" of Schlanger and Douglas (1974)). Instead, the change from ooze to chalk is more closely associated with growth of diagenetic clay within pore space. Although the sediment is firmer, the porosity becomes more variable below the ooze/chalk transition and deviates from the general decrease with depth. This sequence is best developed at Sites 545 and 547 where thick Cenozoic sequences were deposited and approximates Schlanger and Douglas's (1974) "deep burial realm." At Site 546 the diagenetic zones are compressed into a much thinner sequence, presumably resulting from the anomalous pore water chemistry associated with high salinity above the salt (see site chapters, this volume).

SUMMARY

In summary, Cenozoic sediment is first modified by compaction and rearrangement of grains. When compaction reaches a point where carbonate grains start to penetrate one another and recrystallize because of point contact pressure, calcite starts to form overgrowths. With increased burial, dissolution increases by a release of carbonate into the pore water that crystallizes in pore space. However, because of the low solubility of low-magnesium calcite in coccoliths, this process is not sufficient to lithify the ooze into chalk; a process requiring several hundred meters of burial in pure carbonate oozes.

At a depth of approximately 200 m, or at a pore water chemistry approximating those depths, diagenetic clay joins calcite as a cement. Only then is the ooze transformed to chalk. The diagenetic clays contributing to chalk formation result from the recrystallization of detrital clays at these depths. This recrystallization results in variable porosity as fibrous and wispy clays grow in place of detrital flakes. Within some intervals, especially at the initiation of clay growth, porosity increases. With sustained burial, calcite continues to fill pore space and the porosity decreases forming a tightly cemented, but still somewhat porous, clayey chalk.

REFERENCES

Adelseck, C. G., Jr., Greehan, G. W., and Roth, P. H., 1973. Experimental evidence for the selective dissolution and overgrowth of calcareous nannofossils during diagenesis. *Geol. Soc. Am. Bull.*, 84: 2755–2762.

Bathurst, R. G. C., 1971. *Carbonate Sediments and Their Diagenesis:* New York (Elsevier).

Berger, W. H., and Winterer, E. L., 1974. Plate stratigraphy and the fluctuating carbonate line. *In* Hsü, K. J., and Jenkyns, H. C. (Eds.), *Pelagic Sediments: on Land and Under the Sea.* Int. Assoc. Sedimentol., Spec. Publ., 1:11–48.

Davies, T. A., and Supko, P. R., 1973. Oceanic sediments and their diagenesis: some examples from deep-sea drilling. *J. Sedim. Petrol.*, 43:381–390.

Matter, A., 1974. Burial diagenesis of peletic and carbonate deep-sea sediments from the Arabian Sea. *In* Whitmarsh, R. B., Weser, O. E., Ross, D. A., et al., *Init. Repts. DSDP*, 23: Washington (U.S. Govt. Printing Office), 421–469.

Neugebauer, J., 1974. Some aspects of cementation in chalk. *In* Hsü, K. J., and Jenkyns, H. C. (Eds.), *Pelagic Sediments: on Land and Under the Sea.* Int. Assoc. Sedimentol., Spec. Publ., 1:149–176.

Schlanger, S. O., and Douglas, R. G., 1974. Pelagic ooze-chalk-limestone transition and its implications for marine stratigraphy. *In* Hsü, K. J., and Jenkyns, H. C. (Eds.), *Pelagic Sediments: on Land and Under the Sea.* Int. Assoc. Sedimentol., Spec. Publ., 1:117–148.

Schlanger, S. O., Douglas, R. G., Lancelot, Y., Moore, T. C., Jr., and Roth, P. H., 1973. Fossil preservation and diagenesis of pelagic carbonates from the Magellan Rise, Central North Pacific Ocean. *In* Winterer, E. L., Ewing, J. I., et al., *Init. Repts. DSDP*, 17: Washington (U.S. Govt. Printing Office), 407–427.

Date of Initial Receipt: February 18, 1983
Date of Acceptance: October 31, 1983

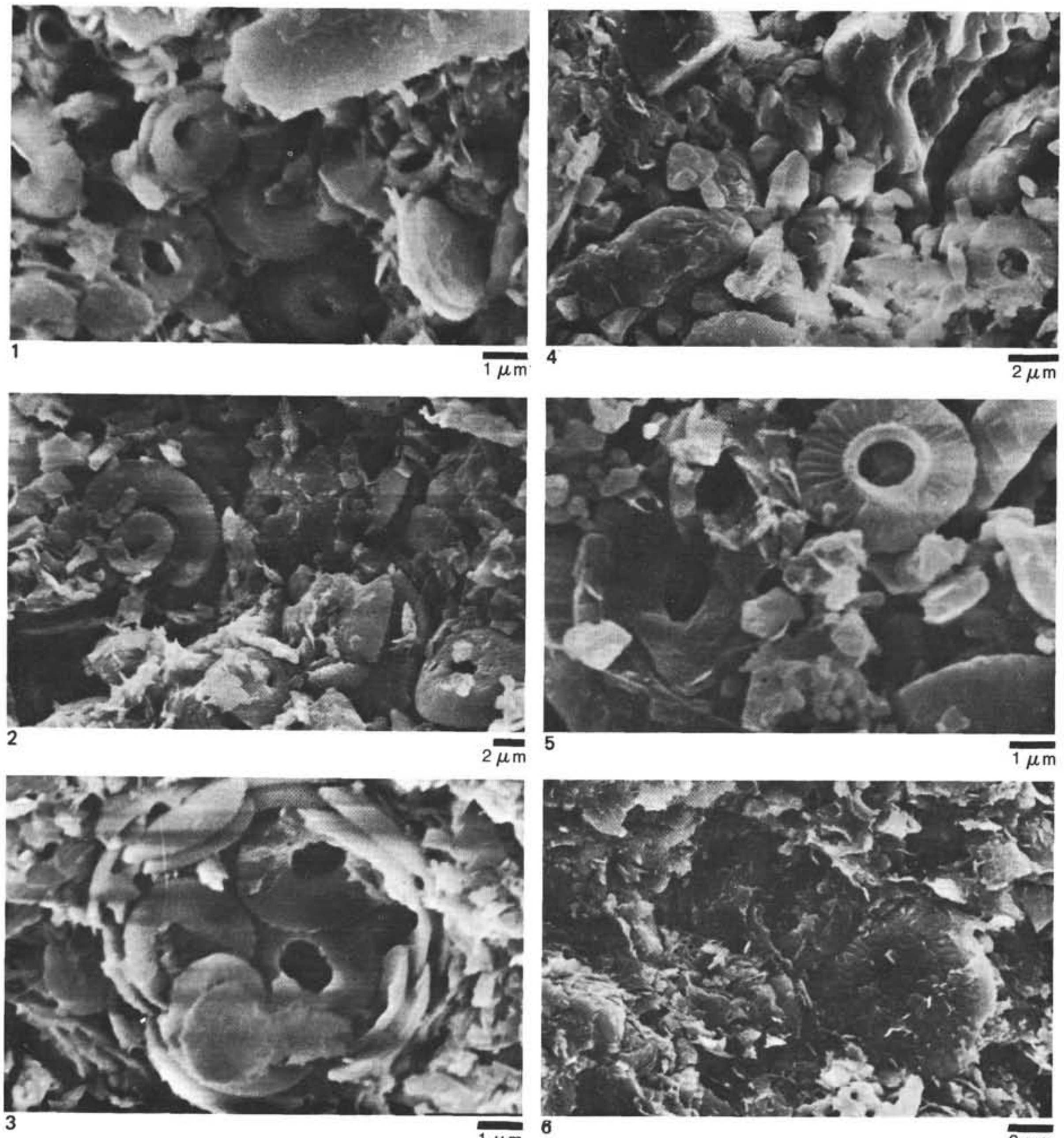

Plate 1. Scanning electron micrographs of sediment from Site 544 (scale in μm). **1.** Sample 544B-4-1, 94–96 cm; 12.2 m. **2.** Sample 544A-7-2, 115–117 cm; 26.0 m. **3.** Sample 544B-12-1, 20–22 cm; 37.6 m. **4–5.** Sample 544A-10-5, 108–110 cm; 90.1 m. **6.** Sample 544A-12-1, 25–27 cm; 102.3 m.

Plate 2. Scanning electron micrographs of sediment from Site 545 (scale in µm). **1.** Sample 545-2-1, 112–114 cm; 9.6 m. **2.** Sample 545-11-4, 133–135 cm; 99.8 m. **3.** Sample 545-14-4, 55–57 cm; 127.6 m. **4.** Sample 545-19-1, 91–93 cm; 170.9 m. **5.** Sample 545-24-2, 110–112 cm; 220.1 m. **6.** Sample 545-27-3, 80–82 cm; 249.8 m.

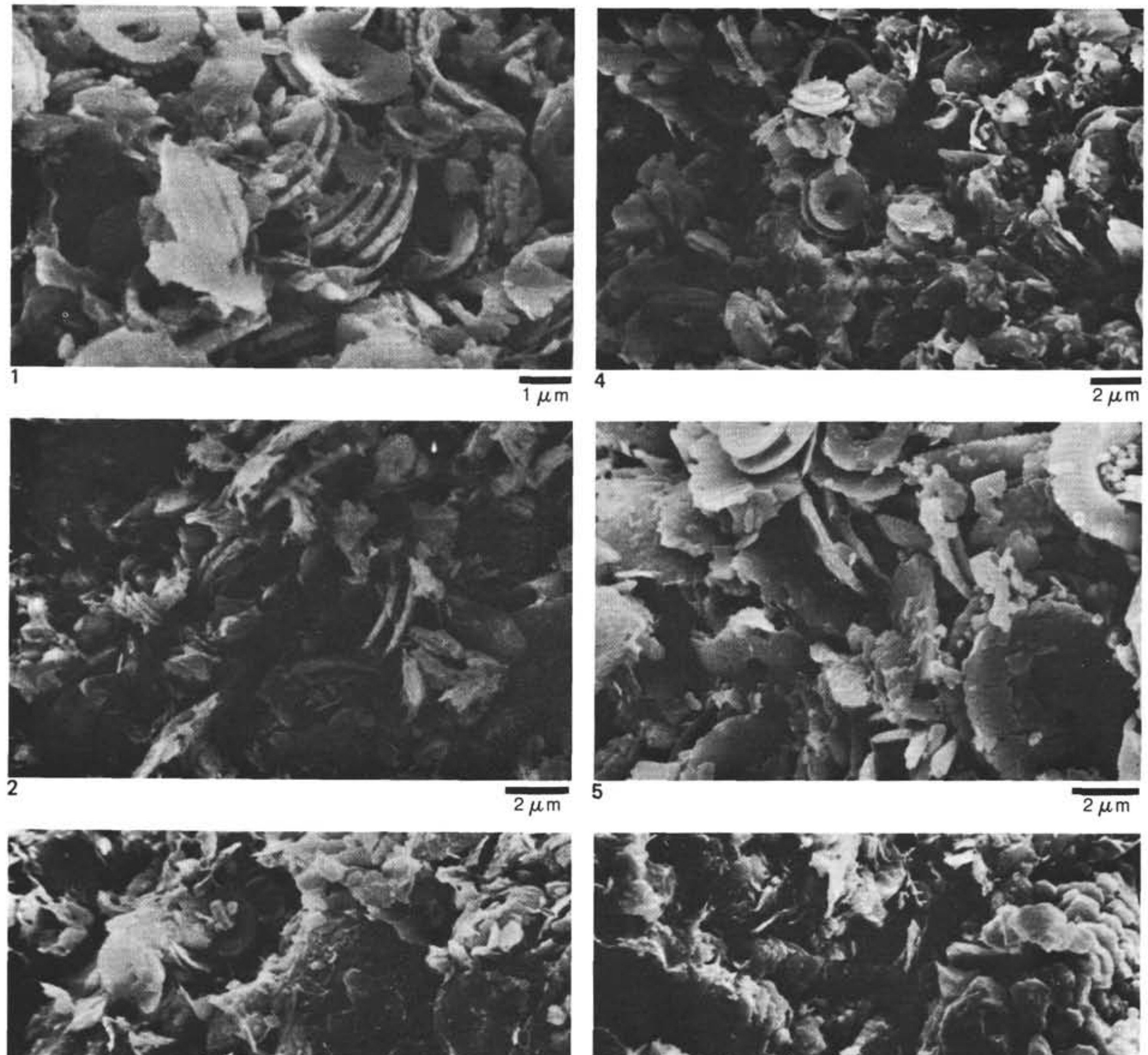

Plate 3. Scanning electron micrographs of sediment from Site 546 (scale in μm). **1.** Sample 546-3-4, 118–120 cm; 17.2 m. **2.** Sample 546-4-3, 134–136 cm; 25.4 m. **3.** Sample 546-7-5, 84–86 cm; 56.4 m. **4.** Sample 546-9-3, 113–115 cm; 72.6 m. **5.** Sample 546-15-1, 68–70 cm; 126.2 m. **6.** Sample 546-16-2, 85–87 cm; 136.1 m.

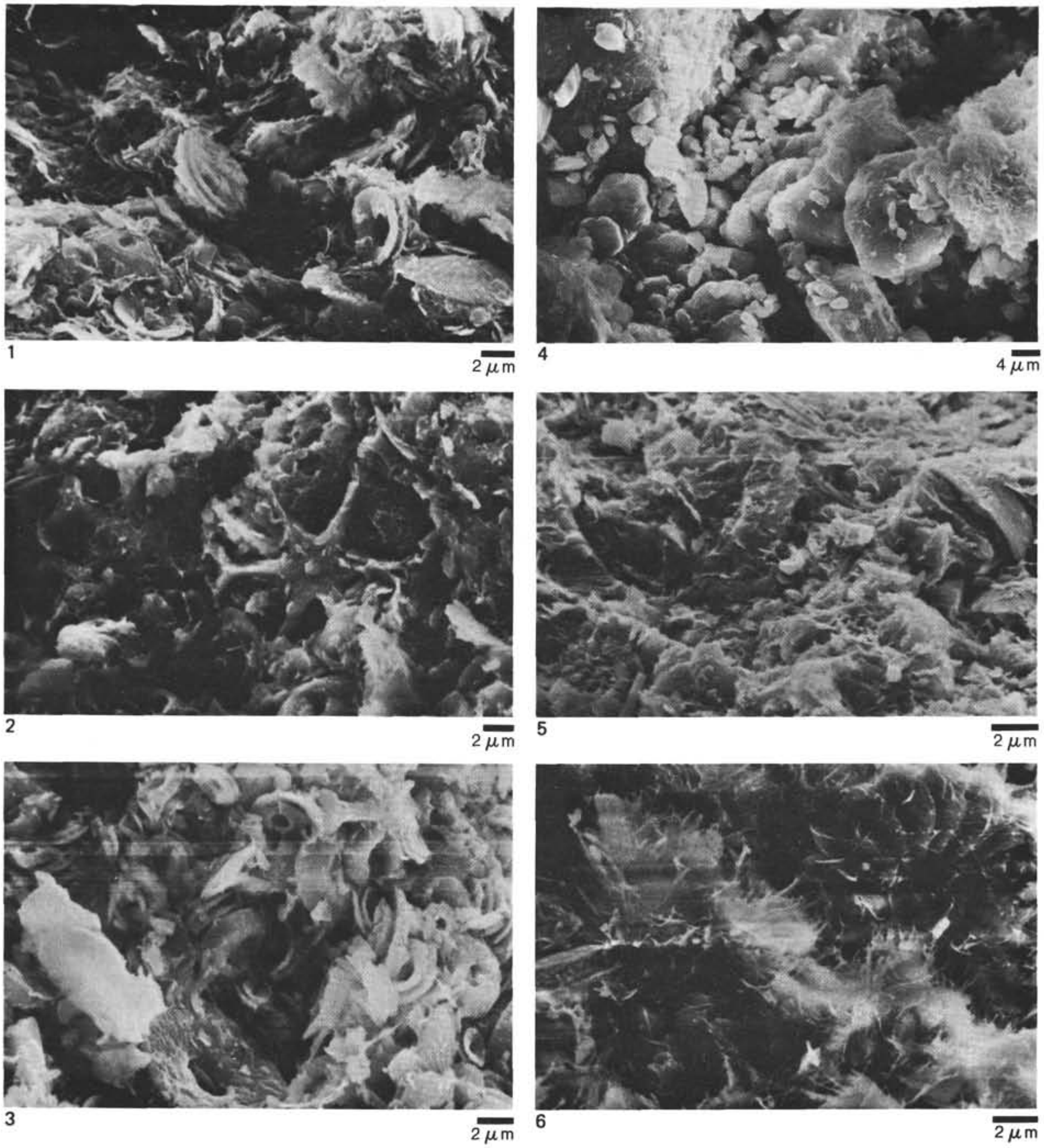

Plate 4. Scanning electron micrographs of sediments from Site 547 (scale in μm). **1.** Sample 547A-1-2, 128–130 cm; 53.8 m. **2.** Sample 547A-7-1, 131–133 cm; 128.3 m. **3.** Sample 547A-12-3, 134–136 cm; 178.9 m. **4.** Sample 547A-16-4, 117–119 cm; 218.2 m. **5.** Sample 547A-20-5, 9–11 cm; 256.6 m. **6.** Sample 547A-23-4, 67–69 cm; 284.2 m.

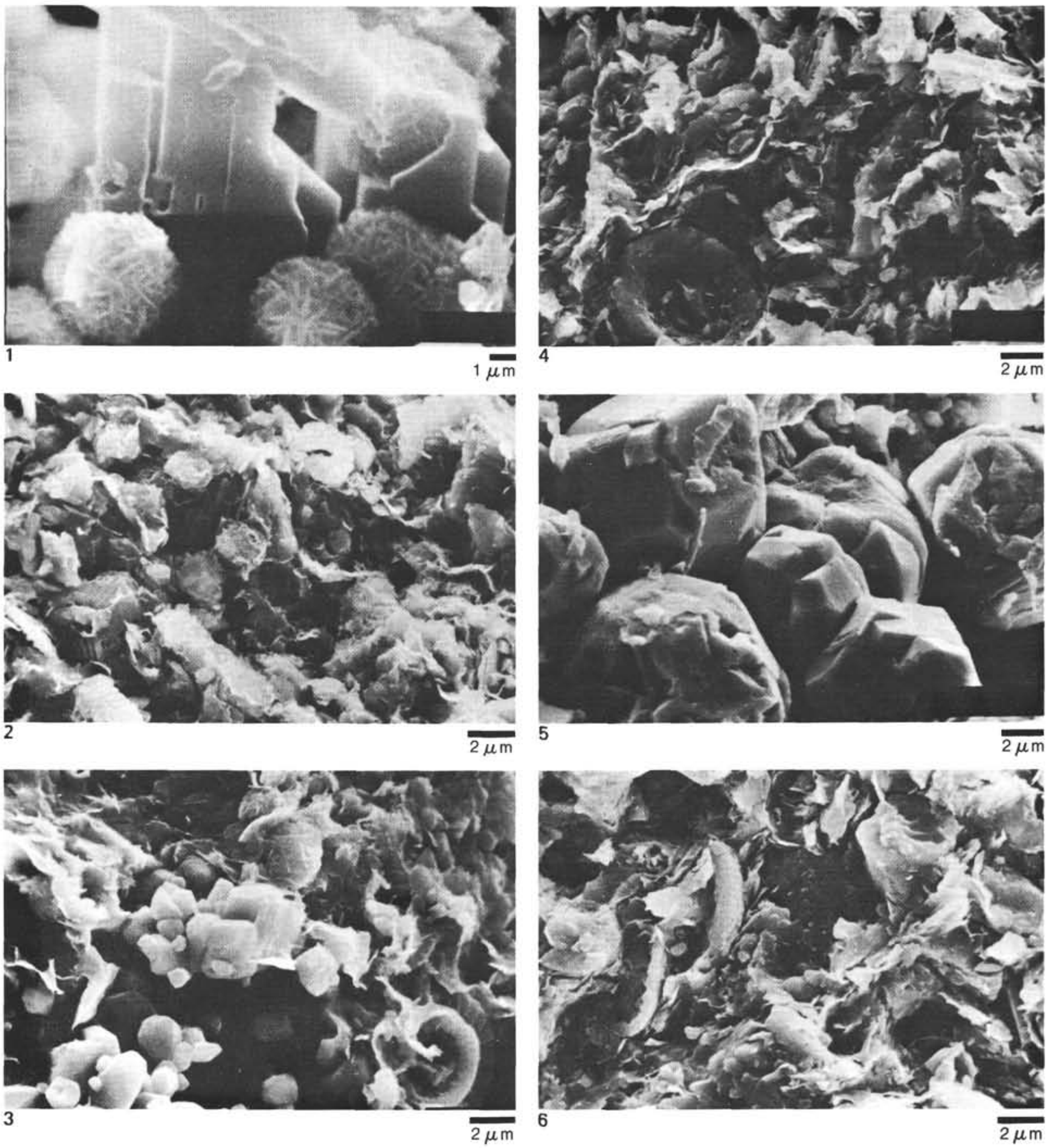

Plate 5. Scanning electron micrographs of sediment from Site 547 (scale in μm). **1.** Sample 547A-26-1, 77–81 cm; 308.2 m. **2.** Sample 547A-28-2, 65–67 cm; 328.7 m. **3.** Sample 547A-30-4, 34–36 cm; 350.4 m. **4.** Sample 547A-34-5, 59–61 cm; 390.1 m. **5.** Sample 547A-37-3, 139–141 cm; 406.9 m. **6.** Sample 547A-39-1, 48–50 cm; 422.0 m.