

30. CARBONATE CHRONOLOGY FOR PLIOCENE DEEP-SEA SEDIMENTS

Ansis Kaneps, Scripps Institution of Oceanography, La Jolla, California

INTRODUCTION

One of the characteristic features of equatorial Pacific deep-sea sediments is a well-developed stratification that is a result primarily of temporal variations in the net accumulation rate of biogenic calcium carbonate (Arrhenius, 1952). It has been shown (Hays et al., 1969) that the record of carbonate fluctuations in these sediments is quasi-cyclical (each cycle for the last 700,000 years having an average duration of 87,500 years) and that it can be correlated over wide areas of the equatorial Pacific region and to variously derived paleotemperature or paleoclimatic curves from the Atlantic Ocean. Moreover, the carbonate fluctuations are not restricted to the Pleistocene, but may extend as far back as the middle Miocene (Tracey, Sutton, et al., 1971, p. 38). For the upper Miocene to Pleistocene they have been tied to paleomagnetic stratigraphy (Hays et al., 1969, and in press). Inasmuch as these fluctuations in carbonate content represent synchronous phenomena linked with the ocean-atmosphere geochemical system, they can be used, in conjunction with paleontological and paleomagnetic data, as a geochronological aid in stratigraphic interpretation.

Carbonate content was routinely determined for Leg 16 cores at intervals generally of 150 cm (on the average, one determination per core section) using methods outlined by Bode and Cronan (Chapter 14, this volume). Samples for carbonate determination were not taken below 330 meters in DSDP 157. Inspection of the percent-carbonate vs. depth plots revealed a close similarity between the plot of DSDP 157 in the Panama Basin and curves for equatorial Pacific piston cores (Hays et al., 1969, and in prep.) and DSDP 132 in the Tyrrhenian Basin of the Mediterranean Sea (Ryan, Hsü, et al., 1973). The similarity of the Panama Basin and other equatorial Pacific sites is not unexpected since they lie in basically the same oceanographic regime: the equatorial belt of high organic productivity and dominantly pelagic sedimentation. However, duplication of the same trends and individual peaks and troughs in carbonate content by the Mediterranean sites indicates that the mechanism producing the fluctuations is a whole-ocean phenomenon (but undoubtedly modified by local conditions).

The purpose of the present paper is to (a) show that correlatable trends in calcium-carbonate content of pelagic sediments occur in widely scattered localities; (b) establish, in association with biostratigraphic and paleomagnetic events, a chronology for the Pliocene; and (c) discuss the implications of the carbonate chronological scale on the biostratigraphy of the calcareous micro- and nannofossils. Station data for the stratigraphic sections considered in the present paper are given in Table 1.

TABLE 1
Sections Used in the Present Paper

Site	Area	Latitude	Longitude	Water Depth (m)	Reference
DSDP 157	Panama Basin	1° 45.70'S	85° 54.17'W	2591	This volume
RC12-66	Equatorial Pacific	2° 36.6'N	148° 12.8'W	4755	Hays et al. (in press)
V24-59	Equatorial Pacific	2° 34'N	145° 32'W	4662	Hays et al. (1969)
RC11-209	Equatorial Pacific	n.a.	n.a.	n.a.	Hays et al. (1969)
Swed. 58	Equatorial Pacific	6° 44'N	129° 28'W	4440	Arrhenius (1952)
DSDP 132	Mediterranean Sea	40° 15.70'N	11° 26.47'E	2835	Ryan, Hsü, et al. (1973)

CORRELATION

Carbonate Correlation

The proposed correlation of carbonate fluctuations for DSDP Sites 157 and 132 and Lamont-Doherty piston core RC12-66 from the equatorial Pacific (Hays et al., in prep.), along with the paleomagnetic stratigraphy of this core (Foster and Opdyke, 1970), is shown in Figure 1. The depth scale in each case has been normalized to give an identical spacing between minima *GU3* and 0. The nomenclature for maxima and minima down to minimum *GU3* is that of Hays et al. (1969); below this horizon, a provisional lettering system has been used for correlatable fluctuations since the number of fluctuations recognized is to a large degree dependent on sedimentation rate and sampling density and may change as more sections are studied. (Compare, for example, the upper portion of core V24-59 and the same sequence in core RC11-209 in Figure 2 of this paper.)

The principal levels of correlation between the three sequences is the double peak *n-o-p*. That this maximum is the same one in all three sequences is supported by biostratigraphic data (see below). The double maximum *e-f-g* can be recognized in DSDP 157 and 132, although it is somewhat different in character in RC12-66. This and other differences in the character of individual curves may be real, but are more likely a result of sampling error, and this is more likely to occur in the drilled sequences, wherein cored intervals are often not fully recovered and where the

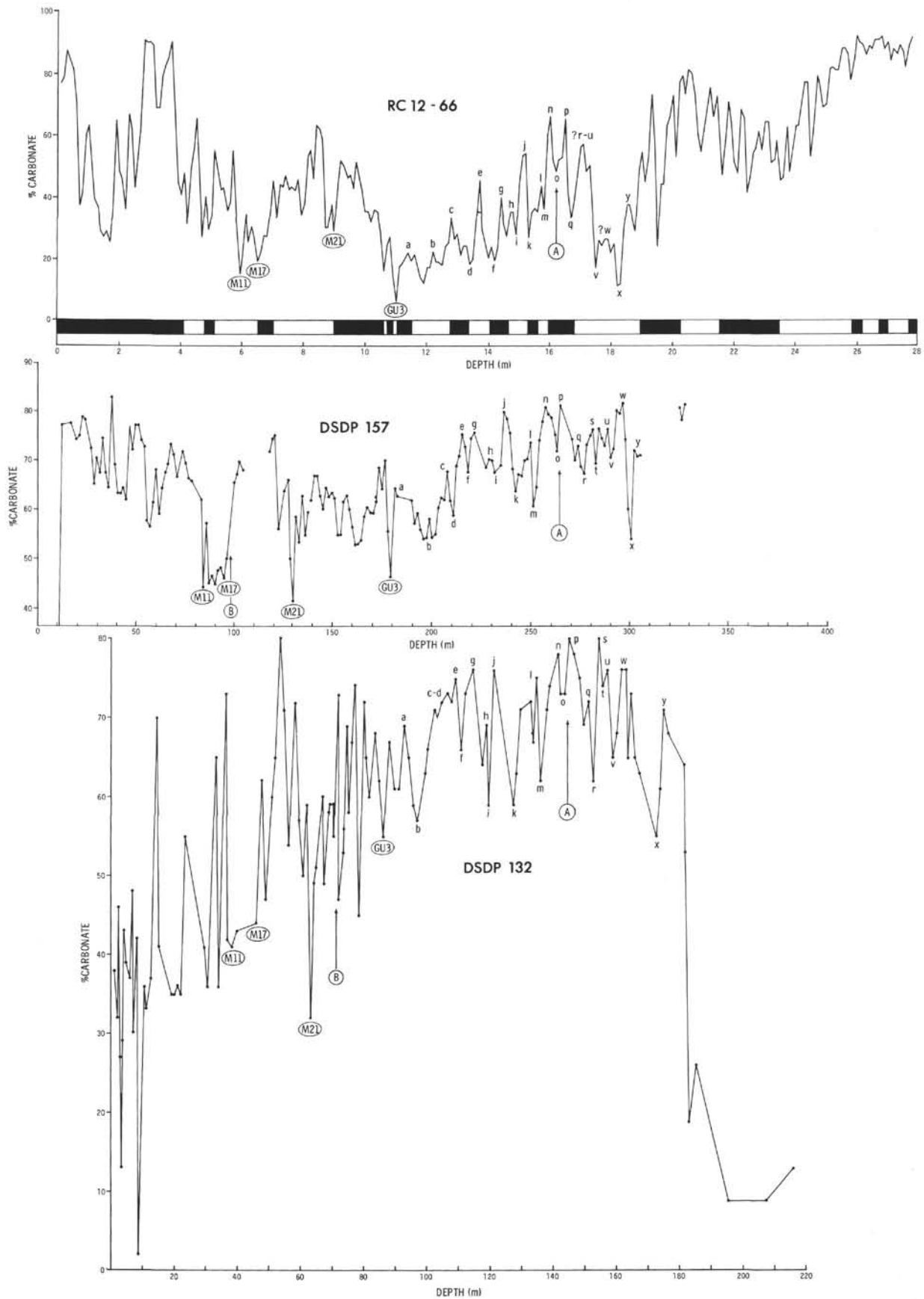


Figure 1. Correlation of carbonate fluctuations of sites DSDP 132 and 157, and piston core RC12-66. The nomenclature for peaks and troughs down to GU3 is that of Hays et al. (1969). Below this a provisional lettering system is used. A-first occurrence of *Ceratolithus rugosus*; B-last occurrence of *Discoaster brouweri*.

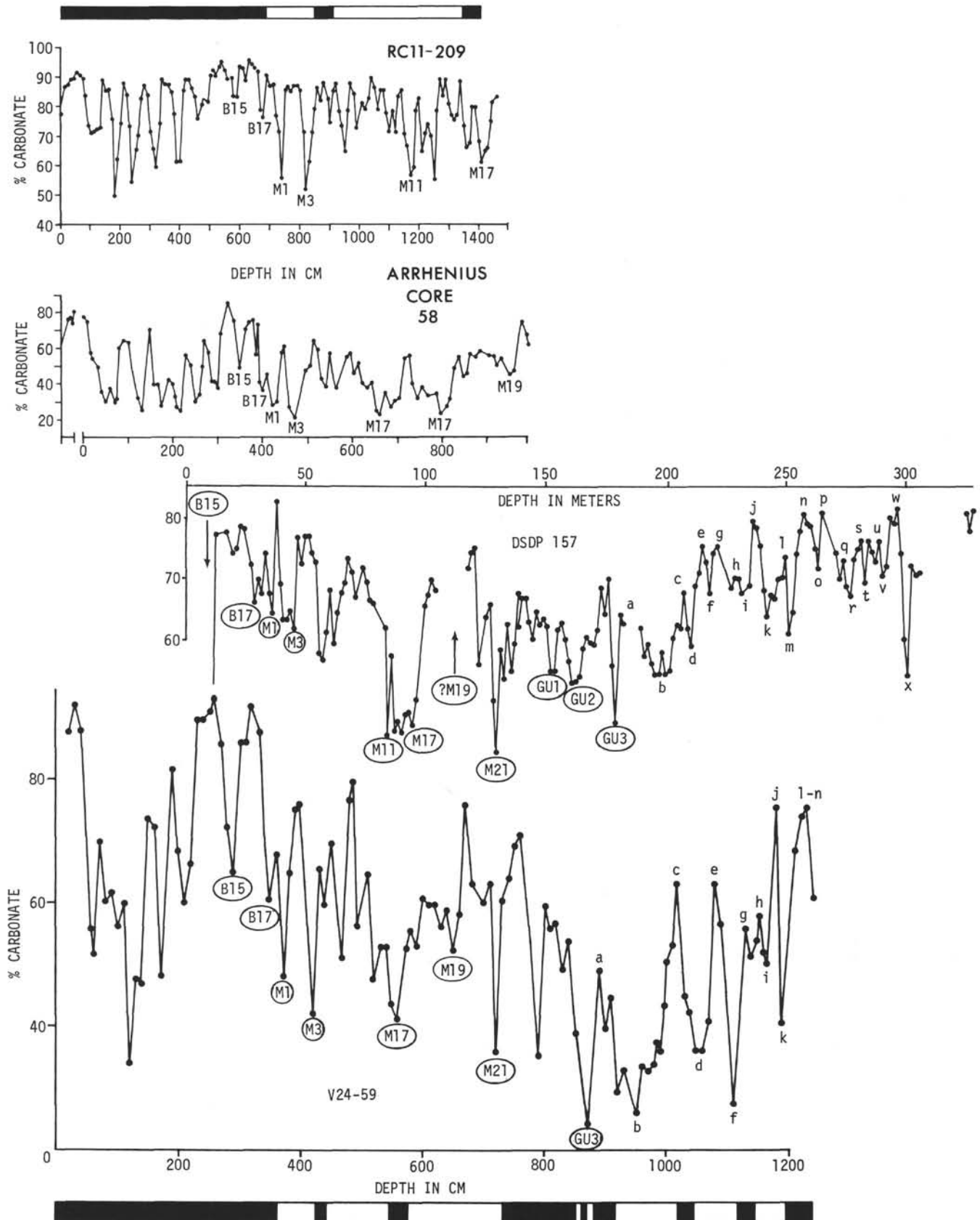


Figure 2. Correlation of carbonate fluctuations of site DSDP 157, and equatorial Pacific piston core sequences RC11-209, V24-59 (Hays et al., 1969) and Swedish Core 58 (Arrhenius, 1952). Nomenclature same as that of Figure 1.

type position of a sample below the sea floor can frequently only be determined to within a few meters. According to the paleomagnetic stratigraphy of RC12-66, double peak *n-o-p* coincides with the *c* event of the Gilbert reversed series, and double peak *e-f-g* is centered on the top of the *b* (Nunivak) event of this series.

Also evident in all three curves is the minimum *GU3*, which coincides with the Mammoth event of the Gauss normal series, and lies above peak *a*, which coincides with the lower, normal event of this series. Biostratigraphic evidence for this correlation is given below. The prominent minimum *M21*, which splits the zone of generally high carbonate values in the upper Gauss and lower Matuyama series and marks the boundary between these series, is also seen in all three curves.

Above the upper-Gauss/lower-Matuyama zone of high carbonate, values drop to another prominent low (*M11-M17*). There are subsidiary maxima within this low in the piston core sequences (see also Figure 2) which are poorly developed at DSDP 157 and absent at DSDP 132; again, this may be real or due to sampling error. The correlation of the *M11-M17* carbonate low is also supported by biostratigraphic evidence, discussed below. The bottom of this zone of low carbonate values is approximately coincident with the Olduvai event of the Matuyama series.

Further correlations of DSDP 157 with piston core sequences are shown in Figure 2. The upper portion of DSDP 157 is especially similar to Swedish core 58 (Arrhenius, 1952). A nearly identical sequence of peaks is present between the minima *M3* and *M11*, and the sequence above *M3*, up through *B15*, appears to be preserved. It will be noted that if the carbonate correlation is valid, the upper 400,000 years or so of the Pleistocene is missing or highly condensed at DSDP 157. This is substantiated by piston cores from this area (van Andel, personal communication).

Biostratigraphic Correlation

The following biostratigraphic evidence lends support to the carbonate correlation:

a) First occurrence of *Ceratolithus rugosus*. This biostratigraphic event occurs at a nearly identical position in each case: within minimum *o* of the double peak *n-o-p* (data for DSDP 157 are from Bukry, this volume; for DSDP 132 from Stradner, 1973, and for RC12-66 from Gartner, in press). In core RC12-66, *C. rugosus* appears precisely at minimum *o*, while at DSDP 132 it appears slightly below this level (see Figure 2). In terms of paleomagnetic stratigraphy this first occurrence is within the lower half of split event *c* of the Gilbert reversed series. This biostratigraphic datum thus demonstrates the equivalence of maximum *n-o-p* in the three sequences.

b) Extinction of *Globoquadrina altispira*. This event occurs in DSDP 157 and V24-59 at the level of carbonate minimum *GU3* (Figure 2)—in the Mammoth event of the Gauss normal series. A similar stratigraphic level for the extinction of *G. altispira* with respect to the paleomagnetic stratigraphy was found in Indian Ocean core V20-163 by Hays et al. (1969). In the Mediterranean, *G. altispira* is poorly represented, undoubtedly due to environmental factors (the Mediterranean faunas throughout the Pliocene and Pleistocene have a distinctly more high-latitude aspect than coeval warm-water faunas, lacking such species as

Globorotalia menardii, *G. tumida*, and *Pulleniatina*), and occurs only in the lower Pliocene (Cita and Ryan, 1973), from carbonate maximum *p* to minimum *k*.

c) Extinction of *Discoaster*. In the equatorial Pacific sequences, this event occurs at carbonate minimum *M17* (Riedel et al., 1963 [core 58]; Hayes et al., 1969 [cores V24-59]; Gartner, in press [core RC12-66]). In DSDP 157 it occurs somewhat higher (minimum *M11*), but this may be due to upward reworking (Bukry, personal communication). In terms of paleomagnetic stratigraphy, this event occurs within or just below the Olduvai event, as has been noted previously (Glass et al., 1967; Hays et al., 1969; Ericson and Wollin, 1968).

It will be observed, however, that if the correlation of DSDP 132 with other sections is correct, then *Discoaster* disappeared from the Mediterranean considerably earlier than in tropical-subtropical regions. Whereas in the latter areas *Discoaster* persists to minimum *M17*, in DSDP 132 it disappears somewhat below *M21* (see Figure 1), or within the upper Gauss series. Two choices are open: either the Mediterranean and equatorial Pacific sequences are misrelated, or the last occurrence horizon of *Discoaster* is diachronous. Given the warm-water affinities of the genus *Discoaster*, and the cooler-water nature of Mediterranean faunas, the latter choice seems to be more probable.

Graphic Correlation

Figure 3 shows the graphic correlation of sites DSDP 157 and RC12-66 according to the method of Shaw (1964), but instead of paleontological datums, correlatable fluctuations of carbonate derived a priori from Figure 1 were used. Owing to the lack of carbonate data in the lower portion of DSDP 157, one paleontological datum point—extinction of *Discoaster quinqueramus*—was used to project the line of correlation back to the base of the section at DSDP 157. This projection, although a very rough extrapolation, indicates that DSDP 157 extends somewhat farther back in time than RC12-66. Extending the paleomagnetic time scale of RC12-66 backward on the basis of the longer stratigraphy of RC12-65 (Foster and Opdyke, 1970), places the base of DSDP 157 within paleomagnetic series 7, at an age of roughly 7.5 m.y.

The line of correlation, which represents the locus of points common to both sections, shows a number of changes in slope, indicating several changes in the relative rate of accumulation at sites RC12-66 and DSDP 157. Were RC12-66 plotted to a linear time scale, the line of correlation would indicate the absolute rate of accumulation at DSDP 157. It can be seen that projection of the line of correlation upward intersects the paleomagnetic scale of RC12-66 at a point near the middle of the Brunhes series; this indicates that the last 400,000 years or so of the section at DSDP 157 are highly condensed or missing.

Confidence in the correlation of Figure 3 is strengthened by the fact that two paleontological datums, which were not used to initially derive the line of correlation, also fall on this line. There are: (a) first occurrence of *Globorotalia tumida*, and (b) first occurrence of *Ceratolithus rugosus*. It will be noted, however, that another paleontological datum, the initial change in coiling direction of *Pulleniatina*

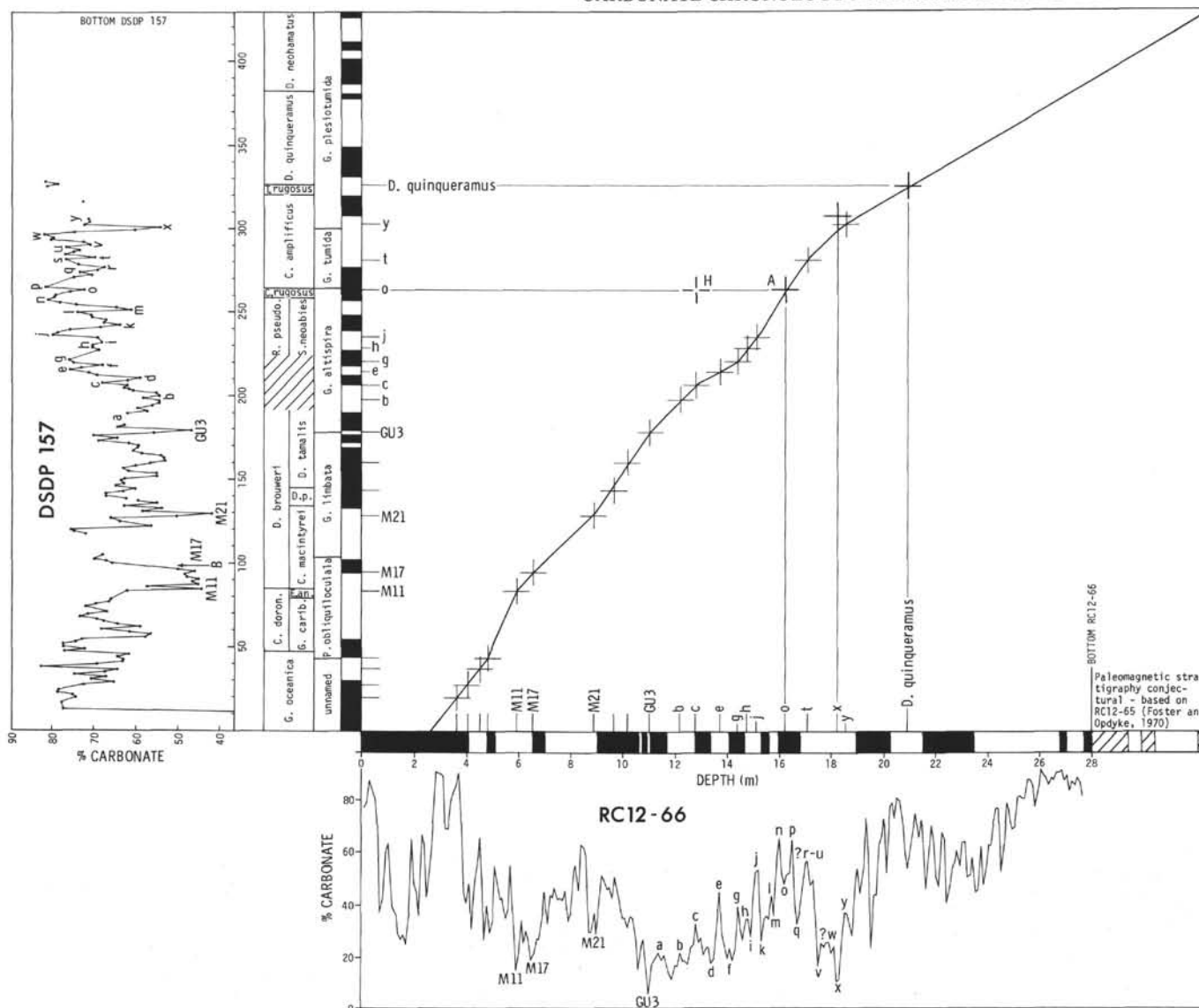


Figure 3. Graphic correlation of site DSDP 157 and piston core RC12-66 (see text). A-first occurrence of *Ceratolithus rugosus*; F-first occurrence of *Globorotalia tumida*; G-last occurrence of *Discoaster quinquaramus*; H-initial change in coiling direction of *Pulleniatina primalis* from left to right.

primalis from left to right, falls considerably above the line of correlation. The explanation for this is that the coiling change must have occurred much earlier at DSDP 157 than at RC12-66. In equatorial Pacific and Indian Ocean piston cores, the coiling shift occurs at the top of the A event of the Gilbert magnetically reversed series (Hays et al., 1969) or at maximum c of the carbonate stratigraphy. At DSDP 157, the coiling shift takes place at carbonate minimum o and coincides with the first occurrence of *Ceratolithus rugosus*. The consequences of this are that (a) the *Globorotalia tumida* Zone of the Panama Basin area, whose top has been defined by this coiling shift (see Chapter 27), is of utility only in the Panama Basin, and (b) the use of coiling changes in *Pulleniatina*, as well as other taxa, should be approached with caution in long-range correlation (also pointed out by Parker, 1967).

By projecting through the line of correlation, it is possible to apply the paleomagnetic stratigraphy of RC12-66 to the paleomagnetically undated DSDP 157. The

derived paleomagnetic stratigraphy for DSDP 157 and its relationship to the biostratigraphic zonations of the foraminifera and nannofossils at this site are shown in Figure 3. It should be noted that the upper limit of *Discoaster brouweri* at DSDP 157 is probably too high because of reworking; in other tropical-subtropical sequences this horizon occurs within or just below the Olduvai event (Hays et al., 1969) and is presently used as one of the criteria for the recognition of the Pliocene-Pleistocene boundary in deep-sea sediments (although the relationship of this boundary to the one in the Mediterranean land sections, which serve as its stratotypes, is still unclear; see discussion in Chapter 27 and below).

The graphic correlation between DSDP 157 and Mediterranean site DSDP 132, similar to that of Figure 3, is shown in Figure 4. Unlike in Figure 3, the line of correlation here approaches a straight line, indicating equivalent relative rates of sedimentation. As for the RC12-66/DSDP 157 plot, the first occurrence of *Ceratolithus rugosus* falls on the line

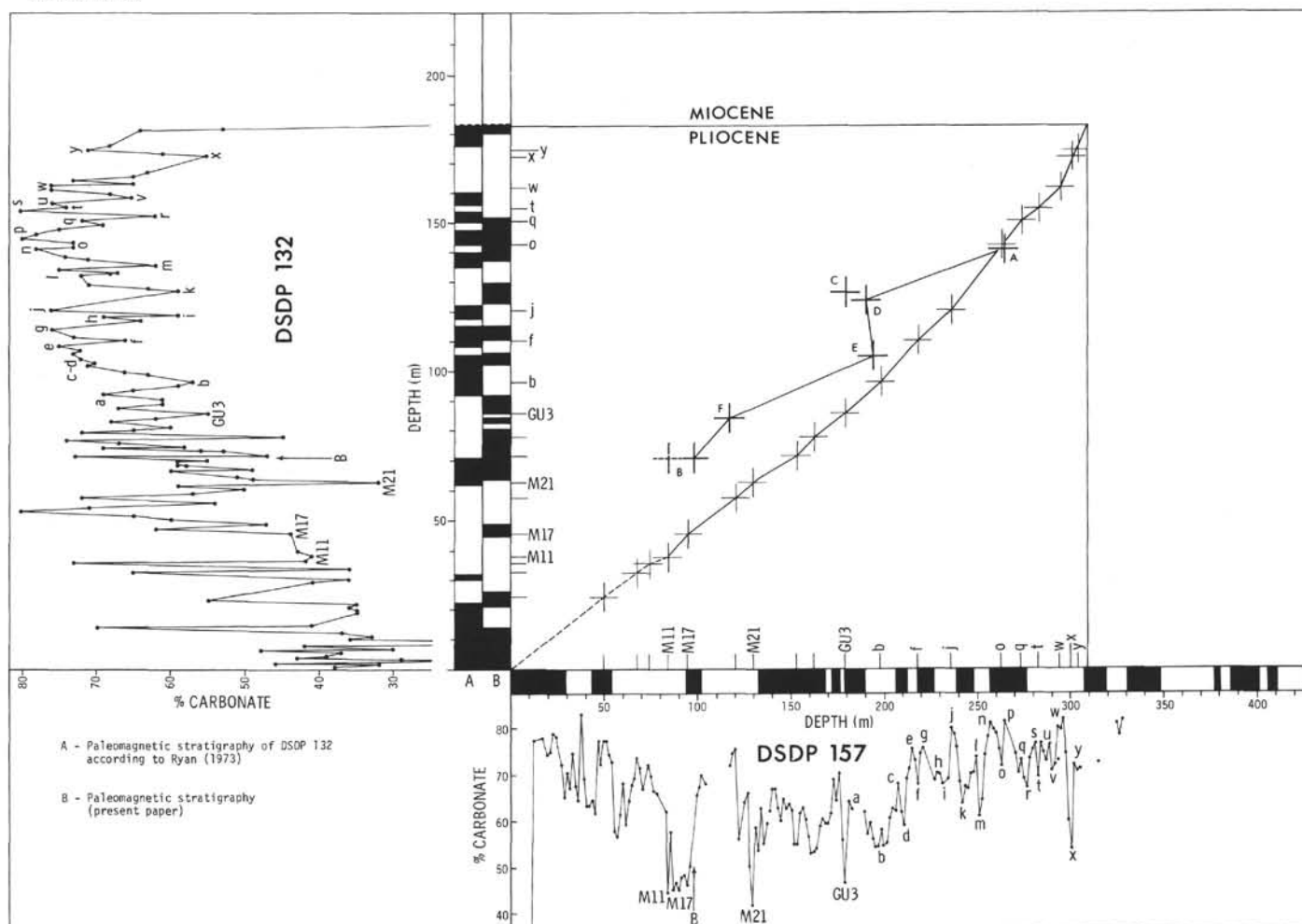


Figure 4. Graphic correlation of sites DSDP 132 and 157 (see text). A-first occurrence of *Ceratolithus rugosus*; B-last occurrence of *Discoaster brouweri*; C-last occurrence of *Globigerinoides extremus*; D-last occurrence of *Sphaeroidinellopsis*; E-last occurrence of *Globorotalia margaritae*.

of correlation, suggesting that the first occurrence of this taxon may serve as a useful biostratigraphic link between temperate and tropical areas. Other, higher biostratigraphic datums, however, fall considerably off the line of correlation because they consistently occur stratigraphically lower in the Mediterranean section than at DSDP 157. This is summarized in Figure 5. It may, of course, be argued that no correlation exists between the carbonate fluctuations, or that it is fortuitous, and that the paleontological datums should be used to determine the line of correlation; but note that whereas the carbonate fluctuations define a nearly straight-line correspondence between the two sections, the line based on paleontological datums is notably dog-legged. It is for this reason and the paleoenvironmental differences between the Mediterranean Sea and equatorial Pacific Ocean, which would be effective in modifying upper and lower limits of species, that the carbonate correlation is considered here to be the more reliable of the two.

The Miocene-Pliocene boundary is defined by the top of the Messinian Stage, which is equivalent to the termination of evaporite deposition in the Mediterranean (see Ryan, Hsü, et al., 1973). This level in DSDP 132 occurs at the sharp rise in carbonate content at about 180 meters, which coincides with the lithologic change from evaporites below

to calcareous pelagic ooze above. By projecting this level through the line of correlation to the derived paleomagnetic stratigraphy of DSDP 157 (see Figure 4), the Miocene-Pliocene boundary falls in the uppermost part of magnetic series 5. This is in substantial agreement with the placement of this boundary by Cita and Ryan (1973).

However, the paleomagnetic stratigraphy of DSDP 132 above this point, as determined by projecting the derived paleomagnetic stratigraphy of DSDP 157, differs from the preliminary interpretation of magnetic inclination measurements in this section by Ryan (1973). A comparison of the paleomagnetic stratigraphy of DSDP 132, as determined by Ryan, and as determined in the present paper, is shown in Figure 4. Except for the top of magnetic series 5, the sequence of reversals as interpreted by Ryan (1973) is shifted downward by as much as thirty meters with respect to that based on the carbonate correlations. It must be remembered, though, that the record of magnetic inclination at DSDP 132 is not very clear, and its interpretation is not unequivocal, as pointed out by Ryan (1973). In addition, because of the obscure nature of the inclination record of DSDP 132, Ryan was forced to use paleontological data to aid his interpretation; the explicit assumption being that the paleontological datums used (extinctions of

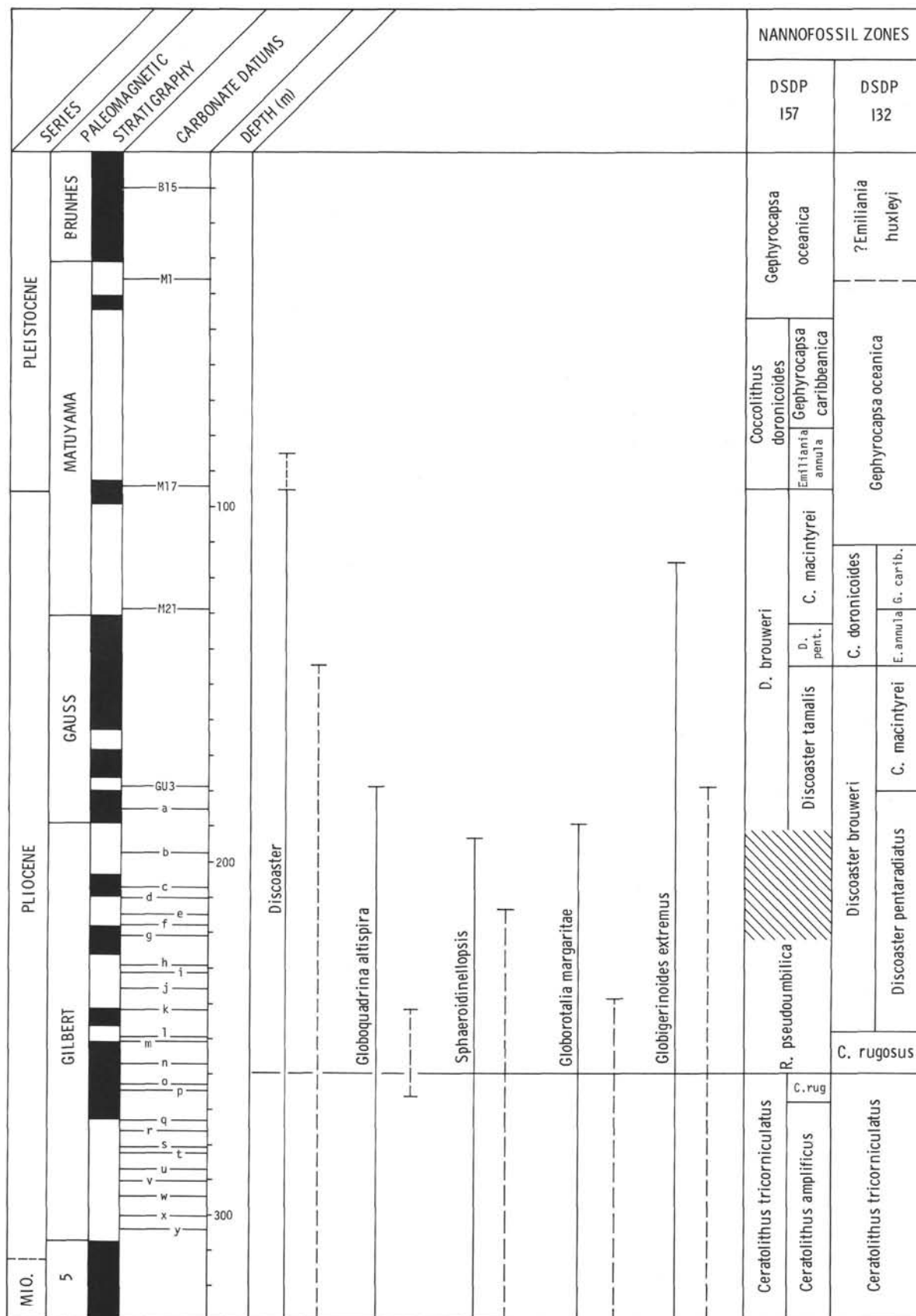


Figure 5. Comparison of ranges of some species of planktonic foraminifera and Discoaster between sites DSDP 132 (dashed lines) and 157 (solid lines). Also shown are a comparison of the nannofossil biostratigraphy at these two sites. The paleomagnetic stratigraphy is that derived from the graphic correlation of site DSDP 157 and paleomagnetically dated piston core RC12-66.

Globorotalia margaritae, *Sphaeroidinellopsis* spp., and *Discoaster brouweri*) occur at identical time horizons in the Mediterranean and equatorial Pacific, the latter being the area where the correspondence of the biostratigraphic datums with the paleomagnetic reversal scale (for this area) was first demonstrated (Hays et al., 1969). That this assumption is not necessarily true is emphasized by the composition of Mediterranean faunal assemblages throughout the Pliocene and Pleistocene; they lack such common tropical-subtropical forms as *Globorotalia menardii*, *G. tumida*, *G. multilocamerata*, *G. miocenica*, *G. exilis*, *G. per-tenuis*, *Pulleniatina*, and other species of uncertain environmental significance such as *Globigerina nepenthes* and *Globigerinoides fistulosus*.

The carbonate correlation of Figure 4 indicates that the extinction datums of *Globorotalia margaritae*, *Globoquad-rina altispira*, *Sphaeroidinellopsis* spp., *Globigerinoides extremus*, and *Discoaster brouweri* occur lower in the Mediterranean than they do in tropical-subtropical sequences. Given the higher-latitude aspect of Mediterranean assemblages, this is not unexpected. In particular, it can be seen (Figure 5) that the last occurrence horizon of *Discoaster* in the Mediterranean is significantly lower than in low-latitude sequences—in the middle of the upper Gauss series (ca. 2.6 m.y.). The equivalence of the *Discoaster* extinction and the Olduvai event has been securely established in both the Atlantic (Ericson and Wollin, 1968; Glass et al., 1967) and Pacific oceans (Hays et al., 1969), and this horizon has become almost synonymous with the Pliocene-Pleistocene boundary in deep-sea sediments. It is not the purpose here to trace the history of development of this concept but to suggest that the Pliocene-Pleistocene boundary issue needs to be reassessed in view of the early disappearance of *Discoaster* in the Mediterranean and the still unclear biostratigraphy of the type sections for this boundary in Italy (e.g. Riedel et al., 1963; Hay and Boudreaux, 1968; Roth, personal communication).

CONCLUSIONS

If the above correlations of temporal fluctuations in carbonate content of deep-sea pelagic sediments are accepted as valid, the following points seem warranted:

1) Given continuous pelagic sedimentary sequences, it is possible to use fluctuations in carbonate content as a tool in correlation. Continuous, or nearly continuous, sequences are needed because no single fluctuation or series of fluctuations is sufficiently unique to unequivocally identify it. Additionally, prior knowledge of the general age of the sequence is necessary.

2) The fluctuations in carbonate content are not restricted to the equatorial Pacific belt of high organic productivity, but occur also in an oceanographically distinct area—the Mediterranean Sea. The generally accepted interpretation of these fluctuations has been that they are essentially productivity controlled. The greater rates of dissolution during glacial epochs are more than compensated for by increases in the productivity of calcareous micro- and nannofossils, resulting in net higher concentrations of calcium carbonate in pelagic sediments. That this may not be the case has been demonstrated by Broecker (1970, 1971b). He proposes that productivity

may have been greater during interglacial epochs and that the increased productivity of calcium carbonate (increased undersaturation of the body of ocean water) would have had to be balanced by increased dissolution at the ocean floor. Since dissolution rate in the ocean is partly or primarily depth-dependent (Peterson, 1967; Berger, 1967), carbonate "compensation" would occur mostly in the Pacific Ocean since it is deeper than the Atlantic. The most telling piece of evidence in support of the above hypothesis is the occurrence of pteropods in glacial sediments of the Atlantic and their absence from interglacial sediments (Broecker, 1971b), indicating greatly reduced rates of dissolution during glacial epochs. In summary, the carbonate profile of deep-sea sediments is determined primarily by changing rates of dissolution rather than productivity.

Why the Mediterranean Sea should behave like the Pacific Ocean with respect to preservation of carbonate, however, is somewhat puzzling. The Mediterranean is, on the average, shallower than either the Pacific or the Atlantic and at the present day behaves like a lagoonal basin, according to the model of Berger (1970). That is, like the Atlantic, it imports surface water and exports deep water across the Gibraltar sill. Thus, because of this and its shallow average depth, the Mediterranean sedimentary carbonate profile should be similar to that of the Atlantic and opposite to that of the Pacific: high carbonate where Pacific carbonate is low, and vice versa.

However, it will be noted that the carbonate curve of DSDP 132 is similar to that of the Pacific sites only in its Pliocene portion. Whereas at the Pacific sites carbonate values increase again in the Pleistocene after a gradual decrease during the Pliocene, in the Mediterranean carbonate values continue to decrease during the Pleistocene. Thus, the Pliocene-Pleistocene boundary may mark the point at which the Mediterranean ceased to be a Pacific-like, estuarine basin (Berger, 1970) and became an Atlantic-like, lagoonal basin, that is, when the pattern of water exchange between the Mediterranean and Atlantic may have changed. As pointed out above, at the present time the Mediterranean receives surface water through the Strait of Gibraltar and returns deep water over the Gibraltar sill. For various isotopic and paleontological reasons, Hsü et al. (1973) have had to postulate that the final flooding of the Mediterranean at the beginning of the Pliocene was with North Atlantic Deep Water rather than surface water, requiring a deeper sill than the present-day one. Perhaps then, if a much deeper connection between the Atlantic and Mediterranean existed during the Pliocene, the water exchange between the two bodies of water may have been fundamentally different; the Mediterranean may have been receiving deep water and returning surface water to the Atlantic, much like the Pacific does today (Berger, 1970). The cause for the divergence of the Mediterranean carbonate profile from that of the Pacific at the beginning of the Pleistocene may have then resulted from renewed tectonic uplift of the Gibraltar area at the beginning of the Pleistocene.

3) Caution must be exercised in equating paleontological datums with time horizons, especially when correlating between environmentally distinct areas. It can be seen that in the case of the Mediterranean site DSDP 132, even

though the low-latitude nannofossil zonation can be recognized, the zones represent homotaxial rather than isochronous intervals; zonal boundaries have been consistently displaced downward by virtue of earlier disappearances of species from the Mediterranean. In addition, as shown by the earlier coiling change of *Pulleniatina primalis* in the Panama Basin than at sites farther west, a paleontologically defined horizon may be diachronous within the same oceanographic region.

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