53. MESSINIAN PALEOENVIRONMENTS

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DEDICATION

This paper is dedicated to the memory of Carlo Sturani, whose tragic death in December 1975 prevented his planned contribution to this article. His illuminating work on the Messinian of the Piedmont Basin, and especially the lecture he gave at the Erice Seminar on the Evaporitic Facies of the Messinian in October 1975, was so significant in relation to Messinian environments and so well documented that we are proud to prepare this paper in his memory.

ABSTRACT

The Messinian denotes a brief period in the latest Miocene during which the Mediterranean region became isolated from the open ocean and experienced fundamental transformations in its local environment. The closure of portals into the Mediterranean was tectonically controlled. Changes in deep circulation indicative of emerging thresholds are geologically expressed in dark non-bioturbated Serravallian shales found at DSDP Sites 126 and 377 in the eastern Mediterranean. Manifestations of the constriction of the Atlantic connections can be seen in deformed thrust nappes of late Miocene age in the Rif Zone of Morocco, and in progressive reduction of the water depth of the middle and late Miocene ostracode fauna in the Betic Zone of Spain.

The sedimentary expression of the onset of the salinity crisis, which in the land record shows evidence of a sudden drop in water level, could not be detected at the only two sites where drilling penetrated through the Mediterranean Evaporite into pre-Messinian bathyal sediments. In fact at Site 372, at the edge of the Balearic Basin, a hiatus corresponding to about the 6 m.y. level is considered to be a Messinian erosional surface. At Site 375 in the Levantine Basin, where the sedimentary record might have been continuous, and where upper Tortonian sediments occur underneath the evaporites, the coring interval was not sufficiently close to detect the onset of the crisis.

The Messinian fossil record denotes strongly variable environmental conditions. Special attention has been paid to the laminites recorded immediately above the stratigraphic gap at Site 372. Qualitative and quantitative studies show that the rich populations of *Ammonia beccarii* are autochthonous, thus indicating shallow hypersaline conditions. The ecological significance of dwarfed faunas commonly preserved in the marls interbedded with the Messinian evaporites (sulfates and halites) is not yet adequately understood in terms of the salinity or water depths of the various Mediterranean basins and embayments.

After the deposition of the upper evaporites, which involved several cycles of evaporitic drawdown with evidence of intermittent subaerial exposure, even on the surface of abyssal plains, the latest stage of the salinity crisis in the eastern Mediterranean was characterized by persistent subaqueous conditions in depressed endoreic basins with strongly evaporated waters. The sediments commonly yield the brackish water "Lago-mare" faunal assemblage with *Cyprideis,* whose autochthony is supported by biometrical analyses. We hypothesize that the invasion of the "Lago-mare" fauna was related to a drainage of the Paratethys.

We were able to investigate the termination of the salinity crisis (Miocene/Pliocene boundary) at six sites. In most cases the contact is sharp, but artificially disturbed during core recovery. Sapropels of earliest Pliocene age (*Sphaeroidinellopsis* Acme Zone M Pl-1) were recovered from basinal settings from the eastern Mediterranean (Sites 374 and 376). They strongly support the hypothesis of high-standing barriers separating the eastern Mediterranean from the western Mediterranean at that time. In the west, closer to the Atlantic Ocean, the lowermost Pliocene sediments indicate active thermohaline circulation at depth after the re-establishment of normal salinity and temperature.

INTRODUCTION

The Messinian denotes a rather narrow slice of time in the latest Miocene during which the Mediterranean region became isolated from the open ocean and experienced rather extreme transformations in its local environment. Some of the events which accompanied these transformations are recorded in remarkable detail within the sedimentary record of the drill cores. Others are unravelled only in the strata exposed on land or explored in seismic profiles. Still others have left their impact primarily outside the Mediterranean, in such faraway places as the deep equatorial Pacific (Schlanger and Douglas, 1974; Ryan et al., 1974).

The aim of this summary paper is to provide up-to-date documentation of the present state of knowledge and experience of the many investigators of the Mediterranean who are concerned with these so-called "Messinian paleoenvironments." In this review we shall attempt to evaluate not only the dramatic response to isolation, evaporitic drawdown, and rapid changes in salinity, but also the circumstances which led to the initial closure of the Atlantic portals and the course of morphologic and climatic evolution which terminated the isolation.

Our text will proceed from the background setting of the pre-salinity-crisis Neogene, through a wide spectrum of events, consequences, and implications of the crisis itself, to the eventual re-establishment of equilibrium conditions in the Pliocene and Quaternary. In other words, we will briefly consider:

1) the conditions which led to isolation of the Mediterranean;
2) the consequences of rapid sea-level changes;
3) the demise of a multitude of faunal groups, induced by changing water depths and salinities;
4) the geodynamic implications of rapid losses and addition of water and the accelerated rates of erosion and deposition;
5) the course of morphologic and climatic evolution which terminated the isolation of the Mediterranean and provided access once again to marine communities and oceanic circulation.

The paper is not a rewrite of the desiccation theory (of Hsü et al., 1973), but a presentation of new data and observations in light of the desiccation hypothesis.

PRE-EVAPORITIC SETTING

Plate Movements and Seaways

Magnetic anomalies (i.e., isochrons) in the North Atlantic (Le Pichon, 1968; Pitman and Talwani, 1972; Dewey et al., 1973) permit palinspastic reconstructions of the relative positions of Africa, Europe, and Asia during the Mesozoic and the Cenozoic. The first complete cutting off of a former marine thruway from the Atlantic to the Indian Ocean via the Mediterranean is recorded by the overland entrance of mammals from Africa into Europe. This significant event, biochronologically dated at approximately 18 to 20 m.y.B.P., belongs to the Burdigalian stage of the early Miocene (Berggren and van Couvering, 1974).

Changes in deep circulation, indicative of emerging thresholds and sills in the Mediterranean Region—especially those which today are represented by the segments of the Apennine arc of Calabria and Sicily—are geologically expressed in the dark non bioturbated shales of Serravallian age at DSDP Sites 126 and 377. This Serravallian interval (approximately 15 to 12 m.y.) of extremely poor ventilation of deep Mediterranean basins is one of general marked cooling of open-ocean bottom waters (Douglas and Savin, 1973; Shackleton and Kennett, 1975), following a brief warm episode in the Langhian. Similar, though not identical, climatic trends have been detected by stable-isotope investigations carried out on both planktonic and benthic foraminifera from western Mediterranean Site 372 (Vergnaud-Grazzini, this volume).

Manifestation of the constriction of the Atlantic portals (for example, the Sub-Rifain and Betic Couloirs) can be seen in deformed thrust nappes of thick Neogene marine covers containing fauna as young as foraminiferal Zone N.17 in the Rif Zone of Morocco (Feinberg and Lorenz, 1970), and in the progressive reduction in water depth of the middle and upper Miocene ostracode fauna in the Betic Zone of Spain (Benson, 1976). Psychrospheric ostracode faunas indicative of a deep thermohaline connection and the entrance of Atlantic bottom water, as recently as 13 to 12 (?) m.y.B.P., were detected in the western Mediterranean (Site 372) and as far east as Gavdos (Benson, 1973, this volume). A continuing subduction of the former Mesozoic seaway between Europe and Africa can today be visualized in the Atlantic on seismic profiles westward of the "Couloir Sub Rifain" off northern Morocco (Figure 1). Regardless of sea-level fluctuations, isolation of the Mediterranean appears to have been predestined by inevitable motions of the African and European plates. With a tectonic closure rate of 1.9 to 1.5 cm/year it can be surmised (but not proved) that the terminal closure phase may have been quite sudden.

ONSET OF THE SALINITY CRISIS

Land Record

The onset of the salinity crisis in the land record has been studied and interpreted in the light of the existing scientific debate on the degree of relief and water depths of the Mediterranean basin(s) in pre-Messinian times by Sturani (1975, in press). In lower Messinian sediments from the distal part of the Periadriatic Trough, he found a very rapid change from open-marine upper bathyal sediments, indicating normal, well-ventilated conditions at the sea floor, to alternating of normal marine and euxinic sediments, still indicating bathyal depths, to evaporitic intertidal to supertidal carbonates. The change from normal, open-marine sediments to euxinic deposits is repetitive and does not involve a detectable change in salinity. The carbonates show desiccation features in the basin of Alba, and expansion cracks with juvenile teepee structures at Moncucco in the Turin Hills and at Giusulana near Sant'Agata Fossili. Sturani draws analogies between this setting and the Santa Barbara Basin of California, with reference to the pre-evaporitic stage.

The direct superposition, without any gradual transition, of intertidal and supertidal carbonates on bathyal hemipelagic sediments is so sharp and dramatic that intervention of a factor entirely foreign to normal geodynamic evolution is required to explain it.

The onset of the salinity crisis as recorded in Sicily is very similar to that described by Sturani in northern Italy, although the stratigraphic control is not as close. The direct superposition of the "Calcare di base" where desiccation features have been described (Schreiber, 1974) on the "Tripoli," whose laminated, unburrowed diatomites suggest high productivity in a restricted basin, also does not follow normal facies relationships, as postulated by Walther's (1894) law. Studies of the Sicilian Messinian sections by Selli (1960), d'Onofrio (1964), Sprovieri (1969), and Bandy (1975) reveal a dramatic change in benthic foraminiferal fauna from a mesobathyal habitat to a shallow restricted setting occurring at or near the base of the evaporitic sequences.

The "Tripoli" varved diatomites, as they occur at Capodarso, neostratotype locality of the Messinian stage, are the sedimentary expression of the euxinification of the Sicilian basin immediately before the onset of the salinity crisis. They do not imply changes in salinity (Sturani, in press) and are not necessarily deep (Lloyd Burckle, personal communication, 1976). Thus, we are impressed that both in Sicily and at Alba the preserved record goes from a marine stenohaline environment to the photic zone environment, with evidence of emergence and subaerial exposure (desiccation cracks, expansion cracks, solution breccias), in less than one meter.

This evidence of a sudden drop in sea level suggests that at the time of the tectonic closure of the last remaining Atlantic portal, the balance of evaporation to precipitation within the Mediterranean watershed was such that sea-level lowering was rapid. This probably implies a delay in the establishment of subterraneous aquifers required to introduce Atlantic saline waters. The occurrence of stromatolitic structures and/or caliche as the first preserved rock unit rather than subaqueous inorganic precipitates argues for the initial drawdown having occurred prior to an increase of the salinity by more than threefold.

Deep-sea Record

The marked break described above from deep to shallow could not be detected in the deep-sea record. Two drilled holes penetrated the Mediterranean Evaporite and pre-evaporitic sediments were recovered (Site 372 on the flank of the Menorca escarpment and Site 375 on the Florence Rise west of Cyprus). Both of these drillsites were located at the margin of abyssal plains, where the Mediterranean Evaporite pinches out. At both drillsites the Messinian lithologies had a total thickness of approximately 50 meters, or one order of magnitude less than the average thickness in basinal settings.

At Site 375, Core 3, cut from 194.5 to 197.5 meters sub-bottom, yields selenitic gypsum and had practically no recovery. Core 4, cut from 245.5 to 252 meters sub-bottom, contains hemipelagic marls and turbidites. The rich foraminiferal faunas indicate open-marine, normal salinity, eutrophic conditions, and depth of deposition in excess of 900 meters. The change from the pre-evaporitic sediments to the evaporites lies somewhere between Cores 3 and 4. Unfortunately, we have no evidence whatever of how the onset of the salinity crisis is expressed in the fossil record in this distal part of the eastern Mediterranean, except that it was rapid. D. Bernoulli (personal communication, 1976) thinks that the dolomitic limestone recovered from the core catcher of Core 3 and the top of Core 4 are altered in the vadose zone and somehow comparable to the "Calcare di base."

The Evaporites/Pre-evaporites Passage at Site 372[1]

Portions of Core 372-9 (197.5-207 m sub-bottom) contain the sedimentary expression of evaporitic conditions. In its topmost part, from 67 to 76.5 cm of Section

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[1] The following description and discussion of Core 372-9 are arranged from the younger levels to the older ones. Readers who are intellectually bound to follow the stratigraphic order might better start reading this subchapter from the end.

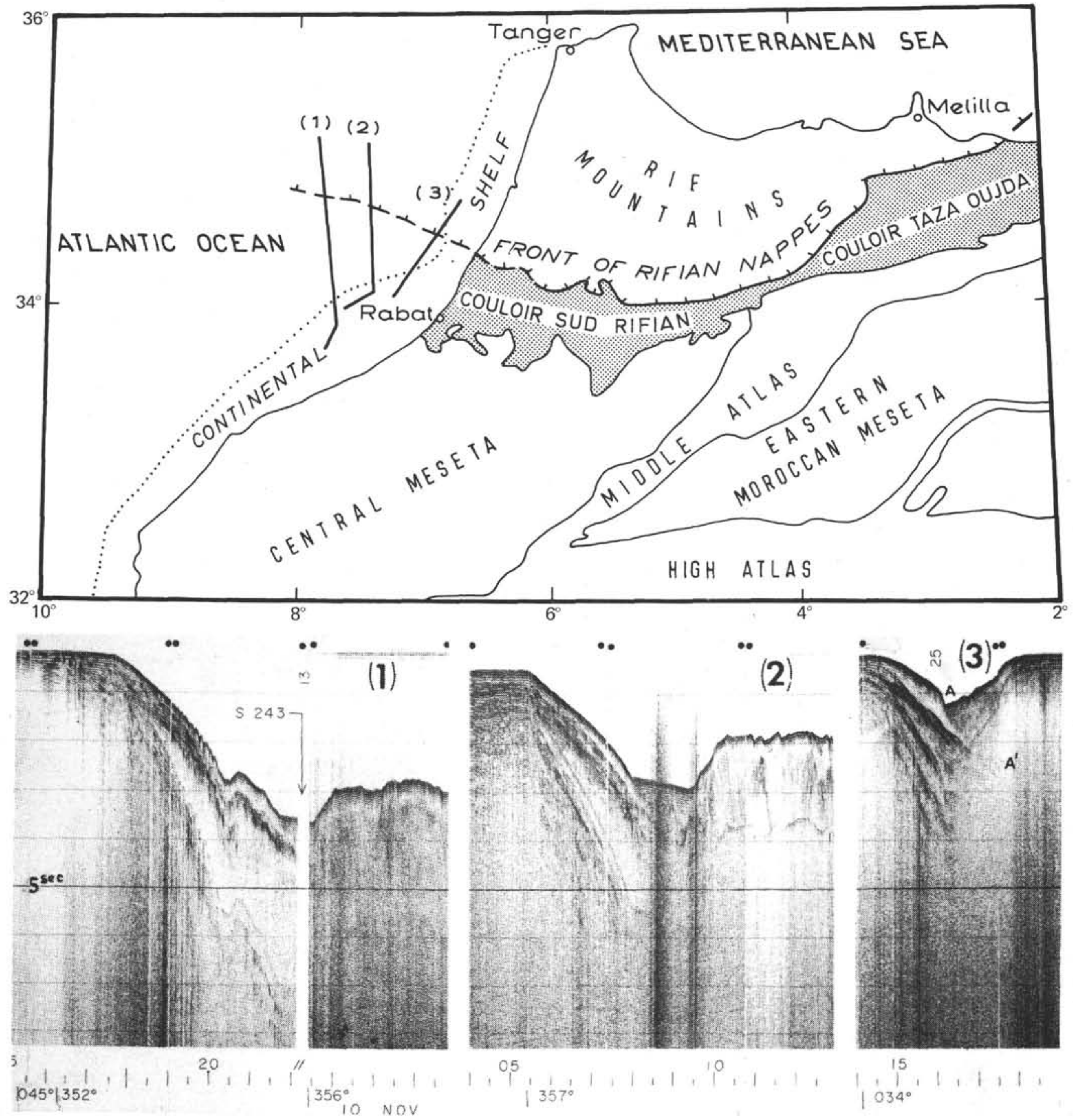


Figure 1. *Documentation of continued tectonic closure in northern Morocco. Underthrusting of the Central Moroccan Meseta occurs beneath northern offshore sedimentary nappes of the Rif zone where they extend westward into the Atlantic. Note particularly on profile (3) a diachronicity of the sedimentary fill in the subduction belt, expressed by a thinning of the superficial acoustic transparent layer down the thrust plane. The strong reflector just beneath the transparent layer is thought to be upper Miocene, as indicated by calibration by piston coring into this horizon south of Casablanca. It can be inferred that up to 20 km of crustal shortening (A-A^1) has taken place since deposition of the strong reflecting interface.*

1, laminated gypsum ("balatino" facies) is present, underlain by dolomitic marls, white, with "cloudy" structures, perhaps induced by coring operations, which extend down to 100 cm. Below 113 cm, where a white, distinct streak of white crystals is visible in Section 1, gypsiferous marls contain foraminiferal assemblages which are extremely specialized, oligotypical, and dominated by *Ammonia beccarii.*

A. beccarii is a euryhaline, eurythermal, stenobathyal form which often dominates inner shelf environments all over the world. When found in hyposaline environments it is usually accompanied by a suite of agglutinated forms *(Ammobaculites, Haplophragmoides, Ammotium, Milliammina,* and *Trochammina)* (Boltovskoy and Wright, 1976, p. 147). None of these are found associated with *Ammonia* in the samples from the pre-evaporitic sequence at Site 372. When found in normal saline waters, *A. beccarii* is usually accompanied by various hyaline forms *(Elphidium* and *Discorbis)* and porcellaneous forms *(Quinqueloculina)*. These associates are absent also. When found in hypersaline waters, *A. beccarii* is usually found alone or with an occasional *Elphidium poeyanum* (Boltovskoy and Wright, 1976, p. 148). Because of the presence of *Ammonia beccarii* alone here, the samples containing them probably represent zones covered by shallow waters with salinities in excess of 40%.

This interval is directly underlain, in the topmost part of Section 2 (0-42 cm) by finely laminated, varved, unburrowed marls. When fresh, these laminites were alternately gray and white: six months after storage, the difference was less noticeable, and the laminae did not show up in radiographs of the core. As shown by Figure 2, the white laminae are all extremely thin, whereas the gray laminae show variable thicknesses, from less than 1 mm (long arrow) to one cm or more (short arrow). Some of the gray laminae truncate the white ones (curved arrow), whereas the white laminae never truncate the gray ones.

When processing the varved sediment using normal laboratory techniques, we consistently obtained mixtures of two faunal assemblages which—according to our personal experience—are mutually exclusive: one consisting of planktonic foraminifers and of deep (mesobathyal) benthic forms, the other one consisting of *Ammonia beccarii.* The faunal assemblages in these samples are confusing and require close examination to be interpreted. Occurring with *A. beccarii* are numerous bathyal species, including *Cibicidoides bradyi, C. kullenbergi, Epistominella exigua, Nuttallides rugosus convexus, Oridorsalis umboniferus, Eponides pusillus,* and numerous *Oolininae,* whose presence is difficult to explain in the same sample as *A. beccarii.* Several hypotheses might be offered to account for this mixed assemblage. Perhaps the most obvious is that the *A.beccarii* specimens have been transported into a deep environment from a shallow zone.

If this were so, the *A.beccarii* specimens should show signs of wear from being transported, and their size-frequency distribution should be log-normal (Bucot, 1953). Examination of *A.beccarii* specimens from three samples (Table 1) reveals that both size (maximum diameter) and age (number of chambers) frequency distribution are skewed toward the larger sizes and more adult specimens. This sort of skewed distribution is usually encountered among in situ specimens. If the *A. beccarii* specimens are autochthonous, then the bathyal species must have been transported into a shallow environment. How can this be? If a deep basin becomes desiccated, the strata exposed on the flanks of this basin after the water level drops will contain a deep water assemblage. Downslope movements or reworking of these sediments into the deeper parts of

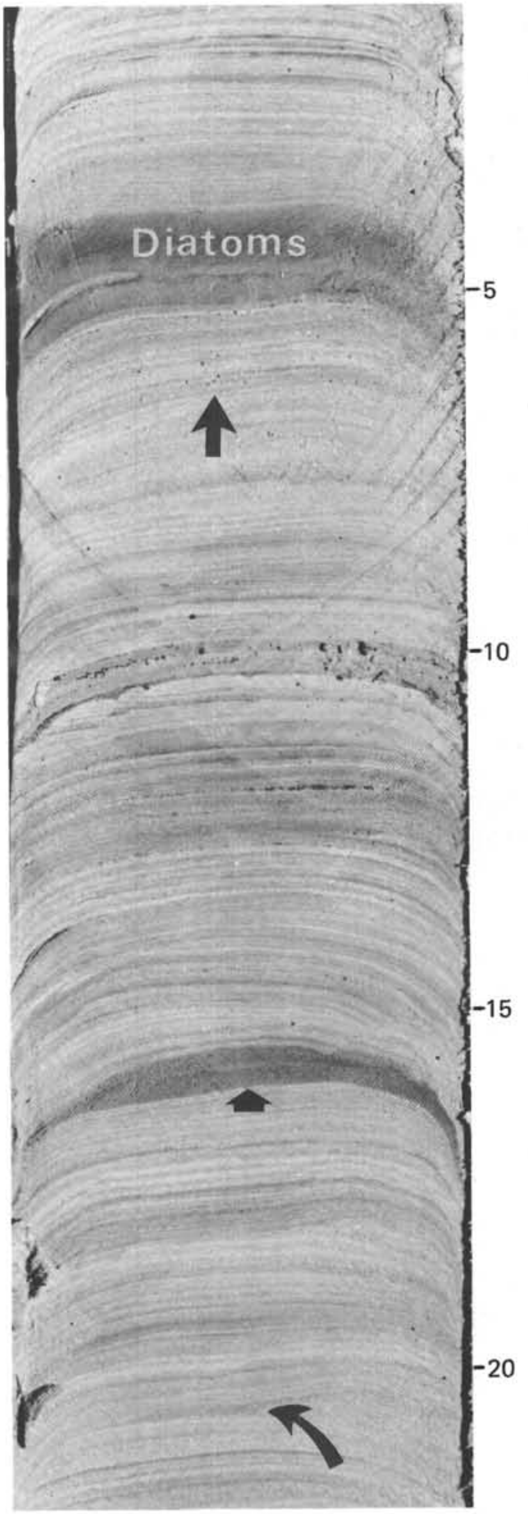


Figure 2. *Upper part of the varved interval recorded in Section 2 of Core 9, Site 372 (Balearic Basin). Explanation of the symbols in the text.*

TABLE 1
Biometric Analysis of *A. beccarii*, Site 372

Sample (Interval in cm)	No. of Specimens	Skewness from Third Moment About Mean		Micro-spheric Forms (%)	Patho-logic Forms (%)	Broken Forms (%)
		Chambers	Diameter			
9-1, 120-122	20	0.07	a	16	15	45
9-2, 0-2	97	0.28	0.20	26	3	30
9-2, 28-34	13	0.73	a	15	8	31

[a] Insufficient whole specimens for analysis.

the Balearic Basin covered with shallow water would displace bathyal species into the shallow water *A. beccarii* biotope.

None of the individual bathyal species were abundant enough to allow the transport hypothesis to be tested by calculating the size-age frequency distribution. However, examination of the size of the entire suite of bathyal species which have subspherical tests did shed some light on whether or not they might have been transported.

Spherical, hollow benthic foraminiferal tests behave hydraulically as quartz grains which are 1/2 to 1/3 the diameter of the test (Haake, 1962). Consequently, where there was abundant detrital material in a sample, the sizes of the clastic grains were compared with the sizes of the foraminiferal tests. If they have different equivalent sizes, they probably were not transported together, particularly if the foraminiferal tests are larger. If they have similar sizes, they may have been transported by the same agent. Table 2 shows that the clastic grains and the bathyal specimens are very similar in size. Because these specimens are partially filled and therefore not completely hollow, the true equivalent diameter probably lies closer to the upper limit of the estimate. The equivalent sizes of the *A. beccarii* specimens are considerably larger than the enclosing sediment particles. The *A. beccarii* fauna therefore appears to be in place and the bathyal species allochthonous.

There are additional indications of reworking among the planktonic foraminifers: the poor preservation of the tests and the co-occurrence of taxa whose ranges are known not to overlap, as *Globigerinoides subquadratus, Globigerina multiloba, Globorotalia siakensis, G. acostaensis, G.* aff. *suterae* (see Cita, Colalongo, et al., this volume).

Our attempt to obtain non-mixed faunal assemblages from pure lithologies was frustrated. The white laminae are too thin for this purpose. The only gray layer thick enough to be carefully sampled (see Figure 2) was an upper one, from 4.5 to 5.5 cm in Section 2. The size of the pure gray sediment processed however was such that the sand-size fraction yielded just a few planktonic foraminifers. No specimens of *Ammonia beccarii* were found. This gray layer is the only level from the varved interval where we found diatoms: they are marine forms, belonging to the genus *Coscinodiscus.* Their presence does not contradict the hypothesis put forward above.

Since *Ammonia beccarii* was consistently recorded in the white sediments overlying the varved interval and underlying the evaporites, but was never recorded in the gray sediment underlying the varved interval (the lowermost record of this euryhaline species is from 41 cm in Section 2, see Figure 3), we surmise that the specimens in the "mixed" assemblages are from the white laminae.

TABLE 2
Comparison of Equivalent Diameters of *Ammonia beccarii*, Sub-spherical Bathyal Specimens, and Clastic Grains, Sample 372-9-2, 0-2 cm

	A. beccarii		Bathyal Sub-spherical Benthic Foraminifera		Clastic Grains
	Actual	Equivalent	Actual	Equivalent	
Mean (μm)	245	82-123	145	48-74	74
Standard Deviation	60		37		25

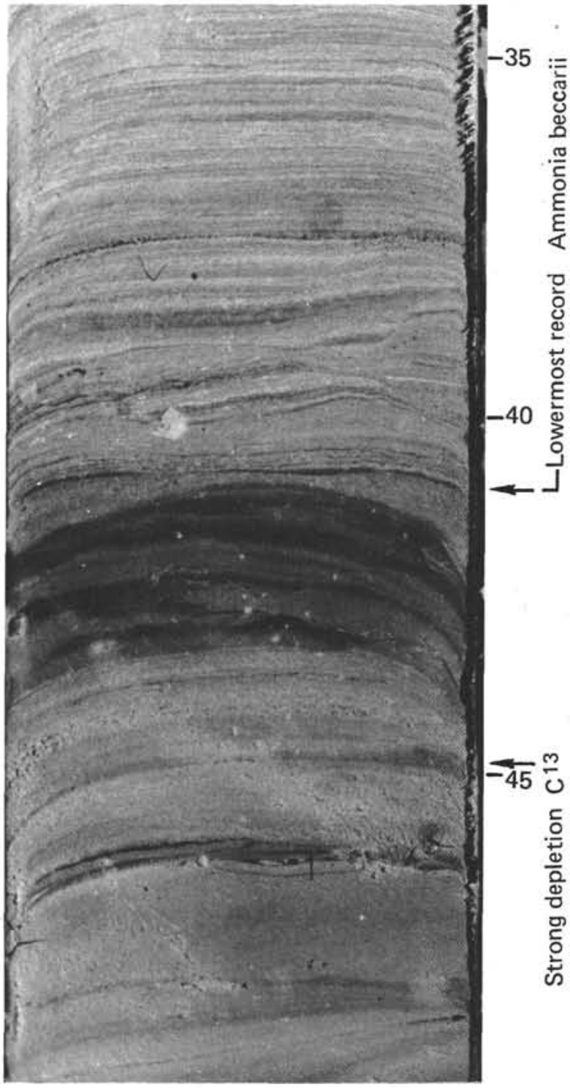


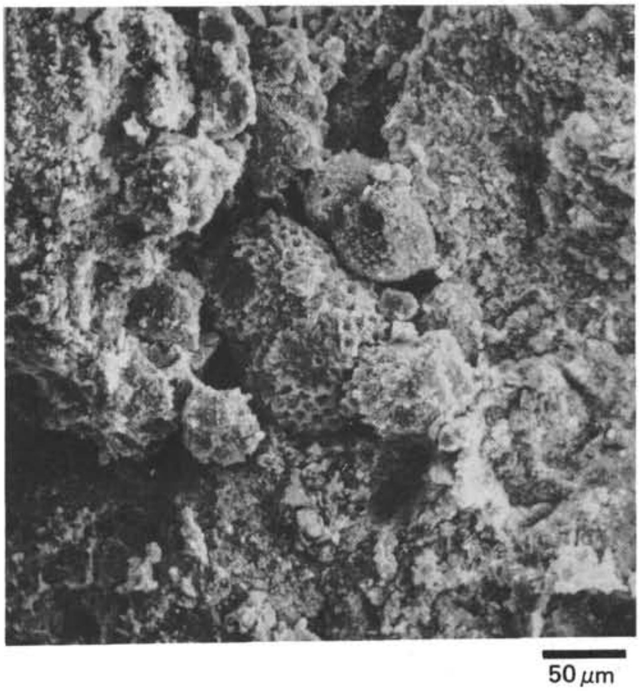
Figure 3. *Lower part of the varved interval recorded in Section 2 of Core 9, Site 372. A hiatus of some 6 m.y. is present at the base of the Messinian laminites.*

There are several indications that conditions were becoming increasingly hostile in this environment just before the onset of an evaporation cycle (see Table 1). The number of *A. beccarii* specimens that are deformed or exhibit pathological characteristics increases upward in the section. This is a well-documented indication of an unfavorable environment (Boltovskoy and Wright, 1976, p. 86). In addition, a large proportion of the specimens of this species has a broken final chamber. This observation also suggests a stressed environment. The proportion of microspheric tests is unusually high for this species. Under normal conditions only about 1-3 per cent of the tests are microspheric. Hofker (1930) observed that a variety of *A. beccarii* showed increasing proportion of microspheric tests when it occurred near its temperature- and salinity-tolerance limits. The relatively high proportions of microspheric tests in the pre-evaporitic sediments may indicate an unfavorable environment, even for the highly tolerant *A. beccarii*. Stable-isotope investigations on the carbonates from Sections 1 and 2, Core 9 by Pierre and Fontes (this volume) and McKenzie and Ricchiuto (this volume) show that moving upward through Core 9, the O^{18} content of the carbonate sediment becomes progressively, although only slightly, more positive. The change in C^{13} is more dramatic. Between 64 cm and 45 cm in Section 2, there is a significant depletion in C^{13} by 3.5‰. This depletion continues to a low value of –5.6‰ at 87 cm in Section 1, and is interpreted as the result of an important terrestrial contribution, suggestive of a lagoonal environment.

Messinian Laminites

Finely laminated, varved, non-evaporitic sediments occur at several levels in the Mediterranean Evaporite. A common characteristic of these laminites is the absence of burrowing (see Figures 2 and 3). Generally speaking, they indicate a low-energy environment with semistagnant bottom conditions. The repetitive alternation of dark and white layers suggests annual or seasonal cyclothems, as is the case for true varves of periglacial lakes. If the cycles were annual, the sedimentation rate must have been extremely high, of the order of 100 cm/1000 yr.

The laminites of Core 9, Section 2, Site 372, when examined along the bedding planes with the binocular microscope, indicate that the white layers are very fine grained and structureless, whereas the gray layers are much coarser and more detrital. The difference is even greater when the laminae are observed with the SEM (Figures 4-6). The gray laminae have no peculiarities (Figure 4); they are fossiliferous, but coccoliths are not abundant and planktonic foraminifers appear to be reworked. The white laminae are much more interesting. Some of them are extremely rich in calcareous nannofossils (Figure 5). The assemblages are poorly diversified: sometimes they appear monospecific (Müller, C., this volume).



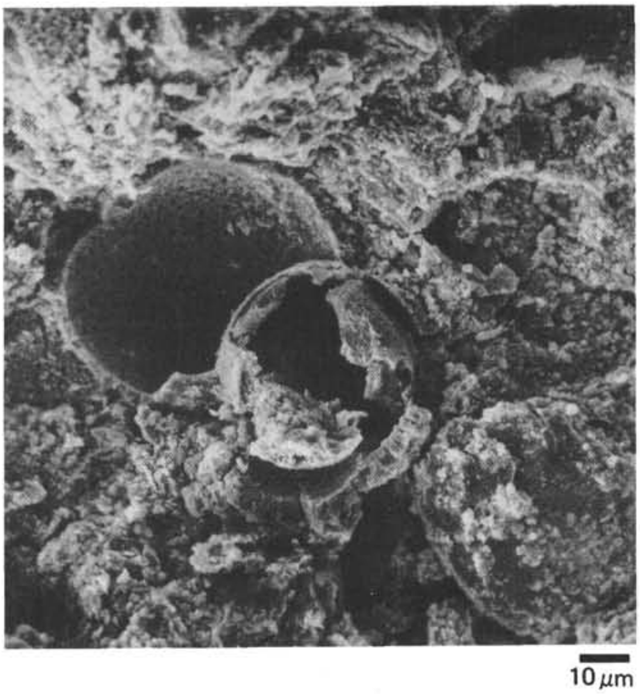


Figure 4. *Gray lamina of the varved interval (Sample 372-9-2, 0-2 cm) parallel to the bedding plane, showing detrital minerals and planktonic foraminifers. The latter are interpreted as reworked.*

The three intervals of white laminae investigated with the SEM, from 0-2 cm, 36-40 cm, and 40-41 cm, respectively, all contain several puzzling submicroscopic organisms (see Figure 6), which have been interpreted as conids of fungi and are described elsewhere in this volume (Franz et al., this volume). It is not known if they are fossil remains or the result of sample contamination. They were commonly found in Oxfordian sapropelic claystones from DSDP Site 330 on the Falkland (Malvinas) Plateau; they are also

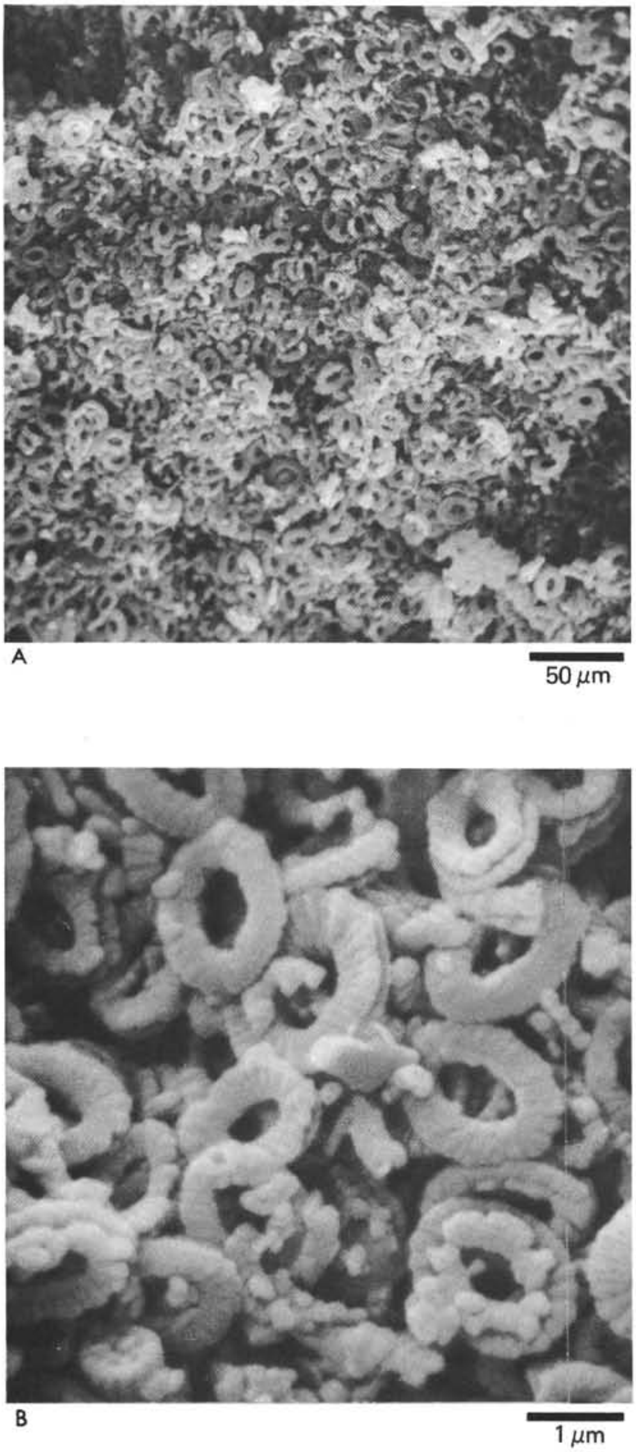


Figure 5. *White lamina of the varved interval (Sample 372-9-2, 0-2 cm) parallel to the bedding plane, showing coccolith blooms, consisting of small forms of* Reticulofenestra *sp.*

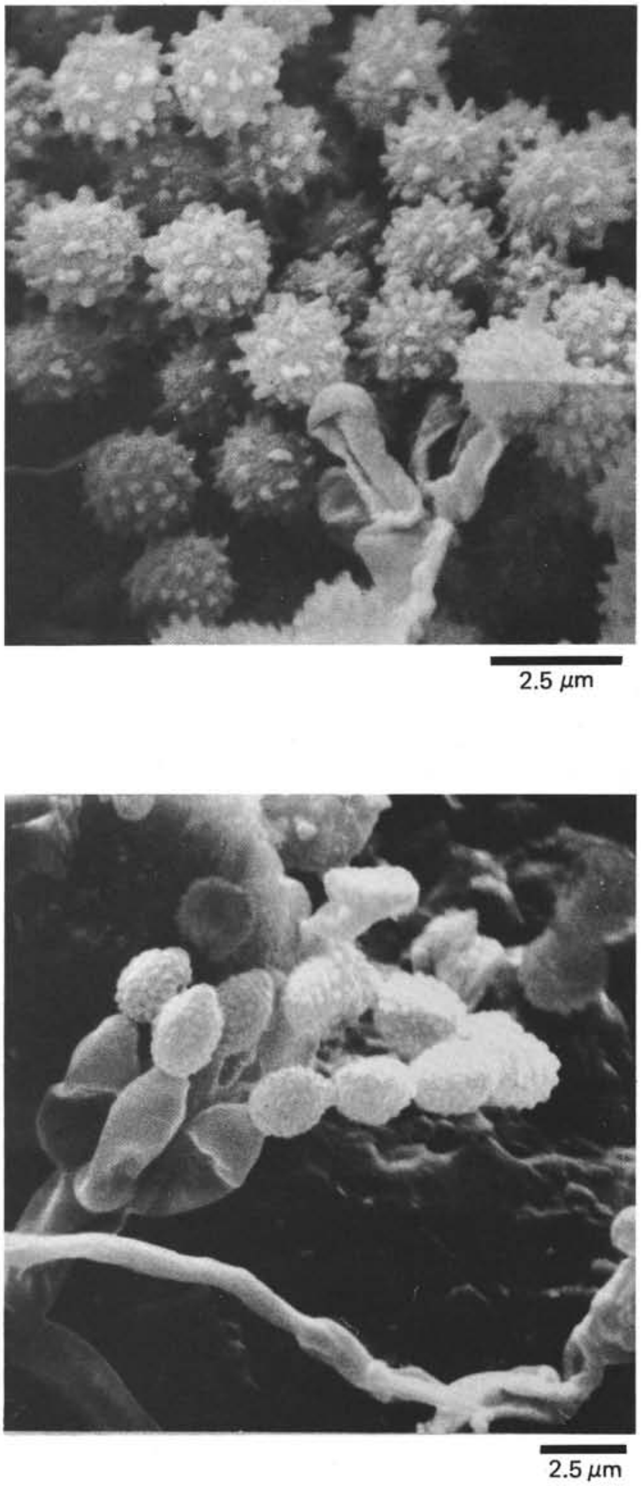


Figure 6. *Conids of fungi found in the white laminae of the varved interval (the SEM photo above is from 0-2 cm in Section 2 of Core 9, Site 372; the photo below is from 40-41 cm in the same section; both are parallel to the bedding plane). Further details on these fossils (?) are in Franz et al., this volume.*

present in Albian, Aptian, and Maestrichtian samples from the same site (Frank Wind, personal communication, 1976).

Similar laminites were recovered at Site 124 (Balearic Basin) and described in detail (Ryan, Hsü, et al., 1973, p. 152-161). A comparison of samples taken from Core 7-1, Site 124, with those from Core 9-2, Site 372, using the same methods described above showed that:

1) the laminites at Site 124 are coarser grained, more silty, and firmer than those from Core 9, Section

2, Site 372. Their color is much more persistent: in fact, after five years of storage, the gray laminae show up much more clearly than in Core 9, Section 2 after five months of storage. This suggests that the dark hues are only in part related to organic matter, which would oxidize very rapidly.

2) In contrast to Site 372, no blooms of coccoliths have been recorded at Site 124. Calcareous nannofossils are present both in the gray and in the white laminae, but are never abundant. No fungi have been recorded in the white laminae at Site 124. The white laminae show textures not unlike those of the gray laminae (Figure 7), whereas at Site 372 there is a marked textural difference in laminae.

3) The sand-size fraction is richer in detrital minerals at Site 124 than at Site 372. The fossil assemblages are similar, including planktonic foraminifers, benthic forms of deep habitat, *Ammonia beccarii,* and fragments of smooth-shelled ostracodes.

The laminite facies is often cyclically repeated between gypsum beds, in both the land outcrops of the Periadriatic Trough, in Sicily,[2] and the drillcores. The laminae are both azoic and biogenic, probably controlled by salinity changes during subaqueous stages. The occurrence of some "lago-mare" fauna suggests episodes of transient filling when river input exceeded that of the open ocean and the sum of both exceeded evaporation. The varve-like appearance, if it represents seasonal blooms or seasonal salinity changes or seasonal input of fine sediments from rivers, delta, and coasts, would suggest sedimentation rates of more than 100 m/m.y.

Caution is needed in deciphering the faunal content of this facies, and that of each alternate sediment color and texture has to be examined individually. Episodes of either transient drying or transient filling could have been accompanied by transport of previously exposed slope sediments into the still-subaqueous basin center, producing a complex mixture of allochthonous and autochthonous faunas, representative of different (a) ecological environments, (b) provenances, i.e., slopes, upper and lower, (c) stratigraphic levels, i.e., either reworked presalinity crisis fauna, or intrasalinity crisis fauna.

Evidence of a Hiatus at the Base of the Varved Interval

Below the finely laminated interval described above, the sediments contained in Section 2 (olive-gray marls) show some peculiarities, as follows: (a) faint white laminae (short arrow in Figure 8); (b) white spots or "clouds" (long arrow); and (c) large subspherical concretions detected in X radiographs, subsequently picked and analyzed with the microprobe.

Seven samples were investigated from this interval. The sand-size fraction obtained from all these samples is essentially biogenic, and indicates open-marine conditions with normal salinity and an estimated depositional depth in excess of 1700 meters. The occurrence of fairly abundant pyrite crystals suggests reducing conditions at the sediment/water interface. Planktonic foraminifers from these samples (see range chart in Cita, Colalongo, et al., this volume) include numerous *Globoquadrina* (with the species *altispira* and *dehiscens*), *Globorotalia praemenardii, G. miozea, G. siakensis, G. opima continuosa, Globigerinoides obliquus obliquus*, and *G. subquadratus.*

The absence of *Globigerina nepenthes, Globorotalia acostaensis* and *Globigerinoides obliquus extremus,* and the recorded occurrence of *Globorotalia siakensis* and *Globigerinoides subquadratus*, indicate that the sediment predates the *Globigerina nepenthes* datum and can be assigned to the youngest part of Zone N. 13. This assignment is supported by the nannofossil biostratigraphy (Müller, this volume). As a consequence, and with reference to the time scale of Ryan et al., (1974), the sedimentary expression of over 6 m.y. is missing at the base of the varved interval.

The existence of a hiatus at or near the base of the pinchout of the Mediterranean Evaporite at Site 372 was long argued during scientific meetings on board. The gap is not so obvious in the sediments, and a critical re-evaluation of the fossil record showed that contrary to the preliminary conclusions drawn on the ship, Core 9 is not the sedimentary expression of the onset of the salinity crisis.

The discontinuity now well documented in Section 2 is such that it is possible that the lower part of the Mediterranean evaporite is missing (erosion ? nondeposition on the continental slope ?). The evaporitic cycle recorded beginning in Section 1 of Core 9 can be any one of several basin-wide cycles. Core recovery was so poor in the Mediterranean Evaporite at Site 372 (less than 10%) that we cannot say how many cycles we cored and which evaporitic facies are present there. Core 9 did not show any of the facies which characterize the onset of the salinity crisis in the land record.

The Hiatus in Section 9-2 and the "Messinian Erosional Surface"

An erosional surface was created along the continental margins of the Mediterranean during periods of evaporitic drawdown. Its geodynamic significance has been recently studied by Ryan (1976), on the basis of the stratigraphy of the commercial wells Tramontane 1, Mistral 1, and Autan 1, in the Gulf of Lyon (Cravatte et al., 1974). No evaporitic sediments were recorded at any of these drillsites, which are on the continental shelf well above the depth of the evaporitic pinchout. In all three of these wells a hiatus separates the lower Pliocene open-marine sediments from the middle Miocene open-marine sediments. Laguno-littoral (maybe also fluviatile) sediments are interbedded between the two in the landward wells Tramontane and Mistral.

Using the biostratigraphic information of Cravatte et al. (1974) and the time scale of Ryan et al. (1974), we put the age of the marine sediments immediately underlying the erosional surface at between 13 and 12 m.y. for all three drillsites. This is very close to that calculated for the Serravallian sediments of Section

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[2] Rouchy (1976) recently described coccoliths from the laminites of the "Balatino" in Sicily.

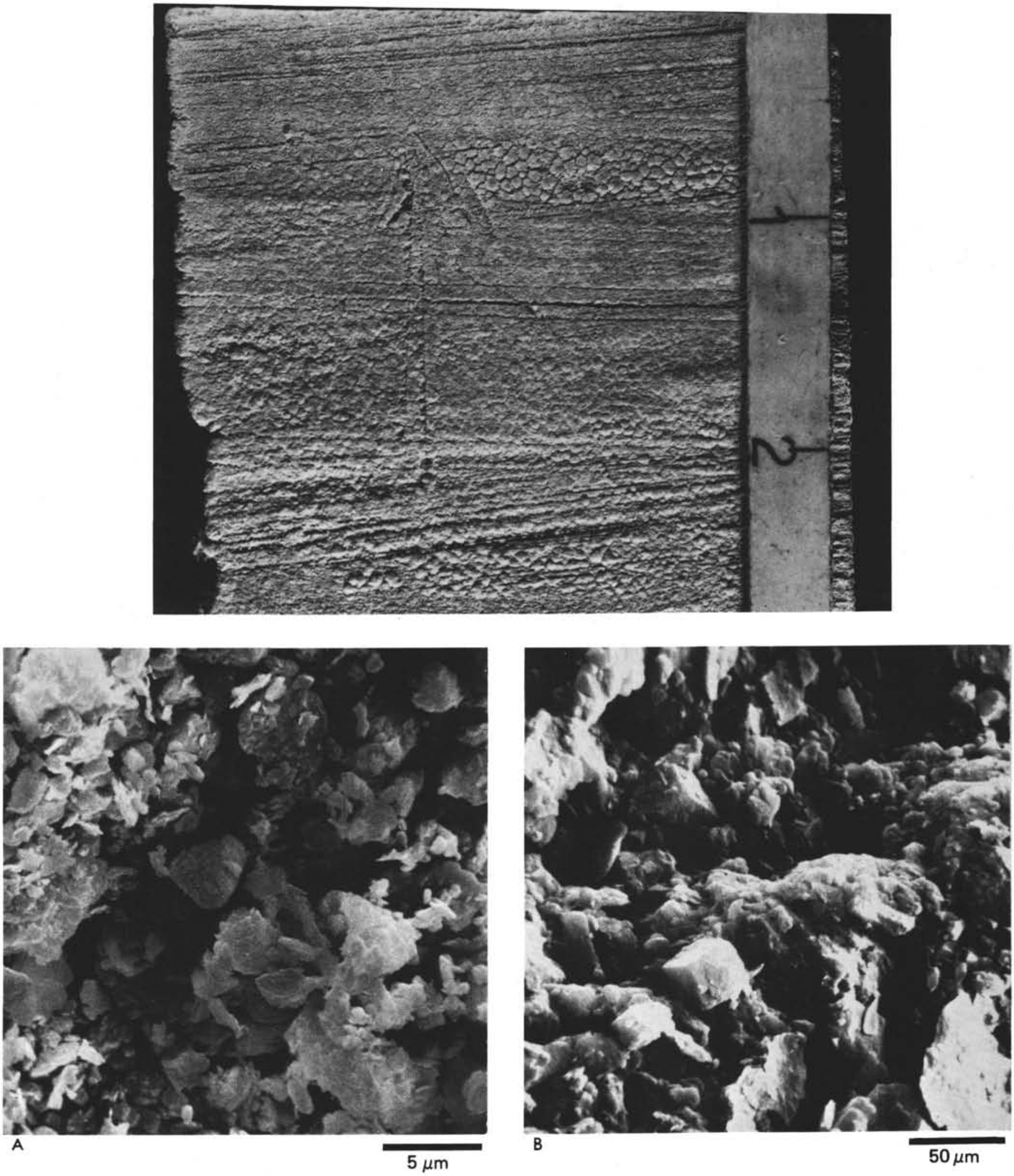

Figure 7. *Laminites from the upper Messinian of the Balearic Basin (DSDP Site 124, Core 7, Section 1, 79-81 cm). Unlike the Messinian laminites cored at Site 372, here the clear laminae (A) do not correspond to coccolith blooms. They do not differ markedly in texture from the gray sandy layers (B).*

9-2, Site 372, using the interpolated age of the *Globigerina nepenthes* datum (12.7 m.y.) and extrapolating uphole the sedimentation rate calculated for a lower interval (see Cita, Ryan and Kidd, this volume).

The Messinian erosional surface extends from the continental shelf across the continental slope, where it has cut away hundreds of meters, and in some instances up to more than one kilometer (Ryan, 1976) of

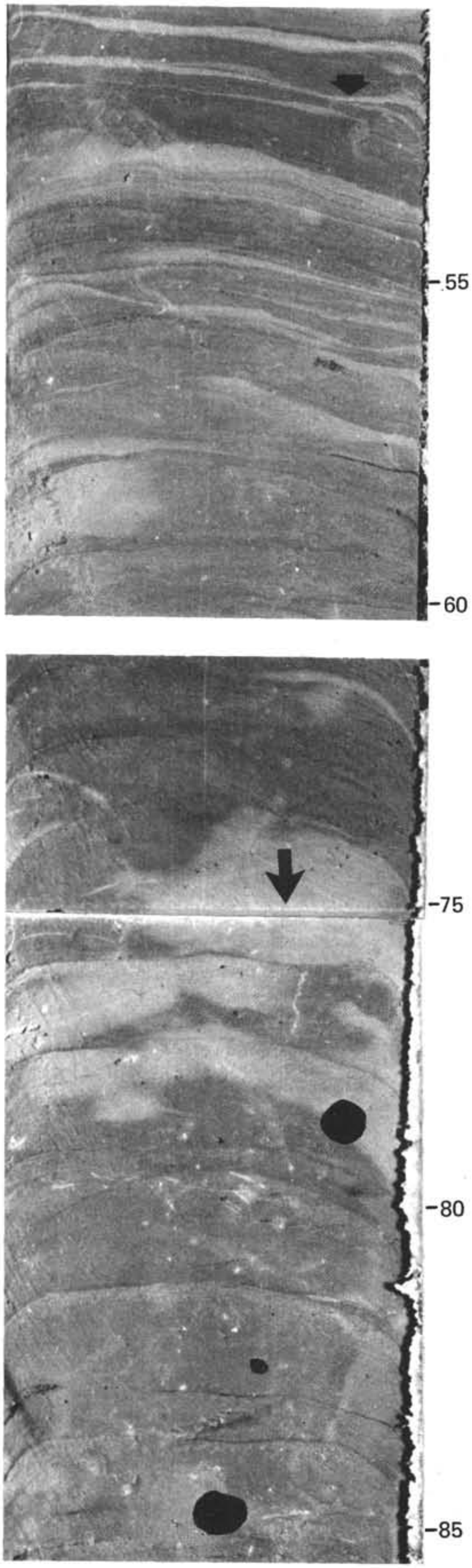

Figure 8. *Olive-gray marls with faint white laminae (short arrow), white spots (long arrow), and manganese concretions (black spots, located after X-radiographs of the core) underlying the varved interval in Section 2 of Core 9, Site 372. The rich foraminiferal faunas indicate the uppermost part of foraminifer Zone N 13 (pre-*Globigerina nepenthes *datum), and the coccoliths are referable to Zones NN7/NN8. The sediment is Serravallian, whereas the youngest elements of the mixed faunal and floral assemblages obtained from the varved interval indicate foraminifer Zone N 17 and nannofossil Zone NN 11 (Messinian).*

sediment. The Messinian erosional surface terminates in the basins below where the evaporites pinch out. It is not yet clear whether it is related to the pinchout of acoustically layered evaporites overlying the flowing salt layer ("couche fluante"), or to the salt body itself, or to the underlying basal evaporites.

The erosional surface in Section 2 of Core 9, Site 372, lies at 200 meters sub-bottom (2895 m sub-sea). The pinchout of the upper evaporites is clearly visible on IFP Profile J 204 (Figure 9), which was used to plan Site 372 and on which the actual drillsite is shown, as well as the pinchout of the salt body (Montadert et al.; Mauffret et al., this volume).

MARINE AND NON-MARINE INTRA-MESSINIAN FOSSIL RECORD

We will discuss here the environmental significance of the fossil assemblages overlying and/or interbedded between the evaporites exclusive of the shallow-water caspi-brackish assemblages, characteristic of the "lago-mare" developed in the latest Messinian in the eastern Mediterranean, which will be dealt with in a later section.

Deep-sea Record

During Leg 13, marine fossil assemblages were consistently recorded in the western Mediterranean drillsites overlying and/or interbedded between evaporitic layers. For further details of faunal lists and environmental interpretations, see the site reports for Sites 124, 132, and 134 (Ryan, Hsü, et al., 1973).

Of the six Leg 42A sites where drilling penetrated the Mediterranean Evaporite, Site 372 is most pertinent to our discussion. No fossils (except a few Upper Cretaceous reworked specimens) were discovered in the only core penetrating the Mediterranean Evaporite at Site 371; all the fossil assemblages from the eastern Mediterranean drillsites (374, 375, 376) involve the problem of the "lago-mare" (see next section).

Core 9, Site 372, and its fossil content and environmental interpretation, have been described in the preceding section. We will treat here Cores 4, 5, and 6, which yield interesting foraminiferal assemblages.

Core 4 consists of olive-gray dolomitic pyritic marl, except for the topmost part of Section 1 (60-62 cm) where lower Pliocene nannofossil-foraminifer ooze is present. The Miocene/Pliocene boundary, as expressed in this core, is considered a drilling artifact.

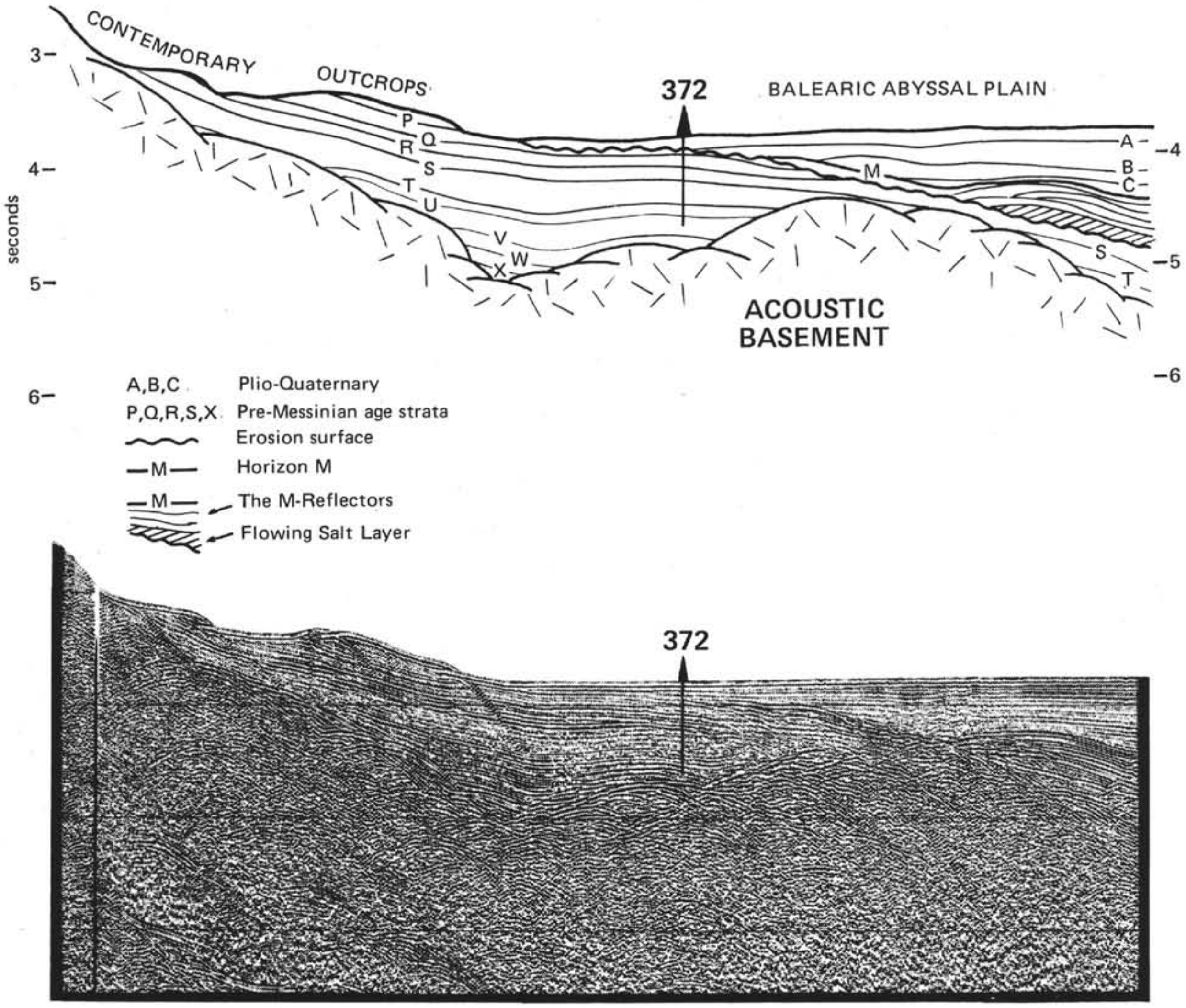

Figure 9. *Configuration of the Messinian erosional surface on IFP Profile J 204, which cuts down to strata 12 or 13 m.y. old at Site 372 (projected). Some of the sediment removed at the site is preserved slightly further upslope. The small trough in the Pliocene-Quaternary cover seaward of the site may be the expression of synsedimentary solution collapse of the underlying flowing salt layer. It is unclear on this profile just how far seaward the erosional surface extends beyond the basin-margin onlap of the salt layer.*

The marls are uniform and structureless. They are unburrowed and contain irregularly spaced thin laminae of pyrite crystals, often oxidized. All the samples investigated are consistently fossiliferous and consistently yield dwarfed foraminiferal assemblages. The presence of dwarfed foraminifers is a common characteristic of not only Core 4 specimens but also of those at Sites 124 and 132 (Cita, 1973a, p. 1052-1053).

Problem of Dwarfed Faunas

The particular environmental conditions which cause foraminifer tests to become larger or smaller than normal are not well understood, although the phenomenon has been often observed. After a study of the literature of dwarfism in benthic foraminifers, Boltovskoy and Wright (1976, p. 90-93) concluded that tests slightly smaller than normal are produced by favorable environmental conditions which allow them to reach early reproductive maturity, but that specimens very much smaller than the ordinary result from inhospitable surroundings which reduce the metabolic rate and therefore the growth process of the organisms. Specimens in Core 4, which are 2 to 3 times smaller than normal, are considered to represent the latter situation.

The occurrence of dwarfed foraminiferal faunas—as distinct from small specimens which are size-sorted by post-mortem transportation in tractive currents or gravity currents—indicates that life was possible in the Mediterranean for organisms adapted to a marine environment, and that ecologic conditions were unfavorable for these organisms. The faunal abundance, faunal diversity, and degree of dwarfness are different, however, at the various levels investigated; this suggests variable degrees of stress. The richest and least restricted faunal assemblage was recorded at 130 cm in Section 9-1, where a number of keeled globorotaliids are present. Similar dwarfed foraminiferal assemblages, even less diversified, occur in the gypsiferous marls interbedded between the finely laminated "balatino" facies gypsum of Section 5-1 and 6-1. We found benthic foraminifers in these samples.

Population Dynamics

We examined benthic foraminifers of Core 4, Site 372, in great detail and used a variety of different approaches to evaluate the environment represented by the sequence. The presence and absence of particular stenobathyal species were noted, as was the proportional contribution of the various species to the fauna. Various measures of population dynamics were calculated to evaluate the stress placed on the fauna by the environment.

The distribution of the depth-significant benthic foraminifers in the sequence is shown in Table 3. These species indicate water depths at least as deep as the upper epibathyal zone. The presence, near the top of the sequence, of such species as *Cibicidoides bradyi, C. kullenbergi,* and *Cibicides wuellerstorfi* argues for water depths in the lower epibathyal or even the upper mesobathyal zone. Littoral and inner shelf species present in the samples, such as *Ammonia beccarii, Bulimina marginata, Discorbis* spp., *Elphidium* spp., *Neoconorbina terquemi,* and *Nonion scaphum,* are represented by large, worn and broken specimens, indicating transport. Transported broken bryozoan fragments also occur in the samples, as do broken carapaces of the euryhaline ostracode *Cyprideis.*

The specimens in all but the uppermost sample (which is lower Pliocene, see above) are significantly smaller than those found in the overlying Pliocene and Pleistocene sediments. A further indication of inhospitable conditions is the proportional contribution of two genera, *Bolivina* and *Cassidulina.* Studies of these two genera in Recent oceans show that their contribution to the benthic foraminiferal fauna is rather constant in the outer shelf and bathyal environments. However, *Bolivina,* and perhaps *Cassidulina,* appears to be more tolerant to oxygen-depleted waters (Smith, 1964; Khusid, 1971; Saidova, 1971; Siellier de Civrieux and Bonilla, 1971; Boltovskoy, 1972; Phleger and Soutar, 1973). Figure 10 shows that the proportions of these two genera in the Messinian faunas are greater than in the overlying strata.

TABLE 3
Percentage Distribution of Selected Benthic Foraminifers, Core 4, Site 372

Taxon	Section and Interval (in cm) 4, CC	2-90	2-60	1-128	1-70	1-60
Articulina tubulosa	2		1			
Astrononion umbilicatulum	1	2	5	3	1	1
Bulimina affecta	2	3	2	6	3	3
B. inflata					1	
Cibicides wuellerstorfi						1
Cibicidoides bradyi			1			1
C. kullenbergi (small)			1	1		
C. kullenbergi (large)						3
Epistominella exigua (deep morphotype)	4	1		1	6	
Eponides pusillus	4	2		1		
Gyroidina umbonata	4	3	2	2	6	
Hyalinea balthica (small)	1	1				
Karreriella bradyi						1
Lagenonodosaria scalaris		1				
Nuttallides rugosus convexus		2			1	
N. umboniferus	2	1	2		1	
Oolininae	1	1	2	3	1	1
Oridorsalis umbonatus		3				8
Pleurostomella acuminata	2	1	3	4	1	3
P. alternans			1	1	1	2
Pullenia bulloides		1				1
Siphonina reticulata		2		1		3
Trifarina occidentalis	3	1		2		1
Number of individuals	180	191	103	157	70	150
Number of taxa	45	67	37	55	34	56

In the Recent Mediterranean, *Bolivina* and *Cassidulina* comprise about 4 and 5 percent, respectively, of the benthic foraminiferal population in the bathyal zone. A possible cause of the abnormally high Messinian proportions is reduced oxygen concentration. Further evidence of oxygen depletion is the absence of burrowing in the sediments and the presence of pyrite.

Not only are the benthic foraminiferal taxa *per se* in a sample indicative of environmental conditions, but so also is the richness of taxa and the evenness of distribution of individuals among the taxa.

Numerous studies of benthic foraminifers indicate that the number of taxa declines under restrictive or stressed conditions. Studies of a variety of organisms

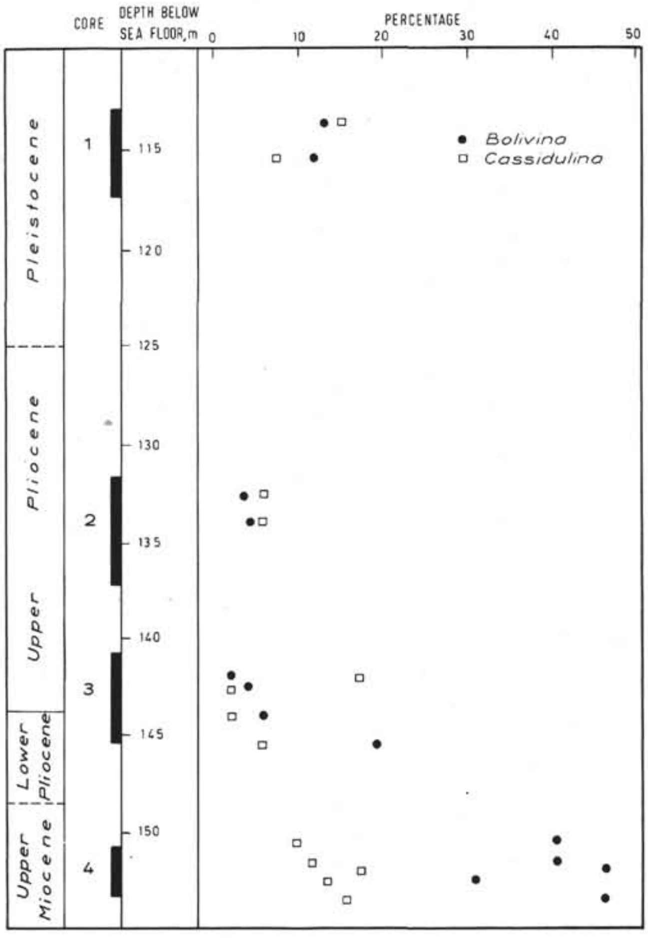

Figure 10. *Distribution of* Bolivina *and* Cassidulina *in Cores 1-4, Site 372.*

including benthic foraminifera seem to indicate that stable environments promote more species evenness (relatively uniform distribution of individuals among taxa; low "dominance") than do environments under stress. A wide variety of indexes have been devised to measure species evenness and/or richness. Figure 11 shows the distribution of species evenness and species richness in the post-evaporitic sequence of Site 372. In the case of species evenness, values range from zero (absolute dominance by a single taxon) to unity (all taxa equally abundant). The measure of evenness shown on the figure is calculated as

$$\sum_{i=1}^{S}\left[1-\frac{\binom{N-Ni}{n}}{\binom{N}{n}}\right]$$

where,

N = number of individuals in the sample,

N_i = number of individuals in the i^{th} sample,

S = number of species in the sample.

This parameter was first used by Pelto (1954) in lithostratigraphic analysis. It and variants on it have been used to examine benthic foraminifers in both Recent (Gibson, 1966; Buzas and Gibson, 1969; Beerbower and Jordan, 1969) and fossil (Gibson, 1968) environments.

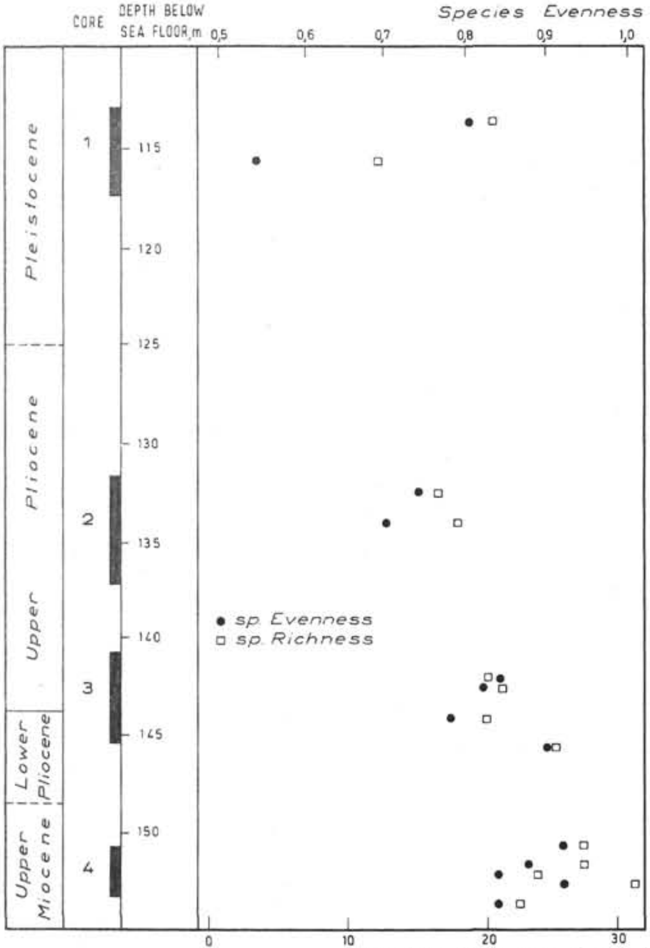

Figure 11. *Population dynamics, Cores 1-4, Site 372.*

In the case of species richness, the problem is to make the sample size uniform by calculating the number of species that would be found if random sampling were conducted on a sample of fixed size whose individuals were distributed among the taxa in the same fashion as in the actual sample. The expected number of species is calculated by summing the probabilities of finding each species in the random sample (Hurlbert, 1971).

$$-\frac{\sum_{i=1}^{S}\frac{Ni}{N}\ln\frac{Ni}{N}}{\ln S}$$

where n = number of individuals in the comparison sample

and $n \leqslant N$.

It is apparent from Figure 11 that both the species richness and evenness show little change from the Messinian (where they are high) to the Pliocene. From the point of view of population dynamics the latest Messinian faunas were rather diverse.

These dwarfed benthic and planktonic foraminiferal faunas of Core 4 may have been deposited under stress conditions which developed during the initial restriction of the basin ("Tripoli" stage). They may then have redeposited by erosion from slopes exposed during evaporite deposition in the deep basins. The benthic tests do not have the appearance of being reworked, however.

Another possibility is that these tests are the result of intra-salinity crisis blooms in a stenohaline transitional belt between hypersaline basin centers and hyposaline delta mouths and lagoons. However, if this is the case, it is difficult to explain the bathyal nature of the foraminiferal assemblages.

The source of the dwarfed faunas is clearly one of the many unresolved questions, and takes its place with the list of such questions at the end of this chapter.

Other Findings

A diatom flora including species epyphitic on bottom-living algae was found at Site 124 in dolomitic marls containing diatomaceous layers (Core 13, approximately 65 m from the top of the Mediterranean Evaporite). The diatom flora was interpreted as follows: "autochthonous brackish-water and fresh-water forms indicate the presence of shallow-water, landlocked littoral area" (Hajos, 1973, p. 949). Restudy of the diatom flora of Site 124, Core 13, by Schrader and Gersonde (this volume) showed an upward change from limnic-brackish to brackish marine conditions in the Messinian. They postulate anoxic bottom conditions in water depths of 0-20 meters, which underwent numerous salinity changes (15-30°/₀₀) caused by periodic influx of marine waters.

Bertolani Marchetti (in Bertolani Marchetti and Cita, 1975) studied the pollens from the Site 132 (Tyrrhenian Rise) Mediterranean Evaporite (Cores 23-26). The good preservation of the pollen grains and the homogeneity of the pollen assemblages argue against long-distance transportation. Arboreous plants are numerically dominant; the climatic conditions differ from one level to another. Non-arboreous plants (including up to 14% *Chenopodiaceae*) in the assemblages indicate marshy, salty coastal plains. There is evidence of depressed vegetational belts, related to low-standing sea level. This interpretation is supported by studies on the clay minerals (H. Chamley, personal communication, 1976). He found clay minerals originating from poorly drained soils of depressed coastal areas.

No ostracode faunas were found in the Messinian marls interbedded with the evaporites, except the *Cyprideis* assemblage in the Levantine Basin (DSDP Site 129A). This type of faunal assemblage will be dealt with in the following section.

From the observations above, it is clear that the deep-sea record shows autochthonous marine faunas in the intra-evaporitic marls, and so indicates marine and non-marine conditions in the Mediterranean during the "salinity crisis."

Land Record

The existence of in situ marine faunas in marls interbedded with gypsum layers in the "Gessoso-solfifera" Formation has recently been questioned (Decima and Sprovieri, 1973). These authors report that in Sicily open-marine bathyal foraminiferal faunas consistently occur with *Cyprideis* and *Ammonia beccarii tepida,* which indicate brackish, shallow water conditions. We concur with Decima and Sprovieri's interpretation that the planktonic and deep benthic foraminifera are reworked. This interpretation is based on the assemblages from the topmost part of the Messinian in Sicily ("Gessi superiori" or "Gessi di Pasquasia" sensu Decima and Wezel, 1973), and cannot be extrapolated to the entire formation.

Sturani (1975, p. 55-56) recorded marine faunas above the gypsum in the Rio Mazzapiedi section, where the stratotype of the Tortonian stage has been defined. The fauna consists of benthic foraminifera *(Elphidium, Ammonia)*, bivalves, including the genus *Pychnodonta,* and brachiopods and *Posidonia.* Sturani insists on the autochthony of the assemblages, as shown by the occurrence of leaves of *Posidonia oceanica,* which cannot be easily transported. Both *Posidonia* and brachiopods are stenohaline, so their occurrence proves the re-appearance of normal, or quasi-normal shallow marine conditions during the Messinian "salinity crisis."

Similar indications of normal marine (though not necessarily deep-marine) conditions re-occurring during the salinity crisis are reported by Salvatorini (1975, p. 45) in the basin of Radicondoli in Tuscany, a tributary of the Tyrrhenian Basin. Salvatorini found marls with the stenohaline ostreid *Pychnodonta navicularis* interbedded between the lower gypsum bed (some 80 m thick) and the second gypsum layer (some 50 m thick). The ostreids are associated with echinoids, small pectinids, and large foraminifera.

These new findings support the evidence previously obtained from the deep-sea record (Ryan, Hsü, et al., 1973; Cita, 1973a, b, c), that marine faunas which can be safely interpreted as autochthonous do exist in the intra-evaporitic marls.

THE LATE MESSINIAN "LAGO-MARE" OF THE EASTERN MEDITERRANEAN BASINS

A Semantic Foreword

This section requires a semantic foreword because it deals with a set of conditions which occurred near the end of the Messinian in the eastern Mediterranean (and perhaps to some extent in the west), and which may have no modern counterpart. Before discussing models, we have to clarify the definitions, significance, and application of some terms which have been used in the past with reference to the late Messinian.

Lac Mer: This term was introduced into the geological literature by Gignoux (1936), who took it from "the Russian geologists" (op. cit., p. 622), with reference to the brackish fauna with *Congeria* characteristic of the Pontian stage.

The Pontian in its type-area (Crimea peninsula) overlies restricted marine sediments of the Sarmatian stage. The lac-mer environment of what is now called the eastern Paratethys (Senes, 1975) is unrelated to the Messinian evaporites. Indeed, there are no upper Miocene evaporites in the eastern Paratethys, but oligohaline facies instead. Also, there is no evidence of a water level different from worldwide sea level in the eastern Paratethys.

Lago-Mare: This term is currently used by Ruggieri, whereas the expression "*Melanopsis* beds" is used in earlier publications (Ruggieri 1962, 1967). Apparently a translation of Gignoux's "lac mer," the term has a somewhat different meaning. Ruggieri (1967, p. 286) says, "The Mediterranean was transformed into a series of lagoons, which either dried up, or became gradually desalinified, as in the present-day Caspian. These basins of reduced salinity are characterized in the western Mediterranean by gastropods of oligohaline, warm-water facies, belonging to the genus *Melanopsis.*"

The concept of a cryptodepression is implicit in Ruggieri's model; the stratigraphic superposition of the "lago-mare" facies to the evaporitic facies is not clearly stated.

Lagoon: The *Glossary of Geology* (AGI, 1973) gives four different definitions of a lagoon. The first is the classical one, referring to a salt-water body communicating with the open sea; the second refers to a shallow fresh-water pond communicating with a larger lake or river; the third applies to atolls; and the fourth to other coastal features.

The term *lagoon* has been used for late Messinian environment of the Mediterranean, though the environmental reconstructions do not correspond exactly to any of the numerous definitions of the term. This is why it is used with quotation marks (see Vismara Schilling et al., in press). The most prominent indication, not present in any of the above definitions, is that of a cryptodepression.

Alkali Lake: The *Glossary of Geology* (AGI, 1973) defines an alkali lake as a salt lake, commonly found in an arid region, whose waters contain in solution large amounts of sodium carbonate and potassium carbonate, as well as sodium chloride and other alkaline compounds. Examples are Lake Magadi in the Eastern Rift Valley of Kenya and soda lakes in Mexico and Nevada.

This term has been used by Cita and Ryan (1973) in the light of the deep-basin desiccation model (see Figure 12) for the latest Messinian of the eastern Mediterranean, on the basis of the findings of DSDP Leg 13 at Site 129.

The term "alkali lago-mare" was used by Sturani (1974, p. 62) with reference to the latest Messinian, as an environment post-dating deposition of the evaporitic facies. We quote (translating): "The continental influx of fresh continental waters would progressively

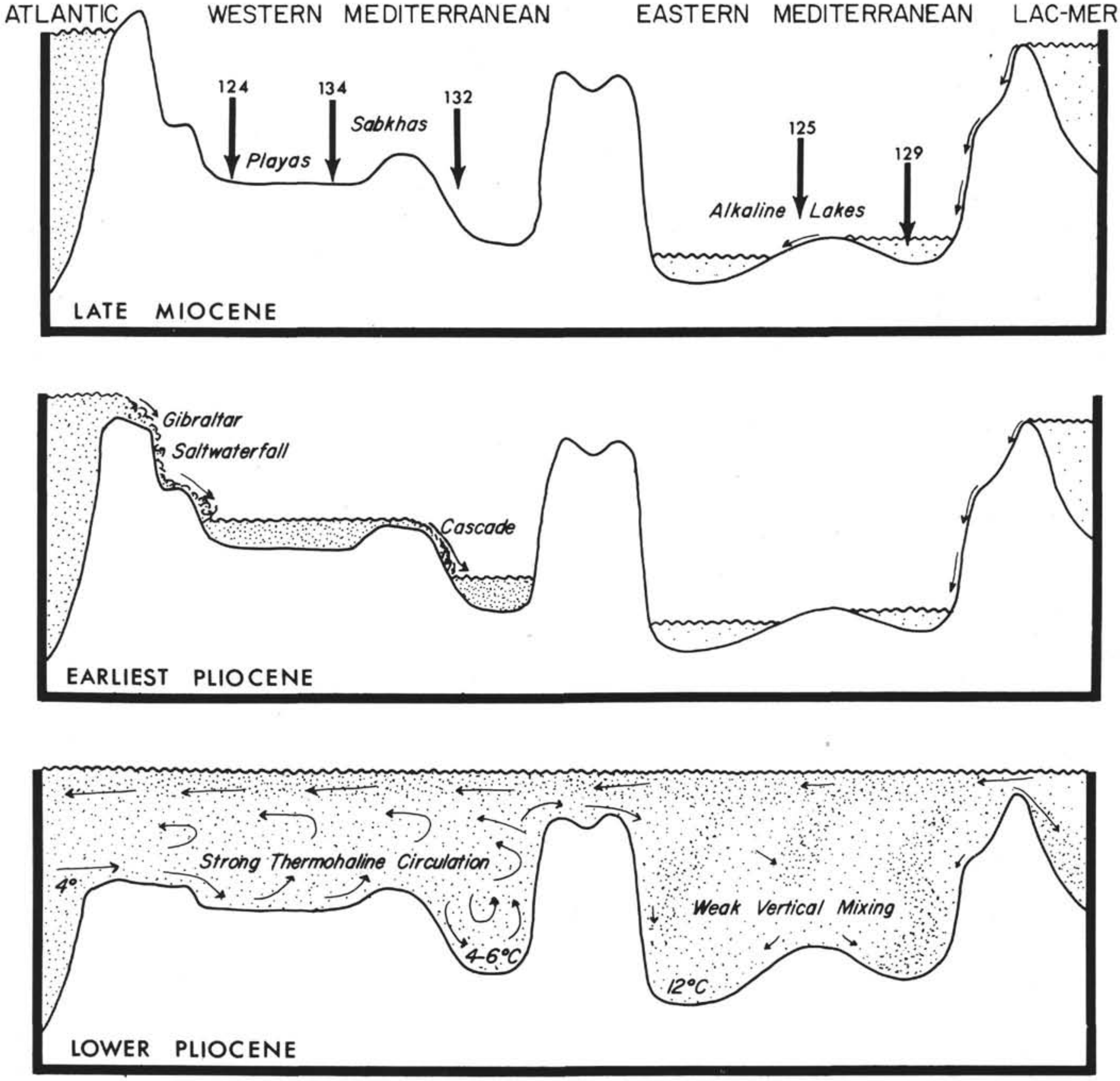

Figure 12. *Stages in the desiccation, flooding, and oceanic circulation in the Mediterranean Sea, at the end of the salinity crisis (after Cita and Ryan, 1973).*

change the residual salinity, finally transforming the entire closed system in an alkali lago-mare."

Colalongo et al. (in press) use the term "alkali-water lagoon" for the upper Messinian "Colombacci Formation" of Emilia. An alkaline condition is recorded by the presence of well-crystallized and abundant montmorillonite (Tomadin, personal communication) and to the presence of precipitated dolomite (Sartori, personal communication).

Deep-sea Record

The most extensive record of unusual conditions in the late Messinian is found at Sites 375 and 376 on the Florence Rise and at the edge of the Antalya Abyssal Plain near Cyprus.

Cyprus Sites (375-376)

Lithologic Unit V, with a total thickness of 85.5 meters in the continuously cored Site 376, consists of nannofossil dolomitic marlstone with interbedded turbiditic sandstone and siltstone. These sediments are described as hemipelagic with proximal turbidites (Chapter 6, this volume). We disagree with the designation of "hemipelagic," since no autochthonous open-marine fossils are present in this unit, and under these circumstances we consider the use of the term "pelagic" incorrect. On the contrary, elements of the caspi-brackish assemblage *Cyprideis* and *Ammonia beccarii* occur consistently (Table 4). This faunal assemblage is also recorded in Core 6, Section 4, from 100 to 141 cm (lithologic Unit IV of Site 375/376 Report, this volume; see Figure 13), and at Site 375, in a 2 cm-thick marly unit (gypsum-bearing nannofossil dolomitic marl, light olive-gray) underlying the lower Pliocene oozes and overlying the evaporites.

The dominant color of the sediment is olive-gray, but black sapropelic layers, rich in organic carbon, indicating stagnant conditions, occur at various levels; for instance, in Core 8, Section 2, Site 376, four discrete sapropelic layers are present. All these sapropelic sediments are unburrowed, which indicates that conditions at the sediment/water interface were unfavorable for life, or were so rapid in sequences as to preclude repopulation.

A 20 cm-thick limestone layer occurs in Core 11, Section 2 (see Figure 14). This white laminated fine-grained limestone is similar in structure, texture, and composition to the "Colombacci" of the Periadriatic Trough (Selli, 1954; Colalongo et al., in press; Casati et al., in press).

Two analytical findings are considered important (see Mélières et al., this volume): (a) the NaCl content in sediments from lithologic Unit V averages 10‰. This value, which is about one-third of NaCl content in normal seawater, is in sharp contrast with those measured in Cores 1-6, Site 376; and (b) the dolomite content unlike the calcite content, is much higher in the upper part of lithologic Unit V than in Cores 1-6. Since dolomite is a precipitate, and calcite a biogenic secretion, the drastic change recorded exactly at the Miocene/Pliocene boundary offers one additional indica-

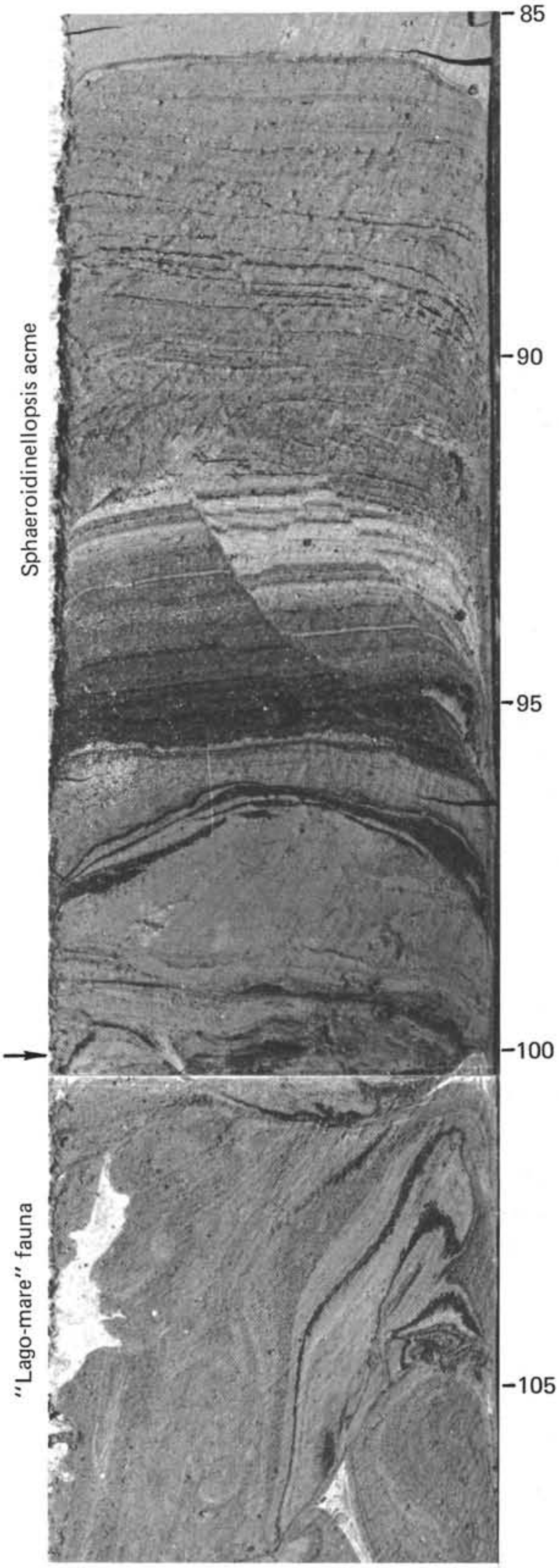

Figure 13. *Core 6, Section 4 of Site 376, showing the position where the highest record of the* Cyprideis pannonica – Ammonia beccarii *faunal assemblage has been recorded (arrow).*

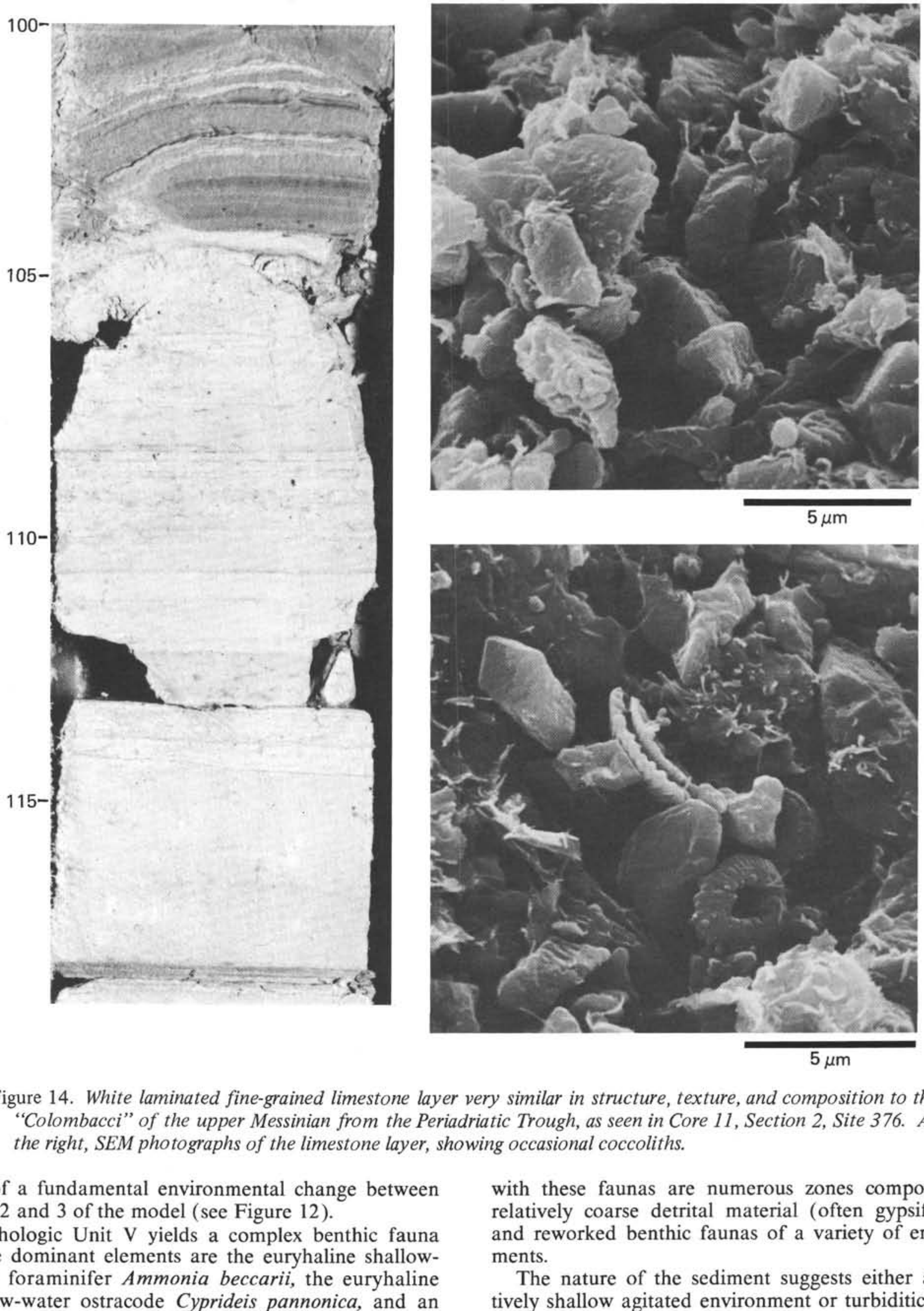

Figure 14. *White laminated fine-grained limestone layer very similar in structure, texture, and composition to the "Colombacci" of the upper Messinian from the Periadriatic Trough, as seen in Core 11, Section 2, Site 376. At the right, SEM photographs of the limestone layer, showing occasional coccoliths.*

tion of a fundamental environmental change between Steps 2 and 3 of the model (see Figure 12).

Lithologic Unit V yields a complex benthic fauna whose dominant elements are the euryhaline shallow-water foraminifer *Ammonia beccarii,* the euryhaline shallow-water ostracode *Cyprideis pannonica,* and an inner-shelf foraminiferal fauna very similar to that found in rocks of comparable but not identical age in the Vienna Basin and the Gulf of Suez region. Mixed with these faunas are numerous zones composed of relatively coarse detrital material (often gypsiferous) and reworked benthic faunas of a variety of environments.

The nature of the sediment suggests either a relatively shallow agitated environment or turbiditic transport of near-shore sediments into a deeper basin. In the latter case the faunas associated with these sediments should show signs of transport and selective sorting by size. These characteristics might occur also in shallow, highly turbulent water, but their absence in a sample is a strong indication of in situ deposition.

The size and age distributions of *A. beccarii* in several samples were studied (Table 4); they show in several cases that the shallow-water assemblage is clearly in place.

The specimens of *Cyprideis pannonica* in Samples 376-9-2, 135 cm and 376-9-2, 138 cm are strongly skewed toward the larger sizes, a characteristic of in situ populations. A biometric examination of the *Cyprideis* fauna in Sample 376-9-2, 135 cm (Figure 15) shows that 5 of 8 larval instars are present and that the proportion of broken carapaces is small. If the specimens had been transported any significant distance, they would be sorted by size and would exhibit a large proportion of broken fragments. An example of an assemblage which probably underwent transport is in Sample 376-9-2, 120 cm, where the specimens of both *A. beccarii* and *C. pannonica* show negative skewness and a relatively high fraction of fragmented carapaces. A biometric study of the *C. pannonica* carapaces in this sample showed far less distinction between instar stages on a length-height plot. This blurring of molt stages is a consequence of selective sorting during transport.

The dominance of *Ammonia beccarii* and *Cyprideis pannonica* in the faunas suggest continental, shallow, brackish water environment. Both these species are, however, tolerant to hypersaline conditions, and such an environment cannot be excluded. Benson (this volume) points out that we know little of deep hyposaline environments and that *Cyprideis* may be able to inhabit such an environment. The same could be said for *Ammonia beccarii.* A shallow-water environment is the most probable, but we cannot completely rule out a deep setting.

The presence of a more normal inner-shelf assemblage in a lower position in the sequence (below Core 10, Section 3), coupled with fewer specimens of *C. pannonica,* may indicate greater marine influence immediately after deposition of the evaporites. The fauna inhabiting this inner shelf environment is very similar to that found in the central Paratethys (the classical Vienna Basin fauna of d'Orbigny, 1846) and the Gulf of Suez (Souaya, 1966). Above Core 10, Section 3, the fauna is more restricted, and suggests continental conditions similar to those of the Paratethys "Lagomare."

Autochthony Versus Allochthony of the Planktonic Assemblages

Planktonic foraminifers in Lithologic Unit V are absent, rare, or extremely abundant, and evidently were sorted by size.

Reworked faunal assemblages can be readily recognized as such when the range of the taxa is incompatible with the age of the sediment in which they actually occur. Only a few among the foraminifera found in the upper Messinian of the Cyprus sites, however, can be considered reworked on the basis of their range:

Sample 376-11, CC: *Globigerinita dissimilis* (range: Oligocene to lower Miocene), *Miogypsina* (range: uppermost Oligocene to lower Miocene), *Lepidocyclina* (range as above),
Sample 376-12, CC: *Globotruncana* (Upper Cretaceous),
Sample 376-13-3 (47-49 cm): *Heterohelicidae* (Upper Cretaceous),
Sample 376-15-3 (50-52 cm): *Globotruncana* (Upper Cretaceous),
Sample 376-15, CC: Globotruncanas and spinulose Globorotalias indicating lower to middle Eocene.

Most of the planktonic foraminifers that we consider reworked, however, range through the Messinian, so that this straightforward argument cannot be used to support the above statement. This is why Cita (1973b, p. 211) wrote, "Discussion whether the fossil assemblages are autochthonous or not, and to what extent they are in place, may continue forever."

There was considerable debate during Leg 42A about the allochthony of the planktonic foraminiferal tests in the upper Messinian of Site 376. These arguments also occur when the land record is considered. Selli (1973) and Bandy (1975) considered as in place those faunas which represent an open, deep marine environment, whereas Decima and Sprovieri (1973), Ruggieri and Sprovieri (1974), and Casati et al. (in press) reached the opposite conclusion.

The purely paleontological arguments in favor of the environment being subaqueous but non-marine, are as follows:

1) The tests of planktonic foraminifera are often worn, and show a state of preservation which is worse than that of the in situ caspi-brackish fauna.

2) The abundance of planktonic foraminifera is extremely variable (Wright, this volume); they are often entirely absent, but occasionally present in enor-

TABLE 4
Biometric Analysis of *Ammonia beccarii* and *Cyprideis pannonica*, Site 376

	Ammonia beccarii			*Cyprideis pannonica*		
Sample (Interval in cm)	No. of Specimens	Skewness from Third Moment About Mean: Chambers	Skewness from Third Moment About Mean: Diameter	No. of Specimens	Skewness From Third Moment About Mean, Length	Fragments / Whole Specimens
9-2, 120-122	154	−0.08	−0.09	100	−0.25	7.3
9-3, 135				114	0.39	3.1
9-3, 138				130	0.29	2.3

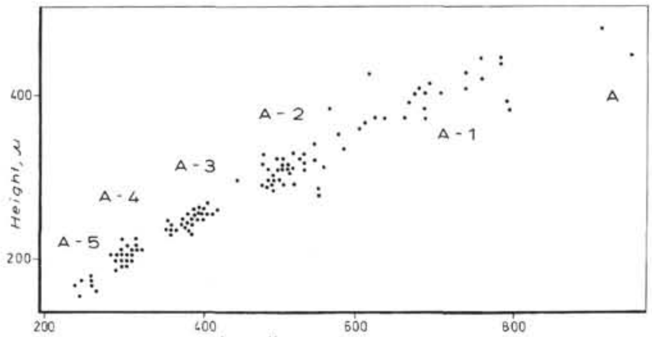

Figure 15. *Length-height relationship observed in* Cyprideis pannonica *at Site 376, Sample 9-3, 138 cm.*

mous amounts. This is seldom observed in true pelagic sediments, where planktonic foraminifers contribute to the makeup of the sediment and are persistently well represented.

3) The co-occurrence of planktonic foraminifers and the assemblage *Cyprideis-Ammonia beccarii* is ecologically implausible. Either the former or the latter have to be reworked; their biotopes are mutually exclusive.

This third argument, which appears the strongest to us, requires elaboration. *Cyprideis* is a bottom-dwelling ostracode without a pelagic larval stage. The large majority of species inhabit brackish (meso-polyhaline) environments (van Morkhoven, 1963, p. 290; Benson, this volume). *Cyprideis* is a major constituent of several of the biofacies in the Sea of Azov and in the Caspian Sea (Zenkovich, in Benson, 1973, p. 1007). With salinities about one-third those of normal marine conditions, no planktonic foraminifers are recorded.

Ammonia beccarii is also a bottom-dwelling euryhaline species. It has been recorded in subrecent sediments from the lagoon of Venice (Cita and Premoli Silva, 1967), occurring with *Cyprideis* (Ascoli, 1967). Present-day salinity of that lagoon ranges from 29 to 31°/₀₀. No planktonic foraminifers are recorded, but this could be because of the low abundances of planktonic foraminifers in the Northern Adriatic (Chierici et al., 1962).

Ramanathan (1975), discussing the ecology and distribution of foraminifers in the Vella estuary, found *Ammonia beccarii tepida* in all stations examined from the marsh, the bay, and the estuary. He did not record any living planktonic foraminifers in the same stations, though he recorded dead ones introduced by wave action (post mortem transportation into an environment which is not their biotope).

J. J. Bizon (personal communication, 1976) said that *Cyprideis* occurs in the lagoon of Arcachon, facing the Atlantic, where the salinity is around 29°/₀₀, in association with planktonic foraminifers. Whether living planktonic foraminifera are recorded is not known, however.

We have discussed the above examples to clarify the concept of ecologic niche. The niches of the various species of planktonic foraminifers are the superficial layers and/or the intermediate layers of the water mass in the open ocean, where little or no changes in salinity occur. They are stenohaline: there have been few verified reports of living planktonic foraminifers in waters of salinity less than 30.5-31.0°/₀₀, and those specimens reported were very dwarfed specimens of only a few species (Boltovskoy, 1970). The upper salinity tolerance appears to be about 37°/₀₀ *(Globigerinoides ruber). Globigerina eggeri* and *G. bulloides* seem to be able to withstand salinity variation, as is exemplified by their presence in exceptional abundance (a) in several sapropels of the Brunhes Epoch in the eastern Mediterranean, where a dilution of the superficial water masses was indicated by changes in isotopic ratios (Vergnaud-Grazzini in Cita et al., in press), and (b) in the "Brunhes-Matuyama sapropels" of the eastern Mediterranean (Cita et al., 1973, p. 1285).

The species of planktonic foraminifers in the uppermost Messinian of the Cyprus sites, however, do not include abundant euryhaline species.

The common ecologic niche of *Cyprideis* and of *Ammonia beccarii* is the sediment/water interface of shallow lagoons or internal water bodies with salinities well below those where living planktonic foraminifers occur. This is why we reiterate that *their ecologic niches are mutually exclusive.* That the *Cyprideis-Ammonia beccarii* assemblage is in primary deposition is demonstrated by the biometric analysis (see Figure 15). That the water body in which they lived had a salinity which is incompatible with that of a sea is demonstrated by the geochemical data of Mélières et al. (this volume) and is supported by some of the results obtained from investigations on stable isotopes (Table 5) (Pierre and Fontes, this volume).

Isotopic Evidence of Strongly Evaporated Freshwaters

The strongly negative values of δO^{18} recorded in Core 10, Section 2, 70-72 cm, and Core 15, Section 2, 70-72 cm, are probably the result of fresh-water influence. If these values resulted from normal marine conditions, they would indicate temperature ranges of 35°-44°C and 43°-52°C, respectively. These values seem far too high. Core 12, Section 3, 30-32 cm, may

TABLE 5
Isotopic Ratios Measured on the Bulk Carbonate From 13 Samples (Cores 10-15, Site 376) Belonging to the "Lago-mare" Facies

Sample (Interval in cm)	δO^{18} (CO_3^{2})	δC^{13} (CO_3^{2})
10-2, 70-72	−2.45	−2.95
11-2, 70-72	+1.01	−0.05
11-2, 105-107	−0.85	−0.83
12-2, 70-72	−0.07	+0.94
12-3, 30-32	−1.89	−1.63
12-4, 75-77	−0.11	+0.45
12-5, 60-62	−0.68	−2.80
13-2, 95-97	−0.12	+0.70
13-3, 47-49	+0.71	+1.35
13-4, 130-132	−0.54	+0.37
15-2, 70-72	−3.80	−3.30
15-3, 50-52	−1.40	−0.70
16-1, 80-82	−1.45	−1.22

also indicate fresh-water influx. Isotopic values similar to those recorded at the Cyprus sites (McKenzie and Ricchiuto, this volume; Pierre and Fontes, this volume) are recorded for the marls of the upper Messinian "Colombacci" Formation of the Periadriatic Trough (Longinelli in Casati et al., in press).

One has to bear in mind that evaporating water—both seawater and fresh water—normally is heavily enriched in O^{18}, because the higher vapor pressure of the H_2O^{16} water molecules favors their escape through the evaporating surface. The fractionation effect can be very marked, particularly in fresh water, even under "normal" climatic conditions. For example, the Bracciano Lake near Rome, Italy, which has no outflowing rivers and is fed only by rain water (average isotopic composition about -6.5 per mil versus SMOW) shows $\delta O^{18}(H_2O)$ of about 0.0 to $+1.0$, due only to evaporation effects. Similar results are obtained for other lakes without outlet, under climatic conditions which are to be considered far from those existing during the Messinian in the eastern Mediterranean: Trasimeno Lake $+0.3$, Bolsena Lake -1.0, whereas the average isotopic composition of rain water over those lakes is again between -6.0 and -7.0 per mil (Cortecci, 1973).

Similar isotopic enrichments could be expected for the evaporating sea water (Craig et al., 1963; Lloyd, 1966), especially when the total volume is reduced by about 50 per cent, even if the evaporation conditions are not exactly the same, since high salinity tends to alter the exchange of water molecules between the atmosphere and the evaporating surface. However, in spite of such a possibility, very positive isotopic values have never been found, as far as we know, either in calcites or in gypsum water.

As regards carbonates, the relatively high water temperatures probably helped to lower the oxygen isotopic composition. A second possibility is that real evaporitic carbonates have never been measured so far in their isotopic composition.

In the case of gypsum, there are relatively few measurements of the isotopic composition of the water of crystallization (Pierre, 1974) and statistical conclusions cannot yet be drawn.

Under these conditions it would follow that—owing to the strong evaporation effects—negative isotopic compositions can be considered exceptions, to be found only in areas where river waters flooded lagoons, maintaining "fresh water" conditions over long intervals. Away from these areas, the isotopic composition of the evaporating water probably reached rather positive values, even under "lago-mare" conditions simulating normal seawater isotopic values though large quantities of fresh water contributed to the basin. This was the case for the eastern Mediterranean, where a large inflow of water was provided by rivers from the Alps and the Apennines and from eastern Europe, Russia (via Black Sea), north Africa, and the Middle East.

The conditions could have been similar in some respects to those existing now in the Kara Bogaz Gol-Caspian Sea system. Water from the Caspian Sea (essentially river waters) flows continuously into Kara Bogaz through a strait, because of a difference in their level, a difference which is maintained by the extremely high evaporation in the latter in an arid climate (Dzens-Litovsky and Vasilyev, 1962). In the Kara-Bogaz gulf, brines accumulate and salts like mirabilite, glauberite, astrakanite, gypsum, epsomite, halite, etc. have been deposited in a lagoonal-lacustrine salt deposit. The thickness of the salts has reached approximately 40 meters in some 10,000 years or so. Unfortunately, no data on the isotopic composition of the water are available. The very high evaporation rate must cause a variation of the isotopic composition of the order of 10‰, or maybe higher, because of the extremely dry atmosphere (drastically influenced by the Ust-Urt and Kara Kum deserts) and the dry winds blowing over the evaporating surface and increasing the rate of isotopic enrichment by kinetic effects. Under similar conditions, the oxygen isotopic composition of Lake Tchad is enriched by about 15‰ and even more, and the deuterium to hydrogen ratio is enriched by more than 100‰ in the isolated areas of the northeastern shore (Fontes et al., 1970).

Going back to the isotopic composition of the late Messinian endoreic "lago-mare," as an example of the intriguing results which can be obtained because of the different conditions, it must be pointed out that tests of planktonic foraminifers and tests of *Cyprideis* from Sample 376-13-3, 47-49 cm yielded the following isotopic values:

Planktonic foraminifers: $\delta O^{18}(CO_3)$ -0.13
$\delta C^{13}(CO_3)$ $+0.84$
Cyprideis: $\delta O^{18}(CO_3)$ -0.04 $\delta C^{13}(CO_3)$ -3.47

The similarity of the oxygen isotopic compositions is in contrast with the difference between the environments in which the two groups of organisms are supposed to grow. The difference between the carbon isotopic composition proves that a marked difference between these conditions did exist. One should conclude that the similarity between the $\delta O^{18}(CO_3)$ values is either the effect of the isotopic fractionation caused by differential evaporation, which can easily lead to errors in the interpretation of the isotopic results, or the effect of mixing of indigenous faunas with reworked allochthonous material.

In other words, when considering isotopic data from evaporitic environments, one has to remember that whereas negative isotopic results definitely prove the existence of fresh water or brackish water conditions, values apparently "normal marine" are not necessarily related to seawater conditions.

During the latest phase of the "salinity crisis," endoreic basins existed in the eastern Mediterranean, whose sedimentary expression is represented by the "lago-mare" facies. Subaqueous conditions were persistent, but the salinity, alkalinity, and isotopic composition of these water bodies were highly variable.

Under certain conditions we have to admit the existence of salt water basins—with salinities as high as 40‰ or more and oxygen isotopic composition of the water about 1‰ or higher—which were not seawater basins but "fresh" water bodies heavily enriched in O^{18} and in their salt content by evaporation and/or redissolution of older evaporites. The abrupt change in the isotopic composition of sulfates recorded by Ricchiuto and McKenzie (this volume) and Pierre and Fontes (both this volume) in the cores immediately underlying those discussed here (17 to 21-1, Site 376) could mark the change between "normal" sedimentation in an evaporating seawater basin and reprecipitation of gypsum (maybe from fresh waters) probably following (1) complete dryness (desiccation), (2) flooding of the area, (3) dissolution of halite and gypsum, and (4) reprecipitation of the gypsum with an isotopic composition which probably averaged a fairly large range of values.

This progression is in good agreement with the studies on sedimentary structures of the evaporites, which show evidence of cyclically repeated desiccation (Garrison et al., this volume), and with the extremely low bromine content in halite at Site 376 (Kuehn and Hsü, this volume) which suggests that the halite has been recycled.

Messina Abyssal Plain, Site 374

Site 374 is in the center of the deepest abyssal plain of the Mediterranean, with a water depth more than 4 km. Its location was carefully selected to provide data on the Messinian facies from the physiographically lowermost setting.

On top of the Mediterranean evaporite, which includes from bottom to top (1) halite, (2) nodular anhydrite, and (3) cyclically repeated alternations of mudstones, dolomite mudstones, and crystalline gypsum (see Chapter 5), we found a lithologic unit, 35 meters thick, consisting of black dolomitic mudstone. This unit is devoid of calcareous micro- and nannofossils, and does not contain any measureable amount of calcite. Generally speaking it is barren, unburrowed, and unfossiliferous, except for a few spores (palynological investigations carried out by D. Bertolani Marchetti on several samples from this interval were unsuccessful, however, with the exception of side-wall Core 25) and some plant debris. These vegetal remains are extraneous to the environment, which was subaqueous but, unlike most subaqueous environments, entirely abiotic and permanently stagnant.

The lowermost part of Core 15 yielded some radiolarians and sponge spicules. The radiolarian assemblage (Caulet in Sanfilippo et al., this volume) is assigned to the *Stycochorys peregrina* Zone. The range of this biozone, with reference to the paleomagnetic time scale (see Ryan et al., 1974, p. 655), is from the middle part of Epoch 6 to the lower part of the Gilbert Epoch (Messinian to early Zanclean). The occurrence of these siliceous microfossils, which had a typical marine habitat, indicates occasional marine influences in the lake existing some 6 m.y. ago[3] in what is today the Messina abyssal plain. Whether the connections were with the Atlantic via the western Mediterranean or with the Indian Ocean via the Red Sea, we cannot say. It is worth mentioning that a black pyrite-rich claystone of the *Discoaster quinqueramus* Zone, apparently similar to those found in the Messina Abyssal Plain was found overlying the upper Miocene evaporites at Site 225 in the Red Sea (Whitmarsh and Ross, 1974).

A peculiar feature of the Site 374 lithologic unit under discussion is a very rare mineral called lueneburgite: it is a magnesium boron phosphate, occurring as white spheres and ranging in size from a few tens of microns up to 1 mm or more. The mineral is formed by "upward migrating brines either from underlying evaporites or from brines associated with oil deposits enriched in borax and phosphates" (Müller and Fabricius, this volume).

The diatom floras of Core 17, this drillsite, show an upward change from brackish to limnic conditions and evidence of fresh-water influx into a non-marine environment whose salinities varied between 0-15°/₀₀ (Schrader and Gersonde, this volume).

Land Record

The post-evaporitic Messinian sediments in the eastern Mediterranean, especially those from the Levantine Basin (DSDP Sites 129A, 375, and 376) are strikingly similar to those recorded in the Periadriatic Trough, which is a tributary of the eastern Mediterranean. Sturani (1975, p. 54-58, and in press) subdivides the Messinian of the Piedmont Basin into three parts: (a) a lower part with marine sediments, (b) a middle part with evaporites, and (c) an upper part with alluvial, marsh, and lacustrine facies.

The post-evaporitic upper part consistently yields a caspi-brackish faunal assemblage containing the molluscs *Congeria, Melanopsis, Melanoides, Limnocardium,* and *Dreissena.* This unit is also known as "*Congeria* beds" *Auct.* and as "Strati a *Melanopsis*" (Ruggieri, 1962).

The typical caspi-brackish faunal assemblage of *Cyprideis* and *Ammonia beccarii* occurs consistently in the upper Messinian "Colombacci" Formation of Emilia and Marche (Colalongo et al., in press; Casati et al., in press), and in the upper Messinian supragypsiferous varved clays and marls associated with alluvial fan conglomerates at Corfu (Vismara Schilling et al., in press).

Isotopic analyses of the "Colombacci" and the intercalated marls (Longinelli, in Casati et al., in press) clearly indicate continental influence, as shown by the strongly negative values of δO^{18}.

The caspi-brackish faunal assemblage with *Congeria, Melanopsis, Cyprideis,* and *Ammonia beccarii* is also consistently recorded in the marls between the gypsum banks in the "Gessi superiori" (of Decima and Wezel, 1973). In particular, it occurs in the olive-gray marls stratigraphically underlying the "Arenazzolo" and overlying the topmost gypsum bank in the section recently described by Brolsma (1975) at Capo Rossello 2.

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[3] Riedel (letter to M. B. C. dated 14 June 1976) recorded in Sample 15, CC. The middle Miocene indicator *Cannartus pettersoni,* whose range is incompatible with that of *S. peregrina.*

In all the land sections mentioned above, the continental, mostly subaqueous sediments, yielding the caspi-brackish faunal assemblage characteristic of the oligohaline "Lago-mare," represent the topmost unit of the Messinian. They are directly and disconformably overlain by lower Pliocene open-marine sediments, which we will discuss later.

The Role of Thresholds

The circulation pattern of the present Mediterranean is controlled by the existence of three major thresholds: the Gibraltar sill, some 350 meters deep, separating the western Mediterranean from the open ocean; the Sicily Channel, some 450 meters deep, separating the western Mediterranean from the eastern Mediterranean; and the Strait of Messina, separating the Tyrrhenian from the eastern Mediterranean. The first and last are related to plate boundaries (Dewey et al., 1973) subject to rapid changes through time.

We have paleontological evidence that in the earliest Pliocene the depth of the Gibraltar sill was much greater than at present, and that an uplift occurred during the Pleistocene (Benson, 1973 and this volume; Cita and Ryan, 1973). The problems are as follows: Besides the threshold(s) flanking the Alboran orocline (sensu Elter and Giglia, 1976), whose existence is postulated in the deep-basin desiccation model of Hsü et al. (1973) (North Betic and South Rifain Straits of Gignoux, 1950), which other thresholds existed in the Mediterranean when the evaporative drawdown began? What role did they play in controlling the facies distribution during the evaporitic stage of the Messinian, and especially after it? Is the continental caspi-brackish oligohaline environment as extensive as the evaporites or not?

Eastern Mediterranean

The drill sites of the eastern Mediterranean at which lacustrine facies occur in the topmost part of the Messinian include Site 129A in the Strabo Trench of the Levantine Basin (water depth 2832 m), Site 375 on the Florence Rise (water depth 1900 m), Site 376 at the edge of the Antalya Basin (water depth 2101 m), and Site 374 in the Messina Abyssal Plain (water depth 4100 m).

The development of the caspi-brackish fauna, which was recorded in all the above drillsites except 374, implies oxygenation of the waters and shallow depth. In fact, the ostracodes, the foraminifera, and (in the land record) the mollusks which characterize this facies are shallow-water forms. The absence of this typical fauna in the Messina Abyssal Plain may indicate that the lake existing there was too deep, or that it was oxygen-depleted, or both. If we assume that the physiography of the latest Messinian in the eastern Mediterranean was similar to the present physiography, we can also imagine a series of water connections between the various basins, from the high-standing ones to the low-standing ones. These waterfalls, even if not permanent according to the local hydrologic budget, would have kept the basins flushed. An intermittent movement of water would account for the alternation of oxygenated and non-oxygenated layers in the subaqueous succession continuously cored at Site 376 (Cores 7-16). Only the lowest standing basin would never have been oxygenated. If we accept this line of reasoning, we can understand why the post-evaporitic sediments of the Messina Abyssal Plain are black and azoic.

Studies on interstitial waters by McDuff and Gieskes (this volume) support the existence of a deep alkali lake in the latest stage of the Messinian salinity crisis at Site 374. That this lake occupied the bottom of a previously desiccated basin is shown by the evaporitic succession underlying the "lago-mare" facies of lithologic Unit 3a, where a number of cycles, including subaerial episodes, have been recognized (Garrison et al., this volume).

The only eastern Mediterranean drillsites where no non-evaporitic sediments occur immediately below the Pliocene oozes are Site 125A, crest of the Mediterranean Ridge in the Ionian Basin, water depth 2782 meters, and Site 378-378A, edge of the Cretan Basin, water depth 1835 meters. In these drillsites we found Pliocene oozes and Miocene evaporites in contact. The Pliocene oozes were not lowermost Pliocene (M Pl 3 Zone at Site 125A, M Pl 2 at Site 378-378A); in other words, the sedimentary expression of the Pliocene initial flooding was not preserved. In all cases the contact looked "artificial" in a core which was not full, and it is possible that the sediments yielding the caspi-brackish fauna were swept away by drilling and coring operations. We consider more likely, however, that these sediments were never deposited in these areas, which were structurally elevated (see Figure 12) and stood above the level of the lakes.

Western Mediterranean

The only records of the caspi-brackish fauna in the western Mediterranean deep-sea record are in Section 372-4-2, where *Cyprideis* specimens occur (Benson, this volume), and in Section 124-7-1, where a few broken valves of smooth shelled ostracodes occur in the laminites. These specimens are probably reworked from shallow circum-Mediterranean basins where this fauna was abundant during the latest Messinian (Benson, personal communication, 1976). This fauna is not recorded in any other western Mediterranean drillsite. Why? The sites were numerous, and several of them were continuously cored across the Miocene/Pliocene boundary, with good core recovery. The assemblage is so obvious, large, and conspicuous that it cannot be overlooked. The sites where the caspi-brackish fauna was not recorded include Site 121, Alboran Sea, water depth 1163 meters; Site 122, Valencia Trough, water depth 2146 meters; Site 134, Balearic abyssal Plain, water depth 2864 meters; Site 371, Balearic Basin, water depth 2750 meters; and Site 132, Tyrrhenian Basin, water depth 2835 meters.

The absence of both the sedimentary facies and the faunal assemblage seems to be independent of (1) water depth, (2) structural setting, and (3) age of the overlying Pliocene sediments.

Ruggieri's (1967) model of Mediterranean desiccation says that the caspi-brackish fauna was basin-wide, being substituted for by the Atlantic marine fauna which was re-introduced into the Mediterranean at the beginning of the Pliocene. Indeed, in the land record, the caspi-brackish faunal assemblage with *Cyprideis, Ammonia beccarii, Melanopsis,* etc., was recorded in Algeria (Yassini, 1975), in Southern Spain (Iaccarino et al., 1975), in Tuscany (Salvatorini, 1975), and in Sicily (Decima, 1964).

Interpretation

The working hypothesis we propose is that in order to have the sedimentary expression of the final stage of the salinity crisis represented by subaqueous oligohaline sediments yielding the caspi-brackish fauna, we need two thresholds separating the basin from the open ocean. The eastern Mediterranean basin was in such a situation. In fact, even if the Sicily channel is post-Miocene, we have to postulate a shallow sill somewhere crossing the Mediterranean on the prolongation of peninsular Italy (Calabrian orocline sensu Elter and Giglia, 1976). The western Mediterranean basin instead communicated directly with the open ocean, or occasionally did not communicate at all. Oligohaline water bodies apparently were not well-developed there after deposition of the Mediterranean Evaporite. The recorded occurrence of the caspi-brackish fauna in circum-Mediterranean basins implies the existence of (local) thresholds permitting the formation of limited endoreic basins, which were flooded by the Pliocene transgression, along with the major basins of which they may have been tributaries.

There is additional evidence for a threshold between the eastern and western Mediterranean. Indeed, the clay mineral data suggest a strong difference between the western and the eastern Mediterranean (Chamley et al., this volume). Chlorite increases in uppermost Messinian sediments at the eastern Mediterranean drill sites, not in the western ones. This might indicate a specific geochemical environment, propitious to some magnesium-rich mineralogical growth. The latter assumption is supported by the occurrence of idiomorphic dolomite crystals, both in the eastern Mediterranean DSDP boreholes, and in sediments yielding the caspi-brackish faunal assemblage from the Periadriatic Trough (Colalongo et al., in press; Casati et al., in press) and from Corfu (Vismara Schilling et al., in press).

One more argument to support the existence of a high-standing barrier separating the western and eastern basins is paleontological: in the lowermost Pliocene sediments of Site 374 on the Messina Abyssal Plain, the dominant benthic foraminifera is *Oridorsalis umbonatus.* This species, although typical of lower epibathyal (>500/700 m) depth, is capable of surviving, in very low abundances, in much shallower depths. Its occurrence as the dominant species in the lower Pliocene sediments overlying the Messinian azoic sediments suggests the presence of a sill over which this tolerant species would be the first to immigrate.

The lagoon model, as suggested by J. J. Bizon (this volume) cannot be applied for the caspi-brackish fauna. A lagoon must permanently communicate with the open ocean. Where was the open ocean from which normal seawater could enter the Levantine Basin? Certainly not from the west, where we had an anoxic, sterile water body in the Messina Abyssal Plain (see above). Even if we cannot exclude a connection with the Indian Ocean along the eastern border of the Central Plate (Neev, 1975), we have no evidence of normal marine upper Miocene sediments in the southern part of Anatolia, where the youngest marine layers are Serravallian (Gelati, 1975).

TERMINATION OF THE SALINITY CRISIS (= MIOCENE/PLIOCENE BOUNDARY)

Deep-sea Record

The nature of the Pliocene transgression—that is, the direct superposition of open-marine deep pelagic sediments on shallow-water Messinian evaporites or associated pyritic marls, with their restricted marine, dwarfed foraminiferal faunas—is one of the main points on which the desiccation model (Hsü et al., 1973) is founded. The Leg 13 cores containing this contact (134-7-4 in the Balearic Basin; 132-21-2 in the Tyrrhenian Basin; 125A-7-1 in the Ionian Basin) are illustrated in color photos on the frontispiece of the *Initial Reports* for that leg. Discovery of this contact was one of the highlights of that cruise. In all drill sites, the Miocene/Pliocene boundary coincides with the contact between two strongly different lithologic units, and coincides with a drastic change in fossil content. Even when the sediments on opposite sides of the boundary represent subaqueous environments, there is a striking contrast between the Messinian olive-gray marls, which are almost completely barren and indicative of reducing conditions at the sediment/water interface, and the biogenic, well-ventilated pink lower Pliocene nannofossil-foraminiferal oozes. Sediments representing a "normal" transgression, showing evidence of progressive deepening of the basin, were never recorded. The sedimentary superposition, as recorded in the three main basins of the Mediterranean, is sharp and requires dramatic explanations.

Of special interest is the sedimentary record of the Tyrrhenian Rise (Site 132), where the oldest known Pliocene sediments were recognized: the sedimentary and paleontological break also coincides with a sharp break recorded in the composition of the water masses, as shown by isotopic geochemistry (Lawrence, 1973). Lawrence showed a drastic change in the stable isotopes of oxygen across the Miocene/Pliocene boundary, from $-2.8\ \delta O^{18}$ to $+1.8\ \delta O^{18}$ in a few centimeters. Later studies by Chamley (1975) revealed a drastic change in the qualitative and quantitative composition of the clay minerals just at the sedimentary break at Sites 132, 134, and 125A. In all drill sites montmorillonite is the dominant mineral in the upper Messinian: it is replaced in the lower Pliocene by different minerals (illite, chlorite, attapulgite, kaolinite) at different drills sites. The sedimentary, paleontological, and geochemical changes are sharp, not transitional.

The Mediterranean Evaporite was penetrated at six of the eight Leg 42A drill sites. The Miocene/Pliocene boundary was cut in a single core, at all six, the only exception being Site 374. At four drill sites (371, 372, 375, and 378A) the contact appears as a drilling artifact (Figure 16). Core recovery is poor in all instances, and the contact does not appear as a depositional one. In all these four drill sites the oldest Pliocene sediments are missing, which is in good agreement with the structural and physiographic settings of the sites: edges of basins, where the Neogene sediments pinch out against the continental slope (372 in the Balearic Basin, 375 in the Levantine Basin), or flanks of structural highs (371 in the Southern Balearic Basin, 378 in the Cretan Basin).

Two drill sites, both in basinal settings and both from the eastern Mediterranean, where the Leg 13 information was poor, are very interesting. At Site 376 a prominent black layer, rich in organic carbon, and approximately 20 cm thick which is finely laminated in its lower part and is lowermost Pliocene (*Sphaeroidinellopsis* Acme-zone M Pl 1), indicates that no effective deep circulation was re-established in the eastern Mediterranean basins immediately after the flooding. This was predicted by the original desiccation model, which postulated high-standing barriers separating the well-ventilated western Mediterranean basins from the eastern Mediterranean basins, barriers which prevented strong circulation at depth (see Figure 12) in the latter. Unfortunately, the anomalous stratigraphic superposition in Core 6, Site 376, prevented detailed study of the evolution of ocean environment immediately after the initial flooding. The disrupted stratigraphic section precludes a clear sequential inspection of the benthic foraminiferal faunas directly above the Miocene-Pliocene contact. Nevertheless, the lowest Pliocene benthic faunas indicate water depths in excess of 500-700 meters. There is an increase in taxa with time. The abundant benthic foraminifers in the M Pl 1 Zone sediments directly above the sapropel (see Figure 17) are *Cassidulina subglobosa, Eggerella bradyi, Epistominella exigua, Eponides pusillus, Oridorsalis umbonatus, Pleurostomella alternans,* and *Trifarina bradyi,* all of which are upper and lower bathyal taxa. A sample taken 10 cm beneath this sapropel contained no benthic foraminifera.

At Site 374, in the deepest abyssal plain of the Mediterranean, the lowermost Pliocene sediments cored at 378-381.5 meters sub-bottom (Core 11 and side-wall Core 25) are strongly altered (Bernoulli and Mélières, this volume). Dolomite crystals form internal molds and casts of planktonic foraminifers, whereas the original calcitic tests have been destroyed (Figure 18). According to McDuff and Gieskes (this volume), dolomitization of this unit resulted from ionic migration across a steep magnesium-concentration gradient; the diagenetic process occurred after burial.

Black layers, rich in organic carbon, also altered and lithified, occur in Sections 1 and 2 of Core 11 (Figure 19), and indicate cyclically repeated stagnant conditions. As a consequence of the extensive dolomitization, we could not date the sediments with precision; they probably belong to the *Sphaeroidinellopsis* Acme-Zone, because of (a) the stratigraphic position (below Zone M Pl 2) and (b) lithostratigraphic correlation with Site

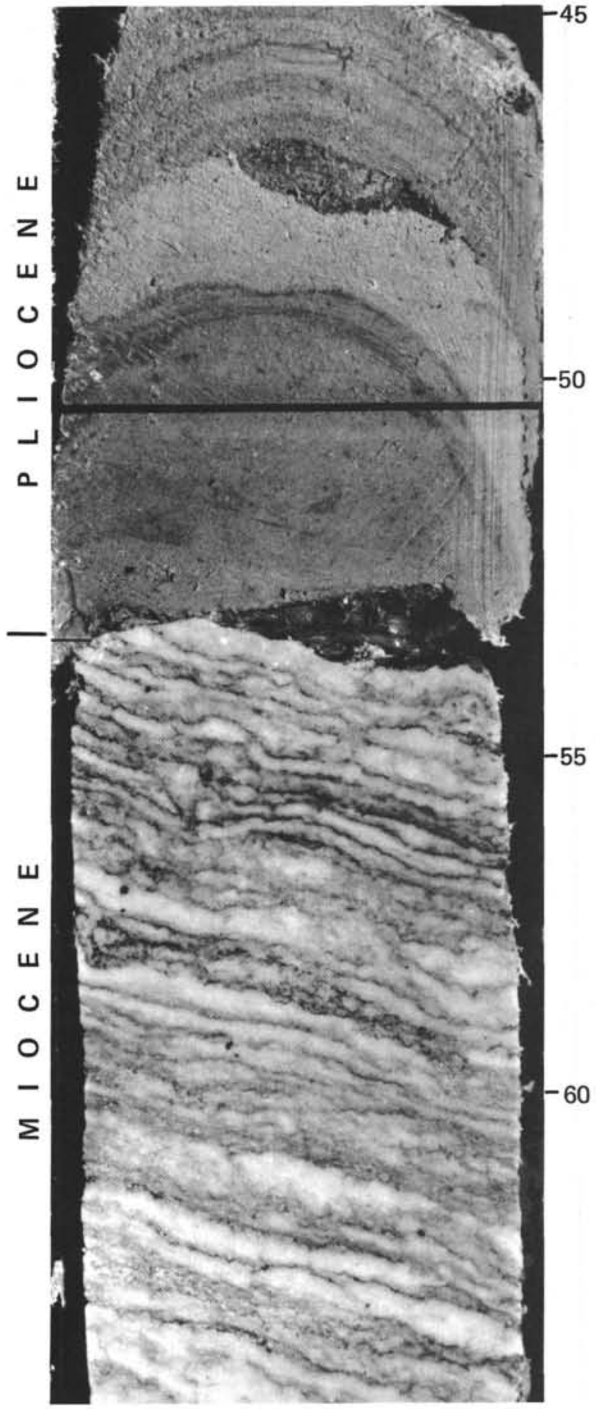

Figure 16. *Artifically induced Miocene/Pliocene contact as recorded at 546 meters sub-bottom at Site 371, Core 8, Section 1. The Pliocene oozes are referred to M Pl 2 Zone. The Messinian evaporites are dated by correlation.*

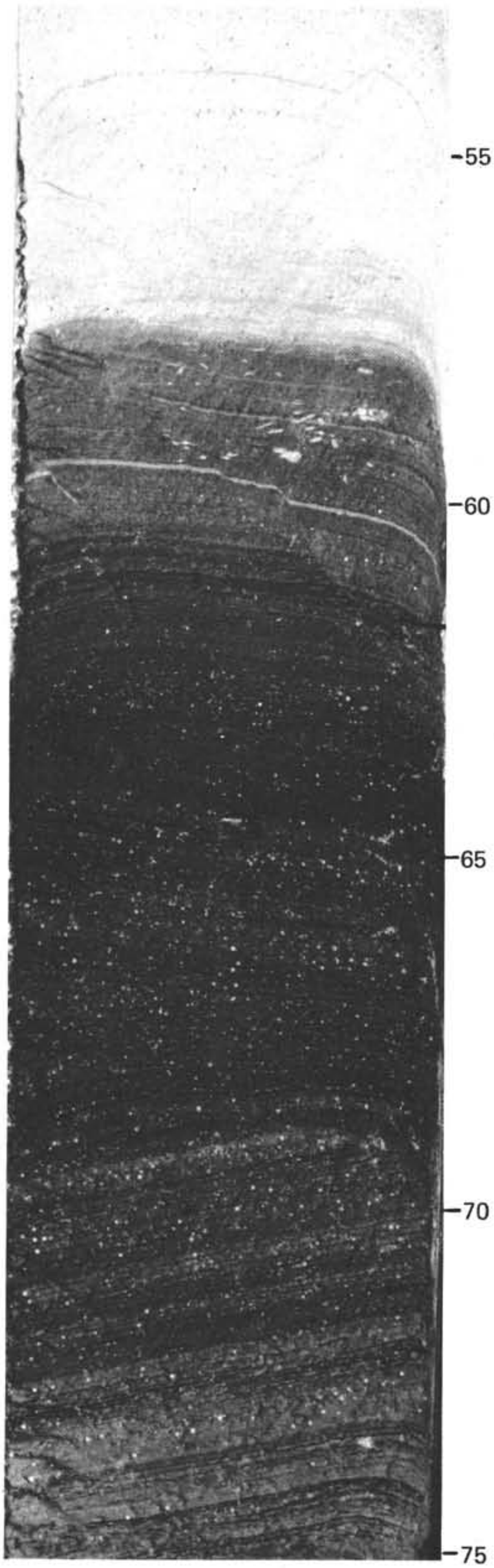

Figure 17. *Mystery sapropel, lowermost Pliocene (M Pl 1 foraminiferal Zone,* Amaurolithus tricorniculatus *nannofossil Zone), recorded in Section 376-6-4. Notice the finely laminated structure at the base and in the upper third, and the giant tests of* Orbulina universa. *Most of the planktonic foraminifers from the sapropel are epipelagic taxa. Benthic foraminifers are absent in the sapropel and beneath it, whereas they are fairly abundant directly above the black layer.*

376, where a stagnant cycle was recorded from the same level (see above).

Because of stagnation of the water mass and/or extensive diagenesis, these sediments do not contain benthic foraminifera. However, sediments of the overlying fossiliferous Pliocene sediments contain a moderately diverse benthic foraminiferal faunal assemblage that is typical of the lower epibathyal and upper mesobathyal depth zones (*Cibicidoides bradyi, C. kullenbergi, Nuttallides rugosus convexus, Eponides pusillus*, and *Oridorsalis umbonatus*). The vertical distribution of number of species (species richness) and number of individuals of each species (species evenness) show that the lowest sample containing benthic foraminifera (374-10, CC) contains a highly stressed fauna, one in which there are few species and high dominance (Figure 20). The dominant species in this zone is *Oridorsalis umbonatus*, which comprises 25%-90% of the assemblage in this interval. *O. umbonatus* is commonly a deep-dwelling foraminifera, and reaches its maximum abundance at depth below 2500 meters in the Gulf of Gascogne, below 875 meters in the northeastern Gulf of Mexico, between 600 and 3300 meters in the Pacific Ocean, and between 1219 and 1524 meters in the Gulf of California. It is recorded from Pleistocene deep-basin core samples in both the eastern and western Mediterranean. Despite its preference for a deep habitat, it can survive at depths as shallow as 42 meters in the Atlantic and 80 meters in the northwest Gulf of Mexico, although it is never present in any abundance at these depths. It appears to be a tolerant species, and its dominance in the lower sequence of Pliocene sediments at Site 374 may further indicate the environmental stress existing during the onset of the Pliocene.

There is some evidence from the benthic foraminifera that the eastern Mediterranean was more isolated and restricted than the western Mediterranean after the onset of Pliocene oceanic conditions. Although the dominant species are very similar in the two areas, a comparison of the population structures of the Pliocene assemblages at Site 372 in the Balearic Basin with those of the same age at Site 374 shows that the taxonomic evenness at Site 372 is 5% to 15% greater, and that the taxonomic richness is 66% greater than that at Site 374. This difference could be due to a greater water depth at Site 374 (today it is 4100 m, compared with 2700 m at Site 372).

The difference may also be due to the presence of a sill between the two areas, as discussed above.

When the lowermost Pliocene benthic foraminifers are compared with those of the overlying Pliocene, there is evidence for partially restricted conditions in

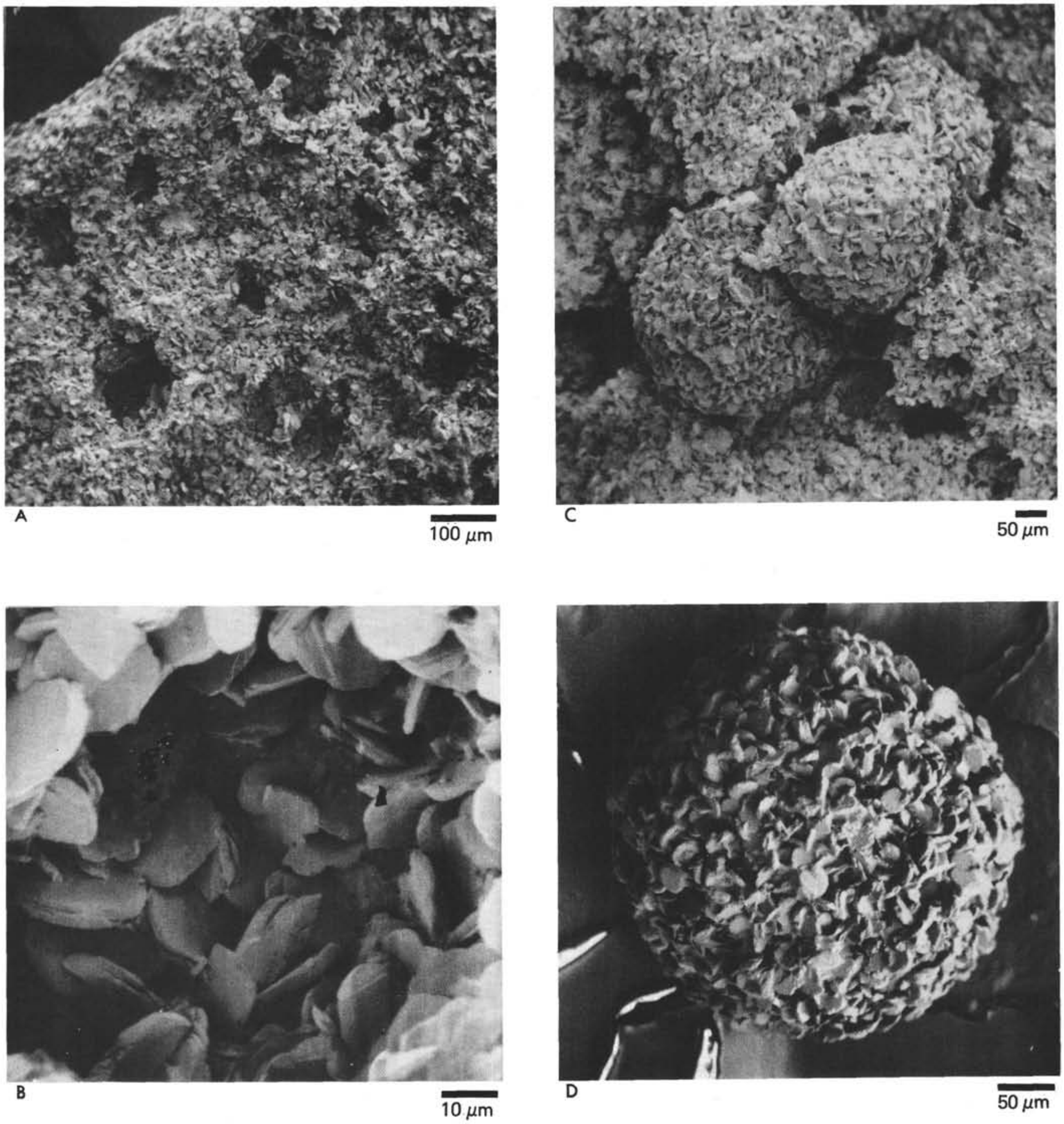

Figure 18. *Extended dolomitization, as seen in side-wall Core 25 (375 m sub-bottom) in the Messina Abyssal Plain, Site 374 (23-24 cm). SEM photos A and B show, at different magnifications, the surficial appearance of the dolomitized ooze. Photo C shows a diagenized internal mold of* Orbulina universa. *Photo D illustrates an internal mold, and cast of a planktonic foraminifer, probably* Sphaeroidinellopsis, *whose calcitic test has been entirely destroyed.*

the earliest Pliocene. The taxonomic richness of the lowermost sediments is only one-half that of the overlying ones. However, the species evenness is no different and the specimens are of normal size. It may be that when normal marine waters flooded the area, some time was required for all elements of the bathyal fauna to become established in the newly created oceanic environment. The most hardy and tolerant species would have repopulated the area at first, followed later by the others. That very little time is required for the establishment of a taxonomically stable and diverse population has been shown for terrestrial environments by Wilson (1969) and suggested for deep ocean environments by Buzas (1972).

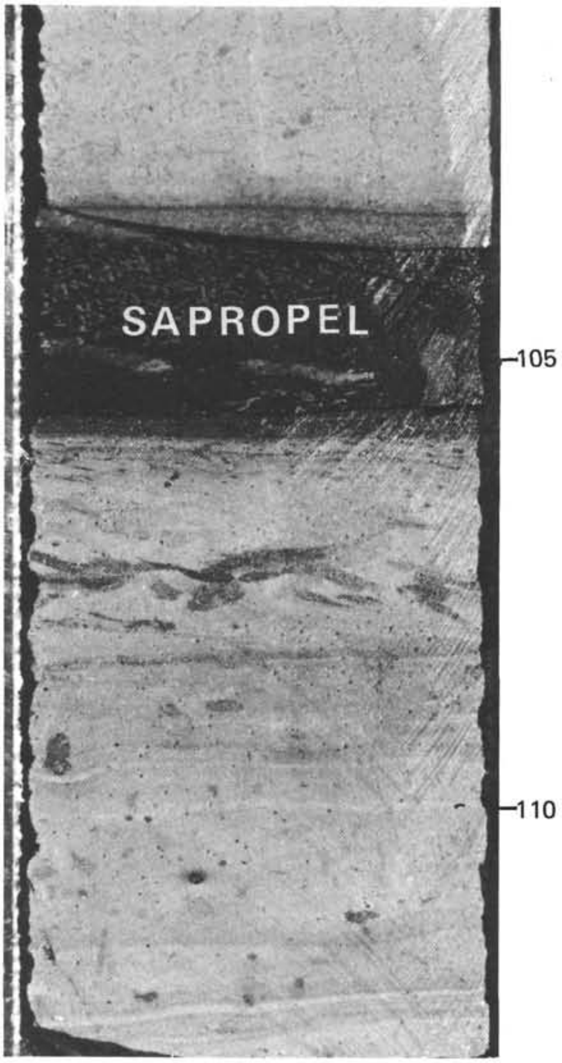

Figure 19. *Black sapropel, burrowed in the upper part, in the diagenetic dolomite characterizing the basal Pliocene (M Pl 1 ? Zone) of the Messina Abyssal Plain. Section 374-11-1.*

Land Record

A test of the "deluge" model (Hsü et al., 1973, see "History of the final deluge", op.cit., p. 1217; "Consequences of a catastrophic flooding" in Cita and Ryan, 1973, p. 1411) on land sections was undertaken immediately after completion of Leg 13 (see Cita, 1972; Cita et al., 1973; Cita and Gartner, 1973). Much of this investigation was conducted in Sicily, where the "Gessoso-solfifera" Formation (= Mediterranean Evaporite) includes the stratotype of the Messinian stage, and where the "Trubi" Formation includes the lower Pliocene Zanclean stage. The nature and age of the contact between these two lithostratigraphic and chronostratigraphic units was found to correspond in both sedimentary and paleontological character to the contact as recorded beneath the floor of the abyssal plains.

The base of the "Trubi" Formation at Capo Rossello in Sicily was formally proposed as boundary-stratotype of the Miocene/Pliocene boundary at the 24th International Geological Congress (Cita, 1975a, b).

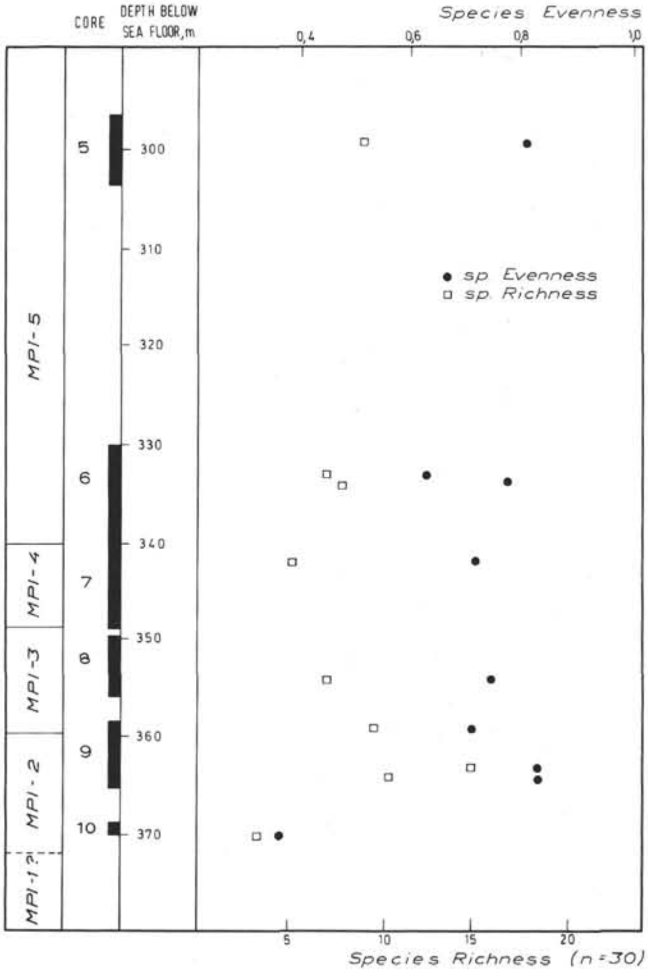

Figure 20. *Population dynamics, Cores 5 to 10, Site 374. The left-hand column contains the Mediterranean Pliocene biozonation of Cita (1975b).*

Investigations by several workers in the Periadriatic Trough (Sturani, 1974, 1975, in press; Colalongo et al., in press; Casati et al., in press) showed that a similar drastic change from the latest Miocene subaqueous, oligohaline, continental sediments and faunas to the earliest Pliocene open-marine, bathyal, stenohaline sediments and faunas is also recorded there. Notwithstanding the apparent lithologic similarity, the sediments across the Miocene/Pliocene boundary differ strongly in their paleontological, mineralogical, and geochemical composition.

The water depth calculated on the basis of benthic foraminiferal density and diversity, as compared to the present distribution in the Mediterranean (Cita, in press; Vismara Schilling et al., in press) varies according to the geological setting, but in all cases the Pliocene water depth is consistently one or two orders of magnitude greater than the depth estimated for the Messinian. No transition of fauna is recorded.

In other words, the careful study of the land record in Sicily and in the Periadriatic Trough, especially oriented to critically evaluate the "deluge" model, resulted in a collection of observational data that strongly support it.

CONCLUSIONS

As a conclusion of the present review of Messinian environments, we can say that the results of Leg 42A strengthen the deep-basin desiccation model formulated after the first drilling campaign of the *Glomar Challenger* in the Mediterranean. Indeed, none of the basic principles of the model was contradicted by the new findings, whereas new evidence was found to support interpretations originally put forward in a highly speculative way. The strongest new evidence supporting the model is the deep-water facies of the pre-Messinian sediments recovered both in the western and in the eastern Mediterranean (Benson, this volume; Wright, this volume).

The problem of the Messinian "salinity crisis" is not entirely solved, however. Several facets of the model are still poorly understood. They will be briefly discussed here, along with an outline of avenues of future research.

Marine Water Movement Across The Mediterranean

The source and/or mechanism of transport of water from the Atlantic into the Mediterranean and the progressive eastward movement of water, resulting in the thickest salt body in the Antalya Basin, are poorly understood.

Boundary condition number one is that a continuous influx of water is required to produce the massive "couche fluante" in the abyssal plains. The "couche fluante" is formed with brine surfaces deeply depressed, so that the unit does not trangress the margins higher than the 4.1 second seismic level in the Balearic Basin. Boundary condition number two is that the upper surface of the "couche fluante" is progressively deeper from the Balearic Basin to the Tyrrhenian Basin to the Ionian Basin to the Antalya Basin. Why?

Water Budget

Not understood is the evaporation/precipitation budget of the Mediterranean in the earliest Messinian, necessary to calculate the flux rate of water from the Atlantic which could have kept a permanent subaqueous environment over the region of "couche fluante" deposition. If we knew the duration of the salt deposition, we could invert the problem, because we would know how much seawater was needed to deposit 0.8 to 1.2 million cubic kilometers of halite and potash (Ryan, 1973). It might be a high priority to log or recore the Sicilian halite body (Decima, 1975) and inventory each varve from base to top.

Climatic Conditions

The evolution of intermediterranean Messinian climates is not understood. Was there an overall progression through time (1) from highly arid to less arid climate, expressed by extremely rapid drawdown at the onset of the salinity crisis, (2) to subaqueous hypersalinity over the abyssal plains, (3) to episodes of being even subaqueous across the deep margins (e.g., Balearic Rise; Tyrrhenian Rise 800 m above the abyssal plain; Mediterranean Ridge 1 km above abyssal plain), but only in the range of sulfate precipitation, (4) to alkali lakes with hyposaline conditions as shallow as the crestal area of the Mediterranean Ridge?

If the progression was rapid in more than one basin, was it brought about by increasing humidity in the Mediterranean watershed, related to worldwide late Miocene climatic deterioration induced by salt extraction itself (Ryan et al., 1974)? (The concept is still in a speculative stage.) Or was the change caused by constriction in the size and shape of orifices connecting (1) the Atlantic to the Mediterranean and/or (2) the Paratethys to the Mediterranean?

For example, the very rapid initial evaporitic drawdown is exemplified by the Messinian erosional surface descending under the level of the halite pinchout, as shown in Figure 9. It may be that at the time of the initial closing of the Atlantic portal, groundwater aquifers did not exist and a large hydrostatic gradient was required to get groundwater moving. Once groundwater routes were established, it is likely that they would have enlarged and become more efficient through time. A profitable line of future research would be to examine the timing and degree of karst formation of the Chaine Calcaire in the Rif Mountains in Morocco, the significance of the Tetuan Gap, and the collapse pattern of post-Tortonian blocks in the Straits of Sicily, with regard to the distribution of underlying late Triassic soluble salts and evaporites.

Lago-mare Invasion

The invasion of the "Lago-mare" faunas in the late Messinian should be investigated with the following questions in mind:

1) Did increasing humidity expand the "Lago-mare" lakes from inland enclosed Bonneville-type lakes to an extent such that they eventually spilled over into cataracts into the Eastern Mediterranean?

2) Did the late Neogene orogeny from Turkey to Oman uplift the drainage of the Paratethys to the Indian Ocean and divert the Aegean, North Carpathian, North Anatolian, and Caucasus watershed into the Mediterranean?

3) Did eventual groundwater seepage from higher standing Paratethys water bodies to lower standing Ionian and Levantine water bodies result in subterranean capture of the Paratethys drainage area?

The first question could be explored by evaluating the degree of freshwater input to the western Mediterranean, as related to European humidity. It might also be explored by isotope profiles through Messinian sediments in the Bay of Biscay, or even off Sahara.

Question two can be explored by studying the timing of the latest Indian Ocean faunas into the Paratethys and the magnitude of eustatic sea level changes along the Paratethyan shorelines.

The third question suggests a latest Messinian catastrophic drainage of the Paratethyan lakes, and overincision of tributary channels into the Paratethyan basins.

There are indications of a regression and catastrophic drainage in the Paratethys (Jiricek, 1975) at 5.5 m.y.B.P. The genesis of coarse breccias in Black Sea drilling of DSDP Leg 42B may also be related to a sudden drop in the water level of that water body during the late Messinian (K. J. Hsü, personal communication, 1976).

Faunal Mixing in Intragypsiferous Marls

Also poorly understood is the complex mixture of allochthonous/autochthonous and parautochthonous faunas and minerals in interbedded marls of the "Gessoso-solfifera" Formation and correlative deep-sea strata. There are outstanding questions related to causes and distribution of dwarfism (pre- or intra-Messinian harsh environments).

The continuity of stenohaline environments during times of depressed water levels is unknown. Approaches to these problems include a detailed isotopic investigation of each faunal component, separated into categories of comparable (a) stratigraphic ages, (b) depositional environments, (c) ecological niches, and (d) different types of diagenetic cement.

The budgeting of sediments removed from above marginal erosion surfaces and those interbedded between gypsum beds should also be attempted. The research includes investigations of detailed changes in the thickness of Reflector M strata, in traverses from the abyssal plain to the continental slope, in conjunction with compressional wave velocities determinations by seismic refraction methods, in order to budget margin-derived clastics and marls, identified by their low compressional wave velocities, and the sulfates and halite with considerably higher values.

Missing Lowermost Pliocene Sediments

What caused the absence of lowermost Pliocene sediments? If they were swept off slopes and rises, to where did they flow? Even the deepest abyssal plain of the Mediterranean, the Messina Abyssal Plain, has anomalously thin lower Pliocene layers. If they were dissolved away, where is the evidence of insoluble residues or strong dissolution in existing DSDP sites or land sections? If they were prevented from accumulating, what was the preventing mechanism? If marine transgression was diachronous over an interval greater than a few thousands years, how was the salinity of the depressed water masses held within the very narrow tolerance of the observed planktonic and benthic communities? An answer to some of these questions is found in Cita, Ryan, and Kidd (this volume), where the geodynamic implications of the Pliocene deep-sea transgression are discussed, but the problem deserves further attention and careful, critical investigations.

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