# 52. SEDIMENTATION RATES IN NEOGENE DEEP-SEA SEDIMENTS FROM THE MEDITERRANEAN AND GEODYNAMIC IMPLICATIONS OF THEIR CHANGES

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## ABSTRACT

Sedimentation rates calculated for Mediterranean deep-sea sediments predating the onset of the salinity crisis range from 2.5 to 9 cm/1000 years. Accumulation rates for the Messinian age evaporites are highly variable and likely to be excessive by more than one order of magnitude (i.e., more than 1 km/m.y.). Sedimentation rates calculated for the Pliocene/Pleistocene range from more than 30 cm/1000 years (Pleistocene of the Nile Cone area) to less than 0.1 cm/1000 years (early Pliocene of the Antalya Basin), the average value (including minor hiatuses) being 5.9 cm/1000 years.

The anomalously low rate of sediment supply in Pliocene times to locations which at the present day are basinal settings is interpreted as a consequence of a rapid eustatic sealevel rise, which accompanied the marine flooding of a depressed water body at the close of the late Miocene salinity crisis. The subsequent increase in the Quaternary to values equivalent to those attained prior to the salinity crisis is an indication that the modern surfaces of deposition are now in equilibrium.

Tectonically controlled facies changes are consistently accompanied by detectable changes in rates of sediment accumulation, as recorded in the Pleistocene of the Levantine and Antalya basins.

## INTRODUCTION

The rate of accumulation of sediments on the ocean floor in deep environments of deposition is a function of the supply of (a) biogenic skeletal components and occasional raw organic matter derived from marine plankton, (b) mineral grains carried in from the continents either airborne as volcanic tephra and eolian dust, or seaborne by currents, and (c) authigenic particles created on and beneath the sea floor.

Some components which arrive onto the sea floor may not be preserved in the geological record due to dissolution, consumption by bottom-living animals, or removal in eroding currents.

In the case of the Mediterranean the role of dissolution is minor except for certain evaporites; the role of authigenic formation is particularly great especially in the evaporites, and that played by currents is significant. In addition, the Mediterranean has also experienced terrestrial types of deposition foreign to the open sea.

Sedimentation rates are recognized as a parameter embodying implications as to the history and geodynamic evolution of the oceanic region and the surrounding landmass.

Because the Mediterranean is practically an isolated sea consisting of several independent, deep and silled basins (Figure 1), the primary effect of deep-sea currents has been one of substantially redistributing sediments from one part of an individual basin to another with little or no transfer across the connecting sills. Hence hiatuses that appear in the depositional record are either the product of redistribution with the drill site being in an area of net sediment removal, or of starvation of sediment on a basin-wide scale.

## SCOPE AND METHODS

The purpose of this paper is to examine geodynamic implications of changing accumulation rates primarily on the basis of values calculated for *instantaneous* deposition. These values provide an indication of mean particle flux to the sea floor at a discrete moment in time. The calculations require measurement of sediment thicknesses occurring between biostratigraphic datum planes which have been located *within* cored intervals. The time scale used is one calibrated to the paleomagnetic reversal sequence of the mid-ocean ridges (Blakely, 1974). No corrections have been employed for compaction of the sediment through time.

Twenty-two drill sites are considered in this compilation, including 14 from the campaign of 1970. They represent a broad spectrum of physiographic settings

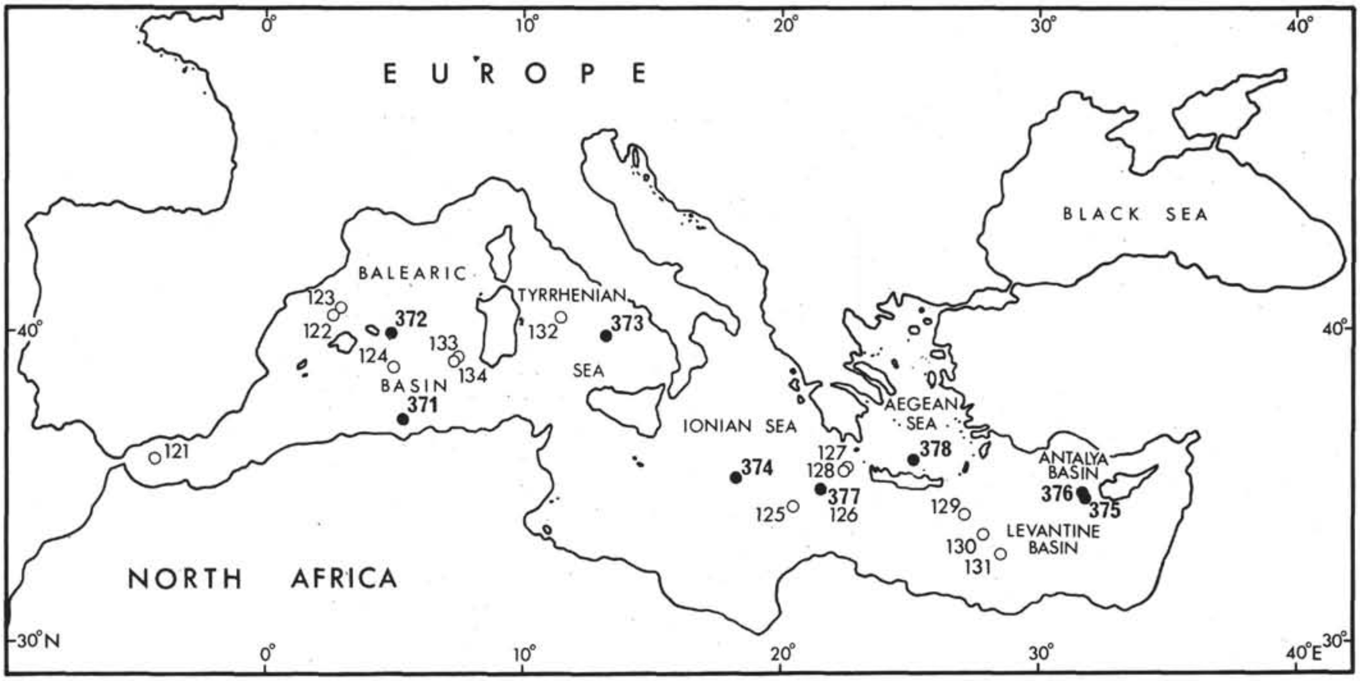


Figure 1. *Location map showing DSDP Mediterranean Sea sites drilled during Leg 42A (●) and Leg 13 (○).*

(basin plains, fans, rises, continental slopes, mid-basin ridges, seamounts, and trenches).

Table 1 lists each of the Mediterranean drill sites recording its location, sedimentary province, drilled intervals, and calculated instantaneous accumulation rates. Also recorded in Table 1 are sedimentation rates calculated (as in the site chapters of this volume) between epoch boundaries located within the drilled sequence, using *all* paleontologic, lithologic, seismic, and drilling data (A.D.). The major reasons for slight differences between these and the instantaneous rates are firstly that some of their epoch boundaries may have been arbitrarily placed in uncored intervals and secondly that, where there was disagreement between paleontologists in the placing of epoch boundaries, a concensus viewpoint was sought. For clarity only instantaneous rates are used in the figures and discussion to follow. Nevertheless it is important to note that all figures were redrawn using only A.D. values. These differed only slightly from those used to illustrate this paper and its conclusions are unaffected.

Figure 2 shows selected curves of cumulative sediment thickness versus geologic time derived from instantaneous values recorded on Table 1.

The time intervals of particular interest are: (1) The Messinian salinity crisis (6.2-5.2 m.y.), (2) The pre-salinity crisis Neogene (24-6.2 m.y.), (3) The post-salinity crisis Pliocene and Quaternary (5.2-0 m.y.).

The degree of resolution of the sedimentation rates differs for drill sites which have been (a) continuously cored, (b) cored at regularly spaced intervals, and (c) cored at widely spaced intervals. Different graphic symbols are employed in the text figures to distinguish these three categories of accuracy. We put in the lowest category (c) the calculations whose low reliability was not necessarily related to the frequency of coring, but to poor biostratigraphic resolution.

## RESULTS

### Sedimentation Rates in Post-Salinity Crisis Time

Sedimentation rates calculated for the Pliocene/Pleistocene range from more than 30 cm/1000 years (category c) calculated for the Pleistocene of the Nile Cone area, to less than 0.1 cm/1000 years (category a) calculated for the early Pliocene of the Antalya Basin edge. This striking difference of two orders of magnitude will be discussed later. The overall mean value calculated for the interval considered in the 22 drill sites is 5.9 cm/1000 years (including minor hiatuses).

The approximately 5-m.y. long time interval considered here has been subsequently divided into three parts on the basis of the following criteria:

**Early Pliocene:** from the re-establishment of permanent open marine conditions in the Mediterranean after the Messinian salinity crisis to the extinction horizon of *Globorotalia margaritae.* The open marine conditions were initiated within the range of *Globorotalia margaritae* and of *Amaurolithus tricorniculatus,* after the extinction of *Discoaster quinqueramus* and prior to the first evolutionary occurrence of *Sphaeroidinella,* evolving from *Sphaeroidinellopsis* (Cita, 1975a). This event lies close to the boundary between paleomagnetic epochs 5 and Gilbert (Ryan et al., 1974).

**Late Pliocene:** from the extinction horizon of *Globorotalia margaritae,* which occurs at or close to the boundary between the Gilbert and Gauss paleomagnetic epochs, to the *Globorotalia truncatulinoides* datum.

## TABLE 1
### Sedimentation Rates in Neogene Sediments of the Mediterranean From Deep Sea Drilling

| SITE | Location | Setting + Water Depth | Cores representing Pliocene & Pleistocene | | SEDIMENTATION RATES IN CM PER THOUSAND YEARS: Pleistocene | | late Pliocene | | early Pliocene | | Plio-Pleistocene average including hiatuses | MESSINIAN (See Table 2) | Tortonian | | middle Miocene | | early Miocene | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Number of cores | Interval in meters | Instns. | A.D. | Instns. | A.D. | Instns. | A.D. | | | Instns. | A.D. | Instns. | A.D. | Instns. | A.D. |
| | | | | | CATEGORIES AND NOTES | | | | | | | | CATEGORIES AND NOTES | | | | | |
| 121 | Alboran Basin | Buried basement ridge 1163 m | 16 | 686 m | 20.0 | 16.1 | (23.0) | (26.2) | (23.0) | (23.0) | 13.2 | | 10.0 | 5.9 | | | | |
| | | | | | ○ | | ○ 13 | | ○ 13 | | | | ◐ | | | | | |
| 122 | Valencia Trough Channel | Basement ridge 2146 m | 3 | 150 m | 10.0 | 6.1 | ? | 3.0 | 3.0 | 1.6 | 3.0 | | | | | | | |
| | | | | | ○ 1 | | ○ 14 | | ○ 14 | | | | | | | | | |
| 123 | Valencia Trough Channel | Basement ridge 2290 m | 6 | 269 m | 8.0 | 8.3 | (5.0) | 13.0 | (5.0) | 3.3 | 5.2 | | | | | | | |
| | | | | | ○ 2 | | ○ 15 | | ○ 15 | | | | | | | | | |
| 124 | Balearic Basin | Buried basement ridge 2726 m | 5 | 350 m | (9.0) | 8.3 | (9.0) | 10.0 | 2.8-9.0 | 5.6 | 6.7 | | | | | | | |
| | | | | | ○ 3 | | ○ 3 | | ◐ 20 | | | | | | | | | |
| 125 | Ionian Basin | Ridge crest 2782 m | 8 | 80 m | 2.3 | 0.9 | (2.6) | 3.3 | (2.6) | 1.2 | | | | | | | | |
| | | | | | ● | | ● 16 | | ● 16 | | | | | | | | | |
| 126* | Ionian Basin | Ridge cleft 3730 m | 3 | 106 m | >5 | 5.9 | | | | | 2.0 | | | | | | | |
| | | | | | ○ | | | | | | | | | | | | | |
| 127 | Ionian Basin | Trench 4654 m | 15 | 420 m | 20-26 | 23.7 | | | | | 8.2 | | | | | | | |
| | | | | | ○ 4 | | | | | | | | | | | | | |
| 128 | Ionian Basin | Trench 4654 m | 11 | 480 m | 20-26 | 26.6 | | | | | 9.1 | | | | | | | |
| | | | | | ○ 5 | | | | | | | | | | | | | |
| 129 | Levantine Basin | Trench 3040 m | 129A 1<br>129B 3 | 23 m<br>42 m | | | | | | | ? | | | | | | | |
| | | | | | 6. | | 6. | | 6. | | | | | | | | | |
| 130 | Levantine Basin | Ridge 2979 m | 7 | 563 m | 7-40 | 31.3 | | | | | 10.8 | | | | | | | |
| | | | | | ○ | | | | | | | | | | | | | |
| 131 | Levantine Basin | Interchannel area on Nile Cone 3035 m | 5 | 272 m | >30 | 15.1 | | | | | 5.2 | | | | | | | |
| | | | | | ○ | | | | | | | | | | | | | |
| 132 | Tyrrhenian Basin | Rise 2835 m | 20 | 182 m | 3.8 | 3.9 | 2.9-4.0 | 3.4 | 3.5 | 3.5 | | | | | | | | |
| | | | | | ● | | ● | | ● | | | | | | | | | |
| 133 | Balearic Basin | Continental Slope 2563 m | 1 | 54 m | ? | 6.0 | | | | | | | | | | | | |
| | | | | | ○ 7 | | 7 | | 7 | | | | | | | | | |
| 134 | Balearic Basin | Edge abyssal plain 1864 m | 7 | 325 m | >13 | 11.1 | 3.5 | 5.2 | 3.5 | 2.4 | | | | | | | | |
| | | | | | ○ 8 | | ○ | | ◐ 21 | | | | | | | | | |
| 371 | Balearic Basin | Basement ridge 2750 m | 8 | 547 m | 13.8 | 15.8 | 16.0 | 13.7 | 5.5 | 3.1 | 10.5 | | | | | | | |
| | | | | | ○ | | ◐ | | ◐ 22 | | | | | | | | | |
| 372 | Balearic Basin (rise) | Rise slope 2695 m | 3 | 150 m | 6.7 | 6.9 | 1.6 | 1.2 | 1.5? | 0.8 | 2.9 | | | | 6.0 | 4.2 | 8.0 | 7.8 |
| | | | | | ○ | | ◐ 17 | | ◐ 23 | | | | | | ● | | ◐ 25 | |
| 373 | Tyrrhenian Basin | Seamount flank on abyssal plain 3517 m | 2 | 269 m | 15.0 | 10.8 | ? | 5 | ? | 0.3 | 5.3 | | | | | | | |
| | | | | | ○ | | ○ | | ● 24 | | | | | | | | | |
| 374 | Ionian Basin | Abyssal plain 4078 m | 11 | 330 m | 14.0 | 15.4 | 5.5 | 4.7 | 2.7-1.3 | 1.7 | 7.3 | | | | | | | |
| | | | | | ○ | | ◐ | | ● | | | | | | | | | |
| 375 | Levantine Basin | Ridge 1900 m | 1 | 138 m | (3.4) | (3.3) | (3.4) | (3.3) | (3.4) | (3.3) | 2.6 | | ~ 9.0 | 6.4 | 2.5 | 3.8 | 2.5 | 3.0 |
| | | | | | ○ 9 | | ○ 9 | | ○ 9 | | | | ○ | | ○ | | ○ 26 | |
| 376 | Levantine Basin | Edge, abyssal Plain 2101 m | 6 | 55 m | 2.0 | 2.2 | 0.6 | 0.6? | 0.1 | 0.1? | 1.1 | | | | | | | |
| | | | | | ● 10 | | ● 19 | | ● | | | | | | | | | |
| 377* | Ionian Basin | Ridge cleft 3718 m | 1 | 193 m | >5 | 10.0 | | | | | 3.9 | | | | | | | |
| | | | | | ○ 11 | | 11 | | ● 11 | | | | | | | | | |
| 378 | Cretan Basin (Aegean Sea) | Basin flank ·1835 m | 15 | 343 m | (15.0) | 7.7 | (15-2) | 9.6 | (2.0) | 1.6 | 6.0 | | | | | | | |
| | | | | | ◐ 12 | | ◐ 12 | | ◐ 12 | | | | | | | | | |

Instns. = "Instantaneous": Sedimentation rates calculated between fossil datum planes of known age (Ryan, et al., 1974) located within cores.

A.D. = "All Data": Sedimentation rates calculated between epoch boundaries located within the hole based on all palaeontologic, lithologic, seismic and drilling data. Boundaries frequently interpolated between cores.

Both types of data exclude hiatuses wherever possible. Plio-Pleistocene average rates include hiatuses.

Caregories

- ● (a) continuously cored
- ◐ (b) cored at regularly spaced intervals, < 50 meters
- ○ (c) cored at widely spaced intervals, > 50 meters

*Site 377 was drilled as a continuation of the Site 126 section.

Notes

No. 1 - (122) Hiatus Pleistocene to Pliocene ~1 m.y.
2 - (123) Hiatus M. Pleist. to L. Plio.
3 - (124) Instns. rate for whole Pleist. and late Plio.
4 - (127) Lowest Pleist. missing.
5 - (128) Lowest Pleist. missing.
6 - (129) Tectonic mixing throughout Plio-Pleistocene.
7 - (133) Hiatus (es) early Pleist. to Messinian.
8 - (134) Hiatus Pleist. to early Plio.
9 - (375) Rates for whole Plio-Pleistocene, hiatus ~1 m.y. at base.
10 - (376) Probably some Pleist. missing.

No. 11 - (377) Hiatus early Pleist. to M. Miocene.
12 - (378) Instns. for whole Pleist. and part late Plio.
13 - (121) Hiatus E. Plio. to L. Tortonian. Rates mostly for late Pliocene.
14 - (122) Hiatuses within Pliocene and at base.
15 - (123) Instns. rates for whole Pliocene. Hiatus E. Plio. to Miocene basement.
16 - (125) Instns. rates fro whole Pliocene. Hiatus E. Plio. to Messinian.
17 - (372) Internal hiatuses.

No. 18 - (373) Condensed.
19 - (376) Highly condensed. Quaternary slump in early Pliocene.
20 - (124) Hiatus E. Plio. to Messinian.
21 - (134) Hiatus E. Plio. to Messinian.
22 - (371) Hiatus E. Plio. to Messinian.
23 - (372) Hiatus E. Plio. to Messinian, 1 m.y.
24 - (373) Highly condensed.
25 - (372) A.D. to base of Burdigalian.
26 - (375) A.D. extrapolated from seismic profile.

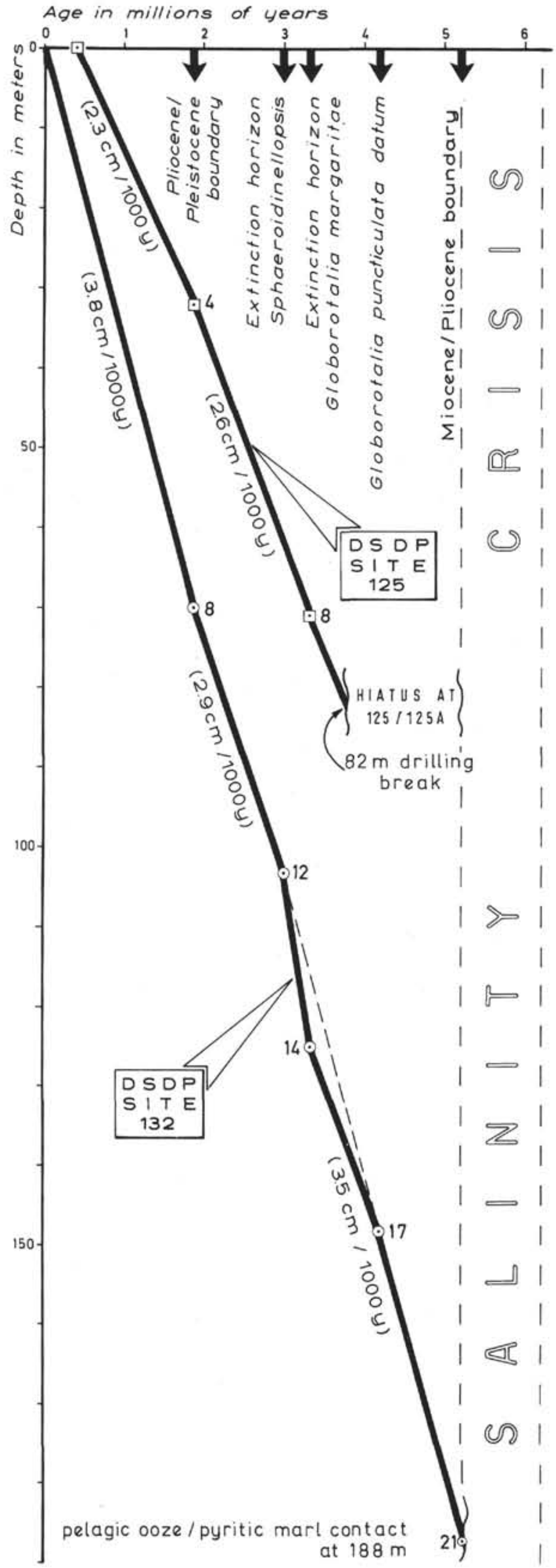


Figure 2. *Selected curves of cumulative sediment thickness versus geologic time. In both examples illustrated (Plio-Pleistocene sediments continuously cored in structurally elevated areas) sedimentation is essentially biogenic, with terrigenous input in the finer fractions and occasional volcanogenic input limited to the Quaternary.*

**Pleistocene:** from the *Globorotalia truncatulinoides* datum, which falls in the lower part of the Olduvai event of the Matuyama epoch (Hays and Berggren, 1971), to the Holocene. The Pliocene/Pleistocene boundary has been subject to intense criticism both in the past and quite recently (see discussion in Cita and Stradner, in press); it is here considered conventionally as above. In terms of calcareous nannofossil zonation, it falls close to the NN 18-NN 19 zonal boundary (extinction horizon of *Discoaster brouweri*).

The Pliocene-Pleistocene sedimentation rates are illustrated in histograms in Figure 3. The overall maximum value is in the Pleistocene and the minimum values are in the Pliocene. A progressive decrease in the mean value for all sites is observed back through time.

In all cases the maximum value represents depositional sites receiving a major supply of sediments by turbidity currents. The minimum value represents those sites with large depositional gaps and omission surfaces.

### Sedimentation Rates During the Salinity Crisis

Accumulation rates during the Messinian salinity crisis can be estimated only if we accept the following boundary conditions:

1) the salinity crisis was basin-wide in the Mediterranean,

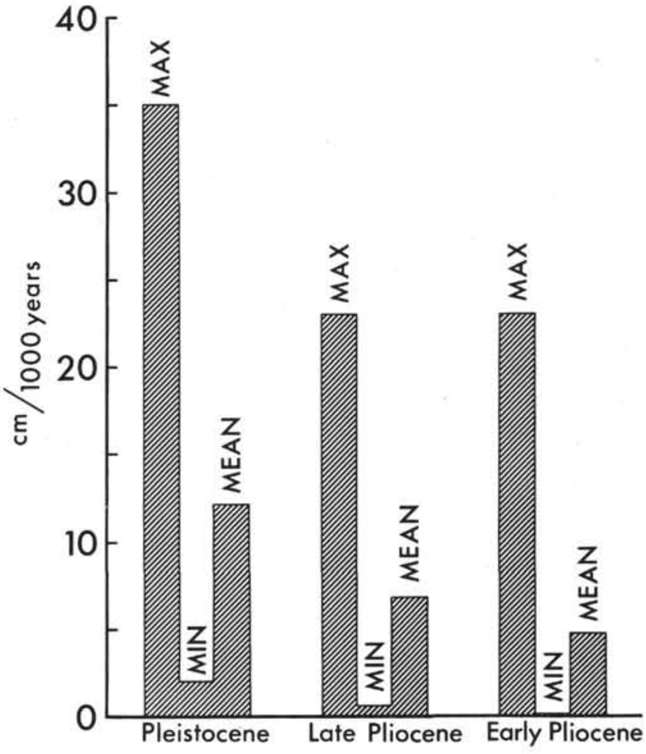


Figure 3. *Maximum, minimum, and average sedimentation rates in post-salinity crisis Mediterranean deep-sea sediments.*

2) the salinity crisis was time-synchronous,
3) the onset of the salinity crisis occurred:
within Zone N 17 (*Globorotalia plesiotumida*),
within Zone NN 11 (*Discoaster quinqueramus*),
near the base of the *Stichocorys peregrina* Zone,
near the base of paleomagnetic Epoch 6.
4) the termination of the salinity crisis (= Miocene/Pliocene boundary, see Cita, 1975a) occurred:
near the base of Zone N 19,
within Zone NN 12 (*Amaurolithus tricorniculatus*),
within the *Stichocorys peregrina* Zone,
very close to the limit between paleomagnetic Epoch 5 and the Gilbert Epoch.

The duration of the salinity crisis which results from the above boundary conditions is approximately 1 m.y.

Sediments which accumulated during this time span and were cored in DSDP drill sites include evaporites and interbedded marls, as recorded at Sites 122, 124, 132, 134, 125, 371, 372, 374, 375, 376, 378; (subaerial) siltites, as recorded at Site 133, and (subaqueous) marls and mudstones either barren, or yielding brackish, shallow-water faunas, as recorded at Sites 129A, 374, and 376. The brackish water marls have been deposited after the evaporites and prior to the Pliocene deep-sea transgression.

Information on thicknesses of Messinian sediments derives from:

a) DSDP drill sites, where the Mediterranean Evaporite has been entirely penetrated only at two drill sites. There, it was particularly thin due to pinch out at the edge of abyssal plains. In the other drill sites the penetration was limited to its uppermost part. Table 2 gives the thicknesses actually penetrated, and the thicknesses inferred from seismic reflection profiles.

b) commercial wells of the Crotone basin of Calabria, where the Messinian evaporites are 800-850 meters in thickness (maximum), of which up to 300 meters is salt (Ercole Martina, personal communication, 1976). According to Roda (1964) the three units of Messinian age overlying the "Tripoli" are, respectively, 150 meters thick (lower evaporitic formation), up to 450 meters thick (detrital-saline formation), and up to 400 meters thick (upper evaporitic formation).

c) land exposures, mines and wells in Sicily, where the thickness is up to 1500 meters (Decima and Wezel, 1973).

In addition, the thickness of the Mediterranean Evaporite beneath the deep abyssal plains of the eastern and western basins can be computed from travel times in multichannel seismic profiles (Finetti and Morelli, 1973; Mauffret et al., 1973; Biju-Duval et al., 1974) and estimates of compressional wave velocities measured on evaporites, salts, and marls (Schreiber et al., 1973). Thicknesses beneath the central Balearic Abyssal Plain exceed 1300 meters and those beneath the Antalya Abyssal Plain approach 2500 meters.

It follows from the above observations that accumulation rates for the Messinian age evaporites are highly variable and likely to be more than two orders of magnitude (i.e., more than 1 km/m.y.) greater than those of pelagic oozes of the open ocean. In fact, halite and related chloride varves in the Realmonte salt mine in Sicily reach 3 to 5 cm in thickness (Decima, 1975) and are interpreted as annual deposits.

**TABLE 2**
**Thickness of the Mediterranean Evaporite Formation in the 10 DSDP Drill Sites Where a Substantial Penetration Was Achieved**

| Drill Site | Meters Cored | Thickness From Seismic Profile (m) | Base Reached | Comments |
|---|---|---|---|---|
| 124 | 65 | More than 550 | No | |
| 134 | 39 | More than 700 | No | |
| 133 | 138 | | | Reached a discontinuity at the base with the Paleozoic (no evaporites) |
| 132 | 35 | More than 700 | No | |
| 125 | 26 | More than 150 | No | |
| 372 | 50 | | Yes | Pinch out: discontinuity at the base with middle Miocene |
| 374 | 75.5 | More than 1200 | No | |
| 375 | 50 | | Yes | Pinch out |
| 376 | 161.5 | More than 300 | No | |
| 378A | 30 | | No | |

## Sedimentation Rates in Pre-Salinity Crisis Times

Figure 4 shows instantaneous sedimentation rate curves drawn for all three drill sites which penetrated into pre-evaporitic Miocene sediments, namely, Site 372 in the Balearic Basin, Site 375 in the Levantine Basin, and Site 121 in the Alboran Basin where the penetration into the Miocene was comparatively minor.

The age of the oldest sediment in contact with basement at Site 121 is here re-estimated at 8 m.y., on the basis of the co-occurrence of *Globorotalia acostaensis* and *G. acostaensis humerosa*, both recorded in Core 24 (see Ryan, Hsü, et al., 1973, p. 55).

At the Balearic site the sedimentation rate increases downhole as a function of age whereas it decreases in the Levantine site. This drop in accumulation rate is consistent with a noticeable variation in lithology from hemipelagic sediments with terrigenous turbidites in the Tortonian to pelagic sediments with pelagic turbidites in the Serravallian and Langhian. The estimated age of 20 m.y. for the bottom of the hole (375) is based on the recognition of the *Discoaster druggi* Zone NN 2, which ranges from 22 to 19.3 m.y. according to Ryan et al. (1974).

The pre-salinity crisis rates are not widely divergent and group between 2.5 and 10 cm/1000 years. Clearly expressed in the marginal setting of the Balearic Site 372 is the wide stratigraphic gap between that which can be definitely assigned to pre-crisis interval and that which belongs to the Messinian and is characterized by oligotypical faunas.

## DISCUSSION

The following discussion focuses on the marked, well-documented, and progressive variations in sedimentation rate recorded for the pelagic, hemipelagic, and turbiditic sediments deposited in the Mediterranean after the termination of the salinity crisis and also on their geodynamic implications.

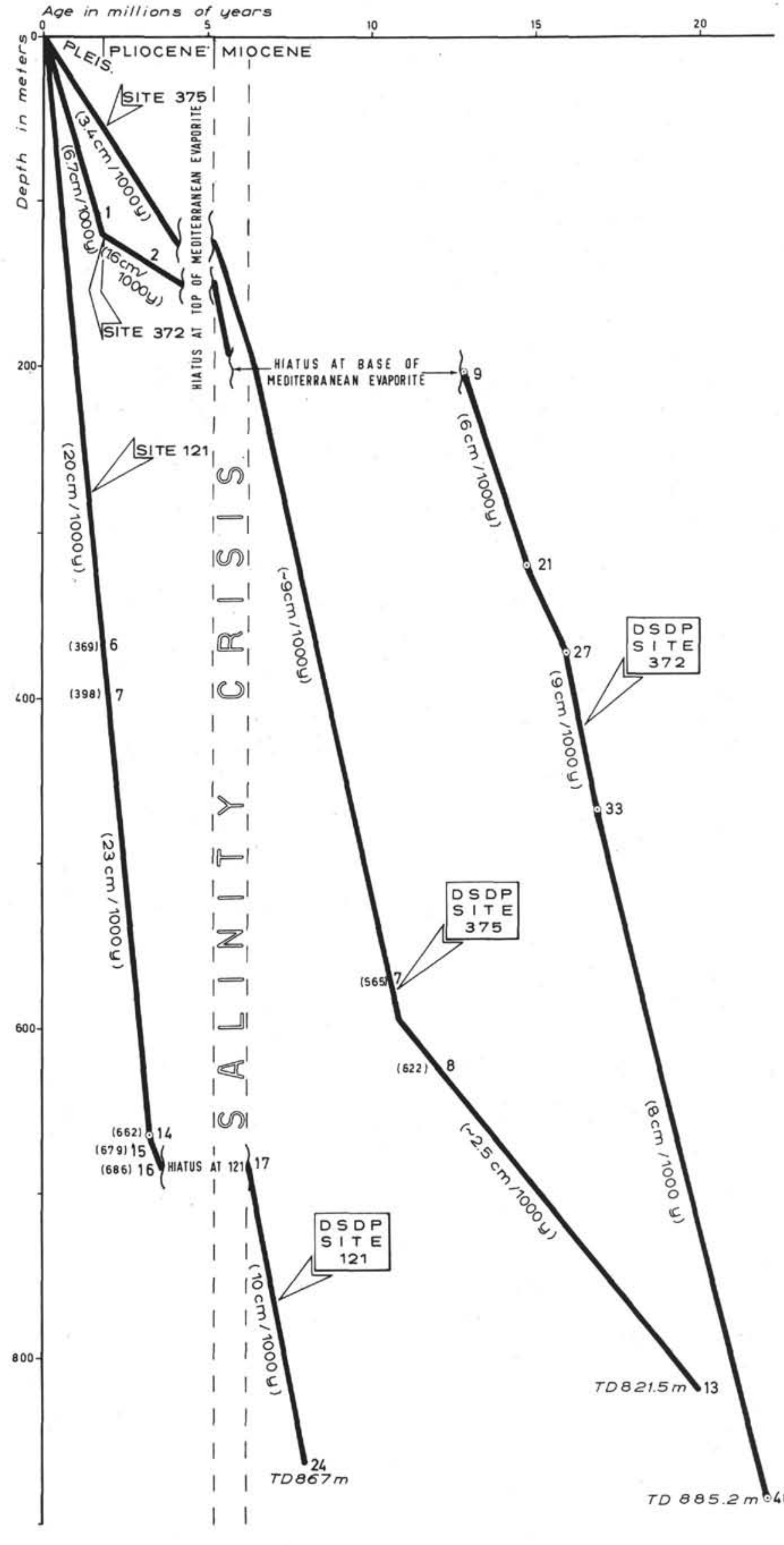


Figure 4. *Instantaneous sedimentation rates calculated for the three drill sites which penetrated into pre-evaporitic Miocene sediments.*

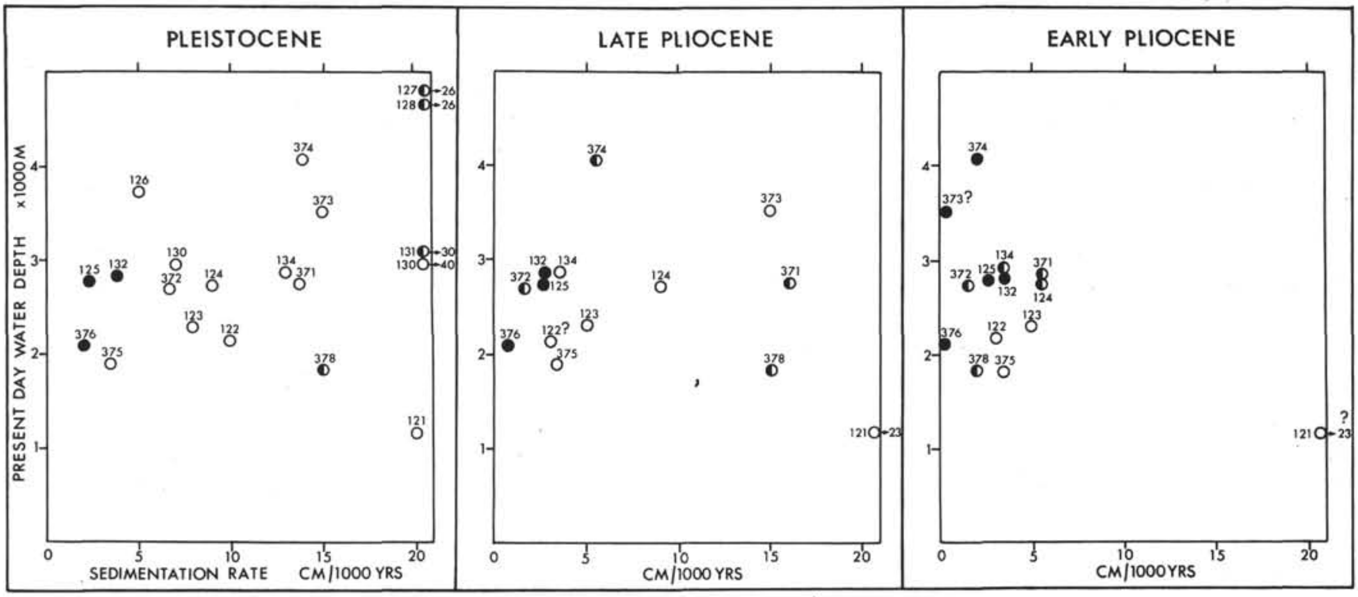


Figure 5. *Scatter diagrams showing instantaneous sedimentation rates for Mediterranean drill sites plotted against present-day bathymetric depth. Values plotted in categories: (a)* ● *continuously cored; (b)* ◐ *cored at regularly spaced intervals* < *50 m; (c)* O *cored at widely spaced intervals* > *50 m. Pleistocene values are widely dispersed. Late Pliocene values group generally into two clusters: one representing basin sites and a second enclosing ridge and rise sites. Early Pliocene values group closely into one cluster, except for Alboran Site 121.*

## Sedimentation Rates Versus Depth and Geological Setting

Figure 5 is a scatter diagram of the instantaneous sedimentation rates versus present-day bathymetric depth for the various drill sites recovering Pliocene and Pleistocene sediments.

In the Pleistocene the range of the sedimentation rates is diverse and there are no strong clusters. In general the highest values are recorded in basinal settings and the lowest on ridges or rises. The physiographic setting affects the sedimentation rate much more than the water depth itself. The anomalously low rate recorded in the basinal Site 376 (Antalya Basin) should not be taken at face value since there is evidence of hiatuses in this Pleistocene section (see Kidd et al., this volume).

In late Pliocene times the ranges of the sedimentation rates fall broadly into two discrete clusters. The first encompasses only sites with basinal settings at the present day, where values close to 15 cm/1000 years are recorded. The second cluster, with rates ranging from 2.5 to 5 cm/1000 years, encompasses all the other drill sites, both those located on present-day ridges or rises and those at the edge of abyssal plains. The strikingly low value of 0.1 cm/1000 years is limited to the *Sphaeroidinellopsis subdehiscens* Partial Range Zone as expressed in the condensed section of the Antalya Basin (Site 376). The large differences recorded are obviously unrelated to present-day water depths.

In the early Pliocene only one cluster is detectable. All the values calculated are lower than 5 cm/1000 years, with the single exception of the Alboran site, the only location where thick clastic turbidites were recorded from this portion of the stratigraphic column. For the rest of the Mediterranean it is apparent that early Pliocene sedimentation rates are independent of both present-day water depth and geological setting.

## Sedimentation Rates Versus Longitude

Figure 6 illustrates individual sedimentation rates calculated separately for the Pleistocene, for the late Pliocene, and for the early Pliocene in 11 selected Mediterranean drill sites and plotted as a function of longitude.

The Pleistocene rates differentiate the topographic highs (e.g., Sites 125 and 132) from the abyssal plains. In the late Pliocene the differentiation is more attenuated and in the early Pliocene it disappears altogether. Only the Alboran site has rates which remain uniform through time.

All the early Pliocene rates, except that of the Alboran site (where the early Pliocene section is very limited, as shown in Figure 4), have magnitudes similar to those values recorded for the Pleistocene for topographic elevations. This similarity suggests that (1) the type of sedimentation characteristic of the highs was dominant throughout the entire Mediterranean during the early Pliocene, (2) the type of sedimentation characteristic of the abyssal plains and their margins was not present during the early Pliocene, and (3) the volcanogenic contribution, which is practically limited to the last million years, is quantitatively irrelevant. Conclusion (2) cannot be taken as a support

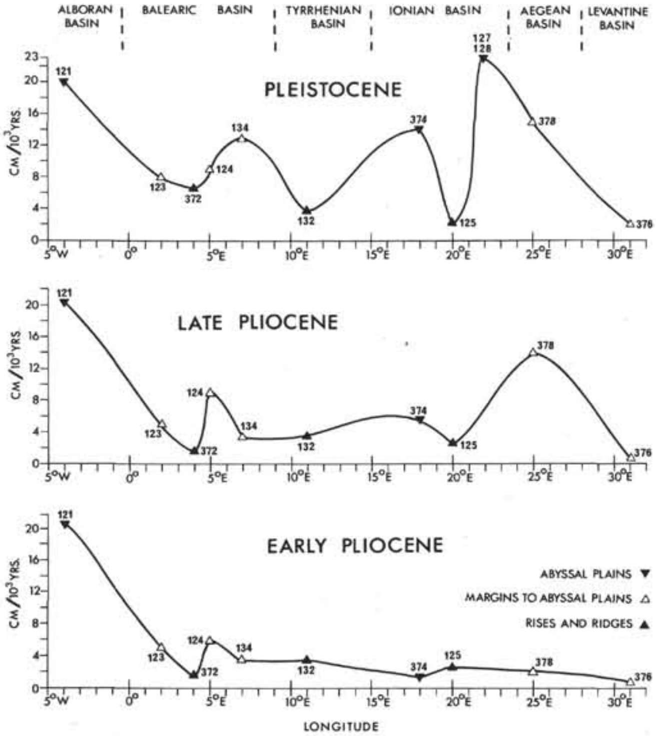


Figure 6. *Instantaneous sedimentation rates for selected sites plotted against longitude. Pleistocene values differentiate topographic highs from abyssal plains. In the late Pliocene this differentiation is less pronounced, while in the early Pliocene the topographic influence almost disappears altogether, except for Alboran Site 121.*

of the so-called "subsidence model" (Nesteroff, 1973), as we will discuss later (see under Geodynamic Implications).

The anomalous sedimentation in the Alboran Basin suggests that this basin behaves more as a gulf of the Atlantic than as a tributary of the Mediterranean. This is confirmed by seismic reflection profiles over the Alboran Basin (see fig. 18-A in Ryan et al., 1970) on which the draping behavior of Pliocene acoustically transparent strata is continued in the younger acoustically stratified series. This is in direct contrast to other Mediterranean basins (e.g., the Tyrrhenian Basin, see Figure 7, or the Cretan Basin, see Figure 2, Chapter 8) where the Pliocene series drapes the underlying Miocene surface and the Pleistocene series ponds the total basin depression.

### Sedimentation Rates as Tectonic Indicators

Greater rates of late Quaternary sedimentation were observed on the landward sides of the Hellenic Trench than on the seaward side (Ryan, Hsü, et al., 1973, Chapter 9, p. 253). The difference is an expression of the progressive northeast downward flexure of the Mediterranean sea floor here as it plunges beneath the Hellenic Arc, and the fact that contemporary sedimentation is attempting to keep the upper surface of the trench plain flat. This style of flexure is seen south of Turkey where the Mediterranean Ridge plunges beneath the Antalya Basin abyssal plain north of Sites 375 and 376 (see fig. 25 of Ryan et al., 1970).

The differences in sedimentation rate in the Hellenic Trench were used to compute a flexure rate of 1° per $10^6$ years which was a measure of a subduction velocity of approximately 1.4 cm/years (Ryan, Hsü, et al., 1973, p. 271).

The depth differences for sediments accumulating at the same time in proximity to each other are hence a record of progressive tectonic deformation and are not an expression of ecological or environmental conditions.

Similarly the changes from very rapid early Pleistocene sedimentation at Site 130 on the Mediterranean Ridge, north of the Nile Cone, to low rates in the late Pleistocene is a consequence of continuing crustal shortening and folding of former basinal deposits. The trend from fast to slow deposition is opposite to that of the pre-flysch to flysch as recorded in alpine thrust belts and is more analogous to the transition from intraplate abyssal plain flysch of Wezel (1974) to the Scaglia facies, which generally precedes the classic interplate flysch of a subducting foredeep (e.g., the Argille scagliose passage upwards into the Macigno, see Ten Haaf, 1959, and Marnoso-arenacea, see Ricci Lucchi, 1969).

### Geodynamic Implications of the Low Rates in the Early Pliocene

The modern Mediterranean consists of several large and deep silled basins with rather narrow shelves and steep slopes. Except for the Nile and Rhone cones, broad sedimentary aprons are generally absent from the continental margins.

Sediment bypass of the shelf and slope provinces is relatively efficient, and as a consequence much of the fine and coarse grain sediments brought out from the continent is delivered either to abyssal plains and fans within the deeper confines of the basins, or to intermediate troughs of the peri-Tyrrhenian type.

Topographic highs such as seamounts, plateaus, and interbasinal ridges receive only minor influxes of the land-derived materials (Venkatarathnam and Ryan, 1971).

Two possibilities can be entertained to explain the extremely low rate of supply of terrigenous sediment to the locations of the basin drill sites during the early Pliocene, as compared to a significantly greater supply in the Quaternary: (1) there was at that time much less runoff and erosion from the surrounding land areas, which also included the large drainage areas of the ancestral Nile, Po, Black Sea, Rhone rivers, etc., because of either a drastically different climate or a lack of mountainous relief; (2) there was a much greater incidence of shelf and slope (intermediate type) storage areas, which deprived the basins of their normal share of sediment input by inhibiting sediment bypass.

In the context of the Pliocene foundering hypothesis (e.g., the Pliocene Revolution of Bourcart, 1960), relief

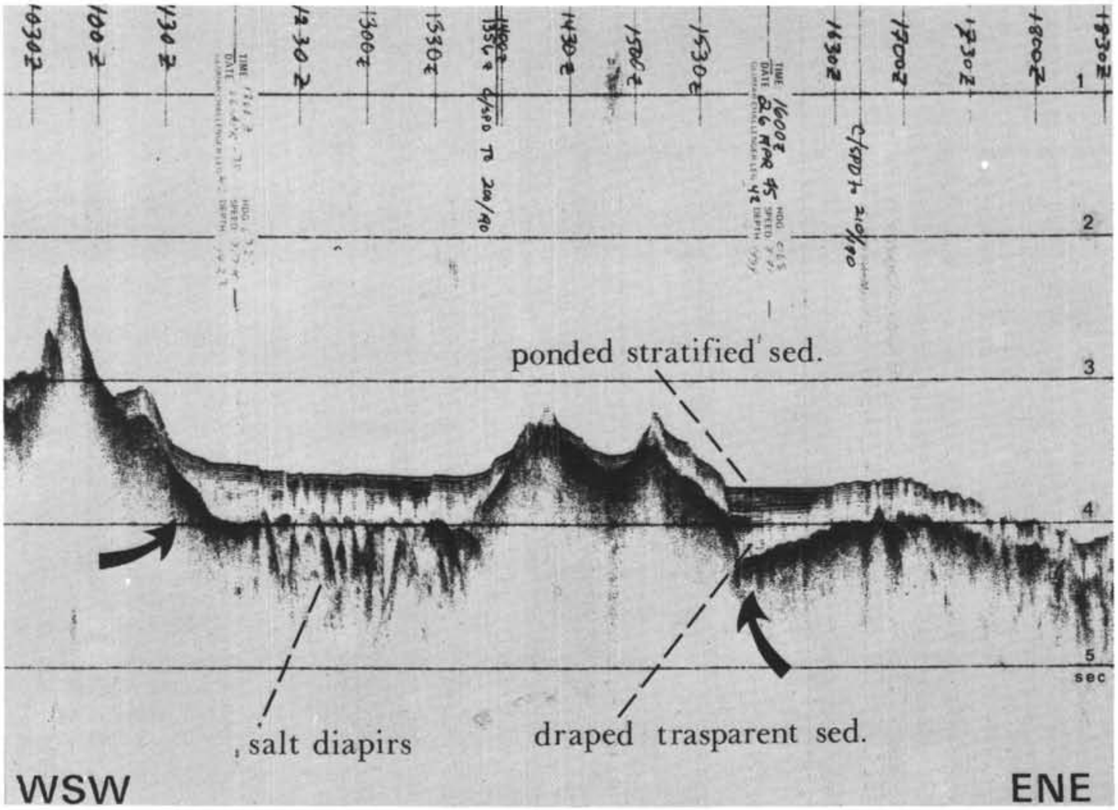


Figure 7. *Seismic reflection profile across the Western Tyrrhenian Basin contrasting the acoustic behavior of young layered sediments ("ponded" facies) and older, transparent sediments. The latter "drape" the Mediterranean Evaporite whose top (to which the arrows point) is Horizon M. Vertical scale in seconds, two-way travel time.*

of the basin edges would be expected to have drastically increased at the end of the late Miocene salinity crisis. The slopes along the margins of the collapsing basins would be fault scarps whose gradients would be expected from structural considerations to have exceeded the angle of repose of loosely consolidated muds, sands, and oozes. The area landward of the boundary faults would be expected to rise and become emerged as a result of isostatic considerations (e.g., the peripheral bulge). Few intermediate storage areas of land-derived sediments are likely to have been formed.

According to the desiccation hypothesis (of Hsü, et al., 1973), evaporitic drawdown of the hypersaline sea would expose the margins to subaerial denudation during the salinity crisis. The gradients of the margin slopes would decrease in response to headward erosion of streams as has been observed on the subsurface of the Gulf of Lion and Rhone Cone (Ryan, 1976) and in the subsurface of the eastern Levantine margin (Ryan, in press).

The rapid filling of the partly desiccated Mediterranean basins would inundate the continental edge and flood far towards the interior along overincised river beds (i.e., 1250 km in the Nile area as demonstrated by Choumakov (1967) and 300 km in the Rhone Valley as discussed by Clauzon (1973). This drowning of the bevelled shelves and slopes and the creation of deep and long estuaries would offer substantial areas as traps for both suspended and bed-load sediments carried from the watersheds by rivers or washed into the sea from the coasts. Volumetrically significant bypass of the continental margin province would not be expected until new equilibrium depositional surfaces were created, predominantly by upbuilding processes in contrast to out-building and delta front progradation.

Evidence of delayed progradation is illustrated in seismic profiles across the eastern margin of the Adriatic (see Figure 8) and the coast of Israel. As a consequence of this delayed input of sediment to the deeper parts of the Mediterranean basins, or even to peri-Tyrrhenian basin slope depressions, all drill sites would be expected to record early Pliocene sedimentation rates similar to those which occur today, only in regions far removed from clastic sediment input (i.e., the plateaus, seamounts, and ridges).

The eustatic process is one which has a modern-day analog in other oceans outside the Mediterranean region. Damuth and Fairbridge (1970) and Milliman et al. (1975) have shown that even the large Amazon River does not at present deliver sediment beyond the confines of its subaerial delta due to the approximately 125-meter Holocene sea level rise, which occurred in that region. Pimm and Hayes (1972) have shown that a similar situation occurred previously at approximately five million years ago, when the retreat of the

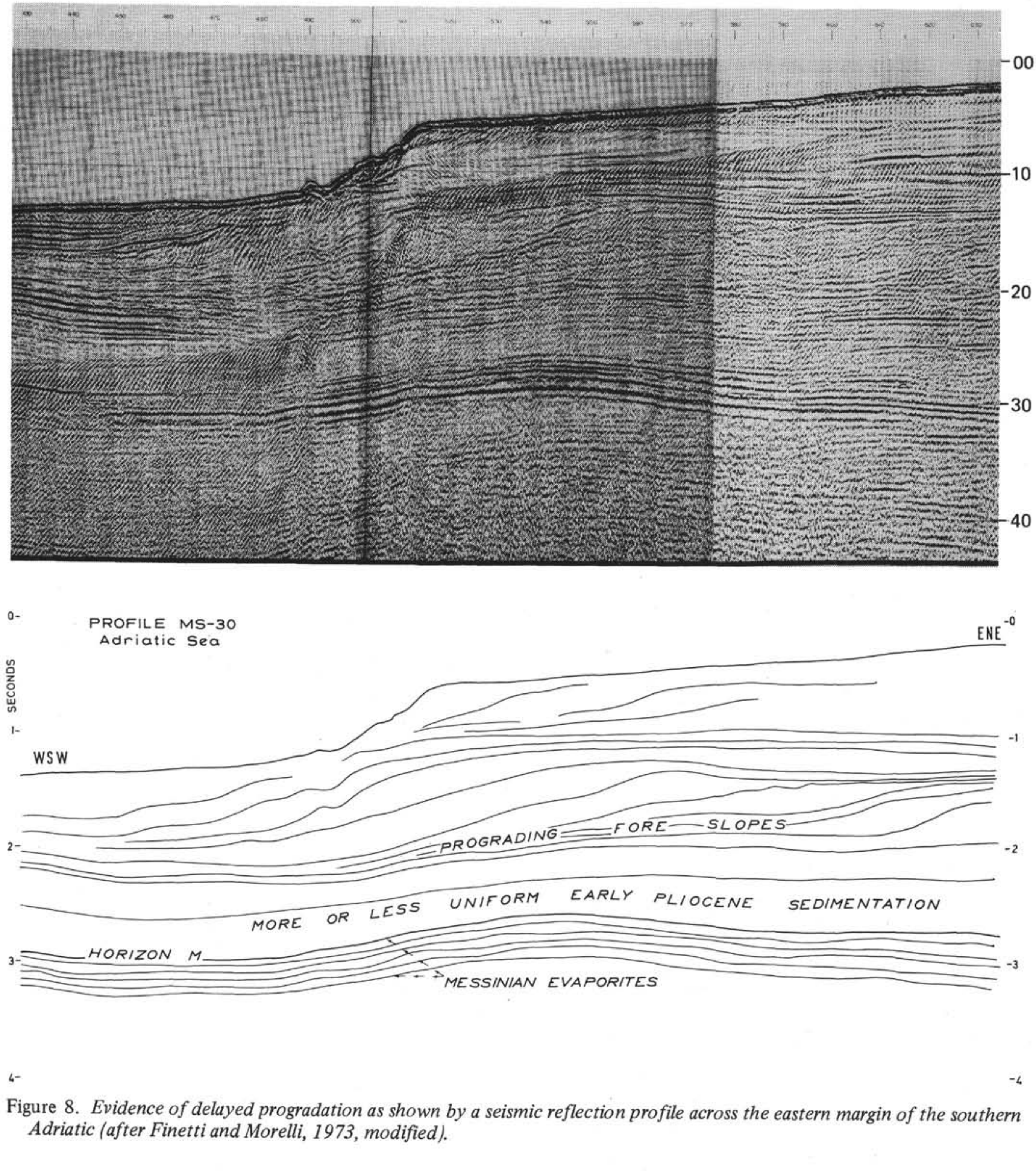


Figure 8. *Evidence of delayed progradation as shown by a seismic reflection profile across the eastern margin of the southern Adriatic (after Finetti and Morelli, 1973, modified).*

late Miocene glaciers induced a coastal transgression of the South American continent that starved the Ceara Abyssal Plain and Rise from clastic input causing an abrupt change in lithology at DSDP Site 142.

## SUMMARY AND CONCLUSIONS

The anomalously low rate of sediment supply to settings within the Pliocene Mediterranean, which are now basinal, is interpreted as the result of a rapid eustatic sea level rise which accompanied the marine flooding of a depressed water body at the close of the late Miocene salinity crisis. The subsequent general increase of the rate of accumulation in the Quaternary to values equivalent to those attained prior to the salinity crisis is an indication that more recent surfaces of deposition are now more or less in equilibrium

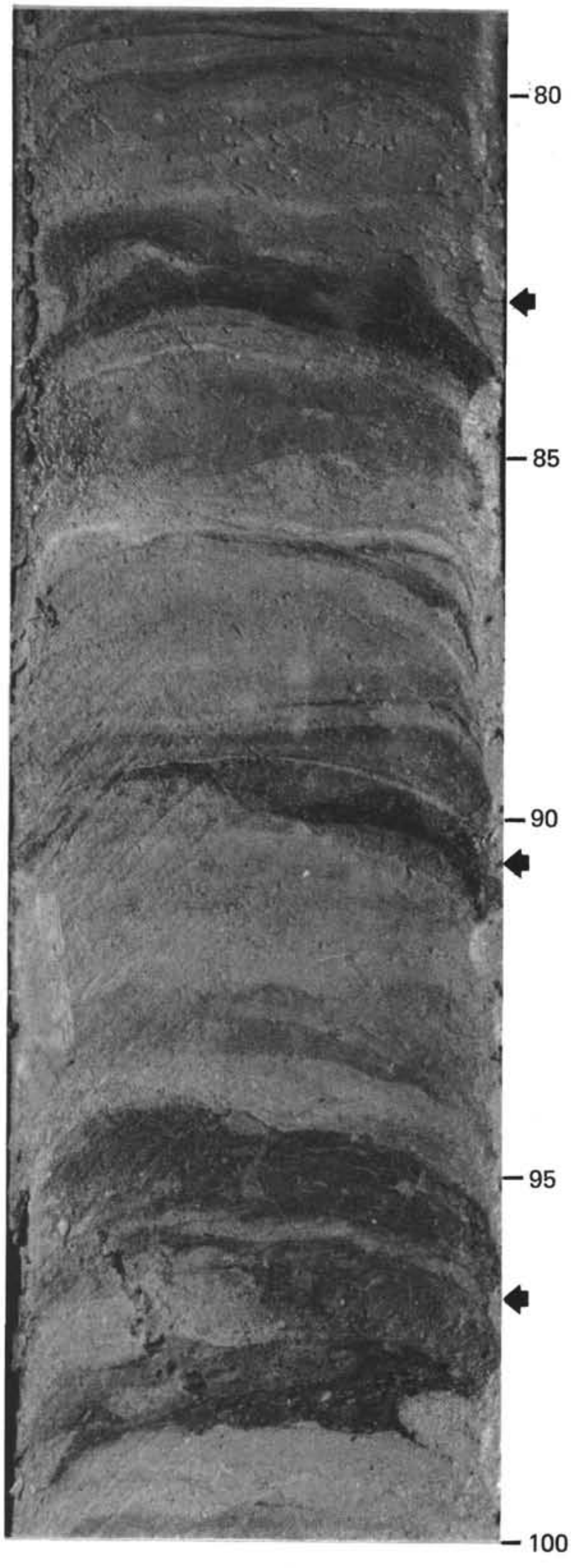


Figure 9. *Pelagic ooze with omission surfaces (arrows) from the early Pliocene of the Antalya Basin (Section 5-5, Site 376). This sediment has been deposited at the incredibly low rate of 0.1 cm/1000 years. Three biozones (MPl2, MPl3, and MPl4 of Cita, 1975b), spanning a time interval of approximately 2 m. y. are represented in 1.5 meters of core. This sediment strongly resembles the condensed sequences of the classic Scaglia or* Ammonitico rosso *formations.*

following the massive disturbance generated by evaporitic drawdown. Biogenic productivity as measured by rates of accumulation of calcareous and siliceous fossils has remained more or less uniform during the Neogene except for the brief ecological demise at the time of the hypersaline Messinian seas and lakes.

Reduced stratigraphic sections on topographic rises, accompanied by surfaces of omission, iron, and manganese crusts and/or winnowed debris (see Figure 9), are interpreted as the result of benthic boundary layer turbulence induced by the impingement of circulating water masses against these upstanding features. Subaqueous debris flows and slumps, containing fragments of exclusively pelagic sedimentary formations, result in local areas of high sedimentation rates in the Mediterranean Ridge province and Messina "Cone" (Calabrian Ridge of Belderson et al., 1974). Some evidence suggests that some of this slope instability may be related to subsurface solution-collapse of the more soluble parts of the Mediterranean Evaporitic formation.

The progressive increase in sediment thickness on the landward side of the Mediterranean trench plains is attributed to the downward flexure of the northern flank of the Mediterranean Ridge where it begins to subduct under the Hellenic Island Arc. The unidirectional change from pure biogenic carbonates in the Pliocene levels at Site 376 to turbidites in the Pleistocene sequence is compared to the transition from preflysch to flysch as observed in Alpine nappes. The trend towards a more coarsely clastic coarsening upwards sequence observed both at Site 376 and in linear flysch belts is a measure of the progressive closure of oceanic regions and the arrival of former pelagic settings into deep-sea trenches along convergence zones.

A reversal of this trend occurs at Site 130 on the Mediterranean Ridge where a sequence of clastic turbidites with high sedimentation rates (greater than 30 cm/1000 years) is replaced by slowly accumulating pelagic oozes (less than 5 cm/1000 years) in the late Quaternary. This has a similar tectonic origin being related to the uplift of a part of the former Levantine Basin floor as a peripheral swell of the type that exists seaward of all oceanic trenches (Watts and Cochran, 1974, 1975). An analog of this facies change is the conspicuous presence of Scaglia-type deep water pelagic deposits above ancient basinal flysch, which are now exposed in thrust sheets within the Apennines.

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