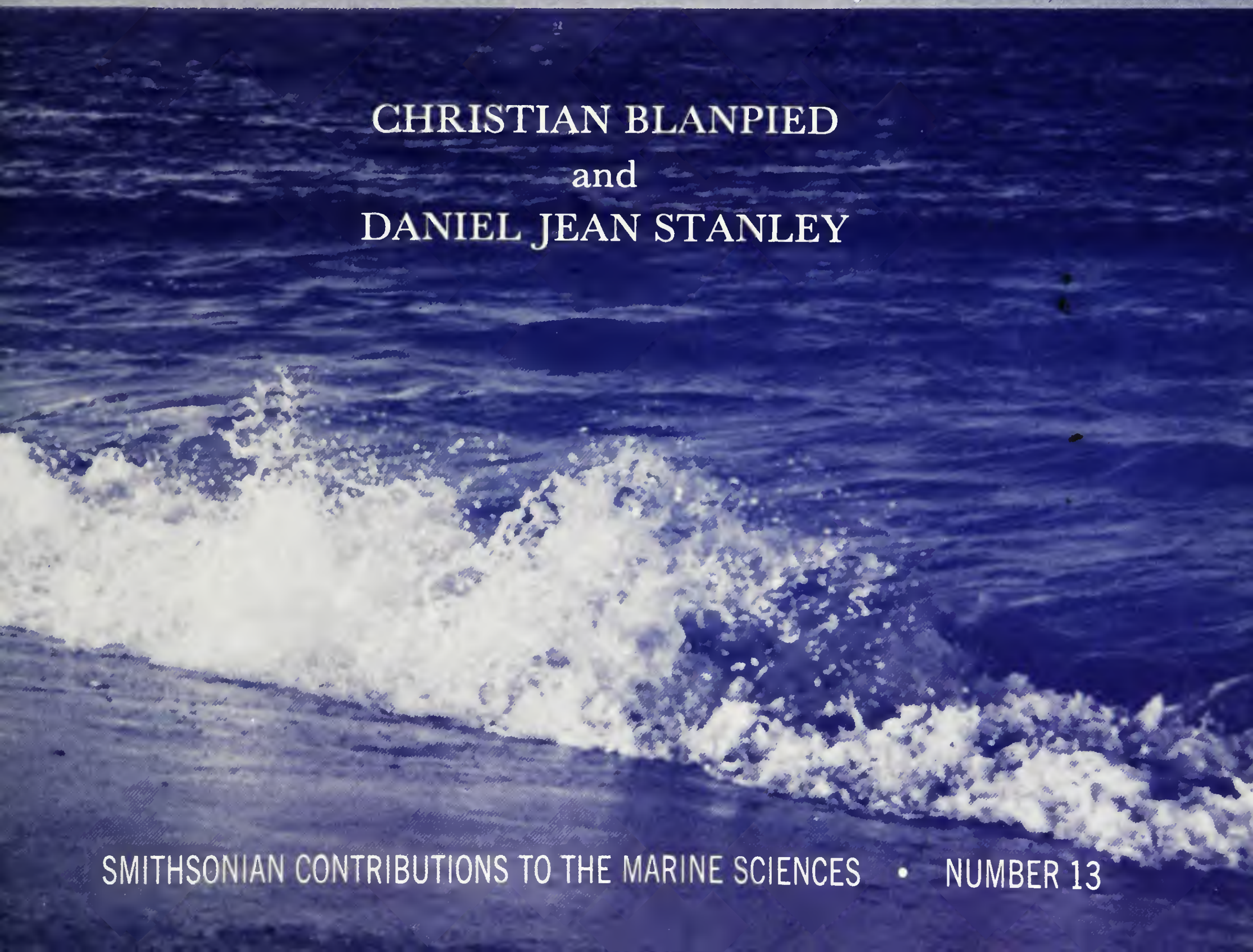
Uniform Mud (Unifite) Deposition in the Hellenic Trench, Eastern Mediterranean



CHRISTIAN BLANPIED
and
DANIEL JEAN STANLEY

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ABSTRACT

Christian Blanpied and Daniel Jean Stanley. Uniform Mud (Unifite) Deposition in the Hellenic Trench, Eastern Mediterranean. *Smithsonian Contributions to the Marine Sciences*, number 13, 40 pages, 15 figures, 2 tables, 1981.—Unifites are nearly structureless, often thick, layers of clayey silt and silty clay that appear compositionally homogeneous and generally show a subtle fining-upward trend. Formed by uniform and faintly laminated muds, unifites are deposited from rapidly emplaced single gravity-flow events. Along the Hellenic Arc, unifites are restricted to small trench basins and interpreted as an end-member gravity-emplaced facies. Unifites are not truly homogeneous and the petrological distinctions observed are closely related with the trench basin depositional site relative to steep margins bounding the trench plain. The faintly laminated portions of unifites contain a higher silt content; the uniform mud portions are slightly better sorted and display an upward increase of planktonic tests. The sand fraction is dominated by clastic aggregates eroded from older margin sediments; unifites also comprise a large silt-size nannofossil content (including reworked forms).

The increased uniformity basinward of unifites records deposition from turbidity current-related flows of diminished concentration that spread over large areas of a flat trench floor. Faint laminae may be related to phases of flocculation and depositional sorting of the sediment load during transport, and to the hydraulic jump affecting a flow upon its arrival on a near-flat basin floor. The slower-moving tail releases the uppermost nonlaminated, graded unifite mud term. The thickness of Hellenic unifites is a function of entrapment of moderate amounts of material in small trench plains. The homogenization process essential for unifite deposition involves relief bypass, i.e., the preferential entrapment of coarser or denser fractions in slope depressions, while finer or less dense particles are transported further downslope across irregular seafloor features. Unifite deposition records the interplay of: (1) complexity of dispersal paths and accessibility of sediment to the trench basin, (2) redepositional processes, grain-support mechanisms and gravity-induced flow characteristics, (3) type of material transported, (4) extent of textural segregation and compositional sorting during flow, (5) slope relief bypassing process, and (6) selective entrapment of essentially fine-grained particles in the more distal trench catchment basins. Mediterranean unifites can serve to interpret uniform mud facies on both active and passive margins and in the rock record.

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Introduction

The increased interest in the depositional origin of fine-grained marine sediments has resulted in the recognition of diverse mud types. Several classifications have called attention to a structureless mud facies reported in some modern deep-sea environments and in the marine rock record (summaries in Piper, 1978, and Stow and Shanmugam, 1980). The premise of this study is that the Mediterranean region, with its well-exposed mudstone formations in the surrounding mountain chains and its thick, mud-rich post-Miocene unconsolidated sequences in the various isolated basins (Stanley, 1977a), should be a particularly suitable sector in which to define the nature, distribution, and origin of such apparently homogeneous lutites. Insofar as the modern Mediterranean Sea is concerned, studies focusing on fine-grained sediment transport have been undertaken in several basin settings. Sedimentological research has advanced during the past fifteen years largely as a result of combined coring and subbottom profiling surveys in diverse topographic settings where unconsolidated deposits of suspension and gravity-emplaced origin have accumulated.

Sedimentological studies of ponded (cf. Hersey, 1965) Mediterranean mud facies have been undertaken in deep depressions, such as the western Alboran Sea (Stanley, Gehin, and Bartolini, 1970), portions of the Algéro-Balearic Basin Plain (Rupke and Stanley, 1974), Tyrrhenian Basin Plain (Ryan, Workum, and Hersey, 1965); Corsican Trough (Stanley, Rehault, and Stuckenrath, 1980); deep troughs in the Strait of Sicily (Maldonado and Stanley, 1976; Blanpied et al., 1979), and some small basins in the Adriatic Sea (van Straaten, 1967), and on the Mediterranean Ridge (Kastens and Cita, in press). In the Hellenic Arc region of the eastern Mediterranean investigations of fine-grained sedimentation have been made by Hersey (1965), Ryan et al. (1973), Vittori (1978), and Maldonado, Kelling, and Anastasakis (1981).

Detailed mapping of Quaternary unconsolidated sediment in different depositional environments of the Hellenic Trench reveals that clayey silt and silty clay, rather than sand, almost invariably dominate the depositional cover of this structurally and morphologically complex region. Seven fine-grained sediment types, or lutites, have been identified by Stanley and Maldonado (1981)

Christian Blanpied, Compagnie Française des Pétroles, Départment d'Exploration, Paris, France. Daniel Jean Stanley, Division of Sedimentology, National Museum of Natural History, Smithsonian Institution, Washington, D.C. 20560.

in a suite of 24 cores collected in eight distinct depositional settings west and south of the Peloponnesus (Figure 1). Four of these mud types (slump, debris flow, turbiditic and hemipelagic) have received considerable attention in earlier studies of both modern and ancient deep marine sediments. A fifth type includes very well-laminated mud facies that accumulated throughout much of the Hellenic area (see Stanley and Maldonado, 1981, fig. 3b, c); this facies formed primarily during periods of marked water mass stratification, such as at time of sapropel formation, which affected most of the eastern Mediterranean. The present study focuses specifically on the other two, apparently related, fine-grained facies that are concentrated primarily in Hellenic Trench basins proper. These types are apparently structureless uniform mud and faintly laminated mud.

Several possible mechanisms have been proposed for the emplacement of these two lutite types in the study area. Earlier studies indicated that homogeneous muds may have been deposited in part by fine pelagic suspension-related processes (Ryan, et al., 1973:268) or, alternately, by "giant" dense mud flows (Stanley and Knight, 1979). More recent detailed analysis of the uniform and faintly laminated muds, however, suggest that these two lutite types most likely represent "single-event" gravitative deposits. The mechanisms involve the settling of material from slow moving and low concentration flows, which are related to turbidity currents that are preferentially ponded in small trench basins (Stanley and Maldonado, 1981, fig. 11).

The term "unifite"[1] (Stanley, 1980) is applied to the nearly structureless, often thick, layers of clayey silt and silty clay that are formed by uniform and faintly laminated mud facies described in this study. Such deposits generally appear, but are not truly, compositionally homogeneous, show various subtle fining-upward trends, and are deposited by gravity flow transport events. The formulation of a depositional model for uniform muds requires a refined description of the petrologic attributes of these fine-grained, structureless deposits. Particular attention is paid here to selected uniform mud sections from seven piston cores collected in three Hellenic Trench basins during cruises of the R/V *Trident* (1975) and the R/V *Marsili* (1976).

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Discussions during the early phases of the Hellenic Trench study with R. J. Knight, Petro-Canada Limited, and A. Maldonado, University of Barcelona, proved most useful. The paper was reviewed by Dr. R. W. Embley, National Ocean Survey, National Oceanic and Atmospheric Administration, Washington, D.C., Mr. P. H. Feldhausen, NUS Corporation, Rockville, Maryland, and Dr. H. D. Palmer, Interstate Electronics Corporation, Arlington, Virginia. The study, part of the continuing Mediterranean Basin (MEDIBA) Project, was supported by a fellowship to C. Blanpied from the French Ministry of Foreign Affairs, Paris, and by Smithsonian Scholarly Studies grant number 1233S101.

Methodology and Abbreviations

The seven western Hellenic Trench cores containing uniform mud (1975 cruise R/V *Trident*,

[1] The term "unifite" was formally introduced by D. J. Stanley in October 1980 at the Conference on "Sedimentary Basins of Mediterranean Margins" sponsored by the Consiglio Nazionale delle Ricerche at the University of Urbino, Italy.

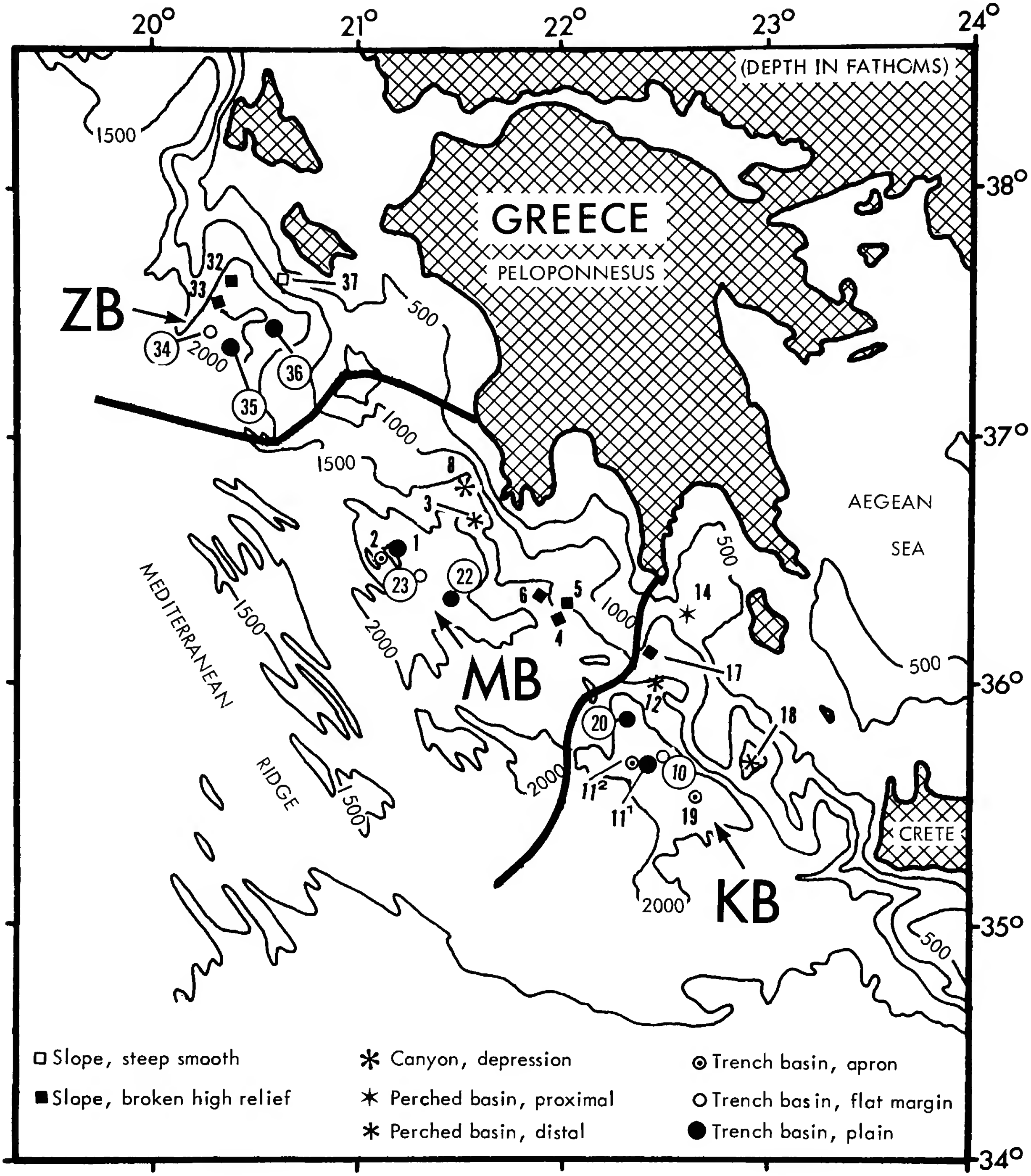


FIGURE 1.—Western Hellenic Trench margin showing the location of R/V *Trident* (TR 34–36) and R/V *Marsili* (MA 10, 20, 22, 23) cores and the physiographic environments in which they were recovered (circled numbers = cores containing unifites; uncircled core numbers do not have obvious unifites; ZB = Zakinthos-Strofádhes Basin, MB = Matapan Deep; KB = Kithera-Antikithera Basin).

or TR, cores 34, 35, 36; 1976 cruise R/V *Marsili*, or MA, cores 10, 20, 22, 23) range in length from 565 to about 1000 cm. For comparison purposes, other cores collected in this region were also examined. Complementary data concerning these and other cores cited in this paper, including core position, depth, and lithological information is provided elsewhere (Stanley, Knight, and Stuckenrath, 1978; Vittori, 1978; Stanley and Maldonado, 1981; Feldhausen et al., 1981). For the petrologic analyses, more than 250 samples were collected from uniform and faintly laminated mud layers at intervals ranging from about 5 to 25 cm. These samples were selected primarily on the basis of x-radiography of split cores, which is the most certain method to recognize both uniform and faintly laminated mud types.

All samples were treated in the same way. The sand fraction (>63 μm) was recovered by sieving, while the silt-clay separation was made using the Andreasen pipette method. Determinations of the complete size distribution of the silt and clay (<2 μm) fractions were completed with a Coulter Counter Model TA-II with two apertures (140 and 30 μm). The distribution (volumetric percent) of the entire silt and clay fraction was determined with the 140 micrometer aperture; selected samples from each core were processed using the 30 micrometer aperture to better define the fine silt and clay size distribution.

In those samples (approximately 150) where sufficient sand size material was available, the composition of 150 to 500 sand grains was identified using a petrographic microscope. Eighteen mineralogic components are recognized, and these are grouped into four major categories: (1) terrigenous (light minerals, heavy minerals, mica); (2) biogenic (planktonic foraminifera, shell fragments, benthic foraminifera, spicules, pyritized planktonic foraminifera, pteropods, pyritized benthic tests, ostracodes, juvenile forms of pelecypods, radiolarians and diatoms); (3) oxidized or reduced aggregates (red, black and plate-shaped); and (4) clastic aggregates consisting of cemented silt-sized particles.

The silt size fraction (2 to 63 μm) of all 250 samples was examined. This fraction includes 13 mineralogical components identified by high-power petrographic microscope and SEM, and these are grouped into five major categories: (1) terrigenous (quartz, feldspar); (2) biogenic (foraminifera, coccoliths, spicules, carbonate shell fragments); (3) volcanic products (palagonite, sideromelane, chlorite and heavy minerals, including microlite); (4) authigenic (recrystallized calcite and dolomite); and (5) clastic aggregates. The proportions of these silt-size groups are determined semiquantitatively by using a relative abundance scale, from 1 (trace amounts) to 5 (abundant).

The composition of the clay size fraction (<2 μm) was determined by x-ray diffraction, SEM, and chemical probe analyses. Forty-four samples were selected from cores MA-10 and MA-20, and twenty additional samples were obtained from the other five uniform mud-bearing cores. In addition, about 105 samples were selected from the other 17 cores shown in Figure 1 to determine the clay mineral composition of silt size.

Calcium carbonate content was determined for all mud samples using the standard ascarite absorption technique. These data were supplemented by thirty radiocarbon dates obtained from the seven uniform mud-bearing cores and two dates from slope core TR-37 (Table 1); nine of these were previously published in Stanley, Knight, and Stuckenrath (1978). Also utilized in this study were high-resolution 3.5 kHz records collected near the core sites during the 1975 *Trident* and 1976 *Marsili* cruises, and a suite of about 300 bottom photographs collected in 1978 in the Kithera Trench by the French Centre National pour l'Exploitation des Océans.

Abbreviations used in this study are as follows: FL = faintly laminated mud, KB = Kithera-Antikithera Trench system, MA = *Marsili* cruise, MB = Matapan Deep Trench system, S = sapropel, TR = *Trident* cruise, U = uniform mud, ZB = Zakinthos-Strofádhes Trench system.

Geological Framework of the Study Area

The study area southwest of the Peloponnesus and west of Crete (Figure 1) occupies a seismically

TABLE 1.—List of 30 radiocarbon dates obtained for seven western Hellenic Trench basin cores containing unifites, and two dates for core TR-37 collected on the steep Zakinthos slope (B.P. = years before present)

Core number	*Sample depth* (cm)	*Radiocarbon date* (B.P.)
MA-10	50- 63	12,775±155
	261-275	15,170±130
	495-507	15,030±125
MA-20	16- 30	12,090± 90
	151-166	11,880±110
	272-287	13,000±120
	392-407	12,450± 95
	589-604	14,045±110
	942-957	14,840±105
MA-22	89-106	11,260±160
	171-185	10,215±130
	239-254	19,290±325
	357-388	19,460±325
	686-698	25,300±370
MA-23	25- 40	11,315± 95
	110-130	28,060±610
	250-264	29,100±550
	415-440	29,700±730
	495-507	26,860±460
TR-34	130-144	14,500±120
	187-200	17,810±175
	339-353	28,730±650
	667-679	25,240±350
TR-35	135-150	10,175± 75
	220-235	16,510±150
	290-310	18,600±140
	470-490	19,710±210
TR-36	240-260	16,510±130
	450-465	16,910±155
	530-550	20,100±220
TR-37	50- 65	17,380±160
	240-255	>43,000

active region in the western part of the Hellenic Arc. Overall, this sector occupies a tectonically complex, largely compressive setting, believed to have experienced subduction and considerable vertical and lateral offset. The roles of plate collision and transform fault motion are discussed by Comninakis and Papazachos (1972), McKenzie (1972), Makris (1976), Biju-Duval, Letouzey, and Montadert (1979), Mascle and Le Quellec (1979), Le Pichon and Angelier (1979), and many others. The structural and stratigraphic configurations of this investigated region have been detailed by means of several closely spaced, high-resolution seismic surveys, the results of which are summarized by Got, Stanley, and Sorel (1977), Vittori (1978), and Le Quellec (1979). These studies reveal a structurally deformed unconsolidated sediment series of highly variable thickness. This series, dated as probable Pliocene and Quaternary age, lies above indurated strata locally comprising deposits of Cretaceous (Ryan, et al., 1973), Miocene, including probable Messinian evaporites, and Pliocene age (Ariane, 1979; Le Pichon, 1980).

Three distinct and well-individualized trench-basin systems, clearly apparent on morphological charts (Carter et al., 1972), result from this geologically recent tectonic activity. The three separate trench slope and basin systems are delineated largely by NW-SE and WSW-ENE tectonic trends, involving some extension (Got, Stanley, and Sorel, 1977), as well as compression. From NW to SE the western Hellenic Trench basin plains lie at depths of about 4150 m, 5000 m and 4615 m, and are named, respectively, the Zakinthos-Strofádhes system (ZB), the Matapan Deep system (MB), and the Kithera-Antikithera system (KB). Bathymetric and seismic profiles show that the trench basins proper are not simple U-shaped, elongated troughs. The trenches proper, as displayed in cross-sections of the Matapan Deep, include small depressions broken by ridges that subdivide, and thus limit, the size of the near-flat basin plains (Vittori, 1978:121; Le Quellec, 1979: 60). The surface area of the flat trench basins proper ranges from little more than 100 (ZB) to about 250 km^2 in the case of the Kithera-Antikithera Basin.

The extremely complex morphology between, and within, each of the trench-slope and basin systems complicates the dispersal pattern of sediments transported from the Peloponnesus land mass and contiguous margin to the distal basin plains (Stanley, 1977b:435). Moreover, morphologic features of high relief which, include ridges

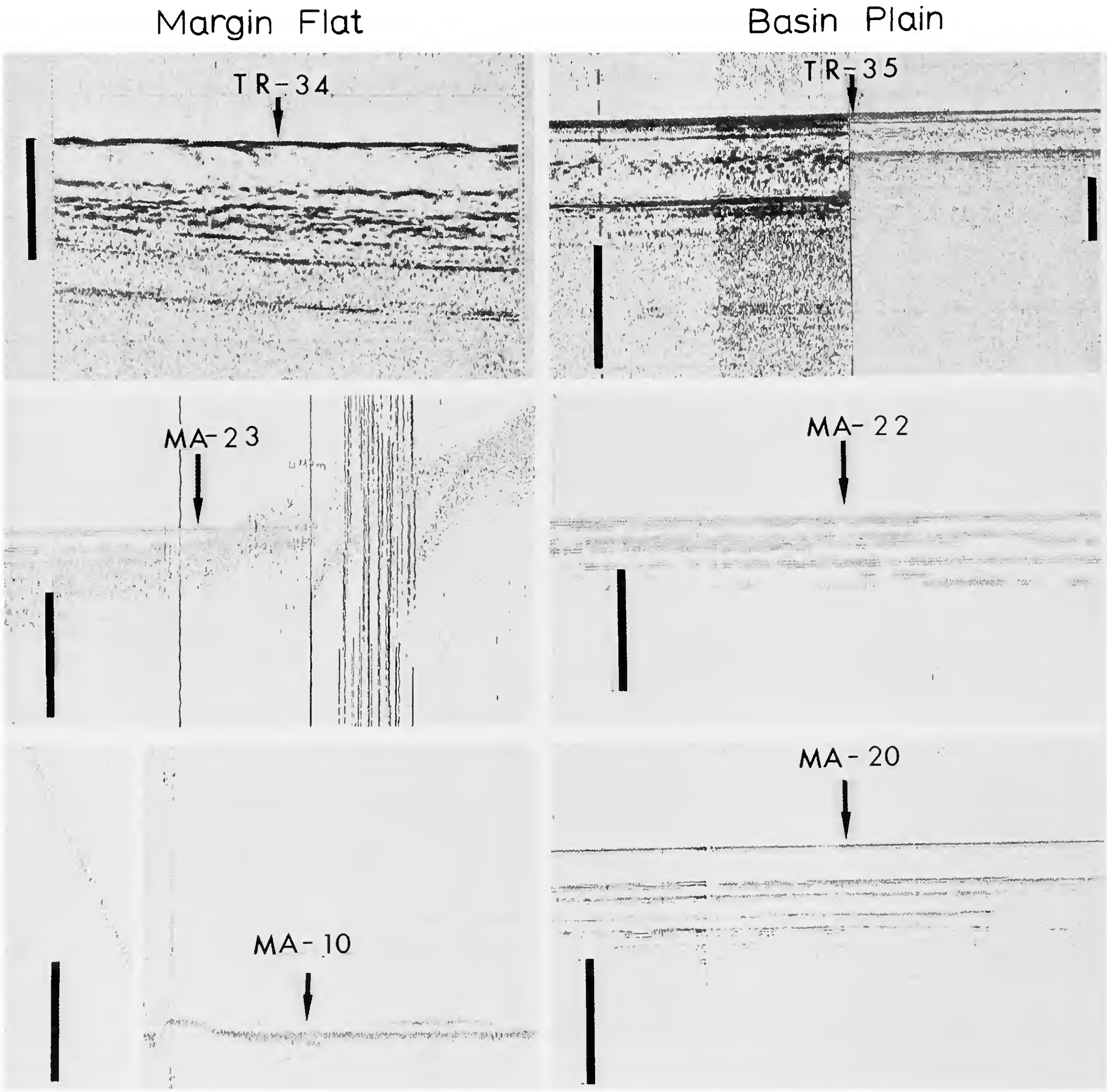


FIGURE 2.—High-resolution 3.5 kHz subbottom profiles of the seafloor at core recovery sites (scale = 50 m). Core pairs, from top to bottom (from NW to SE), are: TR-34 and TR-35 in the Zakinthos-Strofádhes Basin (ZB), respectively 4060 and 4140 m; MA-22 and MA-23 in the Matapan Deep (MB), respectively 4090 and 4120 m; and MA-10 and MA-20 in the Kithera-Antikithera Basin (KB), respectively 4300 and 4510 m. Profiles in the left column show trench margin flat sectors near the base of steep slopes; profiles in the right column illustrate trench basin plain subbottom configuration.

and submarine prolongations of the Peloponnesus, effectively separate trench basins and preclude gravitative transport from one basin to another (Stanley, 1974:248; Vittori, 1978:193). Sediments transported into the trench basin systems within the study area are derived primarily from the adjacent Peloponnesus landmass and its narrow shelf and slope margin (Emelyanov, 1972: 364; Feldhausen and Stanley, 1980:M27–M29; Vittori et al., 1981) and also, to a certain extent, from the Aegean Sea (Stanley and Perissoratis, 1977) and the Mediterranean Ridge, which bounds the trench basins to the west and south. Dispersal is also influenced by the water mass circulation patterns in the eastern Ionian Sea (Venkatarathnam and Ryan, 1971; Lacombe and Tchernia, 1972:33–34; Miller, 1972). From seismic evidence, there appears to be a general increase in the accumulation rate of Pliocene and Quaternary sediments from the NW toward the SE: the thicknness of the ponded unconsolidated strata is locally in excess of 500 m in the ZB basin, over 1000m in the MB basin, and ranges from about 700 to 1200 m in the KB basin. Considering the thickness of this Plio-Quaternary cover, minimal averaged long-term rates of sedimentation since the end of the Miocene (Messinian) range from about 10 to 20 cm per 1000 years. Higher rates are recorded toward the SE. Seismic profiles published by Vittori (1978) and others indicate that these trench basin deposits, including Quaternary strata are, in almost all cases, deformed, thus recording syndepositional tectonic activity.

The two trench basin environments in which unifites are recovered are (1) the margin flat (trench plain near the base of steep basin slopes) and (2) the basin plain (near-flat plains away from steep margins). The configuration of the upper 30 to 70 m of sediment in these two environments is illustrated on 3.5 kHz profiles obtained on the *Trident* 1975 and *Marsili* 1976 traverses (Stanley, 1977b). Selected seismic lines from each of the three basins, showing near-horizontal acoustic reflectors near the sites of cores studied herein, are illustrated in Figure 2. Profiles obtained across the margin flat (close to cores TR-34, MA-23, MA-10) and the basin plain (near cores TR-35, MA-22, MA-20) reveal strong reflectors, probably sandy horizons. This assumption is confirmed by drilling at *Joides* Leg 13 sites 127 and 128 (Ryan et al., 1973:243), which recovered sand layers. Thick (10–15 m) transparent acoustic layers are interpreted as largely mud strata. This is confirmed by the piston cores, particularly in the case of the 10-m long core MA-20 (Figure 2). Close-grid seismic traverses show the lateral continuity and extensive areal coverage of both hard and transparent acoustic layers across the basins and their discontinuity on slopes, thus demonstrating the ponding phenomenon as defined by Hersey (1965) and others.

General Observations

Three criteria enable us to identify unifites composed of *uniform muds* (U), or *faintly laminated muds* (FL), or both. The most obvious criteria used to recognize these two lithofacies are primary bedform stratification and/or bioturbation structures (or their absence) as revealed in x-radiographs (Figure 3), supplemented by color and texture observed in split cores. The stratigraphic position of a unifite can be defined with respect to previously identified diagnostic key horizons such as sapropels, oxidized layers, and/or ash tephra (Stanley, Knight, and Stuckenrath, 1978). Particularly valuable in this respect is the upper sapropel (S_1) dated at about 8000 years before present throughout most of the eastern Mediterranean (Stanley, 1978). Determination of the relative stratigraphic position of the unifites examined in this study is facilitated by the availability of numerous radiocarbon dated core samples (Figure 4, Table 1). Most of these dates, however, prove too old as a result of high proportions of reworked carbonate material incorporated in unifites (page 17).

Only x-radiographic analyses can satisfactorily reveal the absence of any bedform structures, which are characteristic of the uniform mud facies (Figure 3c), and the presence of vague or diffuse stratification that characterizes faintly laminated

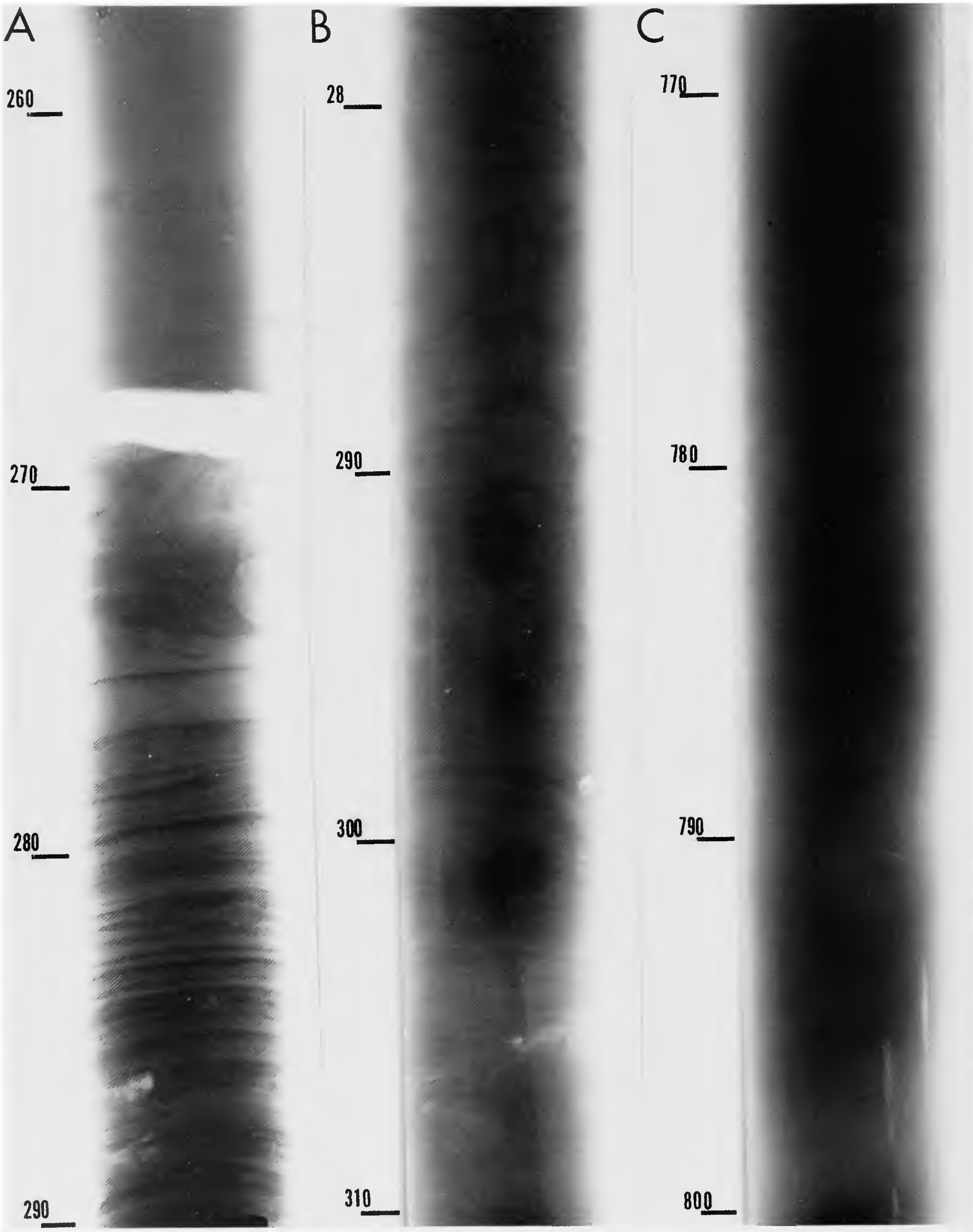


FIGURE 3.—X-radiograph prints of the three fine-grained types discussed in text (core width ~ 6 cm; numbers are depths in cm below core top): A, Well-developed fine-grained mud turbidite showing laminated and graded mud terms (core TR-34, 260–290 cm; see Figure 4). B, Faintly laminated mud overlain by uniform mud defining an FL+U sequence (core MA-23 (unifites), 280–310 cm; see Figure 7). C, Uniform mud showing absence of bedform structures (core MA-20 (unifite), 770–800 cm; see Figure 6).

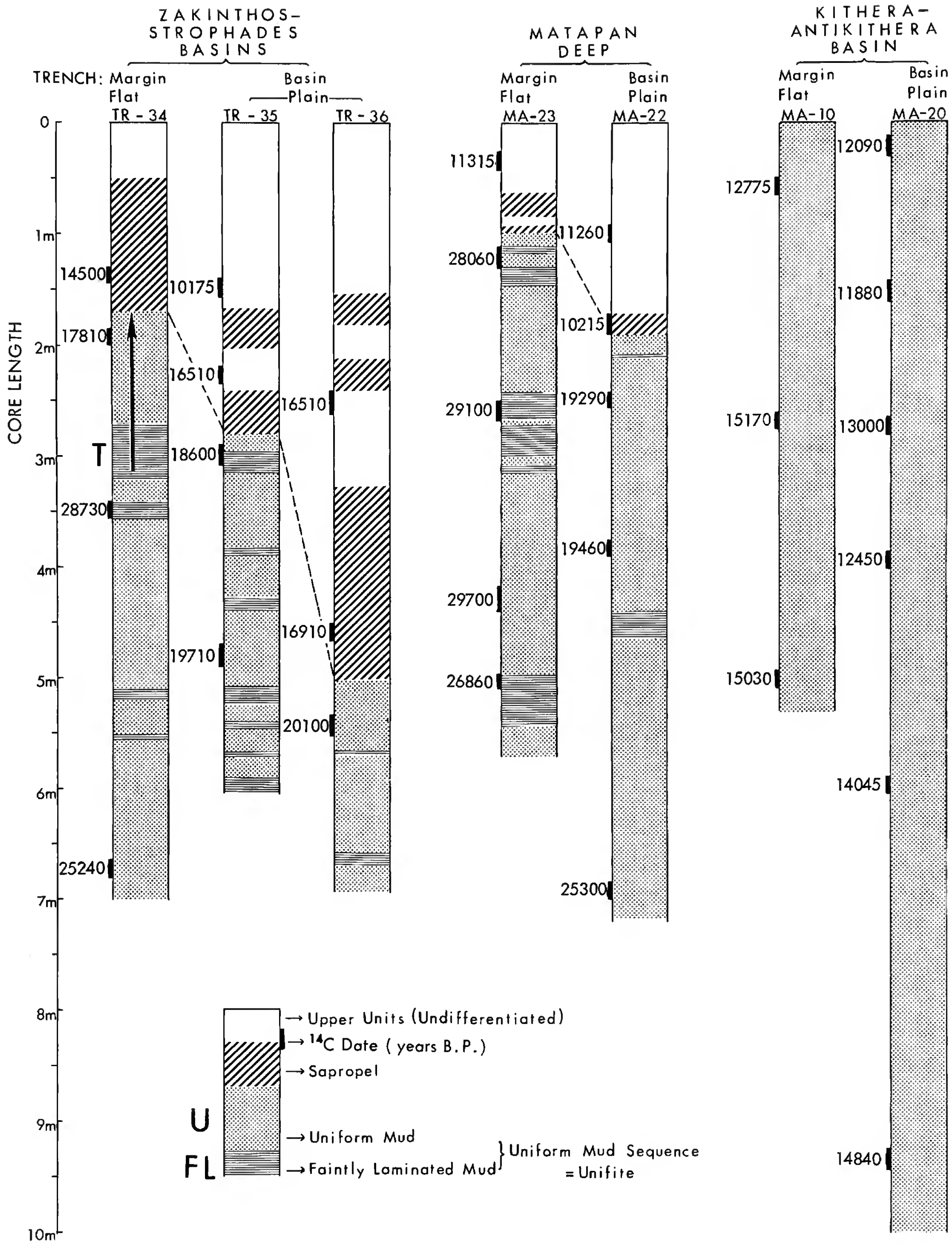


FIGURE 4.—Simplified lithofacies logs of the seven cores containing unifites detailed in this study, showing their stratigraphic position relative to the upper sapropel (S_1) layer. (Numbers on left of logs are radiocarbon age determinations (Table 1), dotted lines correlate stratigraphic sections, age of the S_1 sapropel is ca 8000 years B.P., T and arrow in TR-34 core log denote a classic mud turbidite. Core positions are shown in Figures 1 and 2.)

mud facies (Figure 3B). In some cases uniform mud overlies the faintly laminated mud facies (Figure 3B), while in others uniform mud overlies well-laminated turbidite sands and silts (Figure 3A). The petrology of unifites in the various cores, regardless of stratigraphic position, is quite similar. In split cores, the uniform and faintly laminated sections are generally pale olive to grayish olive (10Y 4/2 to 10Y 6/2), and in few cases (TR-35 at about 450 cm from the core top), are dusky yellow, or 5Y 6/4 to 8/4. These mud types, essentially poorly sorted silt and clay mixtures, have a sticky-plastic consistency, trace sand fractions (generally <1%), and an absence of macrofauna and bioturbation structures. These aspects of unifites result in the textureless and relatively homogeneous deposit observed in split cores.

Typical unifite characteristics include: (1) high clay fraction content (<2 μm, ranging from 35 to 60%) mixed with silt, (2) very low sand fraction, which usually consists of a mixture of both terrigenous and bioclastic (largely planktonic) components, (3) marked thickness (usually >1 m and to as much as 10 m in piston cores, and possibly even thicker in acoustically transparent layers from 3.5 kHz records), (4) continuity of such layers across large areas of the trench basin floors, as revealed by high-resolution subbottom profiles, (5) spatial restriction of the associated structureless and faintly laminated mud facies in trench basins, both on the plains proper and flat basinal sectors near sloping, usually steep margins, and (6) radiocarbon dates showing a consistently narrow range of time interval within any one mud stratum, regardless of the thickness of the unifite layer. Together, these observations and the close association of uniform muds with classic mud turbidites (Stanley and Maldonado, 1981) tend to indicate that unifites were deposited rapidly.

Regional and Environment-related Variations

There are distinct differences in the granulometric and mineralogical characteristics of unifite (uniform and faintly laminated) mud core sections among the geographically separated trench basin systems. The marked regional trends characterizing the Zakinthos-Strofádhes system to the NW and the Kithera-Antikithera system to the SE are summarized in Figure 5. With few exceptions, the Matapan Deep, lying between these two basins, presents intermediate characteristics. These NW to SE regional trends occur regardless of stratigraphic position in a core, time of emplacement, or type of unifite bedform (FL or U) involved. Sediments in the KB system (SE sector of the study area) are characterized by (1) a somewhat coarser (siltier) grain size, (2) a slightly poorer sorting, (3) a sand-size fraction dominated by clastic aggregates and bioclastic fragments, and (4) a silt fraction dominated by coccoliths, recrystallized calcite and dolomite, volcanic products and attapulgite (= palygorskite). In contrast, the finer, somewhat more clay-rich, and better sorted sediments to the northwest (ZB system) are characterized by sand and silt fractions dominated by planktonic foraminifera and associated pyritized tests, and biogenic fragments, together with important proportions of terrigenous material. Sediments in the Matapan Deep, having accumulated in an intermediate geographic position, differ subtly from the ZB and KB trench basins: They have a bioclastic fraction with somewhat higher proportions of pteropods and benthic foraminifera than sediments in the other two trench basins.

A synthesis of all mud (U and FL) sample data recorded for the three basins suggests that factors other than those related to geography account for most core-to-core petrologic differences. We can demonstrate, for example, that some petrologic distinctions are more closely related to specific morphologic attributes of environment than to geography per se. Thus, considerable effort has been made in this study to distinguish between petrologic differences among cores collected in the trench basin *margin flat* environment (i.e., cores MA-10, MA-23, TR-34) and cores recovered in the *basin plain* environment (i.e., cores MA-20, MA-22, TR-35, TR-36). The typical configuration of these two environments is illustrated in Figure 2. We recall that slopes bounding the

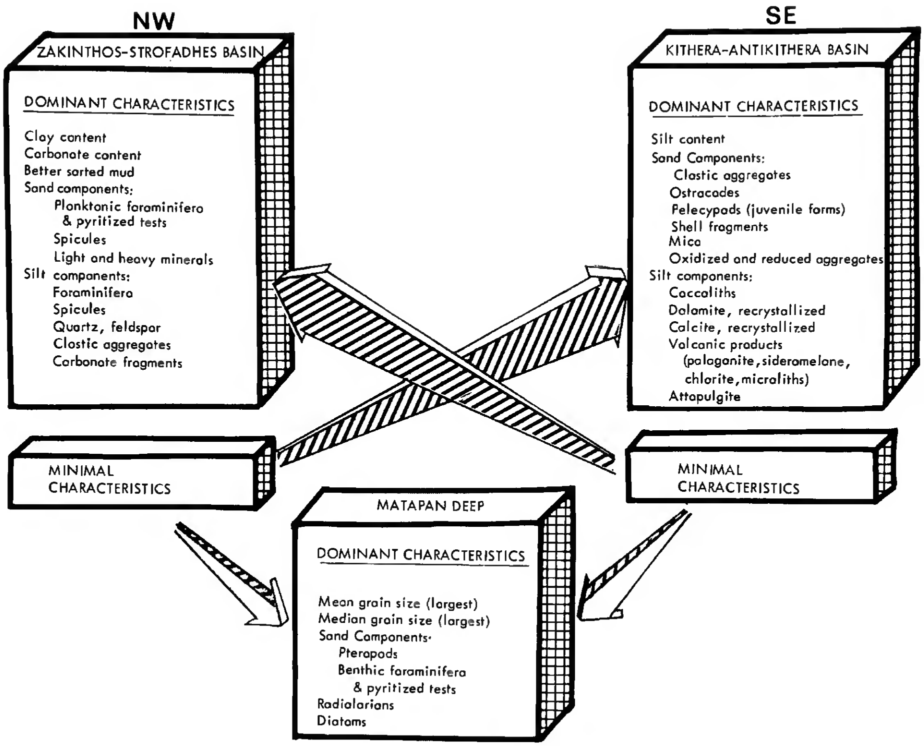


FIGURE 5.—Synthesis of the dominant petrographic characteristics of unifites collected in the three Hellenic Trench basins systems. This scheme emphasizes regional variations from NW to SE, i.e., Zakinthos-Strofádhes (ZB); Matapan Deep (MB); and Kithera-Antikithera (KB) sectors. Arrows show that characteristics that dominate in the KB system are often less important in the ZB system, and vice versa. In some respects, the Matapan Deep cores are intermediate, petrologically, to those of the two other trench systems; the listed sand and silt components of Matapan Deep cores are those that predominate in this basin and serve to distinguish it from the ZB and KB basins.

trench basin floors are generally steep (>10°) as revealed by echograms and seismic records (cf. Vittori, 1978; Le Quellec, 1979).

In general, the margin flat sediments tend to be somewhat less well sorted, display a slightly higher proportion of sand-sized terrigenous (especially light minerals) than biogenic components, and contain more benthic foraminiferal tests and silt-sized recrystallized calcite. In contrast, the basin plain sediments are somewhat better sorted, and contain (in both the sand and silt fractions) higher proportions of clastic aggregates and biogenic components, particularly planktonic tests. In addition, the silt fractions of basin plain core sections tend to contain more palagonite and recrystallized dolomite than the margin flat sediment.

We can demonstrate that the above distinctions are only in part related to regional provenance differences but, more importantly, are related to transport processes effective in the different depositional environments.

Contrasting Uniform and Faintly Laminated Mud Sequences

As noted previously, unifite lithofacies are differentiated primarily by the presence or absence of stratification structures and by comprehensive grain size and compositional analyses. In the following sections we compare petrological attributes of unifite core sequences (Figure 4) formed essentially of structureless mud (U) with those containing faintly laminated mud and the directly overlying structureless mud (FL+U).

Cores MA-10 and MA-20 are designated as the type cores for unifites composed of uniform muds. These cores are, respectively, from the trench margin flat and basin plain environments of the Kithera Trench system (Figures 1, 6). Type

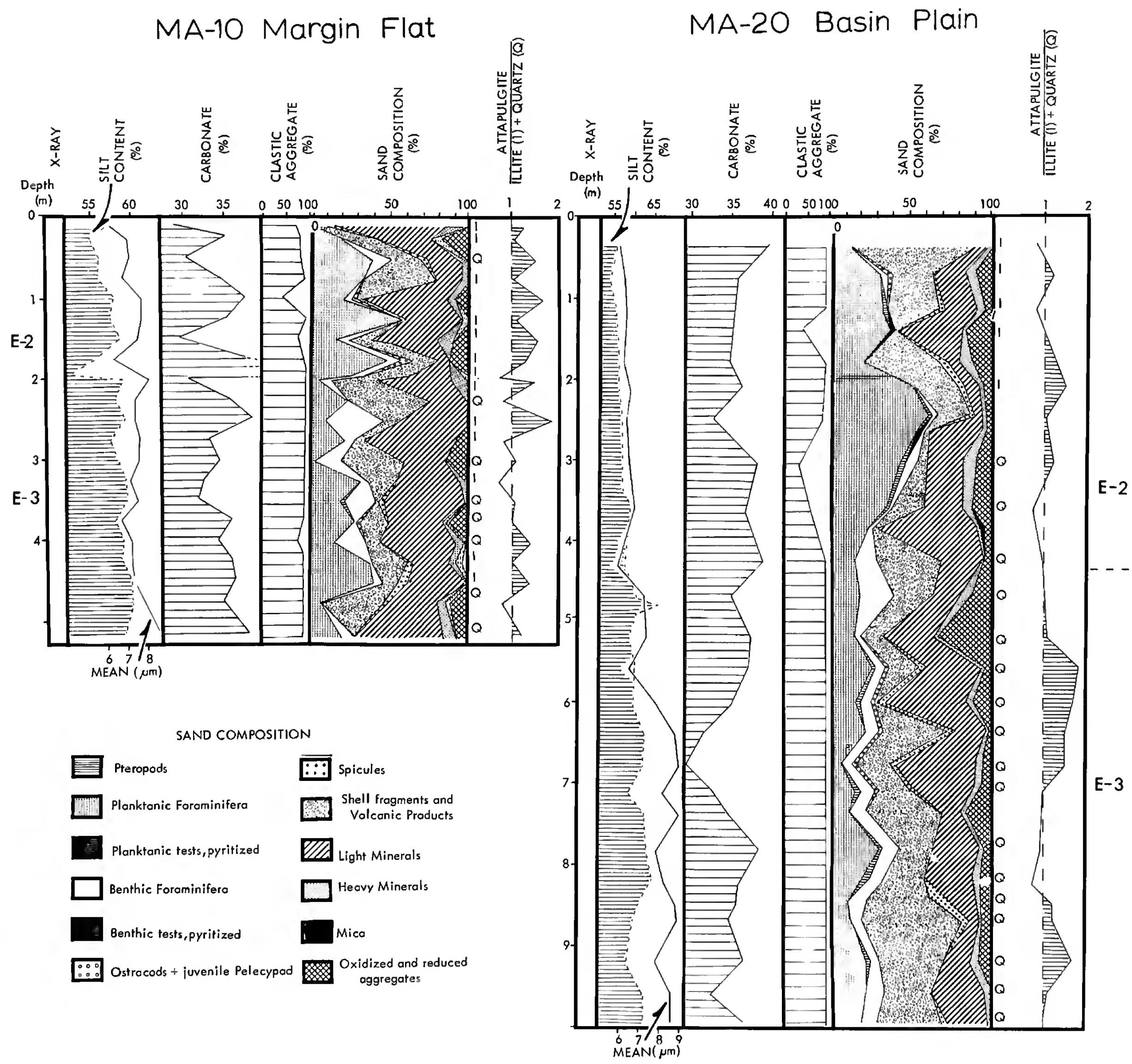


FIGURE 6.—Detailed logs of selected unifites in the Kithera-Antikithera Basin cores MA-10 (trench margin flat) and MA-20 (basin plain). Logs depict major bedform based on x-radiography, grain size (silt content and mean), carbonate content, clastic aggregates, and other sand-size mineralogical components; the sand-size mineralogical components (excluding clastic aggregates) are recalculated to 100%. The abundance of silt-size attapulgite (=palygorskite) relative to dominant quartz (Q) or illite (I) is also shown. (E2 = graded mud term; E3 = ungraded mud term. Explanation in text.)

FL+U core sections are represented by cores MA-23 and MA-22, respectively, from the trench margin flat and basin plain environments of the Matapan Deep (Figures 1, 7). Detailed petrologic sections of cores TR-34, TR-35, and TR-36 (not shown here), recovered from the Zakinthos-Strofádhes Trench system, are most similar to core sequences MA-22 and MA-23. Simplified litho-facies logs of these seven cores may be compared in Figure 4.

Grain Size Analysis

In both U and U+FL mud sequences the relative percent, by weight, of the sand fraction does

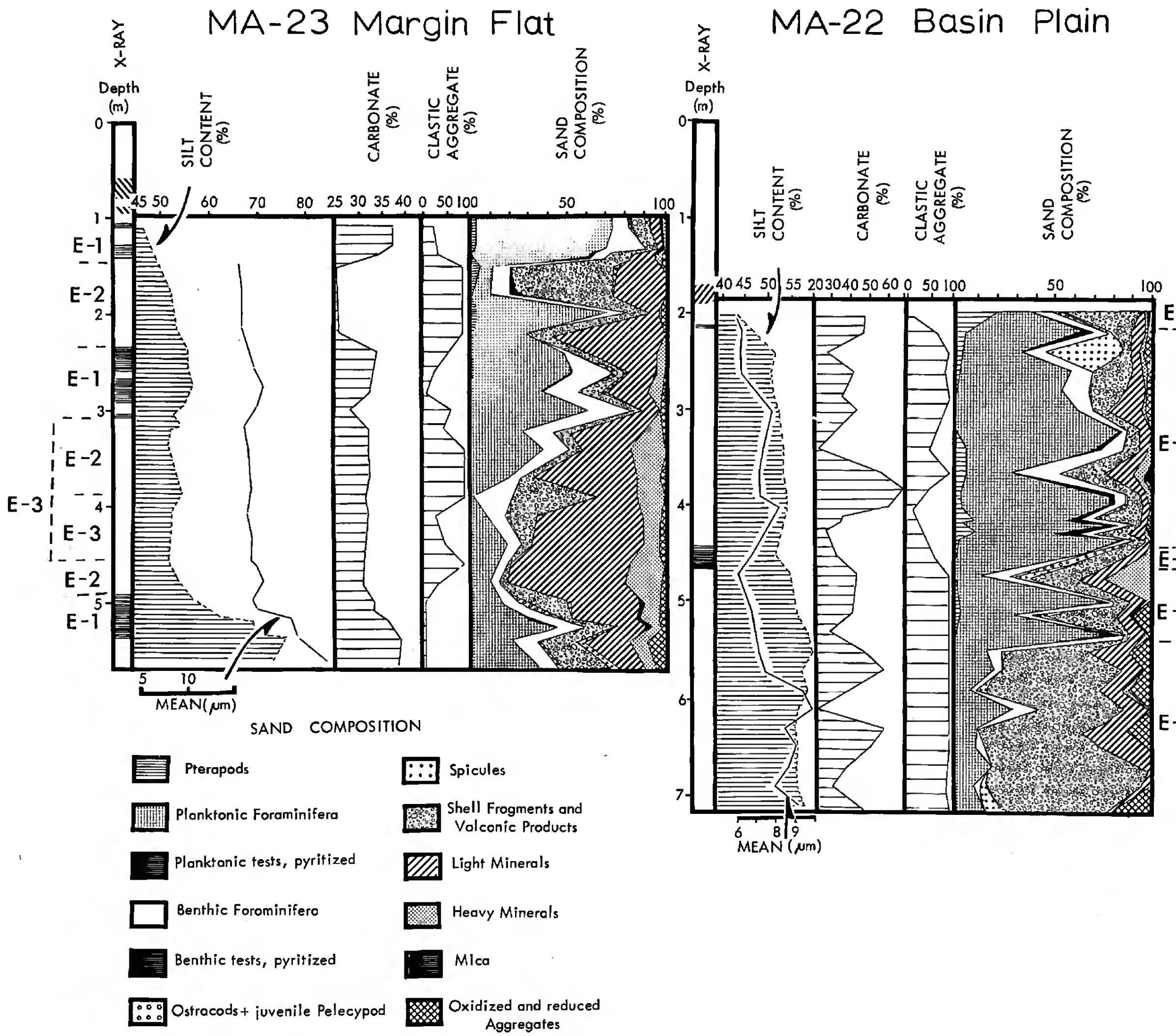
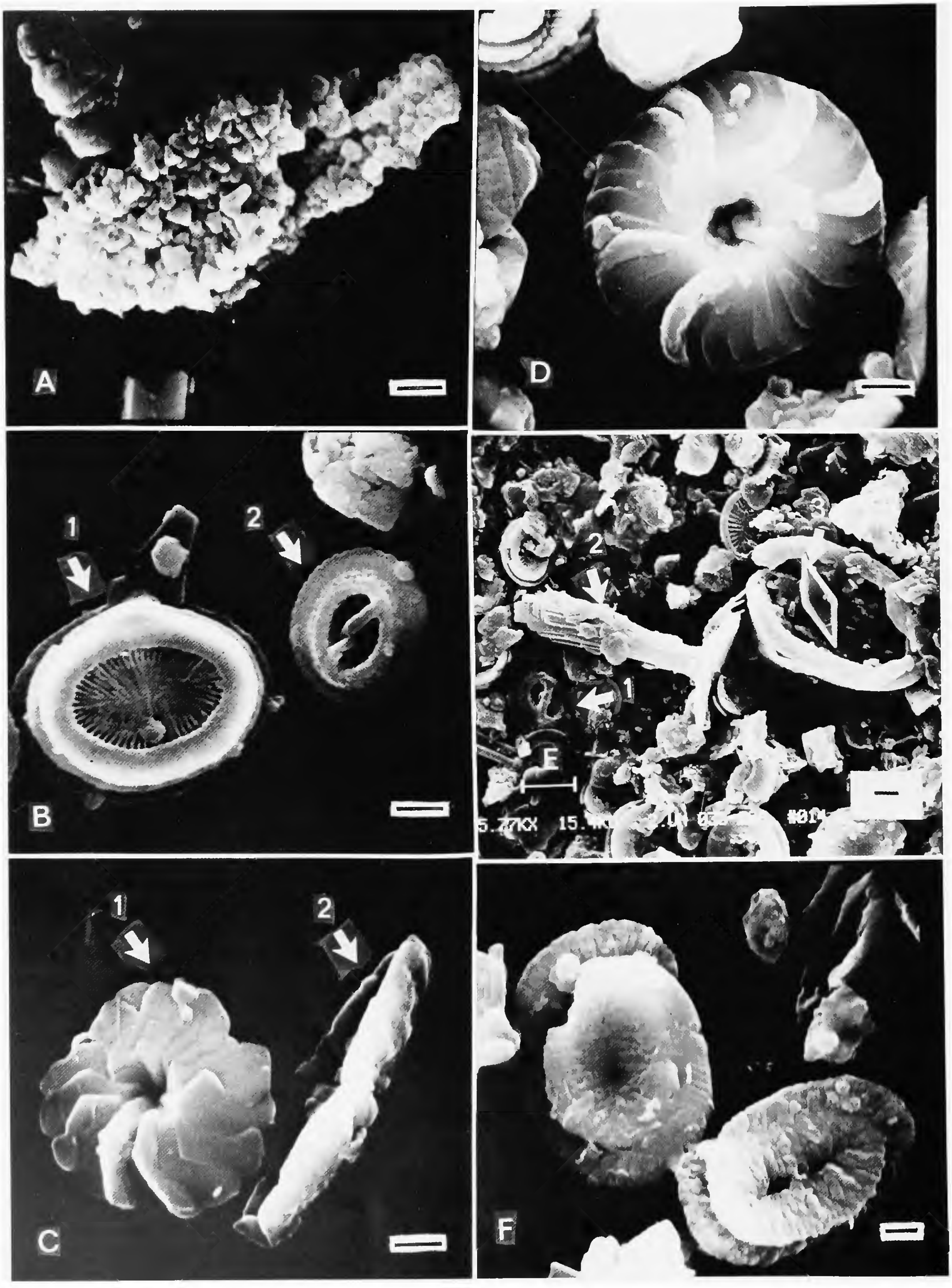


FIGURE 7.—Detailed logs of selected unifites in the Matapan Deep cores MA-23 (trench margin flat) and MA-22 (basin plain). Logs depict major bedform based on x-radiography, grain-size (silt content and mean), carbonate content, clastic aggregates, and other sand-size mineralogical components; the sand-size mineralogical components (excluding clastic aggregates) are recalculated to 100%. (E1 = laminated mud term; E2 = graded mud term; E3 = ungraded mud term; explanation in text.)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not exceed 0.3 percent, and in general, there is more silt than clay (<2 μm). However, the silt content in the U-type section displays a slightly higher average (58%) and a narrower range (50–65%) than in the FL+U sections (average of 56%; range of 44–75%). The latter sequence records an enhanced silt content in the lower faintly laminated muds, and a vertical upward change from clayey silt to fine silty clay. The mean and median grain sizes of the uniform mud are somewhat smaller (range respectively, $\bar{x}$ = 6.4 to 7.5 μm and Md = 5.5 to 7.0 μm) than in the FL+U sequence ($\bar{x}$ = 7.5 to 8.0 μm and Md = 6.5 to 7.5 μm). It is noted that sediment of comparable size (fine silt) was earlier reported in the Matapan Deep by Pareyn (1968:66). Sorting values (cf. Folk and Ward, 1957) indicate that the uniform mud sequences are slightly better sorted (3.6 to 4.6) than FL+U sequences (3.5 to 5.3). These differences reflect the influence of the somewhat higher silt content in the lower, faintly laminated mud portions of the FL+U sequences.

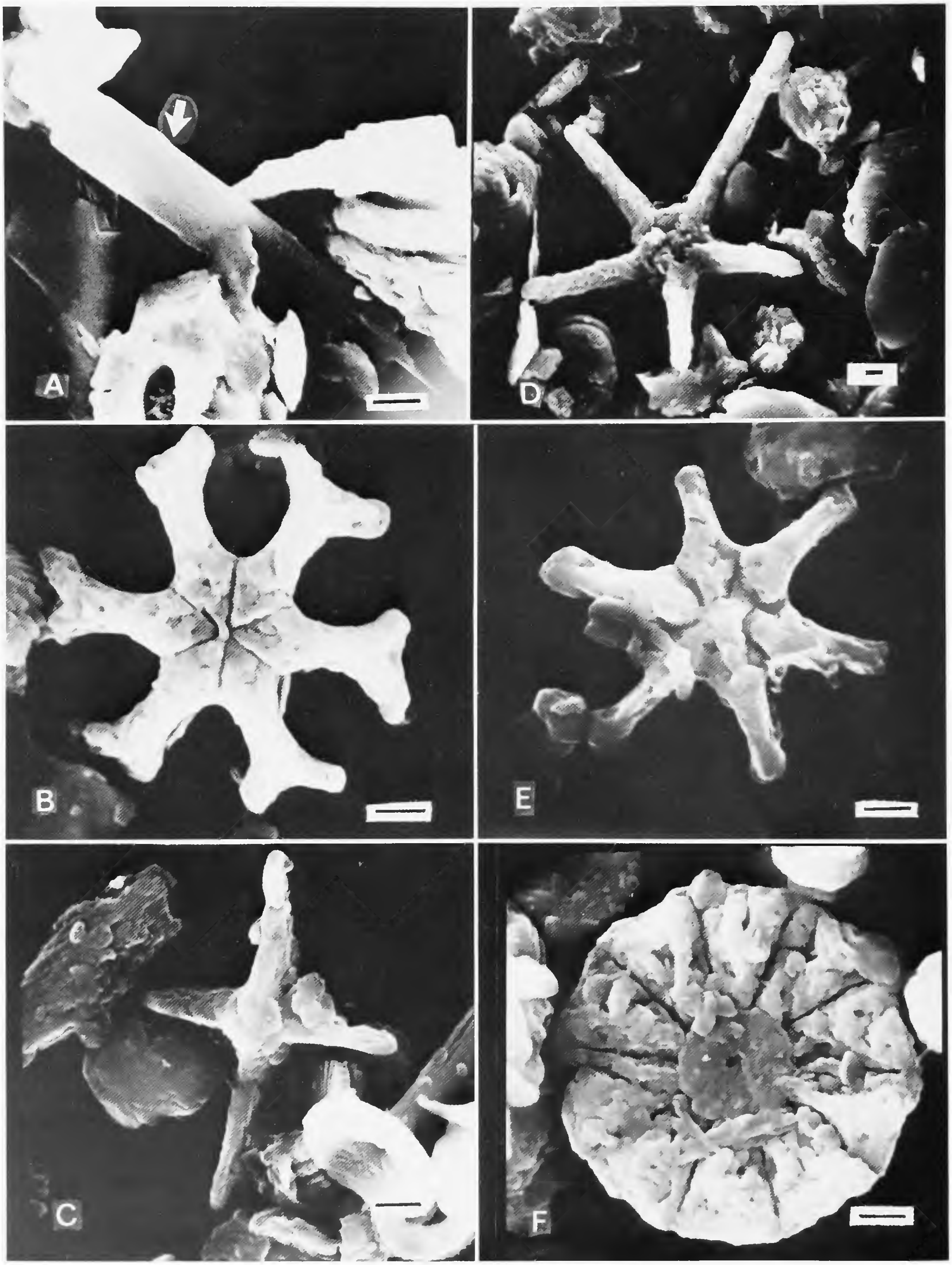
Vertical variations in silt content and mean grain size are apparent on core logs (Figures 6, 7). Both U and FL+U sequences show an upward decrease in grain size. This fining-upward is most obvious in core MA-23 and coincides with a transition from the FL to U mud type; this trend is less well developed in core MA-22 in the same basin. A less pronounced but nevertheless overall fining-upward trend is also apparent in cores MA-10 and MA-20 that contain only by U sections (Figure 4).

Composition

The total calcium carbonate content of U sequences averages 35% and ranges from 30 to 50%; that of FL+U sequences averages 39% and ranges from 26 to 60%. Higher carbonate contents are recorded particularly in some faintly laminated muds, such as those in core MA-23 (Figure 7). In general, carbonate content tends to fluctuate markedly but, unlike grain size, no distinct vertical trend in either U or FL+U sequences is noted.

Grain counts of the sand size fraction in all seven cores reveal a predominance of clastic aggregates formed by poorly cemented silt-size fragments (Figure 8A). Aggregates constitute as much as 90% of the sand fraction, but tend to diminish upward in U-type sequences, as illustrated in logs of MA-10 and MA-20 (Figure 6). In FL+U sequences their upward increase, from about 5 to 80%, is related to the transition from faintly laminated to uniform mud type (see core MA-23, Figure 7). To better evaluate fluctuations of the sand size components, clastic aggregates were excluded in the point-counts of the terrigenous biogenic components (sand composition column in Figures 6 and 7). Although there are compositional differences from core to core, the dominant components almost always comprise planktonic foraminifera, quartz, shell fragments and altered volcanic products. The U sequences generally contain higher proportions of sand-sized biogenic components and planktonic tests than the FL+U sequences. Proportions of planktonic foraminifera tend to be higher in faintly laminated (FL) muds (MA-23, Figure 7). In both U and FL+U sequences, there is an upward increase of planktonic tests in the upper, somewhat finer-grained, sections. Moreover, pyritized foraminiferal tests abound in the FL+U sequences, often in the laminated mud portions. They tend to

FIGURE 8.—Scanning electron micrograph components in Hellenic Trench unifites (scales = 1 μm): A, Clastic aggregate composed of cemented silt-sized grains (from core MA-20, 900 cm from core top, × 10K); B, *Gephyrocapsa oceanica* Kamptner (arrow 1) of Pleistocene to Recent age and *Syracosphaera pulchra* Lohman (arrow 2) of Late Pliocene to Recent age (from core TR-34, 500 cm from core top, × 10K); C, poorly preserved test of *Discoaster* (species not determined, arrow 1) with overgrowth, pre-Pleistocene in age, and *Scapholithus* sp. (arrow 2) (from core MA-20, 900 cm from core top, × 12K); D, *Cyclococcolithus leptoporus* (Murray and Blackman), possibly of Pleistocene to Recent age (from core TR-36, 610 cm from core top, × 10K); E, *Rhabdosphaera clavigera* (Murray and Blackman) (arrow 1), possibly of Pleistocene to Recent age, *Scapholithus fossilis* Deflandre (arrow 2), possibly of Cretaceous to Recent age (from core TR-35, 410 cm from core top, × 5K), and diatom (arrow 3); F, *Helicopontosphaera kamptneri* (Hay and Mohler) of Miocene to Recent age (from core TR-36, 610 cm from core top, × 7K).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increase upward, particularly in cores TR-34, TR-35, and TR-36. This upward increase in the three Zakinthos-Strofádhes Trench basin cores appears related to the presence of the overlying, well-developed sapropels (Figure 4). Pyritized tests associated with sapropels in other regions of the eastern Mediterranean generally signal the development of reducing conditions, the most recent event of this type occurring from about 9000 to 7000 years ago (Ryan et al., 1973:713; Stanley, 1978; Thunell and Lohmann, 1979).

In the silt-size fraction, nannofossils are the dominant component within both U and FL+U sequences in all seven cores; their relative abundance in a core sample is often proportional to the carbonate content. Coccoliths include upper Pleistocene to Holocene species, as well as much older (Miocene and Pliocene) reworked forms (Figures 8, 9). Volcanic products (palagonite, sideromelane, chlorite, microlite) and recrystallized dolomite are somewhat more abundant in the U than in the FL+U sequences. Conversely, quartz and feldspar are somewhat less abundant in U sequences. In the silt fraction of both types of sequences, recrystallized calcite is abundant, while spicules, foraminifera and fragments of carbonate tests occur in lower proportions. No distinct vertical trends of silt size components are recorded.

Illite dominates the clay mineral suite in this region as noted by Venkatarathnam and Ryan (1971) and Vittori (1978:131). Minerals of the attapulgite (palygorskite) group, recorded in many areas of the eastern Mediterranean (Chamley and Millot, 1975), occur only in the silt fraction of uniform muds in cores MA-10 and MA-20 (Figure 9A). Attapulgite (palygorskite) is abundant in these cores (the attapulgite to illite plus quartz ratio generally exceeds unity), but no obvious vertical trend is recorded (Figure 6). The sedimentological significance of the attapulgite distribution as a tracer of disperal is dicussed elsewhere (Stanley, Blanpied, and Sheng, 1981).

FIGURE 9.—Scanning electron micrographs of components in Hellenic Trench unifites (scales = 1 μm): A, Rod-shaped attapulgite (arrow) (from core MA-20, 600 cm from core top, × 10K). B, *Discoaster variabilis* (Martin and Bramlette) from late mid-Miocene to Pliocene in age (from core MA-20, 600 cm from core top, × 9K). C, *Discoaster* cf. *brouweri* Tan Sin Hok (4-ray form), from late Miocene to Pliocene in age (from core TR-36, 550 cm from core top, × 8K). D, *Discoaster asymetricus* Gartner from the middle Pliocene (from core MA-20, 50 cm; × 4.5K). E, *Discoaster* cf. *brouweri* Tan Sin Hok (6-ray form), badly overgrown and poorly preserved, possible late Miocene to Pliocene in age (from core TR-34, 240 cm, × 10K). F, *Discoaster perplexus* Bramlette and Riedel, possibly of late Oligocene to Pliocene age (from core MA-20, 600 cm, × 10K).

Vertical Petrological Changes

Contrasting Margin Flat and Basin Plain Sequences

The marked vertical changes in grain size and compositon recorded in the U and FL+U cores collected in the margin flat and basin plain environments bear on unifite deposition.

Although almost structureless, analysis of core MA-23 recovered in the Matapan Deep margin flat reveals distinct vertical bedform, grain size, and compositional changes. These nonrandom trends are cyclic in nature. The FL+U sequences are about 450 cm thick (100 to 550 cm from the core top). Size histograms (Figure 10) reveal an overall upward size decrease involving two superposed fining-up *cycles.* The latter are revealed by the vertical variations in silt content and mean grain size (Figure 7). The two granulometric "breaks" correlate well with the presence of faintly laminated mud seen in x-radiographs at about 550 and 300 cm from the core top. The lower cycle is coarser (about 60% silt content), and its upward-fining trend is more pronounced (decrease in mean size from about 15 to 7 μm); the upper cycle is finer (about 55% silt content), and shows a more gradual upward diminution in grain size (mean size decreases from 8 to 5 μm). The vertical distribution of the modal class shows a less marked distinction between the two cycles (Figure 10). In this repetitively graded mud section, we find that the lower coarser, faintly laminated *terms* (i.e., any petrologically distinct division of a unifite cycle) contain a somewhat higher carbonate content with higher proportions of silt-sized carbonate components, lower proportions of sand-size clastic aggregates but larger amounts of biogenic components (mainly planktonic tests), and minor amounts of mica than the overlying material. In contrast, the upper finer-grained uniform mud terms in the sequence contain higher amounts of terrigenous components and volcanic products in both the sand- and silt-size fractions.

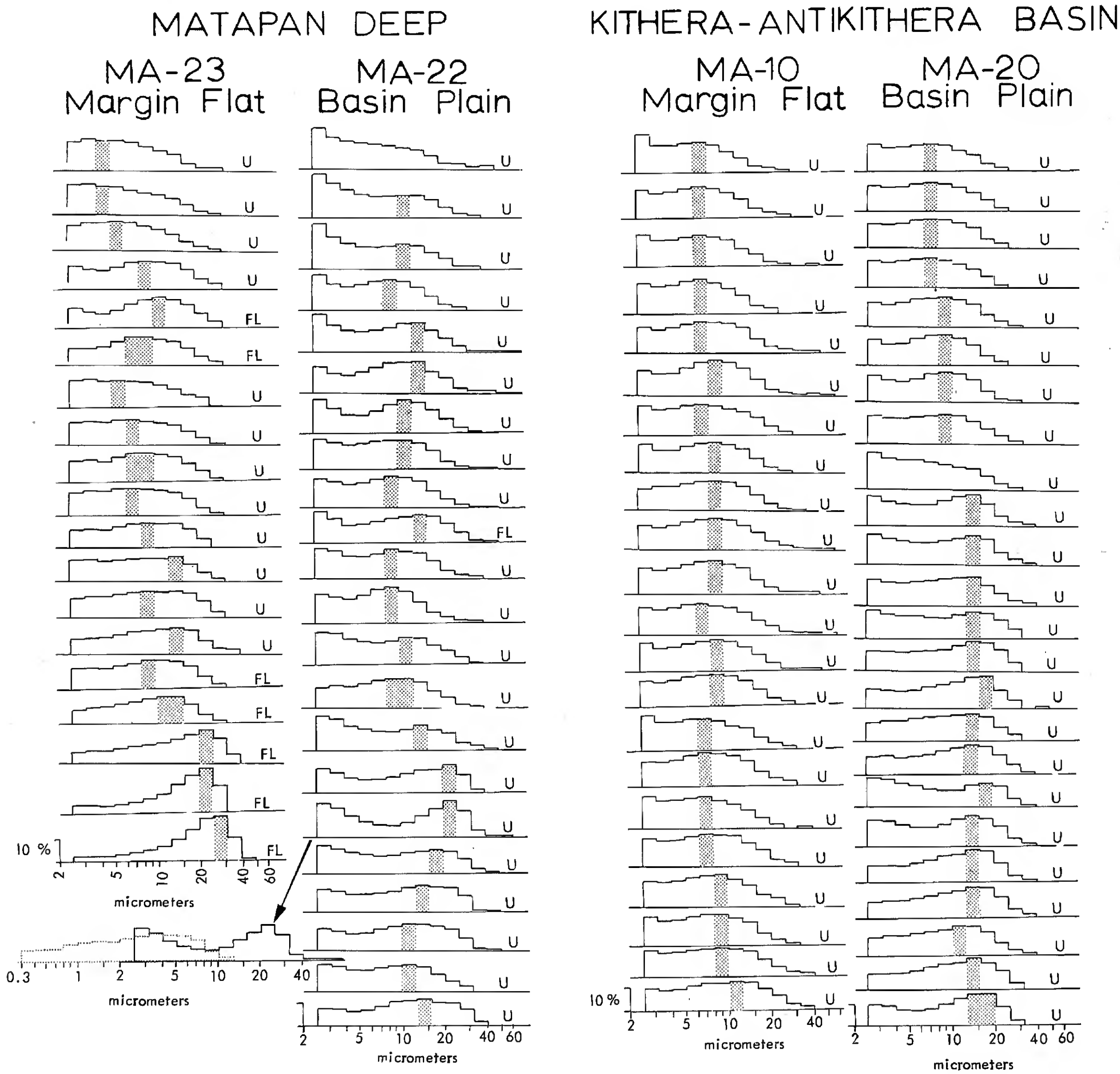


FIGURE 10.—Size distribution histograms of Matapan Deep and Kithera-Antikithera Basin unifite core samples (sample position shown on logs in Figures 6 and 7). Data (in volumetric percent) obtained using a Coulter Counter Model TII-A (size in μm). (Shaded area depicts primary modal class. Note expanded complete size histogram of one core MA-22 sample; dotted portion of histogram depicts finest particle distribution as determined from a separate Coulter Counter run. FL = faintly laminated mud; U = uniform mud.)

The FL+U sequence in core MA-22 in the Matapan Deep basin plain is about 500 cm thick (from 200 to 700 cm from the core top) and, like core MA-23, shows two superposed sequences, revealed by the vertical changes in silt content and mean grain-size distribution. The upward changes shown by these trends, however, are less pronounced than in core MA-23. The major granulometric "break" within this sequence is associated with faintly laminated muds at about 450 cm from the core top (Figure 7). As in core MA-23, the lower cycle is coarser (about 57% silt) than the overlying portion of the cycle (about 53%). An upward decrease in mean grain size ranges from 10 to 6 μm. An examination of the vertical sequence of size histograms (Figure 10) shows less cyclicity of the primary modal class than in core MA-23; a systematic upward size decrease, nevertheless, appears in the upper 200 cm above the faintly laminated term (Figure 7). Moreover, histograms of this core (unlike those of MA-23 core samples) display a slight bimodal size distribution: a primary mode ranging from 8 to 25 μm, and a less pronounced modal class of about 3 μm. An example of an expanded size distribution histogram of the clay and fine silt size range (from 0.3 to 10 μm) is shown in Figure 10. In contrast with the uniform mud term (U), the faintly laminated mud segment at about 450 cm contains a somewhat lower carbonate content, fewer sand-sized clastic aggregates, and a higher proportion of biogenic (more planktonic) components. The major fluctuation in proportions of sand-sized components (Figure 7), particularly the planktonic versus the terrigenous elements, appear closely related to grain size changes. For example, in the lower cycle, the rapid upward decrease in terrigenous components and volcanic products coincides with a decrease in grain size. These concomitant compositonal and grain size fluctuations appear to correlate with tonal (densitometric) variations, recording differences in sediment density observed on x-radiographs; lighter tones generally denote somewhat coarser, or denser, sections.

Observed vertical and core-to-core changes in the largely uniform (U) mud sequences in Kithera-Antikithera Basin cores MA-10 and MA-20 are different than those in the Matapan Deep and Zakinthos-Strofádhes cores. The two MA trench basin cores consist essentially of uniform mud (faintly laminated sections are absent) but nevertheless show an overall upward decrease in silt content and mean grain size.

The margin flat MA-10 core sequence exceeds 5 m in thickness, and displays an overall upward decrease in silt content (from about 60 to 55%), mean grain size (from 8 to 6 μm), and modal class size (12 to 6 μm, Figures 6 and 10). This is accompanied by a slight upward decrease in carbonate content, clastic aggregates, sand-sized terrigenous fraction, and concomitantly, an upward increase in biogenic components (mainly planktonic). The proportions of terrigenous and volcanic components of silt size, and of attapulgite (palygorskite), also increase upward. A major textural break at 200 cm is accompanied by a marked increase in carbonate content and sand-sized planktonic foraminifera, and conversely, a decrease in the terrigenous fraction and clastic aggregates (Figure 6). Many of the compositional variations in this U sequence correlate directly with grain size fluctuations.

Basin plain core MA-20 recovered the thickest section (about 1000 cm) of uniform mud in the study area, and as in MA-10 core, displays an overall upward decrease in both silt content (63 to 54%) and mean grain size (from about 9 to 6 μm). Unlike core MA-10, however, there is no sharp textural break within this vertical sequence and, unlike cores MA-22 and MA-23, no obvious repetitive grading or cycles are noted (Figure 6). While the lower 6 m display some minor textural variations, the upper 4 m fine-upward gradually and are almost uniform in texture. Grain size histograms show an overall range of modal class variation between 8 and 20 μm, and a bimodal distribution in the lower 6 m comparable to that in basin plan core MA-22. Although the vertical textural distribution is fairly constant, there are some marked compositional fluctuations as noted by carbonate content, clastic aggregates, sand-size components (particularly planktonic foraminifera), and attapulgite. Noteworthy are the upward increase in biogenic components and decrease in clastic aggregates. Fluctuations of various compositional components are most closely related to the observed subtle grain size changes. These grain size variations, in turn, correlate with observed tonal-density differences observed on x-radiographs.

Environmental Control

The major overall difference between the margin flat and basin plain unifites in the three trench systems examined is that the former comprise primarily FL+U sequences, while U sequences dominate basin plains proper. Moreover, the basin plain (MA-20, MA-22, TR-35, TR-36) core samples contain, for the most part, somewhat higher carbonate, sand-sized planktonic foraminifera and clastic aggregate contents, but less terrigenous material of sand and silt size than in the basin margin flat (MA-10, MA-23, TR-34).

A synthesis of the petrologic characteristics (Table 2) indicates that vertical variations are environmentally related. There are some compositional components whose proportions are similar in both margin flat and basin plain cores. These are identified as "constants" in Table 2: sand-sized pteropods, shell fragments, mica and silt-sized recrystallized dolomite, and volcanic products prevail in the finer terms of either U or FL+U cycles; sand-sized benthic foraminifera, heavy minerals, oxidized and reduced aggregates and silt-sized foraminifera, coccoliths, spicules, carbonate fragments and volcanic products dominate the coarser terms of either U or FL+U cycles. Overall, however, there are major com-

Table 2.—Comparison of dominant compositional characteristics of unifites collected on trench margin flat and basin plain environments

Fraction	*Trench margin flat dominant characteristics*	*Constant components*	*Trench basin plain dominant characteristics*
		Fine Terms of Cycles	
Sand	Radiolarians & diatoms Benthic tests, pyritized Light & heavy minerals Clastic aggregates	Pterpods & shell fragments Mica	Planktonic species & pyritized planktonic tests Shell fragments Mica
Silt	Chlorite & quartz Foraminifera & coccoliths Sideromelane	Palagonite & sideromelane Dolomite	Feldspars & aggregates Recrystallized calcite Dolomite Carbonate content
		Coarse Terms of Cycles	
Sand	Planktonic species & tests Shell fragments, pyritized Mica	Benthic tests Heavy minerals Aggregates, oxidized & reduced	Radiolarians & diatoms Benthic tests, pyritized Light & heavy minerals Clastic aggregates
Silt	Feldspars, aggregates Recrystallized calcite Dolomite Carbonate content	Palagonite, sideromelane Foraminifera & coccoliths Spicules & carbonate fragments	Chlorite & quartz Foraminifera & coccoliths Sideromelane

positional differences between margin flat and basin plain cores as summarized in Table 2; the coarse terms clearly differ from the fine terms of FL+U and U cycles.

In margin flat cycles, the sand-sized components in the coarser-grained, often faintly laminated terms are generally dominated by planktonic tests (foraminifera, including pyritized tests and pteropods), bioclastic shell fragments and mica; in contrast, the sand fraction in the finer (often U) part of cycles is enriched by terrigenous material, mainly light minerals, and benthic tests (including pyritized benthic foraminifera and spicules). The highest total carbonate content occurs in the coarsest cycles. The silt fraction of the faintly laminated terms of the FL+U cycles shows enhanced amounts of clastic aggregates, feldspars and recrystallized calcite. In the silt fraction of the fine terms of the FL+U cycles, quartz and volcanic products (chlorite, sideromelane) dominate, along with important proportions of planktonic foraminifera and coccolith tests.

In basin plain cycles the above listed components of sand and silt size also occur, but in a reversed order of importance. Table 2 depicts this "reversal" phenomenon: Mineralogical components that are dominant in the coarsest terms of margin flat cycles abound in the finer terms (largely U sequences) of basin plain cycles; components important in the finer terms of the margin flat cycles dominate the coarser, faintly laminated terms of basin plain cycles in those cases where they occur. It is recalled that fine-grained, U-dominated cycles prevail in the basin plain environments.

Discussion

Evidence for Gravitative Origin of Fine-grained Mud Types

An examination of all cores collected in the western Hellenic Trench area (Figure 1) has revealed a high proportion of classic fine-grained turbidites in most environments, including proximal settings, areas of relief, slopes, and perched slope basins and trench plains (Vittori, 1978; Stanley and Maldonado, 1981). In contrast, unifites are restricted to trench basin plains (Stanley and Knight, 1979; Stanley, 1980). In this study we show that trench basin FL+U and U sequences are laterally extensive in each of the basin plains (Figure 2). The emplacement of such unifites is apparently rapid, a contention supported by their stratigraphic position (Figure 4), radiocarbon-14 dates, and the common association of unifites with classic, well-graded mud turbidites (Stanley and Maldonado, 1981, figs. 5, 10). Moreover, statistical analyses of over 450 samples collected from all of the cores shown in Figure 1 show that, regardless of sediment type, there is a general decrease seaward in the percentage of the sand size material in muds. The Hellenic sediments, for the most part mixtures of silt and clay, thus reveal a lateral fining toward the three distal trench basins (Vittori, 1978:177; Feldhausen et al., 1981).

The present study also indicates that the fine-grained lithofacies distribution is not random within basins, but rather is specifically related to trench margin flat and basin plain environments. This distinct relation between environment and mud type is exemplified by the markedly increased proportion of uniform mud relative to faintly laminated mud in basin plains proper, away from basin slopes. We believe that such environment-related lithofacies variations are most readily attributable to the influence of transport processes, and evaluation of all data collected (seismic profiles and petrology) sheds light on the mud emplacement mechanisms involved.

Although the unifites are very fine-grained, usually clayey silt with a fine silt mean size class, deposition from primarily suspension-related processes (hemipelagic "rain") is minimized. The specific restriction of unifites to basin plains would not occur if accumulation was largely by suspension-related mechanisms (related to water mass circulation). The core analysis data base does not support a settling "rain" origin for unifite emplacement. We recall that calculated minimum sedimentation rates for entire thick sequences are extremely high (in some cases >300cm/1000 years). The sand fraction in unifite mud is very low (<0.5%) and comprises mostly clastic aggregates of reworked, indurated silts and only low amounts of planktonic tests. Bioturbation structures are not observed in x-radiographs. Moreover, the proportion of the terrigenous sand-size fraction, excluding clastic aggregates, frequently exceeds 50%, and an important part of the biogenic fraction of silt consists of older, reworked coccolith tests (Figures 8, 9).

Although unifites almost always contain an assemblage of modern and much older reworked fauna and, in some cases, display faint laminae (the only bedform observed in x-radiography), we eliminate strong bottom currents as a dominant transport process. This conclusion is supported by the extensive regional distribution and lateral continuity of the very thick, evenly bedded units within each of the three morphologically isolated deep basins (as noted in 3.5 kHz profiles), the cyclic nature of the almost structureless mud sequences, and poor textural sorting of sediment recorded by size analyses. A bottom current origin would not satisfactorily explain the overall fining-upward trend in all sequences, even the thickest, including the 10-m-thick unifite in core MA-20.

Our study does not lend strong support to pelagic settling, or to erosion of the sea floor by currents, or to combinations thereof for the origin of uniform muds as suggested by Ryan et al. (1973:268) and Kastens and Cita (in press). In contrast, the data base strongly supports a turbidity current-related origin for the thick unifite sequences of both uniform and faintly laminated muds. Numerous size analyses demonstrate that all ponded unifites display an overall upward graded bedding (Figures 6, 7); graded muds are characterized by very poor sorting (Figure 10). Lateral distality-related changes beween the base-of-slope and the basin plain proper include a decrease in laminated mud terms, an increase in the proportion of graded and ungraded mud terms, and a somewhat higher content of sand-sized biogenic (largely planktonic) tests of relatively low density. The basinward increased uniformity of mud bedforms and compositional characteristics suggest deposition from flows moving across, and spreading over, large areas of the flat trench floor. All vertical and lateral petrologic changes observed within the three trench basins examined tend to support deposition from sediment gravity flows of diminished concentration as depicted by the transformation continuum model presented by Stanley and Maldonado (1981, fig. 11).

Classification of Fine-grained Turbidite Mud Sequences

The vertical succession of bedforms and general fining-upward of unifites in the seven cores is generally comparable to that of idealized fine-grained turbidite units, Te^t, defined by Rupke and Stanley (1974:9) and others. The several mud types recognized as a result of detailed petrologic analyses can be related to specific mud turbidite subdivisions defined by Piper (1978:165) and Stow and Shanmugam (1980:38).

The most complete FL+U sequence recovered, that in the core MA-23 (Figure 7), serves as a reference section. The unit, from 530 and 490 cm, corresponds to the vertically graded laminated medium and fine silt, and also to the laminated mud (E1), terms illustrated by Piper (1978:165) and, more specifically, to the indistinct laminated subdivision, T4, of Stow and Shanmugam (1980:38). This is overlain, from 490 to about 470 cm, by a graded mud division, coded respectively E2, or T6, by these authors. This is topped, from 470 to 310 cm, by a mud sequence that shows only vague grading, i.e., the ungraded mud division, E3 or T7. A marked change is observed at about 310 cm: Faint laminae reappear from 320 to 310 cm (E1 or T4); this is followed by graded mud from 230 to 140 cm (E2 or T6), and finally by faint, but graded, laminae at 140 to 110 cm (E1 or T4). The position of the above E terms, corresponding to those defined by Piper (1978), are depicted on the logs in Figure 7.

On closer inspection, the thick, apparently ungraded division (E3, or T7) shows subtle fluctuations of grain size, i.e., a slight upward increase in silt content from 470 to 390 cm (= ungraded mud), and then a slight decrease from 390 to 310 cm (= graded mud). The variations in content of clastic aggregates and sand-sized mineralogic components parallel, and actually magnify, otherwise subtle grain-size fluctuations in both graded and ungraded muds. Thus, grain size and mineralogy, supplementing bedform, reveal from base to top a complex succession of terms: E1→E2→E3→E2; E1→E2; and E1. The three E1 terms are characterized by a high carbonate (mostly silt-size coccoliths) and low clastic aggregate content, and a sand-size fraction dominated by biogenic components. In the E2 terms, the content of carbonate decreases, but that of clastic aggregates is high but fluctuates, and terrigenous components dominate the sand fraction. Proceeding upward in the sequence, each successive faintly laminated E1 term contains progressively larger proportions of clastic aggregates and sand-sized biogenic components. Thus, all three E1 terms in the MA-23 sequence are interpreted as an integral succession emplaced by a single flow event and do not represent the base of three separate deposits. The overall decrease of silt content, and vertical trends of mean (Figure 7) and modal (Figure 10) grain sizes favor this "single event" interpretation. Further support for this is provided by (1) the rapid upward increase in sand-sized planktonic, and concomitant decrease in terrigenous fractions within the lower, ungraded (E3) mud section, and (2) the lack of correlation between planktonic-terrigenous content and grain-size changes associated with the middle laminated E1 division. The overall cyclicity of this Matapan Deep margin flat FL+U sequence, and the variations within both E2 and E3 terms, probably record velocity and turbulence fluctuations in a single flow event.

The FL+U sequence in core MA-22 in the Matapan Deep basin plain reveals trends generally similar to core MA-23 (Figures 7, 10). There is overall fining-upward (decrease in silt content and mean grain size), and cyclicity is apparent, but somewhat less marked than in core MA-23. The vertical succession includes ungraded mud, E3 or T7, from 710 to 550 cm; graded mud, E2 or T6, from 550 to 470 cm; faintly laminated mud E1 or T4, from 470 to 440 cm; graded mud, E2 or T6, from 440 to 220 cm; and faintly laminated mud, E1 or T4, from 220 to about 210 cm. The three cycles in this core are: E3→E2; E1→E2; E1. As in core Ma-23, there are compositional and granulometric fluctuations, sometimes important, within both vaguely graded and ungraded terms. Differences, however, include somewhat less pronounced overall vertical grading, an upward trend in carbonate content that does not parallel grain-size variations, and a higher proportion of clastic aggregates throughout the sequence.

The FL+U sequences recovered in the three Zakinthos-Strofádhes Trench basin cores (Figure 4) display cyclicity involving vertical successions of bedform, grain-size, and composition. This cyclicity is similar to that noted in Matapan Deep cores MA-22 and MA-23. Specific differences in mineralogical components between MB and ZB unifites are related primarily to a different provenance (lateral source input from the northwest Peloponnesus) rather than to transport mechanisms. We interpret the unifite mud sequences in cores MA-22, TR-34, TR-35, and TR-36 as gravitative deposits emplaced by mechanisms similar to that of MA-23, i.e., transport and deposition by turbidity current-related flows of diminishing, but fluctuating, velocities and turbulence. An example of a classic, well-graded mud turbidite occurs above one of the unifites (see section from 310 to 180 cm in core TR-34, marked by T and arrow in Figure 4, and also the x-radiography print in Figure 3A).

Cores MA-10 and MA-20 in the Kithera-Antikithera Basin (Figure 6) differ most obviously from the five above-cited cores in that they comprise only uniform (U) mud sequences and display less obvious vertical cyclicity. The higher proportion of sand-sized clastic aggregates, and silt-size attapulgite and volcanic products (glass shards, etc.) reflect local provenance and dispersal factors rather than a different emplacement process per se. While both cores display an overall fining-upward trend, comparable to the Te^t turbidite sequence of Rupke and Stanley (1974), close inspection shows petrologic "breaks" within the U sequences. In MA-10, this occurs at about 200 cm, separating a lower ungraded mud (E3 or T7) from an upper graded mud (E2 or T6); the break in MA-20, although less well marked, is noted at about 400 cm, separating a lower E3 (or T7) from an upper E2 (or T6) term. Unlike the FL+U sequence in reference core MA-23, the principal mineralogical changes in both MA-10 and MA-20 closely parallel major textural "breaks." A sudden decrease in clastic aggregates and increase in sand-size biogenic components correlates with a decrease in grain size. The "break" between E2 and E3 terms in MA-10 and MA-20 unifites indicates superposition of two important successive depositional episodes. In each case, the superposition is related to a major turbidity current flow event. Vertical variations of both grain size and mineralogical components are observed within the ungraded mud, E3 or T7, terms in these (Figure 6) as well as in cores of other basins (Figure 7).

From this classification we propose a vertical succession of terms that characterizes, from base to top, an idealized complete unifite cycle: (1) a faintly laminated, generally siltier term, which may be graded and contain a sand-size fraction that is largely biogenic; (2) a graded fining-upward mud term with terrigenous components dominating the sand-fraction; (3) an ungraded mud term that, on close inspection, actually shows slight coarsening-upward and/or may display cyclic fluctuations and that contains a sand-size fraction dominated by terrigenous components; and finally (4) a graded mud (fining-upward) term with an enhanced biogenic fraction. This cycle may be repeated and, in thick sequences, some terms may be absent. Cores MA-10 and MA-20 comprise the thickest E2 and E3 terms examined.

Petrologic Variations Related to Flow Fluctuations

The general upward-temporal and lateral-spatial fluctuations (larger scale cycles as well as more subtle changes in bedform, grain size, and composition) are comparable in the three Hellenic basins. Insight on transport mechanisms involved in unifite deposition is provided by the vertical petrologic changes within each core and lateral variations between trench margin flat and basin plain cores. We have shown that a complete unifite sequence includes laminated (E1), graded (E2), and ungraded (E3) mud terms, and that their succession varies within a core, and laterally from core to core. Variations in mud type cyclicity, associated with an overall decrease in grain size, record internal fluctuations within a flow of diminishing velocity and sediment concentration. The development of faint laminae, for example, may be related to phases of flocculation and to the depositional sorting during flow; i.e., a reorganization of mud and silt flocs and their concentration result in their settling through the boundary layer at the base of a flowing turbidity current. Formation of fine-grained laminae by increased shear at the bottom boundary layer, as invoked by Stow and Bowen (1978), seems an appropriate explanation. We note that the faintly laminated E1 terms comprise a unimodal grain-size distribution consisting of a mode generally larger than 20 μm (Figure 10).

We are unable to ascertain why several such flocculation-induced laminated terms appear within a single sequence deposited from one major event (cf. core MA-23, Figure 7). Several possibilities may explain the presence of successive laminated zones within a single unifite. In all cases, the following are considered as constants: (1) steep gradients of the walls that bound trench basins (Le Quellec, 1979:64), (2) irregularities on these steep slope surfaces (Figure 11) and in canyon thalwegs (Vittori, 1978:37–117), (3) flocculation initiated within the flow on the slope as a result of particle collision (Kranck, 1975), and (4) hydraulic jump phenomenon that produces a sudden reduction in velocity and density and thickening of the flow as it reaches the flat basin floor just beyond that base of slope (Komar, 1971). As noted in most experimentally produced sediment gravity flows, larger or denser grains are concentrated at the head and near the base of the body of a rapidly downslope-moving gravity-entrained flow; the upper interface of the flow incorporates ambiant seawater and is thus more dilute (Kuenen, 1965:69). Both large and small topographic irregularities on the slope induce turbulence and, in consequence, a continuous rearrangement of the sediment load and its concentration. Inasmuch as the transported load consists largely of silt and clay particles, continuous flocculation and disaggregation occur within the flow as it moves downslope.

In the simplest case of unifite deposition on the margin flat province, we envision a flow column of roughly even thickness moving along a fairly

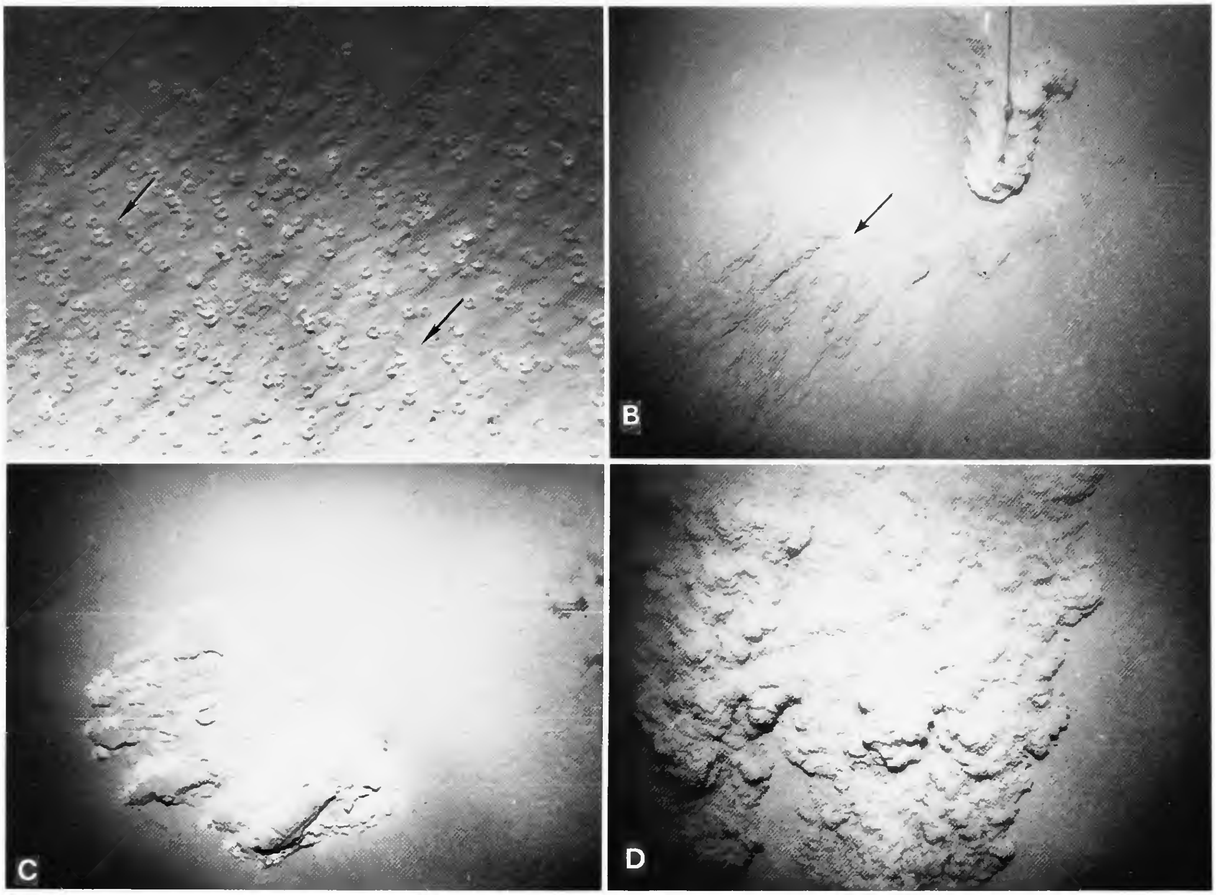
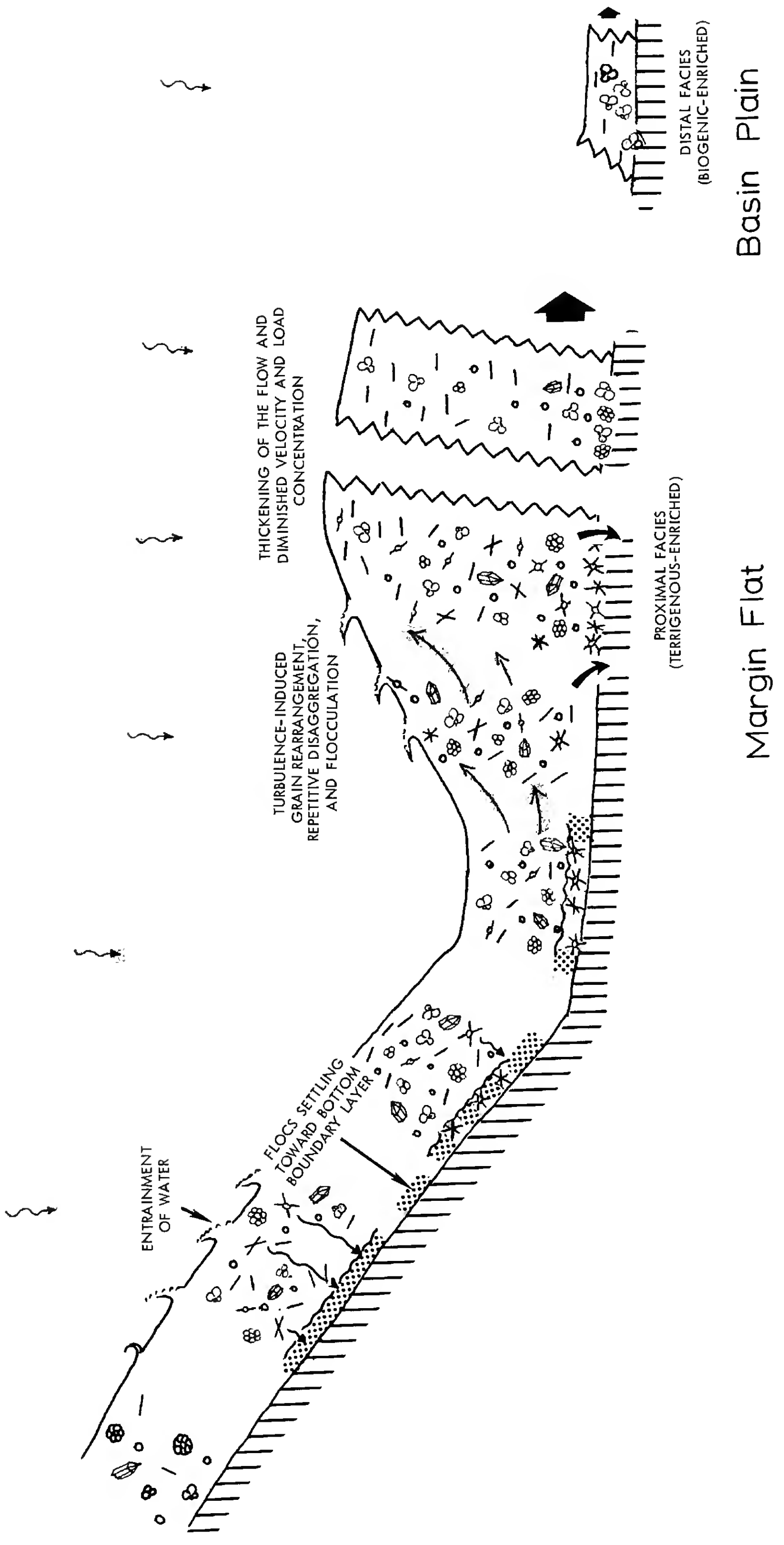


FIGURE 11.—Selected bottom photographs obtained from the deep-tow *Raie* system in the northern part of the Kithera-Antikithera Trench, near location of core MA-20 (1978 cruise *Raicette*, depth about 4400 m, near 35°50′N latitude and 22°13′E longitude): A, Slope swept partially free of thin surficial sediment veneer; note current lineations and minor scour-and-fill structures around burrows (circular structures are about 3 cm in diameter); the arrows are oriented along the predominant downslope transport direction. B, Eroded slope surface (arrow); note stirring of thin surficial sediment veneer by bottom compass. Compass and vane are about 30 cm long. C, Recently eroded block of mud ~1 m in length, lying near base of slope. D, Turbid flow, triggered by deeptow compass touching the slope, displaying multilobe configuration. Much larger flows of this type are believed to displace the thin sediment veneer downslope and probably produce the current-lineated erosional bedforms illustrated in "A" (Photographs generously provided by the Centre National pour l'Exploitation des Océans, Brest, France.)


ENTRAINMENT OF WATER
FLOCS SETTLING TOWARD BOTTOM BOUNDARY LAYER
TURBULENCE-INDUCED GRAIN REARRANGEMENT, REPETITIVE DISAGGREGATION, AND FLOCCULATION
THICKENING OF THE FLOW AND DIMINISHED VELOCITY AND LOAD CONCENTRATION
PROXIMAL FACIES (TERRIGENOUS-ENRICHED)
Margin Flat
DISTAL FACIES (BIOGENIC-ENRICHED)
Basin Plain

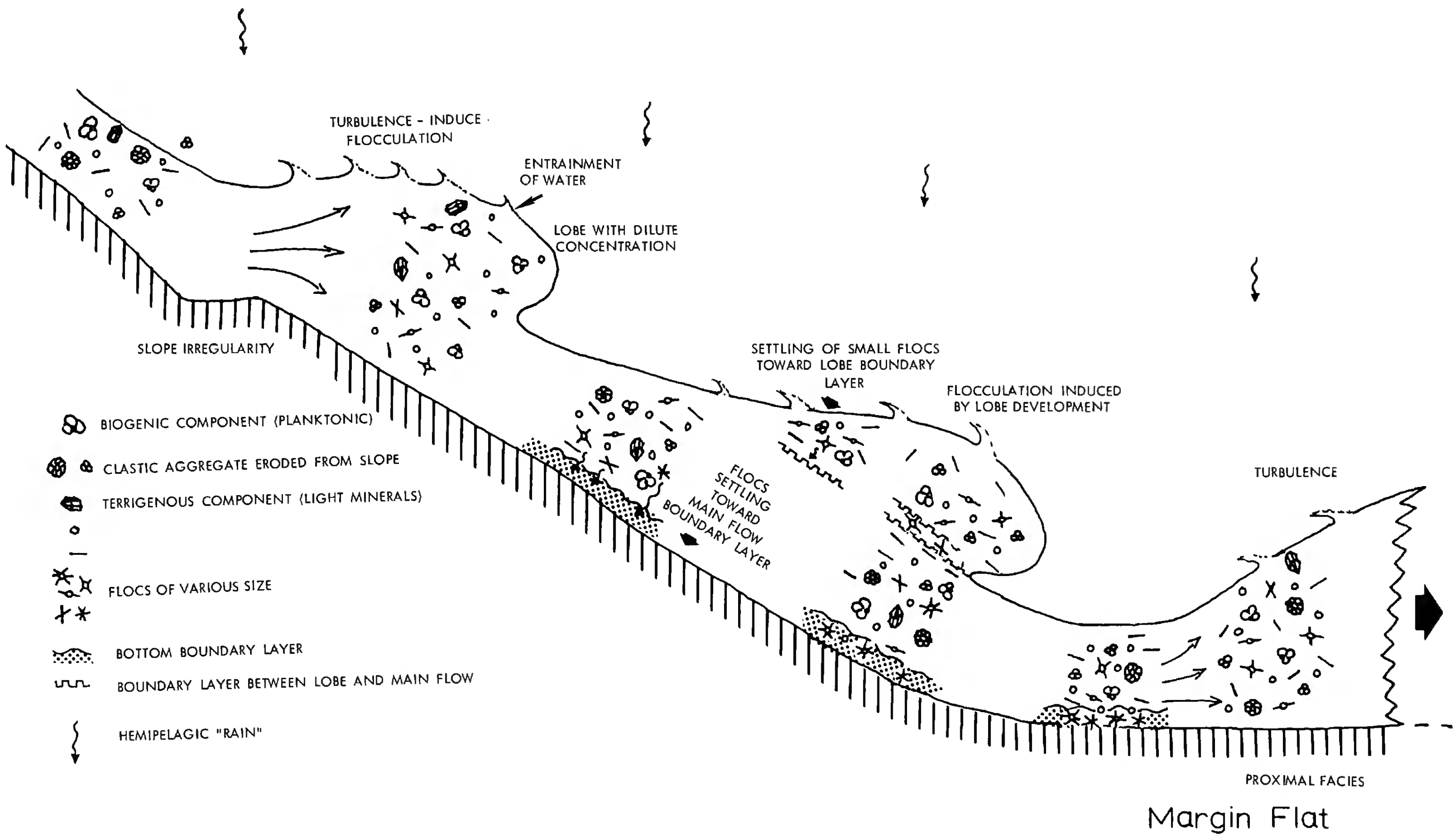


FIGURE 12.—Schemes depicting turbulent sediment gravity flows of the type likely to deposit unifites: A, Transport of largely fine-grained material on a relatively smooth slope. B, transport on an irregular slope produces successive lobes. The diagrams emphasize the effect of grain rearrangement, flocculation, and disaggregation related to the near-bottom boundary layer and the hydraulic jump phenomenon beyond the base-of-slope. These flow-related fluctuations are believed to produce the temporal and spatial petrologic variations of the Hellenic Trench unifites observed in this study. Explanation in text.

smooth slope and which, upon arrival on the near-horizontal basin floor, is subjected to hydraulic jump effects (Figure 12A). As a result of the jump, deposition of larger and denser grains and flocs concentrated at the head and near the base of the flow will settle out through the bottom boundary layer as flow velocity is rapidly reduced; this accounts for the deposition of the lower, faintly laminated E1 term. The rapid settling of finer materials above the basal E1 term produces both graded and ungraded muds (E2 and E3). During and following the passage of the flow head and deposition of this first cycle, the hydraulic jump effect above the same base-of-slope sector continues to induce rearrangement of grains that are entrained by the body of the downslope-moving flow; flocculation occurs again as a result of particle collision (cf. Kranck, 1975) due to temporary intensified turbulence. Thus, larger flocs settle once again, resulting in accumulation of a second cycle of laminated mud, followed by settling of finer, or less dense, material. This repetitive deposition of laminated, graded and ungraded muds continues as long as there is sufficient concentration of material carried by the downslope-moving flow over this sector and as long as flocculation is induced by hydraulic jump turbulence. The final passage of the slower-moving dilute tail is recorded by the uppermost nonlaminated mud.

A somewhat more complex but more probable unifite origin involves a flow column of uneven thickness, characterized by partially superposed and successive, imbricated lobes (Figure 12B). These lobes may record the development of major turbulence within the flow induced by large sea-floor irregularities upslope; the lobes are thus viewed as perturbations produced by a succession of hydraulic jump effects along the flow path. As each major lobe passes above the same base-of-slope sector, it releases material; the resulting deposit resembles that accumulated from a rapid succession of turbid flows. Analysis of the sediment load in each individual imbricated lobe would probably reveal that each has its own distinct, internal grain-to-grain distribution pattern. As each lobe reaches the base-of-slope and, in turn, is affected by the hydraulic jump, a cyclic deposit consisting of superposed E1, E2, and E3 terms will accumulate. Each lobe will release progressively finer material over the same base-of-slope sector.

The minor variations in grain-size and composition within any one cycle is accounted for by smaller-scale fluctuations of turbulence, velocity, and load concentration. Planktonic tests and clastic aggregates, on the one hand, and terrigenous components, on the other, have different densities; inasmuch as they become segregated during transport they are sensitive indicators of turbulence-related changes in a flow. We thus interpret cyclicity, repetition of laminated and uniform muds, and variations in mineralogical components on margin flats as largely the result of hydraulic jump effects both upslope and at the base of the slope. We conclude that the vertical variations observed in unifite sequences illustrated in Figures 6 and 7 do not represent time-separated turbid-layer flows of the type described by Moore (1969:83). Moreover, Hellenic unifites are petrologically unlike lithologic sections emplaced by current flows that cross and repeatedly rebound from basin pond walls, as illustrated by Van Andel and Komar (1969). While not completely ruled out, we tend to discount this latter process primarily on the basis of (1) the observed cyclicity, (2) unusual thickness (as much as 1 m) between each E1 term, (3) narrow range of petrologic variations, (4) very poor sorting of the mud throughout an entire sequence, and (5) the vertical distribution pattern of planktonic tests between the base and top of sequences.

Unifites on the trench basin proper differ markedly from those on margin flat sectors near the steep basin walls, particularly with respect to vertical variations in grain-size and composition, and a higher proportion of planktonic tests. This difference records changes that occur within the gravity-entrained flow as it moves away from the base-of-slope toward the more distal, near-horizontal trench basin plain proper (Figure 12A). The mineralogical "reversal phenomenon" that occurs between these two trench basin environments (Table 2) probably is most closely related to hydraulic jump effects; i.e., a transfer of energy markedly enhances turbulence and grain support characteristics within the turbidity current flow just beyond the base-of-slope break.

The hydraulic jump effect thus induces a sharp modification of the grain-to-grain configuration, which accounts for a temporary disorganization of the sediment load distribution within the flow column. Disaggregation within flow recurs as the turbidity current moves basinward across the plain; an increased regularity in settling of suspended grains accompanies diminished turbulence-related flocculation and floc rearrangement. Thus, the E2 and E3 terms that dominate more distal sectors contain progressively finer uniform mud terms, with lower proportions of denser terrigenous components. The observed subtle normal fining-up and reversed grading highlight a cyclic pattern even in the more distally deposited fine-grained ungraded (E3) unifites (core MA-20, Figure 7). This textural configuration attests to the still turbulent and moderately concentrated character of the slower, basinward moving flow. The uppermost graded mud term of idealized complete unifites on both basin margins and in trench plains proper records final phase settling of the sediment load, over large areas of the basin plain, from the tail of a flow.

Implications of Study and Conclusions

Hellenic Trench unifites have been interpreted as the end-members of a depositional series that are initiated in proximal, generally steep slope settings (Stanley, 1980). A theoretical complete transport continuum from slumps, to dense mass flows (debris flow), to turbidity currents, and eventually to very low concentration but still turbid layer flows, referred to as a transformation series, has been depicted by Stanley and Maldonado (1981, fig. 11). This continuum series depositional model is based on the recovery of a diverse suite of gravitative deposits whose distribution in the western Hellenic Arc study area appears non-random. Slumps, debris and other dense mass flows, and coarse-grained turbidites abound on slopes, while associations of finer deposits, including well-developed, classic silt turbidites and unifites, occur at the base-of-slope and in basin plains.

The thickness of a depositional unit is, in large part, a function of the volume of material transported relative to the surface area on which it accumulates. The remarkable thickness of individual fine-grained Hellenic Trench unifites (>10 m) detailed in this study is closely related to the very small surface area (100 to 250 km^2) of the flat trench basins that trapped the sediment gravity flows. The estimated volume of sediment carried by individual flows that actually reached the trench basin floor ranges from about 0.5 to 1.0 km^3, based on both core and seismic data. Such volumes are moderate when compared to those calculated for turbidites in modern ocean abyssal plains (Normark, 1970; Heezen and Hollister, 1971:183; Pilkey, Locker, and Cleary, 1980) and in the rock record (Scholle, 1971; Hesse, 1975; Rupke, 1976; Mutti, 1977).

In the larger Mediterranean basins, such as the Algéro-Balearic Basin in the western Mediterranean (Rupke and Stanley, 1974:11) and the Ionian and Herodotus Basin plains in the eastern Mediterranean, thin unifites comprising mixes of modern and reworked microfossils in fact are difficult to distinguish from thin mud turbidites and planktonic-rich hemipelagites. The gravitative deposits are more likely to display an absence of bioturbation and contain more reworked microfossils. Mediterranean basins are extremely diverse in terms of shape, size, and depth (Stanley, 1977a:128) and in consequence probably contain unifites of variable thicknesses. Unifite thickness, frequency in cores, and rates of accumulation depend not only on basin size and sediment flux, but also on dispersal and degree of accessibility of sediment to a basin plain.

The western Alboran Basin between Spain and Morocco and the Golo Basin in the Corsican Trough exemplify small ponds that are bounded by smooth slopes and have relatively direct access to substantial volumes of fluvial-derived and biogenic sediment transported basinward by gravity flows. As a result, relatively important proportions of thick structureless mud layers, or unifites, are recovered (cf. Huang and Stanley, 1972:539; Stanley, Rehault, and Stuckenrath, 1980:30). In contrast, other isolated basins are bounded by topographically more complex margins, and have limited or no direct access from land or proximal source terrains. It is noted that some of these basins nevertheless contain thick unifites. Examples include many of the topographically isolated Hellenic Trench basins of the type discussed in this study, as well as depressions on the Mediterranean Ridge, some Tyrrhenian and Aegean Sea basins, and narrow troughs in the Strait of Sicily. Many of the unifites in such settings are most probably related to earthquake tremors that trigger failure, initiate progressive downslope displacement, and in some manner insure sediment entry into basins.

Fine-grained laminated and unlaminated mud alternations usually form sequences 1 to 10 cm thick in most ocean cores and in rock slabs studied to date (Piper, 1978, fig. 12-6; Stow and Shanmugam, 1980, fig. 2). The typical ponded Hellenic unifite serves as an ideal example for study in that its thickness expands almost one hundred times that of commonly studied, much thinner, compacted gravitative deposits and magnifies the fluctuations of fine-grained bedform sequences. The vertical petrologic trends detailed in the expanded sections of such thick, fine-grained units are most valuable in that they record short-term fluctuations of flow characteristics. Important among the latter are changes in turbulence, velocity, grain-support mechanisms, and settling phenomena that may occur over a short time and limited space in small ponded basins.

Petrologic difference between unifites in the three Hellenic Trench basins examined demonstrate that major changes in flow properties affecting largely silt and clay-size loads occur rapidly and over a small area, i.e., within a few kilometers. Both 3.5 kHz profile and core data suggest that, upon entering basins, mud-carrying turbidity current flows deposit laminated sequences that thin distally. Moreover, proportions of larger, more buoyant planktonic tests, tend to increase relative to smaller, denser terrigenous components in a direction away from the site of the flow entry on the basin floor: this in large part accounts for the "reversal" petrologic phenomenon illustrated in Table 2. In the case of larger basins, we postulate that a flow of diminishing turbulence, velocity, and concentration of the type envisioned eventually becomes a dilute, almost stationary cloud. The end-member deposit of such a flow would be difficult to distinguish from hemipelagic, largely suspension-emplaced layers: both are likely to be thin to moderately thick, foraminifera- and coccolith-rich mud layers. The former flow deposits, however, would likely contain somewhat more reworked microfossils than hemipelagites.

Combined factors of accessibility and transport process are largely responsible for the petrologic variations in ponded western Hellenic Trench unifites. We recall that these basins are separated from each other and from the Peloponnesus and Crete by physiographic features of marked relief, and are bounded by steep slopes, many of which include perched basins (Got, Stanley, and Sorel, 1977; Vittori, 1978:44; Le Quellec, 1979:144) likely to trap sediment moving downslope. The physiographic complexity, a result of geologically recent displacement resulting from plate motion, minimizes the paths along which sediment can be moved directly from adjacent land and proximal margin sectors, and from the Mediterranean Ridge, to the trench basin plains. It is our contention that the direct land and shelf→slope→basin plain sediment dispersal pattern, important in some of the larger oceanic trenches (cf. Piper, von Huene, and Duncan, 1973; Schweller and Kulm, 1978; Underwood, Bachman, and Schweller, 1980), does not prevail in the study area.

Our scheme, involving a succession of downslope dispersal events between shallow proximal and deep distal settings, has been depicted by Vittori (1978). This model involves transport through submarine valleys that extend from shallow gulfs to slope depressions and perched basins, and in some cases, further still to the trench basins proper. Sediment is moved from proximal to distal settings by a succession of redepositional events; the time span between gravitative flows is variable, but generally short. The diminished basinward proportions of sand and compositional homogenization of fine-grained sediments in the distally located cores (Figure 1) are accounted for by a barrier or dam effect, resulting from the complex topographic setting. This complexity induces preferential entrapment of coarser fractions in slope-perched catchment basins (Vittori, 1978: 44; Feldhausen and Stanley, 1980; Feldhausen et al., 1981). The major evidence that sediment has been carried into Hellenic Trench basins via submarine valleys is the presence of low-gradient basin aprons localized along some base-of-slope sectors (Figure 13). These aprons are actually small fan deposits. Cores recovered from such canyon-related aprons comprise large proportions of well-developed mud turbidites, a few sandy turbidites, but no thick unifites (Stanley and Maldonado, 1981, figs. 6, 8). Moreover, some core

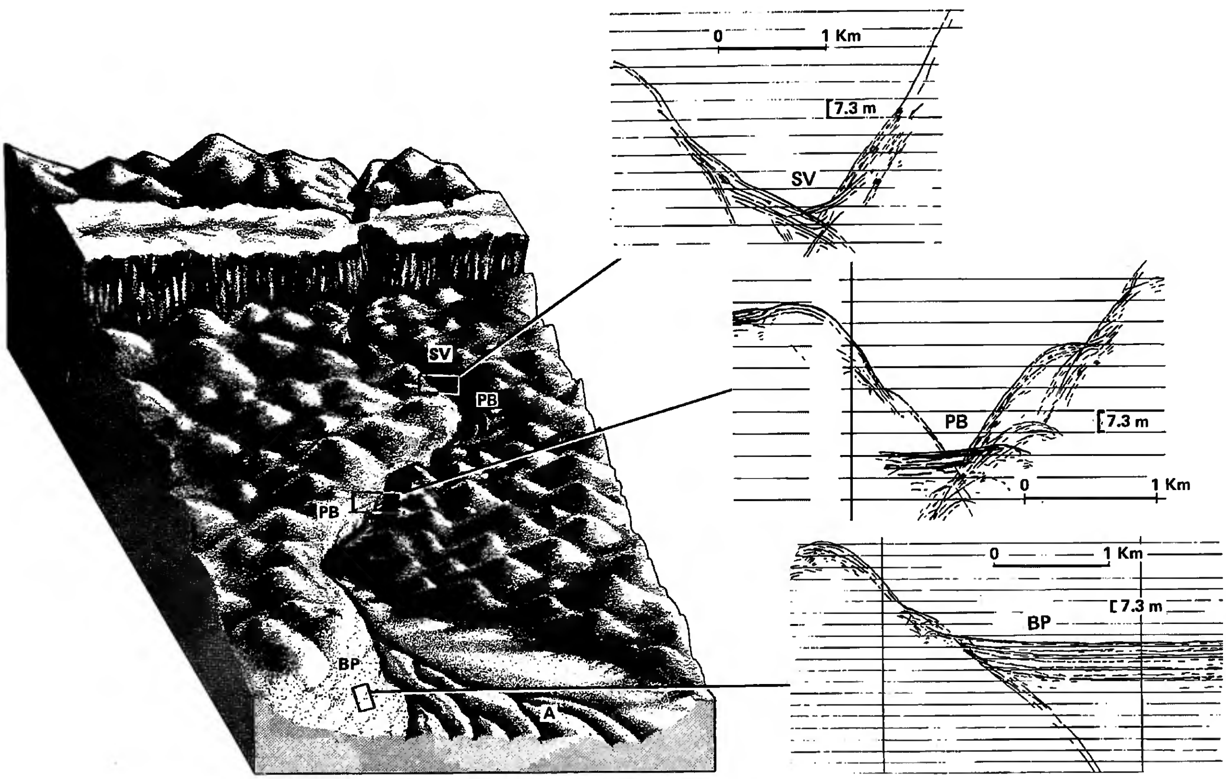


FIGURE 13.—Hellenic sediment dispersal scheme emphasizing near-continuous downslope transport from proximal margin to distal sectors. A sediment gravity flow may be channeled into a submarine valley (SV) and carry material into perched slope basins (PB) and, eventually, onto the trench basin apron (A) and near-flat basin plain (BP). In this manner, coarse material is selectively entrapped in submarine valleys, perched slope basins, and depressions in the cobblestone terrain. Line drawings of selected 3.5 kHz profiles (on the right) from the Zakinthos-Strofádhes Trench system illustrate examples of sediment deposited in a valley (SV), perched basin (PB), and basin plain (BP). Hellenic core surveys indicate that the acoustically transparent layers in the basin (BP) include mud hemipelagites and enhanced proportions of mud turbidites and unifites.

samples from these aprons include reworked shallow water microfossils and volcanic materials, and relatively important contents of terrigenous fractions of both silt and sand size (Feldhausen and Stanley, 1980).

Some unifites, particularly those in the Zakinthos-Strofádhes Trench basin, were probably emplaced by canyon-derived turbidity currents spreading across trench basins. Here the deposits contain sand-size shallow water benthic species derived from the adjacent shallow margin. However, the petrologic characters of most FL+U and U unifite sequences we examined indicate that other types of dispersal were probably even more important in the introduction of fine-grained deposits onto basin floors. For example, the absence of shallow marine faunas and the dominance of clastic aggregates in the sand fraction are noted in many unifites, particularly those in the Kithera-Antikithera Basin. Clastic aggregates (Figure 9A) are almost certainly reworked from older, semi-consolidated sediments that cover slopes and high-relief features, including those adjacent to trench basins. The clastic aggregates (clasts of cemented silt particles) are always associated with reworked microfossils of Pliocene and, in some cases, Miocene age; they sometimes occur with pyritized planktonic tests from resedimented sapropels and with disseminated silt and sand-size volcanic particles (glass shards, palagonite, etc.) reworked from several Quaternary ash layers, including the Ischia Tephra (cf. Ninkovich and Heezen, 1967).

This reworked assemblage records a mixing of slope sediments of different age and origins as a result of successive resedimentation events. The failure of older sediment formations that form slopes constitutes a primary source of material reaching trench basins; this is recorded by direct observation made during submarine dives (Drake and Delauze, 1968; Pareyn, 1968) and from bottom camera photographs. These reveal a thin (or absent) unconsolidated sediment veneer on steep gradients (Figure 11A) that is metastable and easily set in motion (Figure 11D). Downslope-oriented bedforms (Figure 11A, B, arrow) record recent seafloor erosion of the slope. Large individually displaced (allochthonous) blocks observed on high-resolution sparker profiles (Vittori, 1978: 81) and on 3.5 kHz records (Figure 14) and smaller detached blocks of mud directly observed on dives and in photographs (Figure 11c) provide further evidence for the failure of silt and clay on slopes. Graphic depiction of localized slope failure as an important source of trench fill sediments is also presented on the trench deposition models illustrated by Piper, von Huene, and Duncan (1973, fig. 7), Schweller and Kulm (1978, fig. 21) and Underwood, Bachman, and Schweller, (1980).

The episodic, but almost constant, downslope displacement of sediments, involving failure of slope deposits and subsequent movement via canyons is thus envisioned (Figure 13). Sediment gravity flows, sometimes widespread, sometimes localized, are able to displace admixtures of both originally land-derived terrigenous and biogenic fragments and also incorporate during their downslope descent eroded clastic aggregates and planktonic foraminifera. Similar examples of such reworking in ancient marine examples have been described by Scholle (1971). Successive gravitative events apparently result in size-sorting effects and, consequently, in changes downslope in the proportions of mineralogical components. Repeated redeposition may explain, for example, the downslope increase in clastic aggregates and planktonic tests relative to the sand-size terrigenous fraction (Feldhausen and Stanley, 1980). The increased proportion of attapulgite (palygorskite) downslope in the Kithera-Antikithera Trench is still further evidence of gravity-induced processes involving slope erosion (Stanley, Blanpied, and Sheng, 1981). We do not believe, however, that canyon transport and slope erosion models in themselves satisfactorily account for the remarkably limited range of textural and compositional variations that characterize many Hellenic unifite sequences.

The exceptional homogenization of sediment that must occur prior to its arrival at the base-of-slope requires that another phenomenon be considered. We suggest that homogenization results,

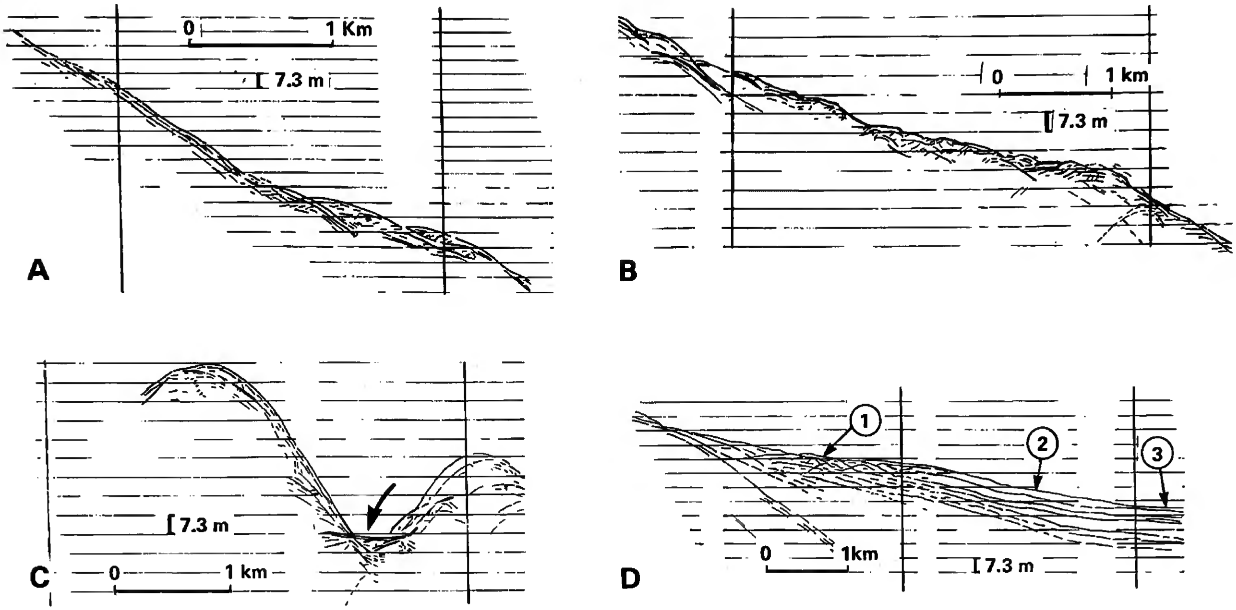


FIGURE 14.—Line drawings of selected 3.5 kHz seismic profiles from the Zakinthos-Strofádhes Trench system that show sediment failure on steep slopes: A, Slumps with poorly defined internal structure. B, Overlapping series of mass failure deposits. C, Failed sediment accumulating in immediately adjacent depression in cobblestone terrain (arrow). D, Slump deposits showing undefined internal structure at base-of-slope (arrow 1); note improved definition of bedding basinward (arrow 2), and well-stratified ponded facies in the basin plain (arrow 3).

to a considerable extent, from a slope relief bypassing-related mechanism (Figure 15); i.e., the upper, less concentrated portions of thick gravitative flows, initiated in canyons or on slopes, probably spill over and carry some of the fine sediment load onto and across topographic highs. In this manner, coarser-grained elements would accumulate preferentially in depressions, including submarine valleys, lows between cobblestone topography (Stanley, 1977b) and perched slope basins (Vittori, 1978:193). This model emphasizes the progressive seggregation of sand from mud and its preferential entrapment on the slope, whereas finer grained sediments are carried further downslope across irregular slope relief features toward the basin plain.

The fine-grained, largely silty clay or clayey silt veneer resides on slopes, particularly the steep ones, only temporarily; this sediment fails easily (Figure 11D) and apparently can be displaced basinward by means of successive gravitative events. Steep slopes are thus locally devoid of unconsolidated sediment cover as observed by Drake and Delauze (1968) and others. Downslope flows that displace the thin sediment veneer can also form erosional bedforms on slopes (figure 11A, B). As they progress downslope, flows pick up and incorporate recent planktonic foraminifera, coccoliths, and clay that settle through the water column over most of the seafloor; these hemipelagic components are eventually transported to trench basins along with the gravity-displaced, size-sorted, fine-grained material. This process helps explain the high proportions of older (pre-Pleistocene) coccoliths.

Earthquake tremors affect most of the Hellenic Arc and are particularly frequent and intense in the study area (Comninakis and Papazachos, 1972). These are the dominant triggers that set in motion material of mixed terrigenous and biogenic origin. The almost continuous failure of slope sections, gravity-induced transport through canyons and channels, and sediment gravity flows spilling over and bypassing areas of relief result

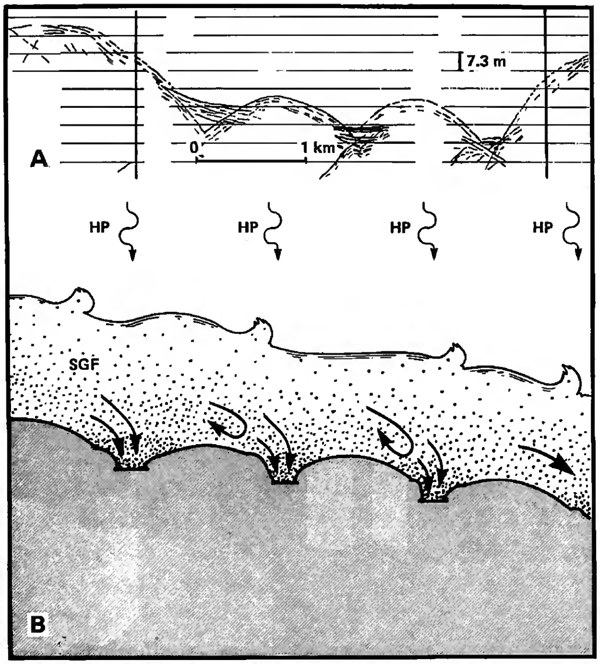


FIGURE 15.—Sedimentation model, depicting relief bypassing along the Hellenic Arc margin, emphasizes textural segregation and progressive fining and homogenization of muds toward base-of-slope and basin plain environments: A, Line drawing of a 3.5 kHz seismic profile in the Zakinthos-Strofádhes Trench sector illustrating preferential sediment entrapment in depressions in cobblestone terrain. B, Schematic profile depicting a thick, turbulent sediment gravity flow (SGF) traversing irregular topography. Arrows show selective deposition in the depressions of coarse or denser particles, released largely from the base of the flow; the less dense and finer material carried in the upper, less concentrated portion of the flow are thus able to bypass relief. (HP = hemipelagic "rain.")

in stratigraphically disrupted (repeated or incomplete) core sections throughout the study area (Stanley, Knight, and Stuckenrath, 1978). Anomalous sequences of radiocarbon-dated core sections (Figure 4), irregular distribution or absence of key horizons (sapropels, oxidized layers, tephra), dilution of sapropels by incorporation of terrigenous material, and the extremely high rates of deposition in trench basins relative to slope environments (Stanley and Maldonado, 1981) support this active and complex provenance-dispersal model.

Depositional events of the type described above have occurred during much of the Quaternary, including the late Pleistocene to the recent. Noted, in this respect, are the unusually thick unifites in the Kithera-Antikithera Trench basin, which consist of material radiocarbon-dated from about 15,000 to 11,000 years B.P. (Figure 4), or from late Pleistocene to early Holocene. It is important, however, to signal the absence in both cores MA-10 and MA-20 of the upper sapropel (S_1), a key stratigraphic layer that is widely distributed throughout the eastern Mediterranean and which is dated about 8000 years B.P. (Stanley, 1978; Thunell and Lohmann, 1979). This absence of the upper sapropel suggests that the two thick unifites were deposited at their present trench basin sites since S_1 time, i.e., in the mid-Holocene or more recently. We recognize that radiocarbon dates are influenced by the presence of older reworked material, and thus likely indicate the time of earlier deposition on the slope, and not the time of final sedimentation of the unifites in the trench plain. It is possible that the final gravity flow emplacement of unifites in the two Kithera-Antikithera Trench cores is related to a regionally widespread tsunami triggered by the major Thera explosive event at about 3500 years B.P., a suggestion proposed by Kastens and Cita (in press). The presence, however, of similar unifites of older but variable ages *below* the upper S_1 sapropel in other cores of this same trench basin indicates that transport events of this type occurred during much of the Quaternary (cf. Lamont-Doherty Geological Observatory core RC-184, illustrated in Stanley, 1974, fig. 8; Joides drilling at sites 127 and 128, in Ryan et al., 1973: 243–322). There is no reason to restrict unifite deposition to tsunami events. Earthquake tremors in this zone of high seismicity are the most likely cause of almost constant remobilization and basinward displacement of the underconsolidated and unstable slope sediments.

Some thick (>1 m) single-event silt and clay-rich shales and marls described in the geological record (e.g., Scholle, 1971; Ricci Lucchi, 1975; Rupke, 1976) may have a similar origin to the

Hellenic unifites. Paleogeographic analyses suggest that most of these ancient examples accumulated in small, or at least topographically restricted, catchment basins. As shown in the present Hellenic study, the thickness of a single redepositional sequence does not necessarily correlate directly with distance from source. Rather than proximity, the fine-grained "distal" characteristics of the Hellenic unifites we examined are primarily the result of progressive sorting by repetitive downslope displacement events across highly irregular slope surfaces, i.e., textural segregation involving the relief bypass phenomenon (Figure 15). We would also expect that in the case of some ancient unifites, this type of textural and compositional sorting prior to final trench basin emplacement also resulted from flow spillover and selective bypassing of progressively finer grains across topographically highly complex slope terrains.

Unifites accumulating on an active margin, such as those along the Hellenic Arc, often do not represent distal facies in the geographic sense. In contrast, however, some thick unifites have accumulated in small to moderate size basins in locales truly distant from shelves and slopes; these geographically distal unifite facies represent a bypassing of morphologically less complex margins. In larger basins, a unifite may represent the low concentration or slow moving end-member of a gravity flow transformation continuum (i.e., settling from the tail of a turbidity current or from a turbid layer flow), or may be deposited from a near-stationary cloud.

In summary, thick unifites are closely related to the interplay of a number of factors: (1) the degree of accessibility to sediment flux, (2) redepositional processes and particularly gravity-induced flow characteristics, (3) type of material transported, (4) degree of textural segregation and compositional sorting during flow, (5) efficiency of slope relief bypassing, and (6) entrapment in relatively restricted catchment basins. We suspect that continued research on unifites will demonstrate that this facies occurs in a diversity of modern ocean and ancient marine settings that include both active and passive margins.

Summary

1. Unifites are nearly structureless muds, usually thick layers of clayey silt and silty clay that appear homogeneous in composition and often show an overall fining-upward trend; along the Hellenic Arc, unifites are restricted to small, isolated trench basins and interpreted as an end-member facies of gravity-emplaced transport processes.

2. Unifites are formed by uniform muds, or faintly laminated muds, or both; uniform mud may overlie either faintly laminated mud or classic mud turbidites, but in either case it appears to be deposited from a single gravity-induced flow event.

3. Rapid deposition of unifites from sediment gravity flows is implicated by the association of unifites with turbidites, their spatial restriction to trench basins, their lateral continuity and consistent thickness across large areas of trench basins, their marked thickness (to >10 m), their high clay fraction (to 60%) and very low sand fraction content ($<0.3\%$), and a consistently small accumulation time range as indicated by radiocarbon dates.

4. This study shows that unifites are not truly homogeneous petrologically, and that the textural and compositional distinctions observed within a unifite appear closely related with the geographic position of a trench basin depositional site relative to the steep margins bounding the trench plain, i.e., the base-of-slope margin flat setting versus the flat, more distal basin floor proper.

5. Unifites recovered well within basin plains tend to comprise higher proportions of uniform mud, are somewhat better sorted texturally, and generally contain higher proportions of planktonic tests, but somewhat fewer benthic forami-

niferal tests and terrigenous components than unifites along trench margins.

6. In detail, unifites display an overall, albeit subtle, fining-upward trend; the faintly laminated portions of unifites contain a somewhat higher silt content, while the uniform mud portions are slightly better sorted.

7. A complete unifite sequence may display a vertical cyclic trend formed by four terms, from the base up: a faintly laminated, generally siltier, fining-up term characterized by a largely biogenic sand-size content; a graded mud term with terrigenous components dominating the sand fraction; an ungraded mud displaying textural fluctuations and an important sand-size terrigenous fraction; and an upper fining-upward term with increased proportions of sand-size biogenic components.

8. The sand fraction of Hellenic Trench unifites is commonly dominated by clastic aggregates eroded and reworked downslope from older margin sediments; unifites also comprise a large silt-size nannofossil content (including an important proportion of reworked pre-Quaternary forms), and an upward increase of planktonic tests.

9. A petrological "reversal" phenomenon, attributable largely to the influence of transport processes, involves a change in the proportion of mineralogical components between the edge and the center of a near-flat trench basin; for example, components that are dominant in the coarsest terms of margin flat cycles may, in contrast, abound in the finer (largely uniform mud) terms of basin plain cycles.

10. The increased uniformity of unifites in a basinward direction indicates deposition from turbidity current-related flows of diminished concentration that move across, and spread over, large areas of a flat trench floor; the observed subtle petrologic variations probably record changes in flow character (turbulence, velocity, grain-support) that likely occur during a single-transport event over a brief time and limited area in a small ponded basin.

11. Faint laminae may be related to phases of flocculation and depositional sorting of the sediment load during flow; a reorganization of mud and silt flocs and changes in their concentration may induce accelerated settling of particles through the boundary layer at the base of a flow.

12. The faintly laminated terms in unifites are herein related to the hydraulic jump effect that produces a sudden rearrangement of the sediment load at the head and in the body of a flow and flocculation upon its arrival on the near-flat trench basin floor; the eventual passage of the slower moving dilute tail of the flow beyond the base-of-slope is recorded by the uppermost non-laminated, graded unifite mud term.

13. The mineralogical "reversal" phenomenon that occurs between the margin flat and somewhat more distal basin plain environments is also attributed to hydraulic jump effects, which induce a transfer of energy and changes in turbulence and grain support characteristics within the flow over a short distance beyond the base-of-slope.

14. Unifite thickness is in large part the result of the available volume of material transported relative to the surface area on which it accumulates, i.e., the thick Hellenic unifites do not necessarily record transport of particularly large sediment loads or a direct dispersal of concentrated flows between proximal and distal environments. Rather the unifites indicate entrapment of moderate amounts of material carried by sediment gravity flows into small trench basins.

15. The homogenization process essential for the deposition of fine-grained unifites along the Hellenic Arc results in large part from a barrier-dam effect, i.e., a modification of flows as they move basinward across the highly irregular slope topography characteristic of this region.

16. Homogenization involves both textural and mineralogical segregation. Coarser or denser fractions are preferentially trapped in slope depressions, while finer or less dense silt and clay particles in thick gravity flows are transported further downslope across irregular seafloor features (relief bypass phenomenon).

17. The failure of the thin, metastable sedimentary veneer on steep slopes is most frequently

triggered by earthquake tremors that affect large sectors of the Hellenic Arc; this episodic but frequent downslope transport of sediment, much of it reworked from older sedimentary strata, deposits by successive basinward displacement of progressively finer material that includes both land-derived terrigenous and biogenic fragments.

18. Much of the thin silty clay veneer on present Hellenic slopes has been emplaced by the relief bypass process and this sediment resides only temporarily on high gradient, seismically unstable features; core analysis shows that during much of the late Quaternary to the present sediments on the margin have been transported basinward through a series of repetitive displacement events that produced textural and compositional sorting on the slope prior to final trench basin accumulation.

19. The petrologic attributes of unifites record the interplay of several factors more important than proximality or distance from source: (1) complexity of dispersal paths and the degree of accessibility of sediment flux to the trench basin, (2) redepositional processes, grain-support mechanisms and gravity-induced flow characteristics, (3) type of material transported, (4) extent of textural seggregation and compositional sorting during flow, (5) role of the slope relief bypassing process, and (6) selective entrapment of essentially fine-grained particles in relatively restricted trench catchment basins.

20. Continuing studies in the Mediterranean Sea indicate that unifites occur in diverse settings on both active and passive margins and that these modern ocean deposits can serve as examples to interpret some uniform mud facies in the rock record.

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Text-reference system (author/year/page within the text, with the full reference in a "Literature Cited" at the end of the text) must be used in place of bibliographic footnotes in all scientific series and is strongly recommended in the history and technology series: "(Jones, 1910:122)" or "... Jones (1910:122)."

Bibliography, depending upon use, is termed "References," "Selected References," or "Literature Cited." Spell out book, journal, and article titles, using initial caps in all major words. For capitalization of titles in foreign languages, follow the national practice of each language. Underline (for italics) book and journal titles. Use the colon-parentheses system for volume/number/page citations: "10(2):5–9." For alinement and arrangement of elements, follow the format of the series for which the manuscript is intended.

Legends for illustrations must not be attached to the art nor included within the text but must be submitted at the end of the manuscript—with as many legends typed, double-spaced, to a page as convenient.

Illustrations must not be included within the manuscript but must be submitted separately as original art (not copies). All illustrations (photographs, line drawings, maps, etc.) can be intermixed throughout the printed text. They should be termed **Figures** and should be numbered consecutively. If several "figures" are treated as components of a single larger figure, they should be designated by lowercase italic letters (underlined in copy) on the illustration, in the legend, and in text references: "Figure 9b." If illustrations are intended to be printed separately on coated stock following the text, they should be termed **Plates** and any components should be lettered as in figures: "Plate 9b." Keys to any symbols within an illustration should appear on the art and not in the legend.

A few points of style: (1) Do not use periods after such abbreviations as "mm, ft, yds, USNM, NNE, AM, BC." (2) Use hyphens in spelled-out fractions: "two-thirds." (3) Spell out numbers "one" through "nine" in expository text, but use numerals in all other cases if possible. (4) Use the metric system of measurement, where possible, instead of the English system. (5) Use the decimal system, where possible, in place of fractions. (6) Use day/month/year sequence for dates: "9 April 1976." (7) For months in tabular listings or data sections, use three-letter abbreviations with no periods: "Jan, Mar, Jun," etc.

Arrange and paginate sequentially EVERY sheet of manuscript—including ALL front matter and ALL legends, etc., at the back of the text—in the following order: (1) title page, (2) abstract, (3) table of contents, (4) foreword and/or preface, (5) text, (6) appendixes, (7) notes, (8) glossary, (9) bibliography, (10) index, (11) legends.