Parallel Laminated Deep-Sea Muds and Coupled Gravity Flow–Hemipelagic Settling in the Mediterranean

DANIEL JEAN STANLEY

SMITHSONIAN CONTRIBUTIONS TO THE MARINE SCIENCES • NUMBER 19

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ABSTRACT

Daniel Jean Stanley. Parallel Laminated Deep-Sea Muds and Coupled Gravity Flow–Hemipelagic Settling in the Mediterranean. *Smithsonian Contributions to the Marine Sciences*, number 19, 19 pages, 7 figures, 1983.—The origin of fine-grained deep-sea facies is often blurred because of interplay of diverse transport mechanisms: sediment gravity flow, traction related to fluid-driven circulation, and pelagic and hemipelagic "rain" mechanisms. Physical and chemical attributes of the Mediterranean amplify petrologic differences, thus facilitating distinction between mud types in this sea. Important attributes include small distances between sediment input and depositional site, generally low bottom current velocities in the deep basins, and shallow depths that permit preservation of carbonate components, an important criterion for mud facies definition. Particularly important in the Mediterranean are periodic development of intense water mass stratification and pycnoclines which act as sediment barriers, i.e., deviation of low concentration sediment gravity flows, and temporary retention of particles from turbid layer flows and hemipelagic settling. Release and differential settling of terrigenous silt and clay flocs and reworked benthic and planktonic (largely coccolith and foraminifera) components from well-marked density interfaces occur in a manner such that particles are segregated according to size and density. The resulting varve-like deposits display fine parallel laminae of alternating coccolith- and terrigenous-rich layers that show diverse fining-upward trends. Finely laminated sections of this type accumulate more rapidly than hemipelagites and are distributed over larger surfaces than mud turbidites. Analysis of bedform, texture-fabric, composition, geometry, and rates of sedimentation help distinguish (1) fine parallel laminated muds derived from coupled sediment gravity flow and hemipelagic settling from (2) laminated mud turbidites, (3) laminated hemipelagites, and (4) contourites as commonly defined. Study of mud lithofacies in small to moderate size seas, such as the Mediterranean, holds promise for better interpretation of deep-marine fine-grained deposits.

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Dedicated to the memory of
Professor Dr. Johan Ferdinand Maurits de Raaf
1902–1982
inspiring leader
astute sedimentologist
friend

Parallel Laminated Deep-Sea Muds and Coupled Gravity Flow–Hemipelagic Settling in the Mediterranean

Daniel Jean Stanley

Introduction

Deposition of silt and clay lithofacies in the marine environment is attributed to settling of particles from suspension, to transport by fluid-driven processes related to ocean circulation (Heezen and Hollister, 1971:335–421; Eittreim and Ewing, 1972), and to sediment gravity flows (Piper, 1978; Stanley and Maldonado, 1981). Theoretical and experimental studies indicate that suspension settling, traction, and gravity-driven high-concentration mass flow and low concentration sediment flow mechanisms each result in characteristic bedforms and textural-fabric and compositional attributes of fine-grained deposits. Distinct facies are thus believed to result from pelagic "rain," tractive mechanisms related to bottom current transport (Stow and Lovell, 1979), and turbidity currents (Stow and Bowen, 1980). Muds from the latter process have received by far the most attention to date.

Conditions in marine settings tend to vary and be more complex than theoretical and experimental examples. For example, the transit of silt and clay flocs to the deep marine floor usually involves two or more processes. Moreover, it is recognized that stratification features in mud deposits result from mechanisms active just prior to, and at, the time of particle emplacement. It has also become apparent that some silty deposits, earlier interpreted as turbidites, actually have a more complex origin.

This paper considers the interplay of transport mechanisms that produces a continuum of mud types and thus blurs the origin of deep-sea fine-grained facies. Specific attention is paid herein to finely laminated muds whose petrology appears to record the combined effects of sediment gravity flow, including turbidity current transport, and hemipelagic settling. The Mediterranean Sea is an appropriate area in which to conduct a study of lamination in that (1) there are suitable numbers of closely spaced core sites, and (2) average basin depths approximate 3000 m, well above the carbonate compensation depth (CCD), such that calcareous components, an important criterion of depositional regime, are fortuitously preserved. Moreover, (3) Mediterranean basins are considerably smaller than those in major world oceans, and present diverse temporal and spatial facies variations, thus allowing more precise interpretation of dispersal and transport patterns. It is also recalled that (4) there is strong evidence of large-scale Quaternary to Recent oceanographic changes in the Mediterranean (Stanley et al., 1975:287–289). These conditions provide an ideal setting in which to assess how climatically in-

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duced changes in water mass stratification affect pelagic settling and sediment gravity flows of low concentration and, in turn, the formation of laminae in mud deposits. Identification of criteria for laminated mud types emplaced by combined sediment gravity flow–suspension settling processes, and distinction of such facies from laminated mud turbidites and hemipelagic end-members, are valuable outgrowths of the study.

ACKNOWLEDGMENTS.—The author acknowledges valuable discussions during the initial phase of the study with P.H. Feldhausen, NUS Corporation; and A. Maldonado, University of Barcelona; and use of coarse fraction mineralogical counts made by R. J. Knight, Petro-Canada Ltd. The paper was reviewed by R. D. Flood, Lamont-Doherty Geological Observatory; and J.W. Pierce, Smithsonian Institution; useful comments were also made by anonymous reviewers. Funding for this investigation, part of the Mediterranean Basin (MEDIBA) Project, was provided by Smithsonian Scholarly Studies grant 1233S101.

Climate, Hydrography, and Sedimentation

It is recalled that a major control of fine-grained sedimentation in the deep sea is ocean circulation whose driving force is the sun (Lisitzin, 1972:30–46). Climatic fluctuations, resulting in displacement of temperature and rainfall belts, modified world ocean circulation in the geologic past (Hay, 1974:1–5). Well documented are the Quarternary climatic oscillations (Climap Project Members, 1976) that markedly altered circulation patterns, even at great depths (Schnitker, 1980). Such changes were of particularly large magnitude in the case of small- to moderate-size basins with silled, restricted passages that limit exchange with adjacent water bodies. The Mediterranean serves as an ideal example in view of its narrow, elongate form between Africa, Southern Europe, and the Middle East, and the restricted exchange with Atlantic and Black Sea waters at the shallow, narrow Gibraltar and Bosporus-Dardanelles straits.

Moreover, Mediterranean circulation patterns have been affected by a complex seafloor configuration, including shallow ridges that separate this sea into a series of quasi-isolated depressions of highly variable size, shape, and depth. The Strait of Sicily and contiguous Siculo-Tunisian (or Pelagian) Platform (Carter et al., 1972; Burollet et al., 1979) is a long broad sill that effectively separates the eastern and western basins, and thus is particularly important in control of Mediterranean circulation (Allan et al., 1972:11–25).

Present excess evaporation relative to precipitation and runoff results in the characteristic Mediterranean hydrographic regime involving the eastward flow of a moderately thin layer of less saline Atlantic water above a relatively isothermal column of westwardly moving, dense intermediate and deep water masses (Wüst, 1961; Lacombe and Tchernia, 1972). Circulation patterns, however, were markedly altered in the past as a result of somewhat lower temperatures and higher rainfall and runoff than at present. Bradley (1938) postulated that basins in the eastern Mediterranean (Ionian, Aegean, and Levantine) were periodically characterized by oceanographic patterns involving Black Sea-type density stratification, in contrast to the present isothermal regime.

What would be the sedimentary responses on the deep-sea floor to such Quarternary climatic-hydrographic oscillations? It can be predicted that gravity-driven, high-concentration mass displacement and dense sediment gravity flows transporting mixes of coarse silt, sand, and coarser particles downslope and onto basin plains would not be markedly influenced by development of water mass stratification. In contrast, it is envisioned that dispersal and the resulting depositional patterns of low concentration flows, carrying mostly fine-grained material in suspension, would have been greatly modified by the development of a distinctly stratified water column of the type that may periodically have prevailed in the Quaternary and Pliocene. This investigation considers the origin of laminated fine-grained facies, other than sapropels (Ryan, 1972), and related organic-rich layers (Maldonado and Stanley, 1976b), that preferentially accumulated at times when conditions of water mass stratification were clearly different than at present.

Density Stratification Phases in the Mediterranean

In a far-sighted essay referring to modifications of Mediterranean hydrography induced by Quaternary oscillations, Bradley predicted (1938:377) that

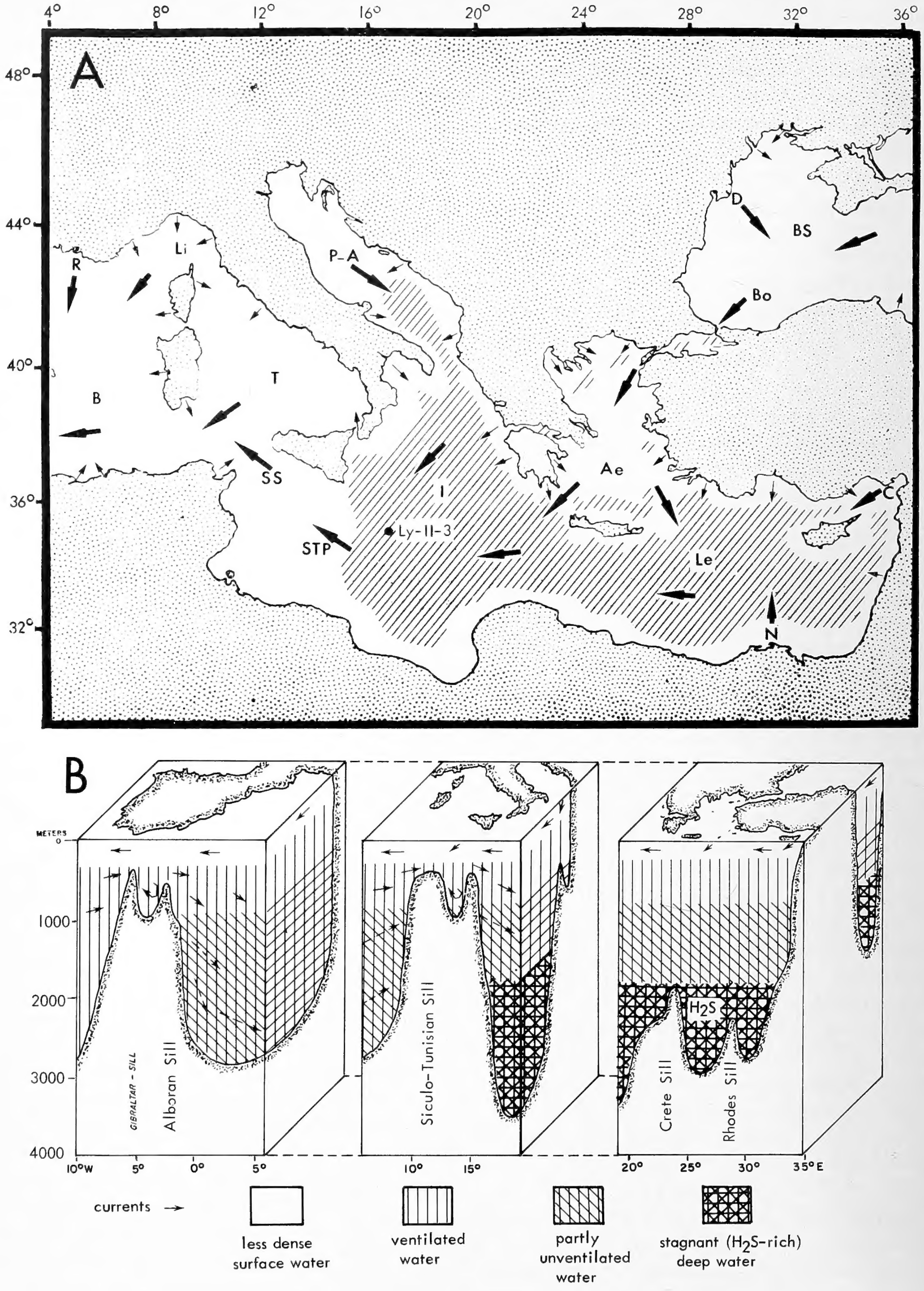
> during the last glacial stage, the Mediterranean, because of the different climate, would have had a surface layer of essentially fresh water overlying the oceanic water that filled the deep basins. Furthermore, the oxygenated Atlantic water would have had free access to the western basin of the Mediterranean through the Straits of Gibraltar beneath the outflowing surface stream of fresh water and in consequence the deep water of the western basin would have continued to be at least partially supplied with oxygen. But with a blanket of essentially fresh water covering the Mediterranean and moving westward there appears to be no way in which significantly large volumes of the oxygen-bearing saline water in the western basin could move across the sill at the Sicily Straits so as to cause circulation and afford an oxygen supply in the deep saline water of the eastern basin. For this reason the water in the eastern deep basin probably would have become stagnant and depleted of oxygen soon after the climatic change permitted fresh water to flood the surface of the Mediterranean.

Indirect, but strong, evidence for such physical oceanographic changes during the late Pleistocene to Holocene has been provided during the past two decades by studies of cores collected in different Mediterranean basins. Radiocarbon dating and facies analysis of cores establish a stratigraphic base for regional correlation of Late Quaternary sediment sections (Stanley and Maldonado, 1979). Noteworthy is the remarkable systematic repetition, or cyclicity, of Quaternary sedimentary sequences recorded by means of lithofacies (Maldonado and Stanley, 1976b), geochemical and isotopic (Vergnaud-Grazzini et al., 1977; Dominik and Mangini, 1979; Luz, 1979), and faunal (Mars, 1963; Ryan, 1972; Thunell and Lohmann, 1979) analyses.

Lithological cyclicity indicates that circulation patterns in both eastern and western basins periodically were altered markedly from those operating at present. Particularly important evidence in this respect is provided by dark, organic-rich fine-grained sapropel layers broadly distributed in the eastern Mediterranean (Figure 1A). There is general agreement that reduced oxygen content favoring anaerobic conditions on the seafloor resulted from density stratification (Kullenberg, 1952; Olausson, 1961). The distribution of dated sapropels indicates that some stagnation phases resulting from temporarily altered water mass stratification were basin-wide and occurred primarily at depths in excess of 800 to 1000 m (Stanley, 1978). The uppermost layer, dated at about 9000 to 7000 year B.P., formed during a warming phase (Ryan, 1972). The two underlying sapropel layers are dated at about 25,000–23,000 years B.P. (possibly during a cooling phase) and at >40,000 years B.P. (Stanley and Maldonado, 1979:40–42).

Sapropels are absent in the three deep (to about 1700 m) Strait of Sicily basins, and in the Ligurian, Tyrrhenian, Algéro-Balearic, and Alboran seas. However, sections in many cores recovered in these central and western Mediterranean depressions, some dated at about 11,000 to 9,000 years B.P., display dark gray-olive streaked mud layers that contain pyritized tests and burrows (see, for example, core logs in Huang and Stanley, 1972:536–538; Rupke and Stanley, 1974;11,25; Maldonado and Stanley, 1976a:53–56). The radiocarbon dates of these core sections may be somewhat older than the age of actual sediment emplacement, due to the presence of reworked calcareous microfossil tests. It is likely that the streaked, gray-olive, pyrite-rich mud sections of western Mediterranean cores are chronologically equivalent to the sapropel zones of basins east of the Strait of Sicily. The reduced, pyrite-rich sections of the western Mediterranean, like sapropels, record phases of density stratification as depicted in oceanographic models presented for the early Holocene (Figure 1B).

In sum, lithofacies data support the hypothesis that an "estuarine-type" circulation regime and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30°
35°E
currents
less dense surface water
ventilated water
partly unventilated water
stagnant (H2S-rich) deep water

current reversal dominated the Mediterranean for short periods of time (Bradley, 1938;377; Mars, 1963;67–71). That the oceanography in the eastern basins at times of sapropel deposition, when oxygen-deficient conditions prevailed, may be likened to that of the present Black Sea is also indicated by analysis of Sea of Marmara cores (Stanley and Blanpied, 1980). It is postulated that excess glacial melt waters moved westward as overflow from the Black Sea across the Bosporus-Dardanelles portals, and then south across the Aegean Sea. After entry into the Levantine and Ionian seas, this less saline surface layer flowed westwardly to and across the strait of Sicily and, eventually, Gibraltar (Figure 1). Denser Atlantic water, flowing eastward below the surface layer, entered the Alboran Sea and western Mediterranean producing some mixing and precluding complete anaerobic conditions of the Algéro-Balearic, Ligurian, and Tyrrhenian seafloor.

Current reversal as outlined above remains within the realm of theory. There is little doubt, however, that the Quaternary sediment cover, showing cyclothemic development of alternately reduced and oxygenated facies across much of the Mediterranean, records the direct interaction between climatically controlled water circulation fluctuations and deep basin sedimentation. Stratigraphically correlated cyclothemic sequences from eastern and western Mediterranean basins highlight the nonrandom vertical and lateral distributions of different fine-grained sediment types (Maldonado and Stanley, 1977; Stanley and Maldonado, 1981). It is useful to compare silt and clay facies that accumulate in isothermal versus stratified water regimens.

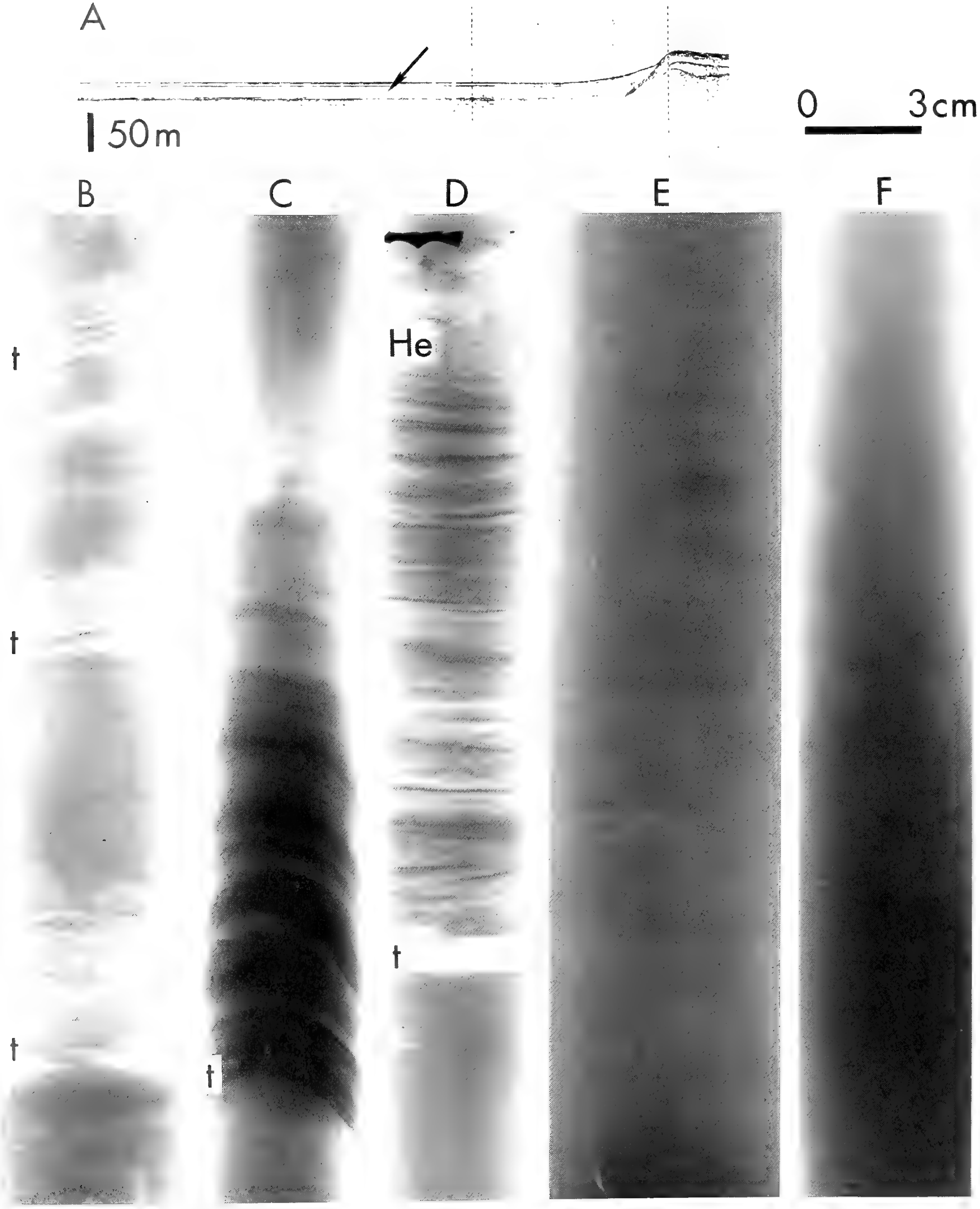
FIGURE 1.—A, Chart showing distribution of youngest organic-rich sapropel, S_1 (diagonal lines), deposited in the eastern Mediterranean at about 9000 to 7000 years B.P., a time when hydrographic conditions were markedly different from those at present. (Heavy arrows depict generalized flow patterns of less dense upper water mass; light arrows show fluvial input; Ae = Aegean Sea; B = Balearic Basin; Bo = Bosporus; BS = Black Sea; D = Danube; I = Ionian Sea; Le = Levantine Sea; Li = Ligurian Sea; N = Nile River input; P-A = Po-Adriatic Sea; R = Rhone River input; SS = Strait of Sicily; STP = Siculo-Tunisian Platform; T = Tyrrhenian Sea; Ly-II-3 = position of core *Lynch* cruise II core 3; after Stanley, 1978.) B, Scheme illustrating "estuarine-type" water mass regime in the Mediterranean at times of sapropel and finely laminated mud deposition. Note marked stratification of water masses and development of Black Sea-type anoxic conditions in the eastern basins unlike those presently existing. (Arrows depict possible flow patterns of water masses; after Stanley et al., 1975.)

Fine-grained Facies and Isothermal Hydrographic Regimes

Mud types, including the fine silt, clayey silt, and silty clay, are most reliably identified as to process of emplacement on the basis of structures visible in radiographs, size analyses, and coarse-fraction composition. Silt and sand-sized terrigenous clasts and carbonate grains of biogenic (largely coccoliths, foraminifera, and shell fragments) and clastic (reworked limestone and dolomite) origin are valuable criteria for distinguishing mud types.

Muddy slump, dense mud flow, and muddy debris flow deposits accumulated throughout the late Quaternary independently of hydrographic fluctuations (Stanley and Maldonada, 1981:278–283). These mass flow units are concentrated in areas of marked seafloor relief (slopes, ridge margins, base-of-slope environments) in association with sand and mud turbidites and hemipelagic muds. In upper Holocene to recent time, mud turbidite–hemipelagic mud assemblages generally prevail on basin margins in areas of low relief, including perched slope basins and small depressions in cobblestone topography. In more distal, low relief environments, such as basin and trench plains, a distinct mud turbidite-unifite–hemipelagic mud assemblage is usually recovered (Figure 2). (Unifite is the descriptive term for uniform, almost structureless mud, cf. Stanley, 1981; Blanpied and Stanley, 1981:2.)

Temporal and spatial distribution patterns of this latter distal basin and trench plain lithofacies assemblage provides insight on the relation between oceanographic conditions and silt and clay transport processes in deep marine settings. Struc-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tureless and vaguely laminated unifites (Figure 2E,F) are distinctly restricted to flat basin and trench plains where they are associated with fine-grained mud turbidites (Figure 2B–D): both mud types are laterally continuous across basins (Figure 2A). Petrologically, unifites appear similar to nearly structureless muds that are referred to as "homogenites" by some workers (cf. Kastens and Cita, 1981). Radiocarbon dating of unifite sections records very high rates (>200 cm/1000 years) of accumulation. Both structureless and vaguely laminated unifites are somewhat finer grained than turbiditic muds with which they are associated. Unifites and turbidites fine upward gradually and contain comparable proportions of terrigenous and reworked fauna carbonate components (usually >30% of the sand-size fraction). Spatial distribution patterns, rapid sedimentation and textural and mineralogical attitudes indicate that both fine-grained, almost structureless turbidites and unifites are released from thick, low density or lower velocity sediment gravity flows (Stanley and Maldonado, 1981:284, 290). Unifites appear to be the dilute end-products from turbidity currents, turbid layer flows, and suspensate-rich clouds (Stanley, 1981; Blanpied and Stanley, 1981:29–35).

Typical Mediterranean hemipelagic mud layers, in contrast to fine-grained turbidites and unifites, are more commonly bioturbated and show speckling as a result of high concentrations of planktonic tests (usually >75% of sand fraction). Moreover, layer thickness and rates of accumulation (<10 cm/1000 years; Rupke and Stanley, 1974:33) of hemipelagites tend to be much lower. Structures and mineralogical composition suggest that hemipelagic muds accumulate largely from suspension "rain" mechanisms rather than from sediment gravity flows.

Under conditions of poorly developed water column stratification, such as that displayed by the present Mediterranean, gravity-driven flows, such as turbitity currents of moderately low density that carry clay- and silt-size flocs primarily in suspension, would likely move downslope. These flows would move relatively unhampered along the bottom, from proximal sites (outer shelf to upper slope, ridge, basin margin) to the base-of-slope and well onto basin plains. The turbulent head of such flows would entrain in a downslope direction pelagic material, settling, or recently deposited, from suspension "rain"; in some cases flows would also resuspend and transport basinward surfical biogenic and clastic material eroded from basin slopes. This process would result in heterogeneous mixtures of displaced planktonic tests, terrigenous grains, and older reworked faunas, typically recovered from associated unifites and fine-grained turbidites restricted to basin plains.

There is a decreased proportion of unifites in the eastern Mediterranean at times of sapropel deposition. This suggests that the flow patterns of low density "clouds" were in some manner modified during downslope movement by a barrier effect resulting from distinct density differences that periodically developed within the water column.

FIGURE 2.—A, Subbottom 3.5 kHz record showing part of the Zakinthos Trench plain in the western Hellenic Arc (arrow points to thick, laterally continuous, acoustically transparent layer, probably a fine-grained turbidite and/or associated unifite). B-D, Radiograph prints of selected core sections showing typical sharp-based, fining-upward laminated mud turbidites (t) and hemipelagic mud (He) with speckling. (Note cross-stratification in B and D, and distinct fining-up trend of entire laminated section in C.) E, Faintly laminated unifite. F, Structureless unifite. (B and D, respectively, *Marsili* cores 12 and 18 in the Kithera Trench sector; F, *Trident* core 172-34 in the Zakinthos Trench, Hellenic Arc (locations shown in Stanley and Maldonado, 1981); C, *Lynch* cruise II core 8A in the Algéro-Balearic Basin; E, Western Alboran Basin core 91 (locations for C and E, respectively, in Rupke and Stanley, 1974, and Huang and Stanley, 1972).)

Fine-grained Sedimentation and Density Stratification

Water masses of different temperature, salinity, or both, are separated by a sharp vertical gradient in density, or pycnocline. Theoretical calculations, supported by field observation, show that sharp density gradients may temporarily retain particles settling through the water column and modify the flow path of very low concentration plumes (Pierce, 1976). Pycnoclines would induce detachment of a suspensate-rich flow from the seafloor into the water column, rather than allowing a bottom-hugging turbid layer flow of the type necessary to deposit a fine-grained mud turbidite with typical structures and/or associated structureless unifite. Flow detachment is expected wherever suspended sediment-enriched water encounters a denser water layer. Off California, for example, Drake et al. (1972:328) have shown that minimal concentrations of 100 mg per liter, and generally much higher (~2500 mg/1; cf. Pierce, 1976:441), are needed to overcome density interfaces resulting from temperature changes in the water column.

In the Mediterranean, much of the fine-grained sediment presently introduced by rivers (notably the Nile, Rhône, Po, Ebro, and Seyhan) and by wind tends to spread out away from the coast along the upper major intermediate and deep water (Emelyanov and Shimkus, 1972). At times when stratification was better developed, depositional patterns almost certainly were more complicated. Particle aggregates settling from the upper pycnocline would reconcentrate along one of several lower density interfaces before finally settling to the bottom. In a multiply stratified column, one envisions a sequence involving (1) detachment of a turbid layer from the bottom, (2) aggregation, (3) particle settling, (4) renewed accumulation along a lower density interface, and (5) subsequent settling across still deeper pycnoclines prior to (6) deposition on the seafloor (cf. Pierce, 1976 Fig. 2).

Open ocean suspended sediment studies show that, eventually, particles either become incorporated in a near-bottom turbid (nepheloid) layer, or settle directly onto the bottom. Still limited investigations of suspended sediment concentrations in the Mediterranean show no well-developed nepheloid layers in the western basins at present (Pierce and Stanley, 1976; Pierce et al., 1981). Nepheloid layers in this sea, however, conceivably may have been important in the past. It is thus possible that midwater and bottom masses transported silt and clay size particles over larger geographical areas than they do today, perhaps in the manner nepheloid layers in other world oceans presently distribute substantial volumes of material (Eittreim and Ewing, 1972).

Some aspects of a generalized model for suspended sediment transport in a stratified system, including detachment (Figure 3), may be applied to the Mediterranean. For example, detailed lithofacies analyses of Nile cone cores indicate that there exists a rather direct relation between rates of sedimentation and the frequency of laminated layers in upper Quaternary sections (Maldonado and Stanley, 1978, 1979). It has been postulated that at times of sapropel formation, low density turbid flows emanating from the mouth of the Nile and moving downslope were retained above the cone as detached layers. Concentration of fine-grained material along pycnoclines on the Nile cone is schematically depicted in Figure 4.

More specific lithologic evidence recording probable influence of density stratification on fine-grained sedimentation is provided by suites of cores recovered from the western Hellenic Trench. These show that the most recent major phase of finely laminated mud deposition occurred from about 17,000 to 6000 years B.P. This period coincides with rapid eustatic sealevel rise and progressive climatic warming at the end of the Pleistocene and early Holocene. It is recalled that the most recent sapropel, S_1, was deposited between about 9000 to 7000 years B.P. (Ryan, 1972:150). The finely laminated mud facies, as the S_1 sapropel layer, was broadly distributed areally over highly diverse and irregular Hellenic Trench slope and basin topography; however, unlike S_1 which accumulated in less than 2000 years, finely laminated muds were deposited during a period lasting 10,000 or more years. Finely laminated muds during this same period also accumulated over large and topographically varied areas in other eastern and western Mediterranean sectors and Strait of Sicily basins. Their rate of accumulation is generally lower (<25 cm/

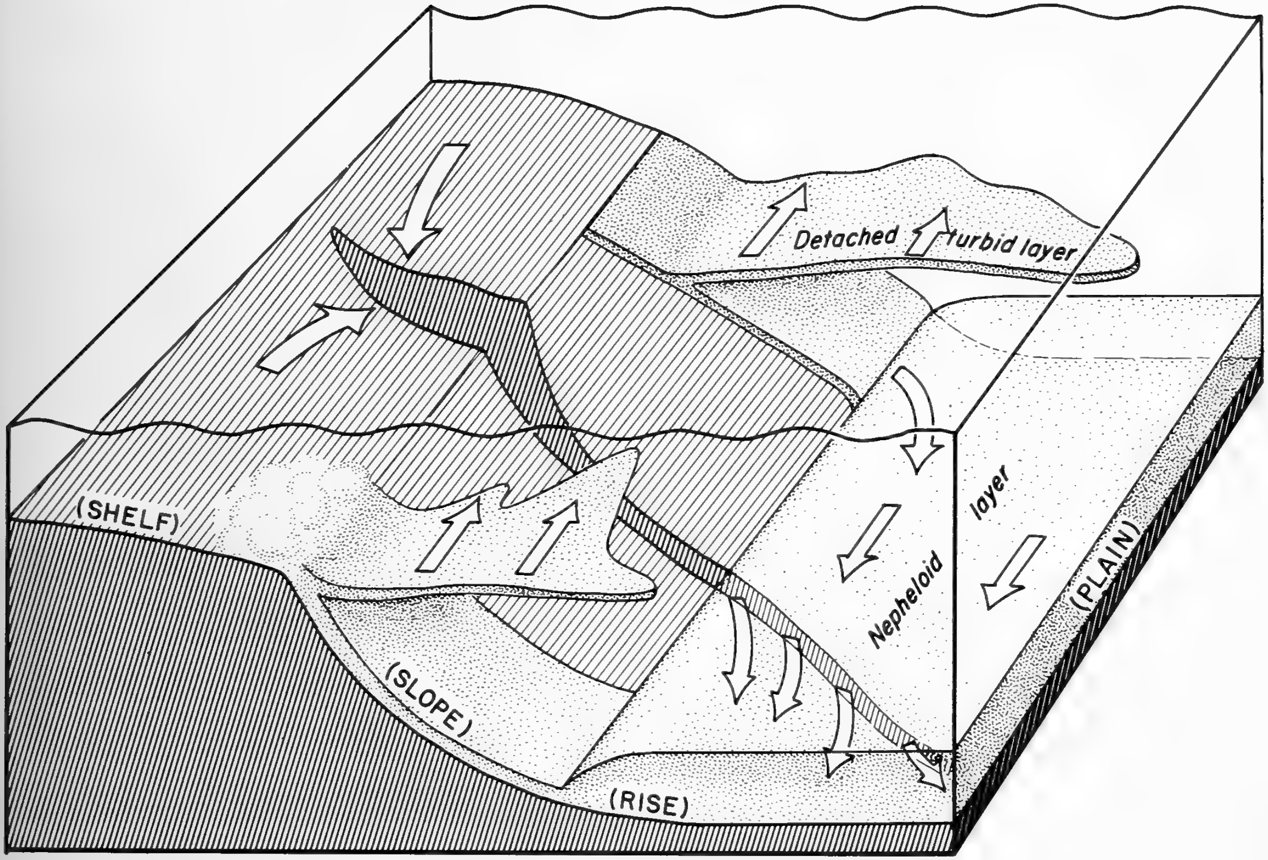


FIGURE 3.—Schematic of suspended sediment transport possibly applicable to the Mediterranean at times when water masses were stratified. Concentrations of suspensates (stippled areas) are shown as detached turbid layers along pycnoclines, and as bottom nepheloid layer, driven by bottom current circulation, on slope to basin plain. (Large arrows depict flow of water masses, a pattern similar to off U.S. East Coast, after Pierce, 1976.)

1000 years) than that of other mud types emplaced by sediment gravity flows, but distinctly higher than that of hemipelagites (<10 cm/1000 years). It is recalled that the proportion of thick unifites, emplaced by low concentration bottom-hugging flows, is reduced during the period of finely laminated mud deposition.

These considerations provide the basis for a generalized depositional model relating finely laminated facies with low concentration flows in a stratified water column (Figure 5). The scheme emphasizes introduction of particles from (1) gravity-driven flows entering along basin margins, and from (2) hemipelagic settling from surface waters. Concentrations of particles spread broadly on density interfaces in the water column as continuous or detached turbid layers. The progressive release of silt and clay size material over large areas of the seafloor is contrasted to material carried along the bottom by turbidity currents which, morphologically constrained, are more limited in seafloor surface distribution. Closer examination of finely laminated mud types elucidates this model.

Finely Laminated Mud Variants

Finely laminated facies are most reliably recognized by combined radiography and petrography. The most diagnostic criterion is closely

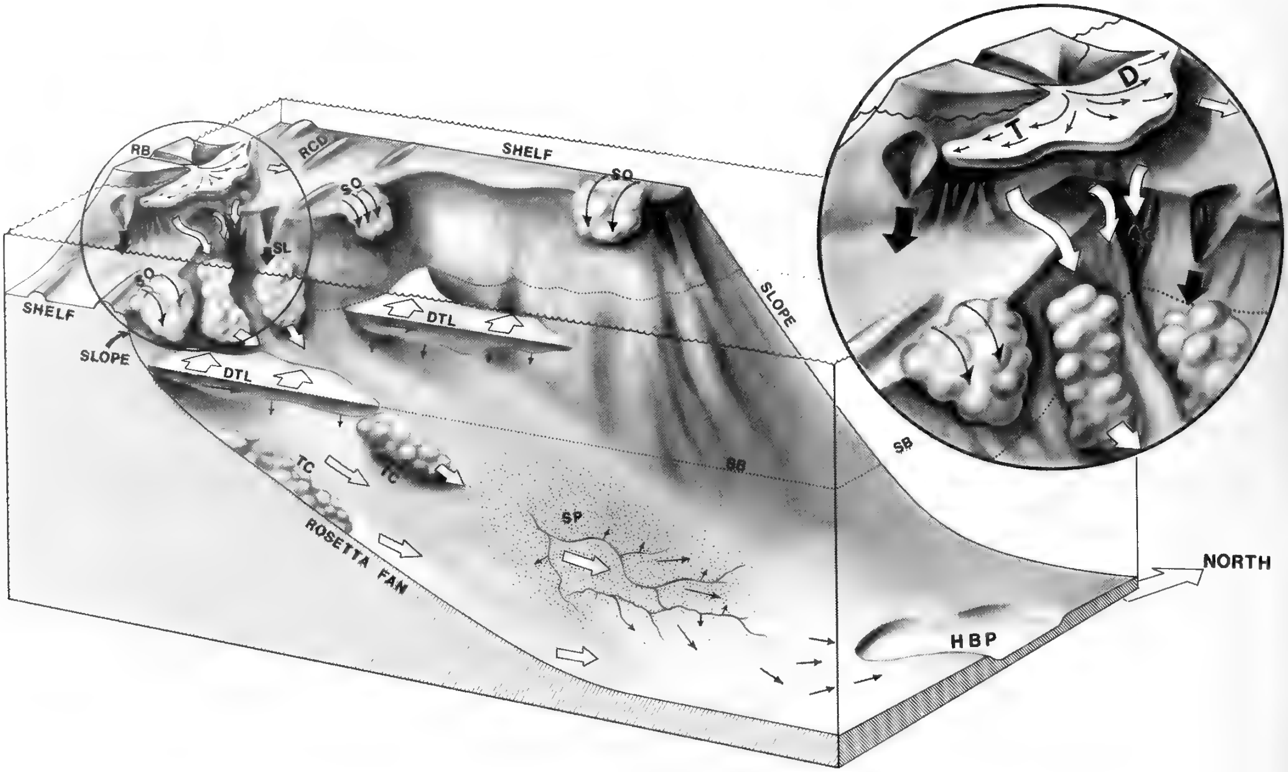


Figure 4.—Plexus of sediment processes on the Nile cone during phases of Mediterranean stratification (after Maldonado and Stanley, 1978). Dense turbidity currents (TC) cross pycnoclines as they flow downslope along the bottom, while lower concentration suspensate-rich zones form detached turbid layers (DTL) on pycnoclines. (Other symbols: AC = Alexandria Canyon; HBP = Herodotus Basin plain; RB = Rosetta Branch; RCD = Relict coastal and neritic deposits; SB = stratification barrier; SL = slump; SO = shelf-edge spill-over; SP = sand pods on Nile cone; TD = sediment turbid discharge off the Rosetta Branch of the Nile.)

spaced, parallel (<0.5–5.0 mm) laminae. These are sometimes visible in split cores (Ryan et al., 1973; Hsü et al., 1978), but always much better defined by density differences observed in radiographs (Figure 6). Parallel laminae in some Mediterranean basins are often indistinct, particularly in shallower (<1500 m) settings (Figure 6b). In contrast, they are well developed in deeper basins and particularly those in the Hellenic Trench area (Got et al. 1977, fig. 4; Stanley and Maldonado, 1981, fig. 3).

Core sections that comprise largely fine laminated facies in some of the deeper Hellenic Trench basins are dark olive gray. Most laminae are varve-like in that they consist of paired alternating layers of different mineralogy; a lamellar pair is termed a couplet. Some individual laminae, or couplets, do not clearly display a fining-upward texture (Figure 6d). Commonly, however, laminae couplets show diverse fining-upward trends (Figure 6c, e–g) involving changes from clayey silt to silty clay (textural data from Smithsonian Sedimentology Laboratory data base).

SEM analysis of the silt fraction shows that the layering apparent in radiographs consists of alternating coccolith- and silty clay-enriched oozes.

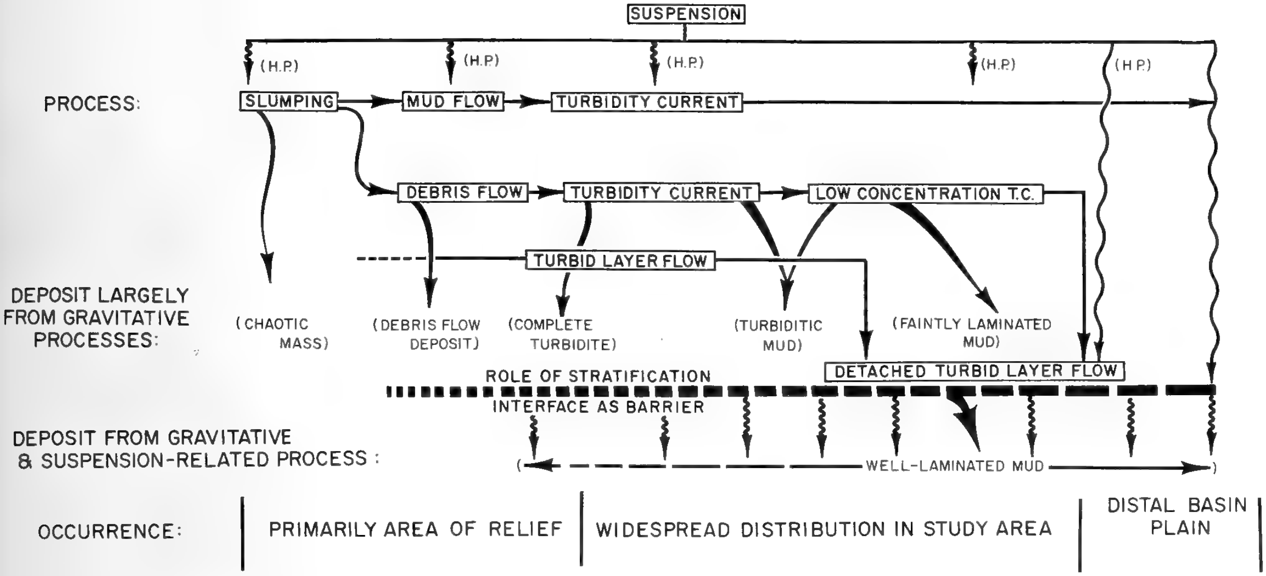
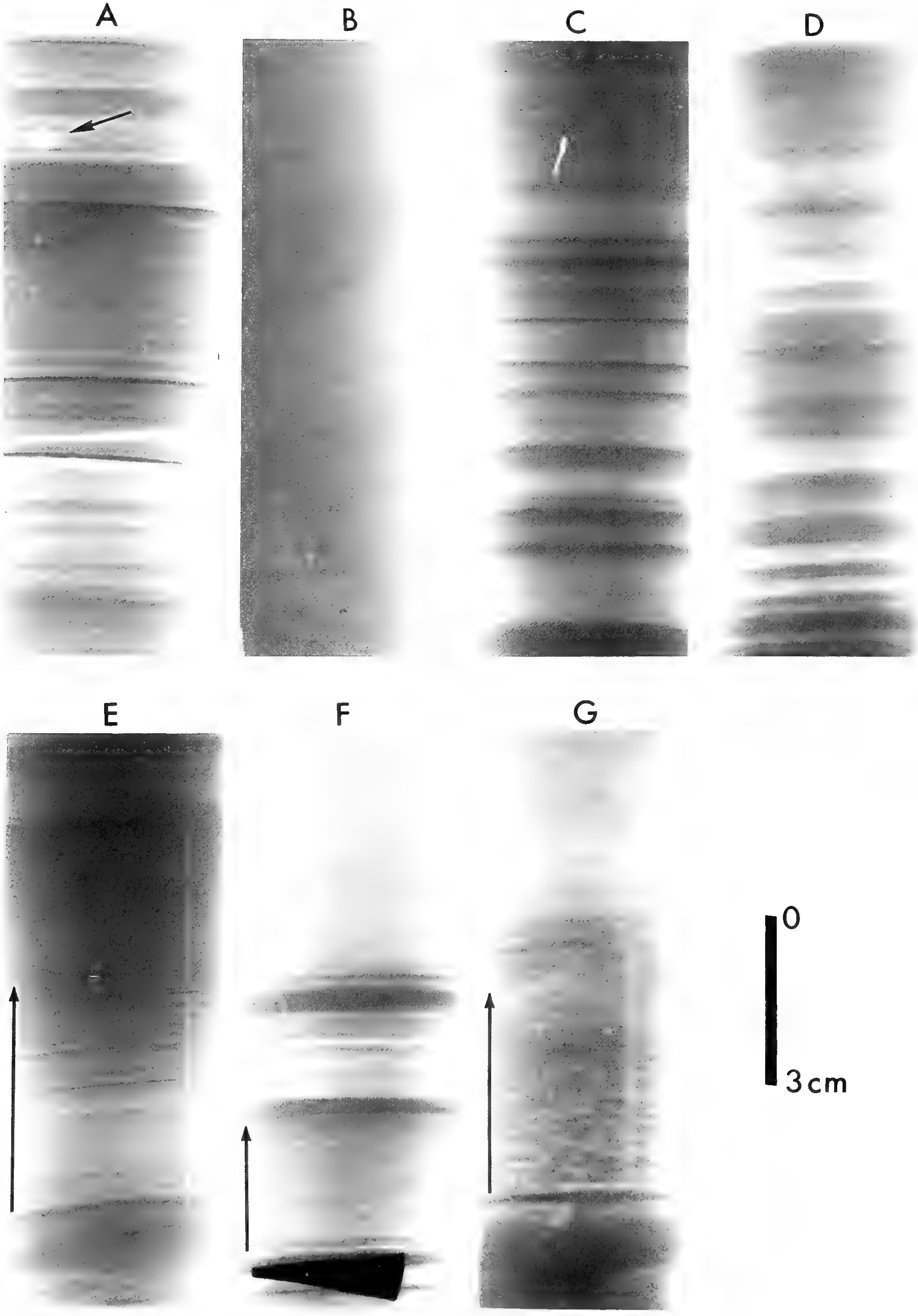


FIGURE 5.—Depositional model showing a basinward transformation continuum of gravity-driven processes, i.e., mechanisms of decreasing concentrations, from slumping to low density turbid layer flows. An important stratification interface in the water column serves as a barrier to particles released from low concentration turbidity currents and turbid layer flows and also from hemipelagic (H.P.) suspension settling. As a result of the interface, particles are distributed over large areas of a basin and eventually settle out as finely laminated layers, often graded. The nature of the stratification interface controls the degree of grain retention and ultimate release of terrigenous grains and pelagic components particles, which settle according to size and density. Periodic variations in organic productivity and fluctuations in particle density and settling rate give rise to varve-like alternations of coccolith- and terrigenous-rich layers, many of which display fining-upward trends (see Figure 6E–F).

Radiographs reveal no two identical sequences of parallel laminated structures. Variations occur with respect to proportions and thicknesses of coccoliths and silty clay-rich layers (compare, for example, Figure 6C and D). Varved and graded finely laminated sections also vary with respect to coarseness of material. Occasionally, large planktonic tests such as pteropod shells are observed, and these usually are flat-lying and buried by fine laminae (Figure 6A). Alternations of coccoliths and clastic silt and clay aggregates may in some instances enclose important proportions of larger particles, such as disseminated organic matter (Figure 7A, B) and concentrations of planktonic tests (usually foraminifera, Figure 7C).

Petrographic examination of the coarse fraction (>62 μm), separated from finely laminated mud from different parts of the Mediterranean, reveals that in almost all instances, the bulk (>70%) of the coarse fraction comprises planktonic tests. Foraminifera dominate, but pteropods may be locally important. Benthic shell material usually accounts for less than 10%, while terrigenous grains generally exceed 10%. Within-core and core-to-core variations in the above-cited proportions of these mineralogical components are observed.

On the basis of structure, texture, and composition the Mediterranean deep-water finely laminated facies generally can be distinguished from muds of purely pelagic (with little or no terrigenous components) suspension and even from those of essentially hemipelagic (mixed planktonic and terrigenous components) settling origin.


A
B
C
D
E
F
G
0
3cm

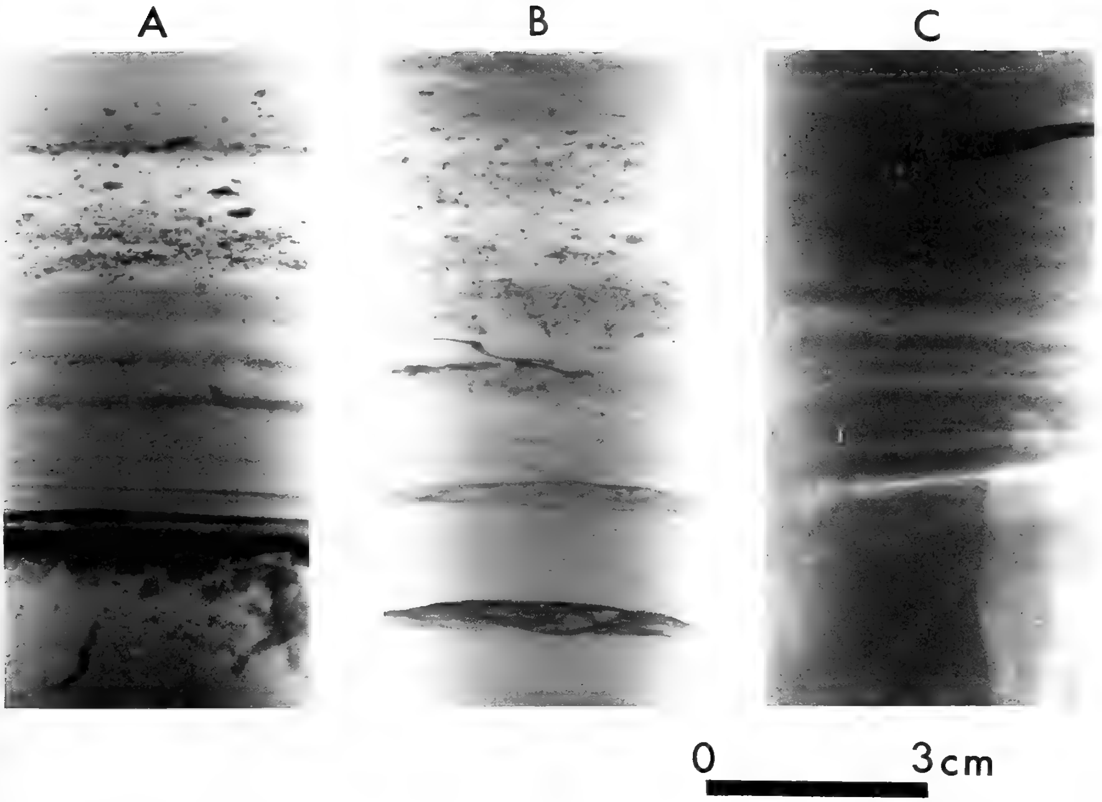


FIGURE 7.—Selected radiograph prints: A,B, disseminated organic matter (some pyritized); C, concentrations of planktonic foraminiferal tests in finely laminated core sections. (Cores are from the western Hellenic Trench: A, *Trident* core 172-34, Zakinthos Trench; B, *Marsili* core 8, Matapan Deep; C, *Marsili* core 14, Gulf of Laconia, south of Peloponnesus; locations shown in Stanley and Maldonado, 1981.)

The amount of sand fraction in laminated mud (about 2% by weight) is lower than that in typical Mediterranean hemipelagic muds (to >5% by weight); sand in the latter commonly produces speckling observed in radiographs (He in Figure 2D). Moreover, hemipelagite sections, such as those in the Hellenic Trench, generally contain higher (>80%) contents of foraminifera and pteropods in the sand fraction and contain coccoliths in the silt fraction.

FIGURE 6.—Selected radiograph prints showing variations of finely laminated muds: A,B, examples of distinct and vague fine parallel laminations; C,D, two different types of varve-like stratification, both showing importance of coccolith (light) layers; individual pairs, or couplet, of laminae show fining-upward trends, but overall the entire laminated sequence is not graded (unlike turbidite section in Figure 2C); E-G, thicker fining-upward (arrows) type of finely laminated sections, comprising largely coccoliths and pelagic components rather than terrigenous silty clay in typical laminated mud turbidites (Figure 2B-D). (Arrow in A points to pteropod buried by finely laminated coccolith ooze; A,D, *Trident* core 172-34 in Zakinthos Trench basin; C, E-G, *Trident* core 172-36 in Strofádhes Trench basin, in western Hellenic Arc (core locations shown in Got et al., 1977).)

Parallel laminated muds also can be distinguished from some laminated mud turbidites on the basis of associated structures and composition. Unlike laminated mud turbidites (Figure 2C; also examples in Stow and Bowen, 1980), fine parallel laminated deposits (Figure 2B-D) are not sharp-based nor are they texturally graded, i.e., showing a progressive decrease in mean grain size and lamina thickness from the base to the top of the laminated bed. Moreover, bedforms commonly attributed to traction, such as wave ripples and cross-laminations that commonly occur in mud turbidites (Figure 2B, D), are absent from finely laminated facies. Finely laminated muds do not show load structures and only rarely do they show bioturbation.

Both laminated mud turbidites and finely laminated muds may contain comparable proportions of sand (to about 2% by weight), but sand in turbidites usually contain a higher (to >30%) terrigenous grain content (from mineral count data base, R.J. Knight, in litt.). SEM analyses reveal reworked biogenic components, including pre-Pleistocene coccoliths, in both mud turbidites and finely laminated facies. However, there is a higher proportion of coccoliths in the silt fraction and foraminifera in the sand fraction of some finely laminated mud couplets than in turbidites.

It is noted that some fining-upward laminated core sections cannot strictly be attributed to fine parallel laminated mud, laminated mud turbidite, or hemipelagic mud facies. Apparently there exists a petrologic continuum among these types.

Implications and Conclusions

An association of different laminated end-member mud types most likely occurs in settings where two or more transport processes are involved. A continuum of fine-grained facies and a blurring of their origin should be expected where long distance transport increases the possibility of interplay among turbiditic, traction, and hemipelagic settling mechanisms. The Northwest Atlantic margin off the U.S. East Coast and Canadian Maritime Provinces, where most sedimentologic studies of fine-grained deposits have been made, serves as a good example. In this region the possible origins for lamination are reviewed by Stow and Bowen (1980). In the case of the mud turbidite end-member, these authors propose a model involving thick flows of low concentration in which laminae formation results from depositional sorting by increased shear near the base of the bottom boundary layer.

Theoretical considerations and textural-fabric analysis of laminated turbidite core sections call attention to systematic upward and lateral-downslope decreases in modal grain size and laminae thickness. In contrast, lamination in typical fine-grained contourites (the term is used here as applied by Heezen and Hollister, 1971:420) results from fluctuations in sediment flux and accumulation by both traction and suspension release mechanisms. Some criteria of mud contourites are sharp base and top of bedding contacts, both normal and reverse grading, common cross-lamination, and preferred grain orientation parallel to the bedding plane throughout a bed (Hollister and Heezen, 1972; Stow and Lovell, 1979). However, review of published radiographs and descriptions of laminated mud core sections in large basins, such as the Atlantic, show that petrologic distinction between fine-grained turbidites and contourites is by no means clear-cut. The petrology of certain laminated mud sections interpreted as turbidites suggests a more complex origin involving release from suspension and/or fluid-driven circulation; other sections interpreted as contourites appear difficult to distinguish from low concentration turbidity current or turbid layer deposits.

Physical and chemical attributes of the much smaller and shallower Mediterranean serve to amplify petrologic differences that are not so apparent among fine-grained, deep-water deposits in large ocean basins. Important Mediterranean characteristics include periodic development of well-stratified water masses, relatively small distance between point of sediment input and final depositional site, generally low bottom current velocities in deep basins, and preservation of carbonate components. During specific periods in the recent past, oceanographic conditions, and thus sedimentation in the Mediterranean were somewhat more comparable to other world oceans. Sediment transport involved (1) periodic injection of sediments and their displacement downslope by gravity flows of low concentration, (2) deviation of such flows diagonally or parallel to the margin by current-driven circulation, (3), incorporation, concentration, and displacement of particles from turbidity current-derived suspensates and hemipelagic settling on pycnoclines and in near-bottom nepheloid layers, and (4) eventual release of these particles through density interfaces and from nepheloid layers to the seafloor. A laminated sequence resulting from this plexus of mechanisms is neither a mud turbidite, hemipelagite, or contourite in the strict sense.

On the basis of the petrology of Mediterranean laminated muds, described in the previous section, it is possible to distinguish (1) laminated mud turbidite and (2) hemipelagic mud end-members from (3) a deposit originating by coupled sediment gravity flow–hemipelagic settling. The multiple-origin deposits, "(3)," are varve-like and record episodic fluxes preserved as thin, alternating sequences of clastic components that include reworked benthic and planktonic faunas mixed with clayey silt and layers comprising almost entirely tests of recent pelagic organisms. Two other diagnostic criteria of these finely laminated sequences are rates of deposition and areal distribution. Core sections show that fine parallel laminated facies, like those of hemipelagites, tend to accumulate over broad areas of a basin and its contiguous margins (cf. Stanley and Maldonado, 1981, fig. 7). These muds, recording periodic injection by sediment gravity flows, accumulate at higher rates (>15 cm/1000 years) than hemipelagic deposits. In contrast to turbidites and unifites that are somewhat richer in terrigenous components and accumulate at higher rates, regional core surveys show that finely laminated muds display a regionally more consistent thickness and broader distribution, and are less restricted to specific depositional environments.

The model emphasized here (Figure 5) indicates that stratification interfaces in the water column that affect particle retention are important for interpreting some types of fine-grained lamination. This scheme suggests that distinct pycnoclines modify particle concentration and particle release rates through the water column so as to segregate terrigenous silt and clay flocs from planktonic tests. A well-marked density interface amplifies differences in particle release and settling rates through the column by density and size, thus resulting in (1) more effective separation of coccolith from terrigenous silty clay layers and (2) better development of fining-upward trends of laminae sets (Figure 6E–G). The varve-like configurations in Figure 6A–D record repetition of depositional events and modifying effects of pycnoclines, i.e., injection of material by turbidity currents and turbid layers, retention of periodic planktonic blooms, largely coccoliths, and their subsequent settling to the seafloor. Compositional segregation of coccoliths from terrigenous clayey silts, as distinct laminae, appears less well developed in laminated mud turbidites than in the fine parallel mud facies. On the basis of an averaged depositional rate of 20 cm/1000 years, each laminae couplet is deposited during a 2 to 20 year period.

On the other hand, the downslope decrease of grain size and laminae thickness measured in mud turbidites (cf. Stow and Bowen, 1980) is less obvious in finely laminated facies. In this respect, the geometry of Mediterranean upper Pleistocene to lower Holocene finely laminated facies (Huang and Stanley, 1972; Maldonado and Stanley, 1976a; Stanley and Maldonado, 1981), recalls the configuration and distribution of fine parallel, silt-rich layers mapped over large sectors of the Delaware River Basin of Texas–New Mexico in middle Permian time. These latter laminated, not conspicuously graded, facies, deposited as a function of density-stratified water mass conditions, show no obvious proximal to distal changes (Harms, 1974). Hydrography and sediment gravity flows are major factors in both these modern and ancient deposits. Sediment gravity flows that displace at least 1 km^3 of sediment are not uncommon in Mediterranean basins (Blanpied and Stanley, 1981:29). Flows of this magnitude introduced into the isothermal regime, which has prevailed during the past 6000 years, are responsible for turbidites and unifites ranging in thickness from 30 cm to over 1000 cm in small basins, such as those of the Hellenic Trench. However, displacement of equivalent sediment volumes as low concentration flows, at times of a stratified water regime, would result in much broader distribution of material. Varve-like sets released from about 1 km^3 of sediment spread over large parts of basins, such as the Ionian or Algéro-Balearic, would likely be less than 1 cm thick (Stanley, 1981:83).

Laminae preservation also sheds light on depositional origin. Some cores from the Aegean, Siculo-Tunisian (Pelagian) Platform (Maldonado and Stanley, 1976a; Blanpied, 1978), Corsican Trough (Stanley et al., 1980), Alboran Sea (Huang and Stanley, 1972), and other areas show indistinct (Figure 6B) or disturbed laminae recording the influence of bottom currents, or organisms, or both. In contrast, 10 to 40 cm-thick sections of undisturbed laminated units in the Hellenic Trench region indicate that deposition was rapid, that the influence of bottom currents was negligible and, more importantly, unfavorable oxygen-deficient conditions on the seafloor reduced benthic populations, thus minimizing disturbance of surficial sediments. Moreover, it is recalled that the well-preserved finely laminated mud sections have a basin-wide and temporally extensive distribution. It thus appears that upper Pleistocene to Holocene lamination in the Mediterranean was not produced by an oxygen minimum layer restricted to a specific horizon in the water column as recorded in the present Gulf of California (Calvert, 1964). Preservation of laminae is most likely related to the formation of thicker, more extensive columns of oxygen-deficient water and to anoxic seafloor conditions of the Black Sea (Arkhangel'skiy, 1927) and deep fjord (Strom, 1939) types; the absence of benthic organisms is an important factor in the preservation of well-defined parallel laminae, as illustrated by Müller and Stoffers (1974, fig. 4).

The varved aspect calls to mind the relation between sedimentary structures and organisms in some stratified basins off Southern California. There, it has been shown that small-scale and short-term changes in oxygen content can induce rather significant alterations in organic productivity, including coccolith and foraminiferal blooms, and modifications of benthic populations. Physico-chemical changes needed to transform hospitable to inhospitable conditions at depth may be small; moreover, such changes may occur suddenly or gradually and, as in the case of lakes, seasonally (cf., Hülseman and Emery, 1961:289). Inhospitable conditions on the seafloor, such as at times of sapropel formation, result in diminution or absence of benthic populations and enhanced probability of lamina preservation (Moore and Scruton, 1957). Bottom camera and sediment sampling surveys in various Mediterranean basins demonstrate that, at present, conditions above the seafloor are highly suitable for sustaining important benthic populations. High concentrations of feeding and burrowing structures indicate that fine lamination developed in recent time, at least since about 6000 years B.P., would not likely be preserved.

In summary, the study emphasizes the significance of climatic-oceanographic factors, the involvement of two or more processes in the development of lamination of fine facies in deep-marine environments, and that laminated muds are not necessarily turbidites or contourites in the strict sense. Observations made here commonly prevail and are not unique to the Mediterranean. In consequence, mud deposits of the type described herein—redeposition of margin sediments by gravity flows coupled with hemipelagic settling through a stratified water column—could probably be recognized in diverse marine settings. The mechanism deserves to be quantified. Continuing investigation of mud lithofacies in small to moderate seas holds promise for better interpretation of fine-grained deposits in the larger world oceans and the sedimentary rock record.

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Text-reference system (author, year:page used within the text, with full citation in "Literature Cited" at the end of the text) must be used in place of bibliographic footnotes in all Contributions Series and is strongly recommended in the Studies Series: "(Jones, 1910:122)" or ". . . Jones (1910:122)." If bibliographic footnotes are required, use the short form (author, brief title, page) with the full citation in the bibliography.

Footnotes, when few in number, whether annotative or bibliographic, should be typed on separate sheets and inserted immediately after the text pages on which the references occur. Extensive notes must be gathered together and placed at the end of the text in a notes section.

Bibliography, depending upon use, is termed "Literature Cited," "References," or "Bibliography." Spell out titles of books, articles, journals, and monographic series. For book and article titles use sentence-style capitalization according to the rules of the language employed (exception: capitalize all major words in English). For journal and series titles, capitalize the initial word and all subsequent words except articles, conjunctions, and prepositions. Transliterate languages that use a non-Roman alphabet according to the Library of Congress system. Underline (for italics) titles of journals and series and titles of books that are not part of a series. Use the parentheses/colon system for volume(number):pagination: "10(2):5–9." For alignment and arrangement of elements, follow the format of recent publications in the series for which the manuscript is intended. Guidelines for preparing bibliography may be secured from Series Section, SI Press.

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Some points of style: Do not use periods after such abbreviations as "mm, ft, USNM, NNE." Spell out numbers "one" through "nine" in expository text, but use digits in all other cases if possible. Use of the metric system of measurement is preferable; where use of the English system is unavoidable, supply metric equivalents in parentheses. Use the decimal system for precise measurements and relationships, common fractions for approximations. Use day/month/year sequence for dates: "9 April 1976." For months in tabular listings or data sections, use three-letter abbreviations with no periods: "Jan, Mar, Jun," etc. Omit space between initials of a personal name: "J.B. Jones."

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