2. PALEOCEANOGRAPHY AND SAPROPEL INTRODUCTION[1]

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INTRODUCTION

Sediment cores from the Mediterranean Sea and land sections in southern Italy and Crete contain numerous dark-colored layers that are rich in organic carbon and are commonly laminated. These layers, termed sapropels, are intercalated with carbonate-rich and organic-carbon-poor hemipelagic sediments of Pliocene to Holocene age (Fig. 1). They appear to be a characteristic deposit of many silled marginal seas (e.g., Japan Sea and Red Sea). In all cases it seems that the deposition of organic-rich sediments in the geological past occurred in response to significant changes of climate, circulation, and biogeochemical cycling. The Mediterranean sapropels of late Pleistocene to Holocene age have been particularly well studied and a series of—in part, contradictory—hypotheses on their origin and significance has been published in the last three decades. A broad consensus is that the sapropels represent a paleoceanographic showcase, because they contain high-resolution records of key processes leading to enhanced burial and preservation of carbon at the seafloor.

Leg 160 made an effort to develop this showcase fully. Drilling on a transect of sites recovered several complete Pliocene to Holocene sediment sequences that represent a range of depositional environments, water depths, and oceanographic and biological characteristics in the modern Mediterranean (Fig. 2). As an introduction to the results of Leg 160 (see the site chapters, this volume), some of the facts and hypotheses concerning sapropel formation are briefly laid out in the following paragraphs and a summary of drilling results is given.

CIRCULATION AND WATER-MASS DISTRIBUTION IN THE MODERN MEDITERRANEAN SEA

The Mediterranean's physical circulation is driven mainly by the surface wind field, which creates a pronounced eddy circulation in the surface layer, together with the thermohaline gradients that drive intermediate- and deep-water circulation (Fig. 3). In the present situation, evaporation in the eastern basin exceeds precipitation and river runoff, and the negative water balance is compensated by the inflow of Atlantic waters through the Strait of Gibraltar. Inflowing Atlantic waters are warmer (15°C), poorer in nutrients (0.24 µmol/kg PO_4), and less saline (36.2 g/kg) compared to the outflowing deeper water masses (13°C, 0.40 µmol/kg, and 38.45 g/kg, respectively; Béthoux, 1989; Sarmiento et al., 1988). Inflowing Atlantic waters affect the circulation of the entire Mediterranean basin in that they generate cyclonic gyres in the Balearic and Tyrrhenian Seas. Atlantic water is transported into the eastern Mediterranean basin by way of the North African Current, which flows along the African coast and passes through the Strait of Sicily. Once Atlantic water has reached the far eastern parts of the eastern basin, evaporation is high enough to increase surface salinities to an extent that convection of the surface water occurs to greater depth. In this way, Levantine Intermediate Water (LIW) is formed and flows westward into the western Mediterranean and farther through the Strait of Gibraltar into the Gulf of Cadiz and the North Atlantic (Wüst, 1961; see Fig. 3A).

Eastern Mediterranean Deep Water (EMDW) originates in the northern Adriatic Sea during the winter months. It is the bottom-water mass that fills the deep basins and ventilates them. Cold, oxygen-rich, and relatively fresh surface waters sink when cooled by the Bora winds, mix with deeper waters, and cascade into the Ionian Basin before spilling into the Levantine Basin at depth. The areal extent of the EMDW is limited to the eastern basin because the shallow topography of the Strait of Sicily prevents any exchange of abyssal water masses between the eastern and western basins (Fig. 3B).

The circulation pattern of the Mediterranean Sea is antiestuarine and defines the distribution of biological productivity in the Mediterranean, which tends to be higher in the western basin than in the eastern basin. In terms of nutrient concentrations and nutrient levels, the Eastern Mediterranean is a nutrient desert in a nutrient desert, because nutrients are exported to the western basin by outflowing LIW; the western basin is in turn depleted by water flowing out to the Atlantic. Surface waters entering the eastern basin across the Strait of Sicily have phosphate concentrations as low as 0.126 µmol/kg, whereas the Mediterranean Intermediate Water flowing westward has concentrations of 0.21 µmol/kg. The close connection between the Mediterranean's general circulation and the asymmetric distribution of trophic levels between its western and eastern basins points to the importance of understanding the past variability of the Mediterranean's physical oceanography as a whole so as to unravel the origin of sapropel formation in the east.

MODELS OF SAPROPEL FORMATION

According to one hypothesis (the preservation model) sapropels signal anoxic conditions in the bottom water of the Mediterranean Sea. This model, first proposed by Bradley (1938) and adopted by many scientists since, is based on the assumption that organic carbon preservation is enhanced when molecular oxygen concentrations are low or absent in bottom waters. Aside from sedimentological and geochemical data, the strongest support for this model comes from negative oxygen isotope anomalies in planktonic foraminiferal tests that are associated with the sapropels (e.g., Williams et al., 1978; Vergnaud-Grazzini et al., 1986). The negative isotope anomalies have been interpreted as signals of freshening surface water in the Eastern Mediterranean at times of sapropel deposition. As a result, stable density stratification is thought to have prevented deep-water formation and caused anoxia in the deep-water masses. High abundances of planktonic foraminiferal species calcifying preferentially under low-salinity conditions provide supporting evidence for marine-brackish surface waters during deposition of most of the upper Pleistocene sapropels (Thunell et al., 1984).

The model poses two key questions: Where did the fresh water originate and is the increased organic carbon burial an effect of simultaneously increased productivity? Deglacial meltwater provides an answer, because early studies reported a close link between the timing of sapropel deposition and the history of Northern Hemisphere glacial/interglacial cycles (Olausson, 1961). Rossignol-Strick

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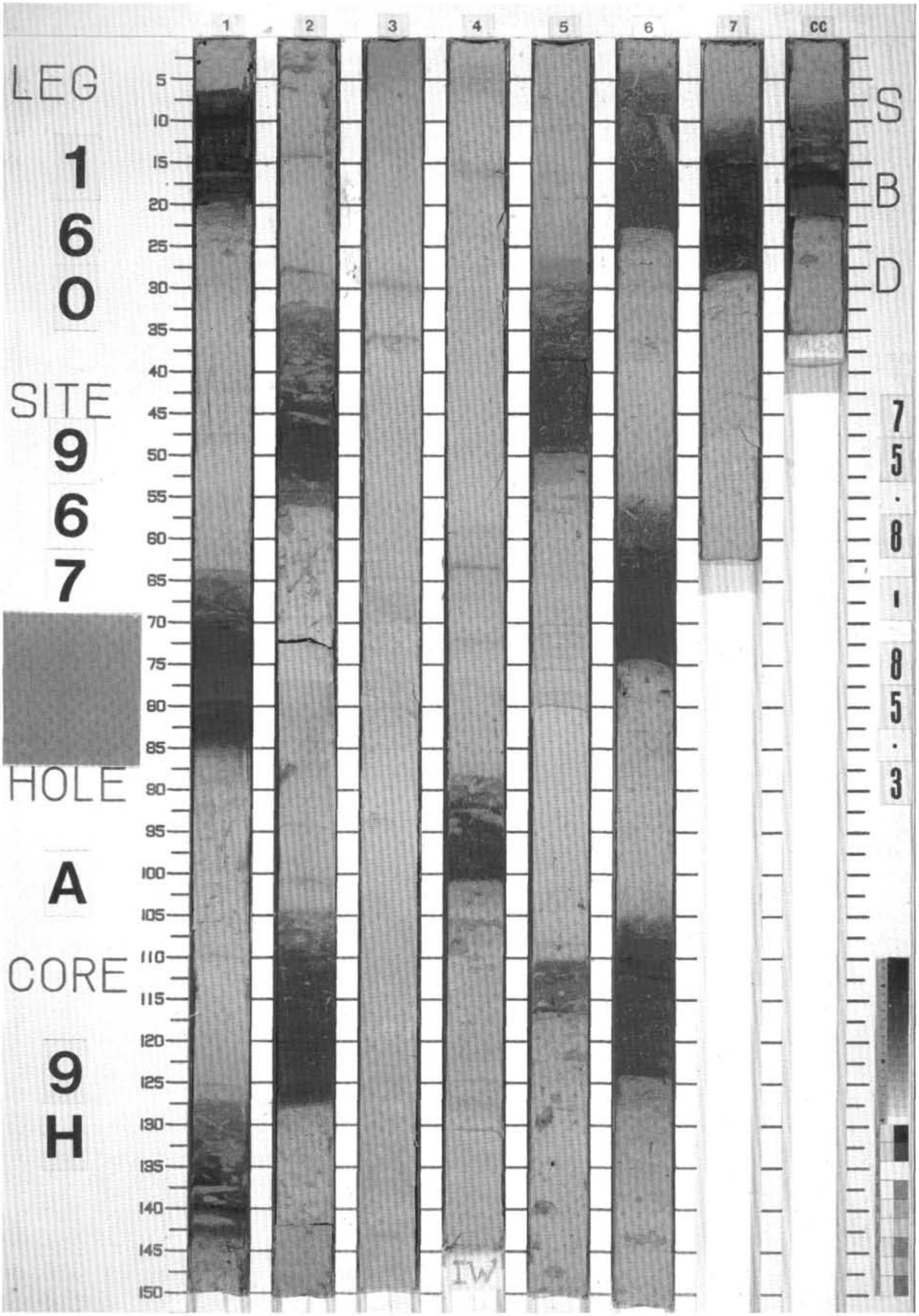

Figure 1. Example of sapropels interlayered in organic-carbon-poor sediments at ODP Site 967 (Core 160-967A-9H, 75.8 to 85.3 m below seafloor).

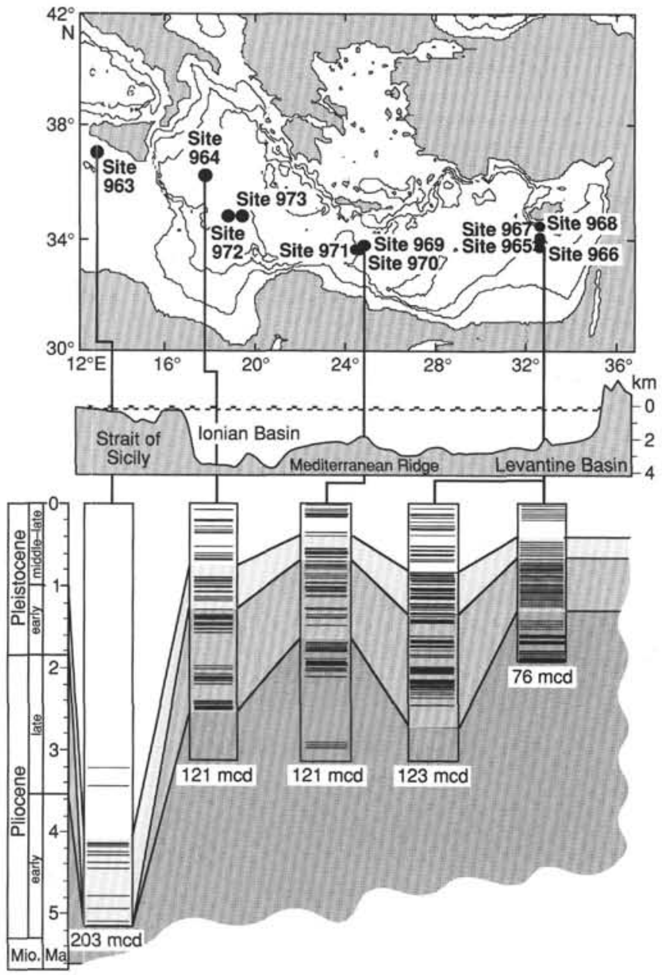

Figure 2. Overview map of the eastern Mediterranean Sea showing the site locations occupied during Leg 160 and a diagrammatic presentation of sapropel occurrences through time at paleoceanographic sites (mcd = meters composite depth from the holes at a site).

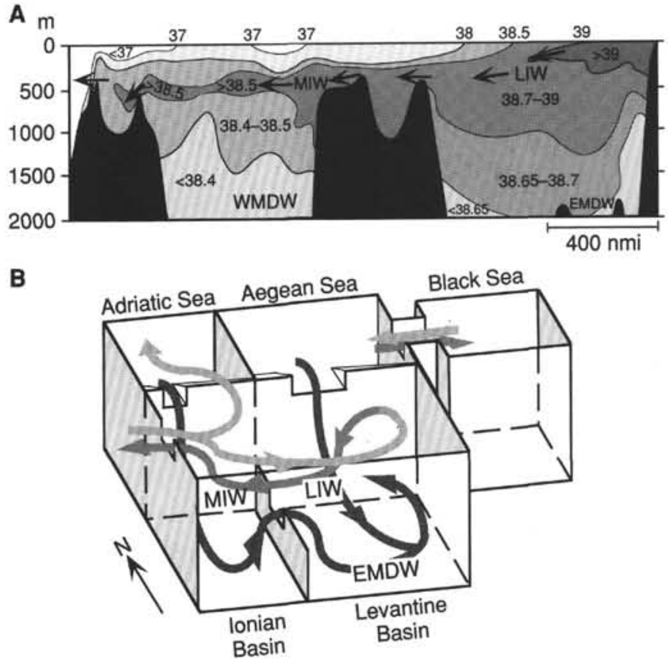

Figure 3. Schematic drawings of water masses in the Mediterranean Sea. **A.** Depth distribution of salinity during summer months. WMDW = Western Mediterranean Deep Water; EMDW = Eastern Mediterranean Deep Water; MIW = Mediterranean Intermediate Water; LIW = Levantine Intermediate Water. Values and isolines are the salinities (g/kg). Simplified after Wüst (1961). **B.** Schematic drawing of water circulation in the Eastern Mediterranean (after Malanotte-Rizzoli and Hecht, 1988).

(1983) demonstrated that the temporal distribution of the Eastern Mediterranean sapropels correlates with the maximum potential strength of African monsoons (a function of the orbital precession), which would have resulted in maximum discharge from the Nile River (see below). Cramp et al. (1988) and Rohling and Hilgen (1991) postulated that increased precipitation in the northern borderlands of the Eastern Mediterranean caused decreased surface salinity. In all of these scenarios, a sharp change in the ratio of evaporation to precipitation plus runoff occurred, which currently is significantly higher than unity; it has resulted in a periodic reversal of water exchange between the eastern and western Mediterranean basins, during which the Eastern Mediterranean became a nutrient trap. Increased nutrient loads cause increases in productivity and oxygen demand in the deep water column, which may have resulted in episodic anoxia (Fig. 4).

Sarmiento et al. (1988) analyzed different scenarios of water exchange to explain sapropel formation and postulated that anoxia in the eastern basin could occur only through a significant increase in the nutrients being transferred to the deep water of the Eastern Mediterranean. According to their model, a sevenfold increase in deep-water phosphate (from 0.2 to 1.4 µmol/kg) and an equivalent amount of reduced carbon sinking out of the surface mixed layer are needed to deplete the deep-water oxygen pool at today's temperatures. The only viable way to achieve this under conditions of constantly low external nutrient input is to change the water circulation across the Sicily sill from an antiestuarine circulation (such as present today) to an estuarine circulation mode. Other possible mechanisms are significant changes in the ratio of evaporation to precipitation and river runoff; in the models discussed by Sarmiento et al. (1988), however, all alternatives require unrealistically high and improbable changes in water (and nutrient) exchange across the Strait of Sicily. Furthermore, there is no evidence for a reversal of current direction in either the Strait of Sicily or the Strait of Gibraltar during deposition of the most recently deposited sapropel S1, some 8000 yr ago (Zahn et al., 1987).

There are other hypotheses: enhanced productivity, which is among the primary factors controlling the concentration and accumulation of organic carbon in seafloor sediments, has been suggested as the reason for sapropel formation. One can combine the empirically derived relationship between carbon production in the surface waters and carbon burial rates at the seafloor (Müller and Suess, 1979) with dry-bulk densities (1.4 g/cm^3) and sedimentation rates (1 to 10 cm/k.y.) for the sapropels and calculate productivity rates in the surface waters. To produce the carbon concentrations (5%–10%) typical of sapropels, primary productivities in excess of 500 $gCm^{-2}yr^{-1}$ are required. In contrast, estimates of the present-day annual primary production range from 25–50 gCm^{-2} for the open Mediterranean to 60–75 gCm^{-2} in some coastal zones (Béthoux, 1989). The discrepancy shows that a significant increase in the productivity (to levels usually found only in coastal upwelling areas) is required to produce sapropels without the aid of preservation at low-oxygen conditions at the seafloor. Isotopic and geochemical tracers point to a predominantly marine origin of the sapropel organic carbon (Sutherland et al., 1984; Smith et al., 1986; ten Haven et al., 1987). They are inconclusive as to the preservation state of the organic material, and there is good evidence that at least part of it is derived from land or recycled from marine sources.

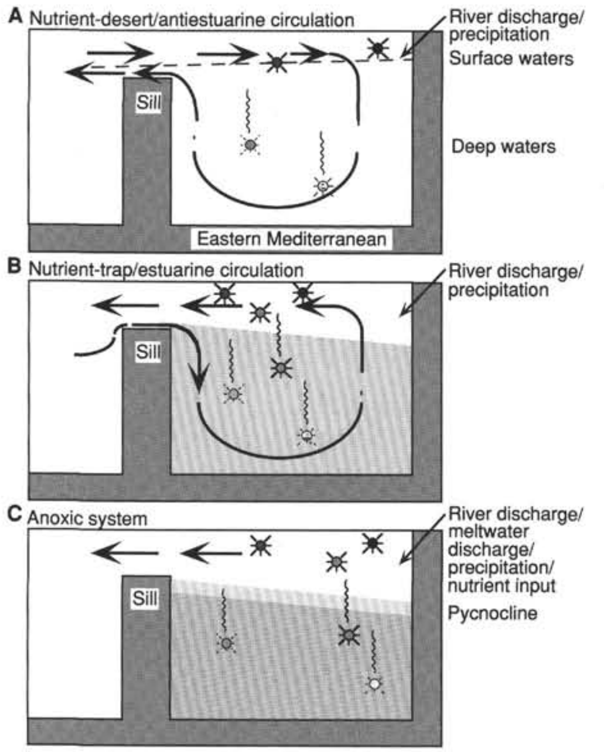

Figure 4. Schematic representation of circulation in a nutrient-desert (**A**), nutrient-trap (**B**), and anoxic (**C**) Eastern Mediterranean Sea. (A) corresponds to the circulation today, which is antiestuarine and exports nutrients via deep-water outflow. (B) is an estuarine circulation pattern caused by a dominance of precipitation (or river/meltwater inflow) over evaporation. This tends to raise nutrient concentrations in the basin and promote productivity, which is a possible scenario for circulation in the Mediterranean during times of sapropel deposition. (C) is an extreme scenario of (B), when stratification isolates deep waters and causes anoxia in the deep water. Many researchers have proposed this circulation mode during times of sapropel deposition in the Eastern Mediterranean. Fresh water is assumed to have originated from either the Nile River, the Black Sea, or increased precipitation in southern Europe.

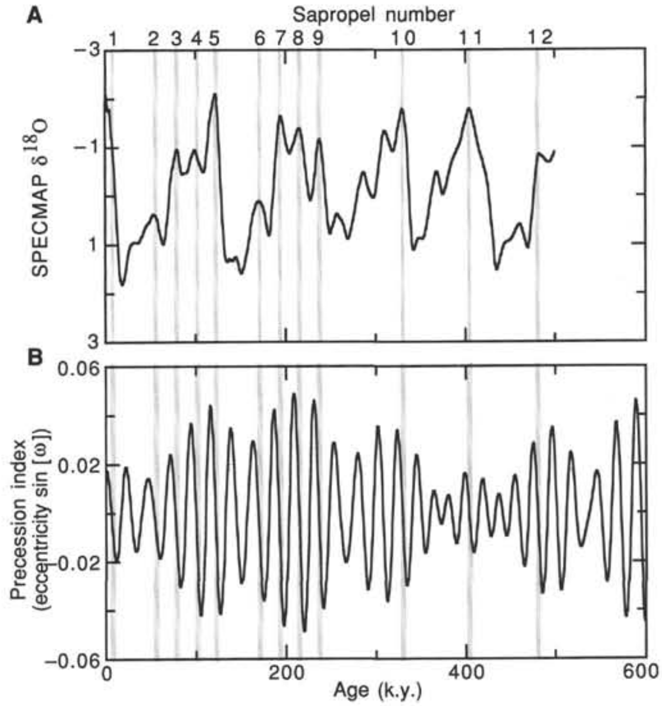

Figure 5. **A.** Stratigraphic position of Eastern Mediterranean sapropels S1–S12 in the SPECMAP global mean oxygen isotope record (Imbrie et al., 1984). **B.** Distribution of sapropels through time compared to the orbital precession index (Berger and Loutre, 1991).

TIMING OF SAPROPEL DEPOSITION AND THE CLIMATE CONNECTION

Data from relatively short piston cores and limited drilling have indicated that sapropel formation occurred within the entire Eastern Mediterranean throughout Pliocene-Holocene times. Correlation with standard oxygen isotope stratigraphy has provided an excellent framework in which to evaluate the occurrence of the late Pleistocene sapropels with respect to the state of global climate (Fig. 5A) (e.g., Vergnaud-Grazzini et al., 1977; Cita et al., 1977).

A systematic correlation has been observed between the distribution of sapropels and maxima of the so-called orbital insolation monsoon index, which is a function of precessional insolation anomalies (Rossignol-Strick, 1983; Hilgen, 1991a, 1991b) (Fig. 5B). Maxima in the monsoon index point to an intensified Indian Ocean summer monsoon, which in the interpretation of Rossignol-Strick (1983) leads to enhanced continental humidity in tropical Africa and, ultimately, enhanced discharge rates of the Nile. New compilations of paleoclimatologic data also point to the importance of humid phases in the northern borderlands of the Eastern Mediterranean for stimulating the formation of sapropels (Rohling and Hilgen, 1991; Rohling, 1994). Apparently, increased summer precipitation along the borderlands was due to increased activity of Mediterranean depressions, which tend to lower evaporation rates over the Eastern Mediterranean, thus redistributing fresh water between the eastern and western Mediterranean basins. Increased rates of continental runoff are strong candidates for the likely external forcing that changed the circulation of the Mediterranean from today's antiestuarine system toward an estuarine pattern, thereby preconditioning the Eastern Mediterranean toward sapropel formation.

Conceivably, formation of the Mediterranean sapropels may be the result of a combination of factors: whereas the mechanism of sedimentation and carbon burial can be linked to changes within the depositional environment, these very changes are most likely forced by processes outside the basin. External forcing is evident from the synchroneity of sapropel deposition in the entire Eastern Mediterranean. Moreover, the rhythmic recurrence of environmental conditions that produce sapropels on schedules of precession points to a climatically driven chain of events culminating in sapropel deposition. A tentative chain of events postulates that carbon burial may have been promoted by enhanced rates of marine productivity, a corresponding increase in oxygen utilization in deep water, and a weakening of deep-water oxygen recharge, which all occurred at the same time and were driven by the same external motor. All environmental factors within the basin can be expected to leave distinct sedimentological, paleontological, and geochemical signals that can be analyzed in great detail by shore-based research.

OBJECTIVES OF LEG 160

The existence of early Pleistocene, Pliocene, and Miocene age sapropels is known from well-studied land sections in southern Italy and on Crete (for a recent review see Hilgen, 1991a) and from Mediterranean Deep Sea Drilling Project (DSDP) and ODP sites (Ryan, Hsü, et al., 1973; Hsü, Montadert, et al., 1978; Kastens, Mascle, Auroux, et al., 1987). However, a detailed evaluation and comparison of these sapropels from deep-sea sequences with those of land sections has not been possible because of the lack of stratigraphic continuity. The preservation of sapropel deposits in land exposures is not good and many labile geochemical and lithological tracers have been overprinted. On the other hand, an enormous amount of stratigraphic information is available on the lower Pleistocene to Pliocene land sections, making it a stratigraphic record of unprecedented resolution (Hilgen, 1991a, 1991b). Should we be able to correlate complete marine records of sedimentation to land sections, much additional information could emerge that will help in the reconstruction of changes of Mediterranean climate, water-mass properties, and atmospheric circulation.

In order to determine the external and internal forcing mechanisms of sapropel formation, the Leg 160 sapropel sites were selected to core the eastern limb of an east-west transect across the entire Mediterranean (Fig. 2). The east-west transect permits the reconstruction of gradients and patterns in depositional, paleoceanographic, and climatic conditions for the entire basin in high resolution. The gradients and patterns will allow us to determine the driving forces behind sapropel formation at different times, and how the physical circulation and chemical cycling has preconditioned the eastern basin toward sapropel formation.

To achieve these scientific goals, the drill sites were selected to fulfill three essential requirements.

1. *Stratigraphic continuity.* Sedimentary sections at paleoceanography sites have to be complete, undisturbed, hemipelagic and pelagic, and shielded from the sporadic significant effects of submarine morphology and tectonics of the Mediterranean.
2. *Optimum areal and water-mass coverage.* The drill sites were targeted to cover the entire Mediterranean basin in order to permit the evaluation of paleoceanographic, paleochemical, and paleontological zonality throughout the basin. Key locations are close to the Nile Cone (Eratosthenes Seamount Sites 966 and 967) as a potential freshwater source and the Strait of Sicily (Site 963) as the seaway determining water-mass exchange between the eastern and western basins. Furthermore, we occupied watchdog sites for monitoring changes in water-mass character in mid-water (on the Mediterranean Ridge, Site 969) and in deep-water formation of the Eastern Mediterranean (in the Ionian Basin, Sites 964 and 972). Because the sites bracket a water depth interval of 600 to 4100 m, we expected to be able to reconstruct water-depth dependent processes by comparing coeval sapropels from different water depths.
3. *Potential for high-resolution stratigraphies.* In order to ensure that the information on the depositional environment during sapropel formation is of the highest quality, sampling density in the sapropel layers, as well as in the "normal" sediments directly below and above the sapropels, must be on scales of centimeters to millimeters. Such a high sampling resolution is essential for determining the factors that have led to the formation of the sapropels and that have helped maintain an environment favorable to the formation of sapropels over time scales of 10^2 to 10^3 yr (or even less). Multiple holes were cored with the advanced piston corer at all paleoceanographic sites to provide material to allow such intense sampling at the proposed Eastern Mediterranean sites where the sapropels occur. A second reason for the multiple recovery was to ensure that complete records were cored. The composite records constructed from the continuously logged cores represent the best possible starting point for establishing high-resolution stratigraphies during onshore studies. These high-resolution stratigraphies will include micropaleontological, paleomagnetic, tephrochronological, and isotopic studies. Once the stratigraphic spine for each site is assembled, intersite correlations and basin-wide reconstructions are possible.

RESULTS OF DRILLING ON LEG 160

In the sediments recovered from the Pliocene to Holocene hemipelagic sequence, more than 80 discrete sapropels were recovered (Fig. 6). The sapropels occur in distinctive packets in well-defined time brackets and are separated by intervals of yellowish brown, oxidized sediment. Many individual sapropels are extraordinarily rich in organic carbon (up to 30% by weight and predominantly marine in origin), laminated, and display highly unusual magnetic properties. Other sapropels were bioturbated or oxidized to a considerable extent and discernable only as burnt-out (or completely oxidized) "ghosts" in carbonate oozes. The packets, which contain up to 16 individual sapropels, are characterized by discrete faunal and floral assemblages and by distinct sedimentological, geochemical, and physical properties. Individual beds were correlated between holes separated by several hundred meters and the packets were matched between sites that are several hundred kilometers apart.

Preliminary shipboard investigations suggest that the pattern of sapropel occurrences marks periods when the Mediterranean catchment area experienced increased humidity and high average temperatures. These conditions resulted in cyclical and significant changes of conditions both in the biologically active surface layer and at the seafloor. A general dependence on global climate is evident in the pattern of sapropel frequency during the Pliocene: before the onset of glaciations in the Northern Hemisphere (at approximately 2.6 Ma), sapropels occurred frequently, simultaneously, and irrespective of paleo-water depth at all sites. After the onset of glaciations, their occurrence was less frequent, the concentrations of organic carbon varied with water depth, and periods of sapropel deposition were separated by well-oxygenated red sediment intervals. The occurrence of sapropel packets during this later interval coincided with times when the global climatic background was warm and ice volume was at a minimum. An initial interpretation from shipboard study is that anoxic conditions in the deep water could be a primary contributor to sapropel formation. The link to the climatic background implies a dependence on deep-water formation rates, which may be amplified by simultaneous changes in physical water-mass structure and characteristics and in processes in the biologically active surface layer.

Aside from their paleoceanographic significance, the sapropels recovered during Leg 160 represent a rare and excellent opportunity to study the mechanisms and conditions of organic-carbon-rich sediment formation in the marine environment. Together with detailed stratigraphic work, questions concerning the nature of the environment during sapropel events will be the focus of land-based research.

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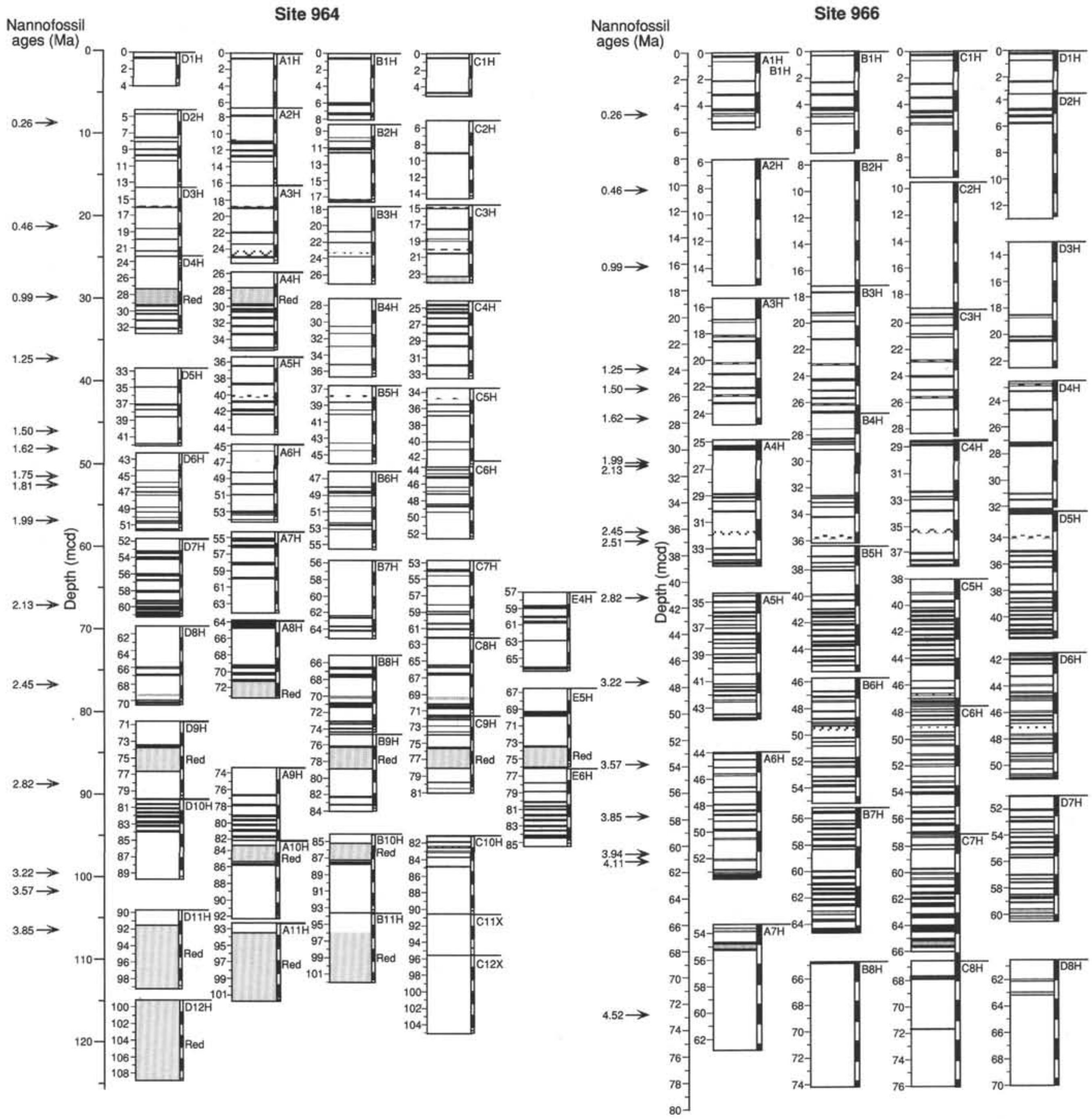

Figure 6. Generalized stratigraphic columns of individual drill holes cored at Sites 964, 966, 967, and 969 plotted against meters composite depth. The occurrence of sapropels and red intervals is marked in the logs and preliminary age determinations are indicated on the left side of the mcd scale. Note that both the mcd and age assignments are preliminary and are likely to change based on shore-based studies. Details of the lithologic successions are given in the individual "Lithostratigraphy" sections of the site chapters (this volume). Sediments recovered from Hole 969D are distinguished by a dashed line because they did undergo shipboard paleomagnetic or stratigraphic dating.

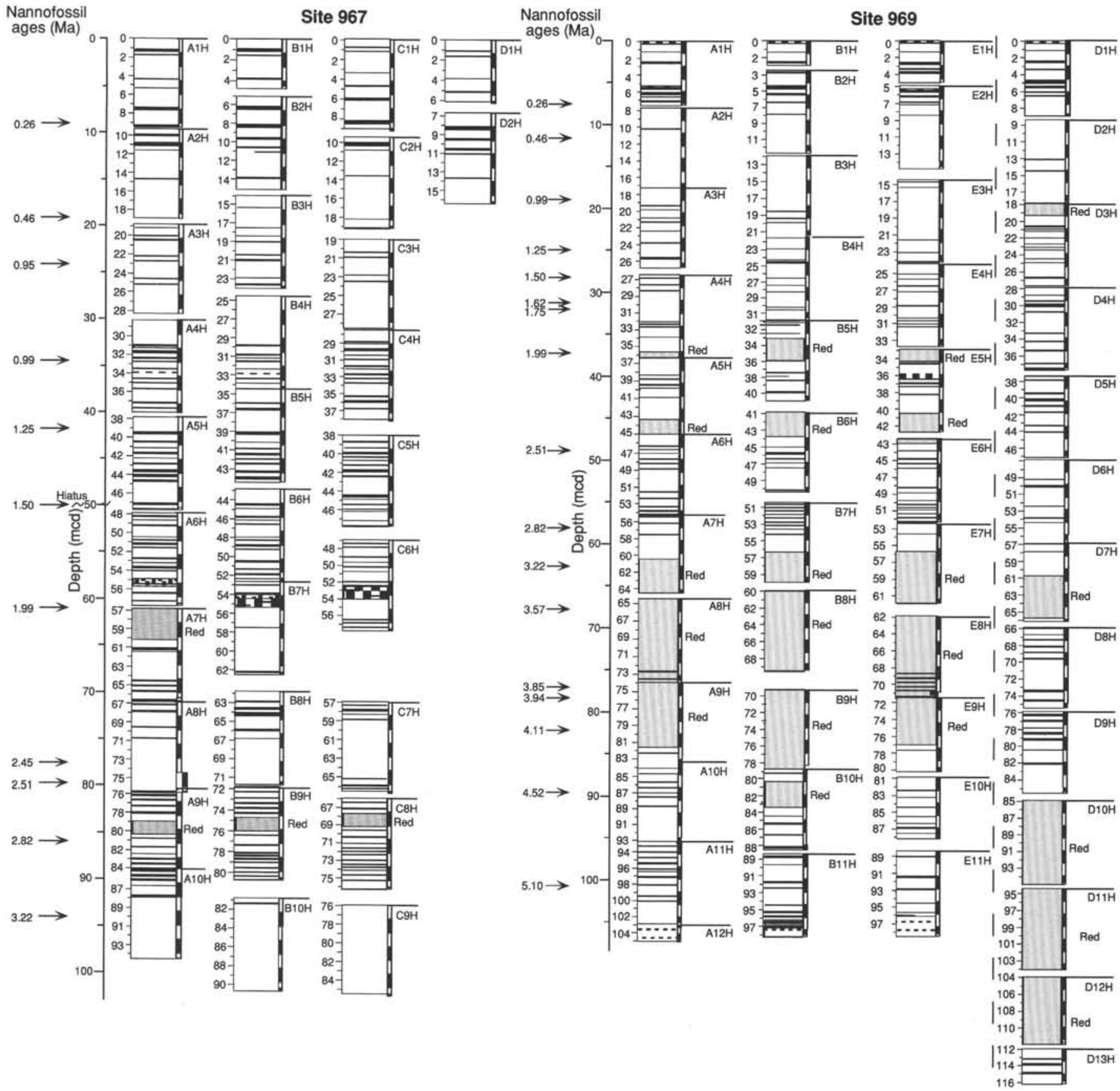

Figure 6 (continued).