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Editorial

Five decades of Mediterranean palaeoclimate and sapropel studies

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Much research has been devoted to the study of organic carbon enriched layers (sapropels, Kidd et al., 1978) that have been deposited periodically in the eastern Mediterranean basin since Miocene times (for reviews, see Cita and Grignani, 1982; Vergnaud-Grazzini, 1985; Rohling, 1994; Cramp and O'Sullivan, this volume). Sapropels were first discovered in cores from the eastern Mediterranean during the Swedish Deep-Sea Expedition of 1947/48 (Kullenberg, 1952).

Great emphasis has been placed on the unravelling of climate-related changes in oceanic circulation and productivity associated with the formation of sapropels. The majority of this process-oriented work was based on high-resolution studies of late Quaternary sapropels recovered from the seafloor using piston and gravity cores. Several DSDP/ODP expeditions in the Mediterranean added crucial insight into lateral continuity and temporal absence/presence patterns of sapropels, and placement of sapropels within a broader tectonic, oceanographic and climatological context.

Sapropelic sediments are also known from a range of high-quality outcropping sections of Mio–Pliocene sediments, found especially in southern Italy, Sicily and Crete. These sections provided essential information on the temporal distribution of sapropels even before long cores were obtained by DSDP/ODP. In spite of extensive study of outcropping sapropels regarding their formation mechanisms and relation to general development of the Mediterranean basin and its climate, uncertainty remained as to the regional or basin-wide nature of their distribution. It could only be inferred from the piston core results with Quaternary sapropels that the older equivalents should be found basin-wide. The DSDP/ODP cores successfully corroborated this expectation.

The combined sapropel succession from outcrops and sediment cores has been related to astronomical forcing of climate and the development of glacial cycles. Sapropels were found to be associated with high-amplitude precession minima, characterised by intensified monsoonal circulation, with the mid-point of sapropels lagging about 3 ka behind the precession minimum (e.g., Rossignol-Strick, 1985; Hilgen, 1991a,b; Hilgen et al., 1993; Vergnaud-Grazzini et al., 1993). Using this relationship, the sapropel succession has been successfully employed in exercises to astronomically calibrate the geomagnetic polarity time-scale (e.g., Hilgen, 1991a,b; Lourens et al., 1996).

Nijenhuis et al. (1996) compared geochemical and micropalaeontological characteristics of Quaternary and Pliocene sapropels with those obtained from their detailed investigation of Late Miocene sapropelic sediments. On that basis, these authors inferred that a similar basic mechanism of sapropel formation prevailed, characterised by a combination of increased export productivity and decreased deep water formation, as was proposed for Quaternary

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sapropels (Rohling and Gieskes, 1989; Howell and Thunell, 1992; Castradori, 1993; Rohling, 1994).

The conclusion reached by Nijenhuis et al. (1996) that a similar mechanism was responsible for sapropel formation during the Late Miocene and during the Pliocene–Quaternary, would imply that no net changes have occurred in Mediterranean physiography and general climatic regime over the last 7 m.y., although temporary interludes of different climate modes might have occurred. The implication would be that the great Messinian salinity crisis should be viewed as one such 'interlude', leaving no long-lasting imprint on these general conditions that was sufficient to change the basin's basic sensitivity to the climatic disturbances that drive sapropel formation.

It is hard to think of the great Messinian salinity crisis like this, as a transient 'anomaly'. It is even harder to accept that the development of Northern Hemisphere glaciation with its associated major re-arrangement of climatic zones, which started around 3.2–3.1 Ma (Shackleton and Opdyke, 1977; Thunell and Williams, 1983; Prell, 1984), would not have dramatically altered the magnitude and rate of Mediterranean response to climate fluctuations. In fact, the Mediterranean environment is well known to have been substantially affected by the Northern Hemisphere glaciation (e.g., Vergnaud-Grazzini, 1985; Thunell et al., 1987, 1991). Ruddiman et al. (1987) showed the first clear evidence for ice-rafting in the North Atlantic around 2.55 Ma, and Zachariasse and Spaak (1983) demonstrated that present-day type biogeographic patterns originated around that time in both the Atlantic, and the Mediterranean. The early development of Northern Hemisphere glaciation was associated with climatic change over the Mediterranean basin, characterised by increasing seasonal contrasts with very dry summers (Suc, 1984; Thunell, 1986). Suc (1984) argued that the 'modern' conditions with cool wet winters and dry summers first developed around 3.2 Ma, and that summer drought became more persistent after 2.8 Ma. Global atmospheric circulation modelling by Ruddiman and Kutzbach (1989) suggested that these developments reflect climatic change resulting from uplift of the Tibetan plateau, while the periodical appearance of steppe vegetation in the Mediterranean realm since 2.3 Ma (Suc, 1984) would be related to large-scale expansions of Northern Hemisphere ice-sheets. The mean 41 ka period of early glacial cycles changed to a predominant 100 ka period after the mid-Pleistocene isotopic stage 22/23 boundary (Shackleton and Opdyke, 1973, 1976; Pisias and Moore, 1981; Ruddiman et al., 1986, 1989), and this change also is well represented in Mediterranean isotopic, faunal, and floral records (e.g., Zachariasse et al., 1989, 1990; Thunell et al., 1991; Lourens et al., 1992; Vergnaud-Grazzini et al., 1993).

In view of these great climatic changes that have taken place during the Plio–Pleistocene, it would be surprising to see continuity of 'forcing conditions' that favour sapropel formation from the Late Miocene to the present. Indeed, the early work of Thunell et al. (1984) indicated that the mechanism of sapropel formation differed significantly between the Early to mid-Pliocene and the Late Pliocene to Pleistocene time periods. Thus, the inference made by Nijenhuis et al. (1996) merits substantial attention in the future, since, if true, it would indicate that the Mediterranean sensitivity to climatic perturbations is not related to the overall climatic state of the basin. Knowledge on whether this is true or not would greatly advance our understanding of the basin's potential response to future climate change.

Work on Neogene Mediterranean climate development and the characterisation of processes of sapropel formation, although within its fifth decade of study, still has significant unanswered questions. Further investigations are needed to: (1) develop a better understanding of the depositional conditions of both the most recent (Holocene) and older late Quaternary sapropels from as close a geographic grid within the basin as possible; (2) increase the number of records through Pliocene sapropels, both from exposed sections and ODP cores, in as much detail as is currently common for Holocene studies (century-scale resolution or better); (3) corroborate the results for Late Miocene sapropels by studying these from as many different localities as available, again at comparable resolutions. All studies should include substantial intervals before and after the sapropel, to (4) properly characterise changes associated with the onset and ending of sapropel formation. Meanwhile, targeted 'vertical' studies are needed on sub-Milankovitch (millennium-scale) resolutions, to (5) establish proper stratigraphic control, refine the theory of astronomical 'timing', and portray in detail the general climatic and physiographic developments that affected the basin.

This issue is dedicated to two late researchers who through their efforts have helped to greatly advance our knowledge of the geological, palaeoceanographic, and palaeoclimatological developments of the Mediterranean Sea: Dr. Colette Vergnaud-Grazzini and Dr. Robert Kidd. It comprises twenty contributions, addressing various aspects of the Neogene Mediterranean history.

Cramp and O'Sullivan review past and recent advances in the understanding of mechanisms of sapropel formation. Bethoux and Pierre review mechanisms for sapropel formation on the basis of analytical arguments of circulation response to 'preconditioning', strait control, and buoyancy loss. Pierre presents a detailed discussion of the present-day stable oxygen and carbon isotope distributions in the Mediterranean Sea. Rohling and De Rijk provide a compilation and statistical assessment of existing/available stable oxygen isotope data to characterise basin-wide surface water gradients, and so the freshwater cycle, during the last glacial maximum and early Holocene, relative to the present.

Thomson et al. review the recent wealth of new high-resolution geochemical information regarding the (detailed) formation and early diagenetic history of the youngest, early Holocene, sapropel. Jorissen reviews the changes in benthic foraminiferal associations associated with onset and termination of sapropel formation. Roberts et al. assess the magnetic properties of sapropels, to determine whether environmental magnetic properties may be used to as a proxy for diagenesis in these sediments.

Schenau et al. investigate the oldest sapropels discussed in this issue, to evaluate whether the mode of formation was significantly different from that of the younger sapropels. Sierro et al. discuss the origins of sedimentary cycles, including sapropels, in the Sorbas Basin (Betic Corridor, SE Spain) in the interval just prior to Messinian evaporite deposition. Krijgsman et al. assess the formation and closure history of the Rifian Corridor (N Morocco), between 8 and 6 Ma.

Wehausen and Brumsack report analyses of minor and major elements from two Pliocene sapropels, characterising their relationship with alternations between high river discharge and enhanced Saharan dust input. Bouloubassi et al. present organic geochemical arguments to characterise mechanisms of sapropel formation in the eastern and western Mediterranean basins, and to identify the origin of organic matter in Plio–Pleistocene sapropels. Passier et al. discuss the implications of pyrite characteristics for the formation of two Plio–Pleistocene sapropels.

Rossignol-Strick and Paterne use stable oxygen isotope and pollen data to reconstruct changes in the climatic state of the Mediterranean during episodes of sapropel formation over the last 1 m.y. Hayes et al. evaluate the development of planktonic foraminiferal faunas throughout the Mediterranean Sea over the last glacial cycle. Capotondi et al. assess the central Mediterranean planktonic foraminiferal record of the last 23,000 years in great detail.

Aksu et al. (a) report geophysical results from the Sea of Marmara characterising the history of Black Sea–Aegean Sea reconnection during the last deglaciation, and Aksu et al. (b) assess the origin of organic matter in early Holocene sapropel S1 in the Aegean Sea. Rutten et al. investigate compositional differences between Holocene sediments deposited in a (previously) brine-filled basin, and those deposited in 'normal' open settings. De Rijk et al. present a very high resolution record through sapropel S1 with a genuine double-layer appearance, and relate the interval 'separating' the two S1 units to cold arid events found elsewhere around the Mediterranean basin.

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