Collision-related break-up of a carbonate platform (Eratosthenes Seamount) and mud volcanism on the Mediterranean Ridge: preliminary synthesis and implications of tectonic results of ODP Leg 160 in the Eastern Mediterranean Sea

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Abstract: Drilling of the Eratosthenes Seamount south of Cyprus documented incipient collision of the African and Eurasian plates. The oldest sediments recovered, mid?-Cretaceous shallow-water limestones, are overlain by Upper Cretaceous to Lower Oligocene pelagic carbonates, with several hiatuses. Following uplift, a carbonate platform was established in the Miocene; Eratosthenes was then below eustatic sea level during the Messinian desiccation crisis. The platform subsided to bathyal depths during the Lower Pliocene, associated with localized breccia deposition. Further subsidence occurred in Late Pliocene–early Quaternary, coeval with strong surface uplift of southern Cyprus. Subsidence and break-up of Eratosthenes was achieved by a combination of flexural loading and normal faulting. In addition, the Milano and Napoli mud volcanoes were drilled on the northern flank of the Mediterranean Ridge accretionary complex, south of Crete. A mainly extrusive, sedimentary origin is indicated. Multiple debris flows include clasts of sandstone and limestone of at least partly Miocene age. Both mud volcanoes are dated as >1 Ma old and have been active episodically. Hydrocarbon gas is associated with both mud volcanoes, while methane hydrates (clathrates) exist locally at Milano. The driving force of mud volcanism is overpressuring caused by incipient plate collision. Messinian evaporites may have acted as a localized seal. Material escaped through a zone of backthrusting against rigid Cretan crust to the north.

This paper's aim is to present a preliminary summary and synthesis of the tectonic results of drilling in the Eastern Mediterranean Sea during Ocean Drilling Program (ODP) Leg 160 (April, May, 1995), and to integrate these results within a regional tectonic context. Some of the results have implications for fundamental processes, including the preservation of crustal fragments in subduction/accretion complexes, and the role of mud volcanism in accretionary prisms.

The drilling during Leg 160 investigated two tectonic aspects. The first was concerned with the process of break-up of a carbonate platform, the Eratosthenes Seamount, at a subducting plate boundary, represented by the Cyprus active margin (Sites 965–968; Fig 1). The second objective concerned the origin of two mud volcanoes, the Milano (Site 970) and Napoli (Site 971) mud domes, located on the northern part of the Mediterranean Ridge accretionary complex, south of Crete (Fig. 1).

The Eastern Mediterranean Sea is an ideal location for study of crustal processes related to the collision of continental plates. The northern, passive margin of the African plate (i.e. Gondwana) was rifted in the Early Mesozoic, giving rise to an irregular pattern of embayments and promontories. Continental fragments were rifted from Gondwana and then drifted northwards into the Tethys Ocean. The opposing, northern margin of Neotethys (i.e.

ROBERTSON, A. H. F., EMEIS, K.-C., RICHTER, C. *ET AL.* 1998. Collision-related break-up of a carbonate platform (Eratosthenes Seamount) and mud volcanism on the Mediterranean Ridge: preliminary synthesis and implications of tectonic results of ODP Leg 160 in the Eastern Mediterranean Sea. *In*: CRAMP, A., MACLEOD, C. J., LEE, S. V. & JONES, E. J. W. (eds) *Geological Evolution of Ocean Basins: Results from the Ocean Drilling Program*. Geological Society, London, Special Publications, **131**, 243–271.

the southern margin of Eurasia) was initially located well to the north, extending from northern Greece through the Pontides of northern Turkey to the Caucasus. Africa and Eurasia converged in the Late Mesozoic–Early Tertiary, as a result of northward subduction. As northward subduction progressed, a number of continental fragments (previously rifted from Gondwana) were accreted to the active southern margin of Eurasia. The overall subduction front migrated southwards with time. By the Miocene the front was located in the vicinity of the present convergent plate boundary that extends across the Eastern Mediterranean Sea south of Crete, and then south of Cyprus, to connect with the Tethys suture zone further east (Fig. 1). At the present time, the Eastern Mediterranean Sea can be considered as a final remnant of the southerly Mesozoic Neotethys that is now in its final stages of closure associated with diachronous collision of the African and Eurasian plates.

Collisional emplacement of a carbonate platform: the Eratosthenes Seamount

The Eratosthenes Seamount is located in the easternmost Mediterranean Sea south of Cyprus and north of the Nile cone, with the passive margin of the Levant to the east (Fig. 1). The term 'seamount' has given rise to some confusion in the past as to many it implies an origin mainly as extrusive igneous rocks, whereas drilling during Leg 160 has shown that at least the upper part is composed mainly of limestones without igneous rocks. For this reason the term 'Eratosthenes platform' is preferred here.

Drilling during Leg 160 followed on from the earlier results obtained during Deep Sea Drilling Project (DSDP) Leg 13 (Ryan *et al.* 1973) and Leg 42 (Hsü *et al.* 1978). In particular, drilling of the Florence Rise, west of Cyprus, during Leg 42 revealed a deep-sea Plio-Quaternary succession underlain by Late Miocene sediments, including evaporites. However, at that stage of research the plate tectonic setting of the easternmost Mediterranean remained obscure, prior to obtaining more extensive seismic reflection and refraction data.

The easternmost Mediterranean is a part of the wider Eastern Mediterranean Sea, formed by rifting of the northern margin of Gondwana in the Triassic (Garfunkel & Derin 1984). The Eratosthenes platform is generally envisaged as a carbonate platform constructed on rifted continental crust. Oceanic crust was formed in the easternmost Mediterranean by the Late Triassic and is repre-

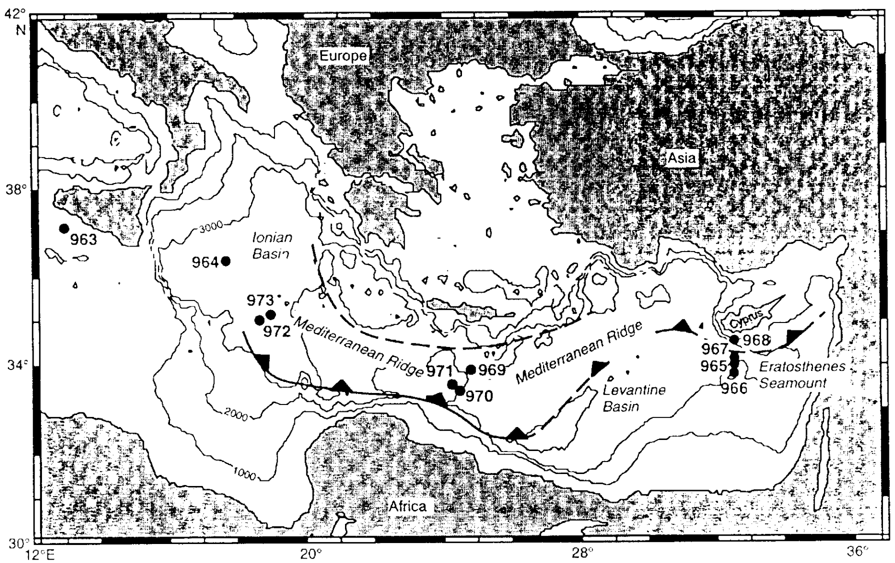


Fig. 1. Outline map of the Mediterranean region showing the main tectonic features and the locations of the sites drilled during Leg 160, specifically the Eratosthenes platform and the mud volcanoes south of Crete.

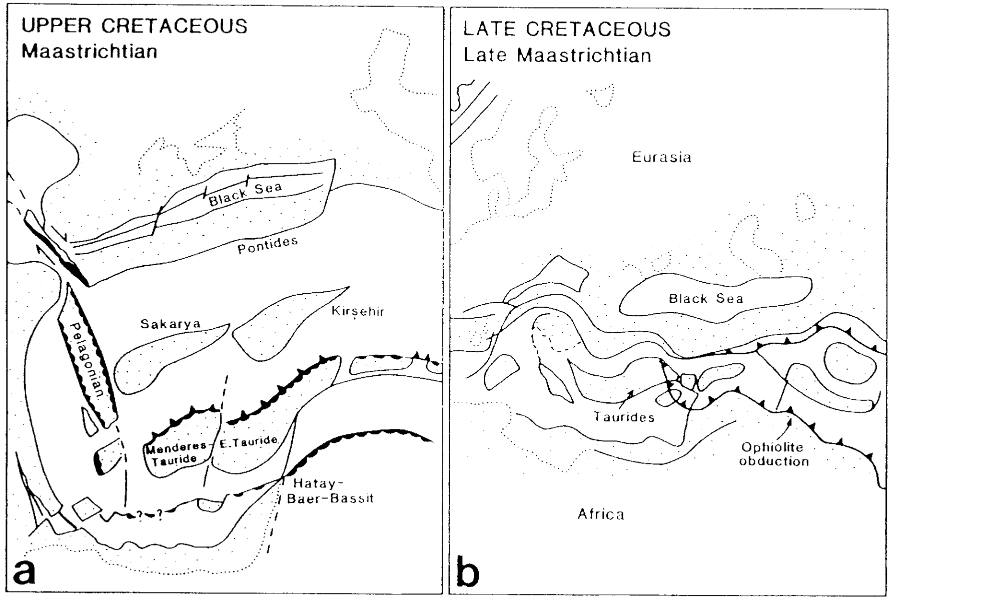


Fig. 2. Plate tectonic sketch maps showing alternative reconstructions of the Eastern Mediterranean during the Upper Cretaceous: **(a)** with the Eastern Mediterranean as a southerly Neotethyan Ocean basin, bordered by microcontinents rifted from Gondwana to the north. Ophiolites formed above subduction zones and were emplaced onto the Arabian shelf to the east and onto microcontinents. The Cyprus ophiolite represents part of the southerly Neotethys that was not obducted in the Upper Cretaceous but remained within the ocean; it is only now being emplaced related to collision with the continental fragment represented by the Eratosthenes platform (from Robertson & Dixon 1984). **(b)** In this case an ocean basin is envisaged to have formed in the Eastern Mediterranean, but all the ophiolites, including the Troodos, are seen as having been thrust from far to the north (simplified from Dercourt *et al.* 1993). Recent data, including the Leg 160 results favour model (a).

sented by 'accreted' fragments in SW Cyprus (Mamonia Complex), SW Turkey (Antalya Complex) and northern Syria (Baer-Bassit) (e.g. Robertson *et al.* 1991*a*). The easternmost Mediterranean oceanic basin formed the most southerly of a number of oceanic stands, separated by continental slivers rifted from Gondwana, including the Tauride carbonate platforms of southern Turkey. In the Cretaceous, relative motion of the African and Eurasian plates became convergent, coupled with opening of the south Atlantic (Livermore & Smith 1984). In response to regional plate convergence, subduction was initiated within the southerly Eastern Mediterranean ocean basin (and more northerly basins also), leading to genesis of the Troodos ophiolite by spreading above a subduction zone (see Robertson & Xenophontos 1993; Fig. 2a). The subduction zone probably dipped northward and was located south of Cyprus. During the Late Cretaceous–Early Eocene, much of Cyprus underwent anticlockwise rotation as a discrete microplate (Clube & Robertson 1986; Morris *et al.* 1990). Northward subduction of remaining oceanic crust in the easternmost Mediterranean to the south of Cyprus probably began at the beginning of the Miocene and the North African plate, including the Eratosthenes platform, began its final northward drift towards Cyprus (Dewey & Şengör 1979; Dercourt *et al.* 1993). During this time, southern Cyprus was located on the leading edge of what was, by then, effectively part of the Eurasian plate.

The Eratosthenes platform is a large subrectangular, elevated feature in the Mediterranean Sea south of Cyprus. Geophysical data indicate the presence of a regional magnetic anomaly, that is more extensive than the Eratosthenes platform. Previous work had suggested that the 'seamount' was in the process of collision with the Cyprus active margin to the north (Ben-Avraham *et al.*

1976; Robertson 1990; Robertson *et al.* 1991*b*; Woodside 1991; Kempler 1993), but it was the TREDMAR cruise that produced the key seismic evidence of collision and underthrusting (Limonov *et al.* 1994; Robertson *et al.* 1994, 1995*a,b*; Fig. 3). There is some evidence of collapse and underthrusting also to the south, beneath the Levantine Basin (Limonov *et al.* 1994). Dredging results also suggested that Eratosthenes includes some limestone (Krasheninnikov *et al.* 1994) and this was confirmed by drilling during Leg 160.

Any collision-related tectonic hypothesis for the emplacement of the Eratosthenes platform could only be tested by drilling: the test had to involve only relatively shallow penetration (i.e. a few hundred metres), as time and safety considerations precluded deeper penetration. Key questions were the nature of the Eratosthenes platform, and the timing and processes of its subsidence related to collision with the Cyprus active margin to the north.

Suture zones in Greece, Turkey and other Tethyan areas include numerous deformed carbonate platforms. These platforms commonly overlie rifted continental crust, although some may overlie oceanic crust (i.e. volcanic seamounts). Examples include the Mesozoic Tauride carbonate platforms of southern Turkey and counterparts in Greece. An important question is how these platforms came to be incorporated into the Tethyan orogenic collage. Drilling of the Eratosthenes platform also had the potential to shed light on this problem.

Summary of drilling results

A transect of four holes was drilled, from south to north: one on the northern crestal area of the Eratosthenes platform (Site 966), one on the upper northern flanks (Site 965), one at the base of the northern slope (Site 967), and one at the base of the opposing slope of the Cyprus active margin (Site 968) (Fig. 4). Neither time nor site survey data allowed drilling of the interesting southern margin of the Eratosthenes platform and related basin bordering the Levantine Basin. Details of the recovery at each of the four sites occupied are given in Emeis *et al.* (1996) and Robertson *et al.* (1995*a*). The main results are summarized here in terms of four time slices: (i) Mid-Cretaceous–Early Tertiary; (ii) Messinian (latest Miocene); (iii) Early Pliocene; and (iv) Plio-Pleistocene, Fig. 5).

Mid-Cretaceous to Early Tertiary

The evolution of the Eratosthenes platform, as recorded by drilling (at Site 967), commenced with the accumulation of shallow-water carbonates that are assumed to be of mid-Cretaceous age, based on micropalaeontological data and lithological correlation with similar limestones onshore in the Levant to the east (Mart *et al.* 1997). This unit is overlain by Late Cretaceous deep-water carbonates of Coniacian to Maastrichtian age, dated by calcareous nannofossils and planktonic foraminifera, followed by a hiatus until Early Tertiary time. Initial shipboard results suggested that these limestones were Middle Eocene in age. However, post-cruise studies indicate that Late Eocene to Early Oligocene planktonic foraminifera are present, mixed with abundant Middle Eocene foraminifera (S. Spezzaferri, pers. comm. 1996). Rare Palaeocene planktonic foraminifera are also present. Similar pelagic carbonates with reworked Middle Eocene foraminifera were recovered further south, at Site 966. Sedimentary structures and the nature of benthic foraminifera indicate a bathyal, relatively deep-water environment, with pelagic

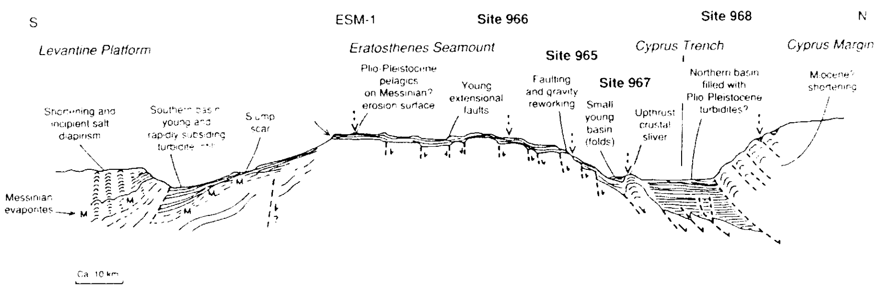


Fig. 3. Tectonic setting of the Eratosthenes platform as envisaged based on the 1993 TREDMAR site survey data (Limonov *et al.* 1994; Robertson *et al.* 1995*a*).

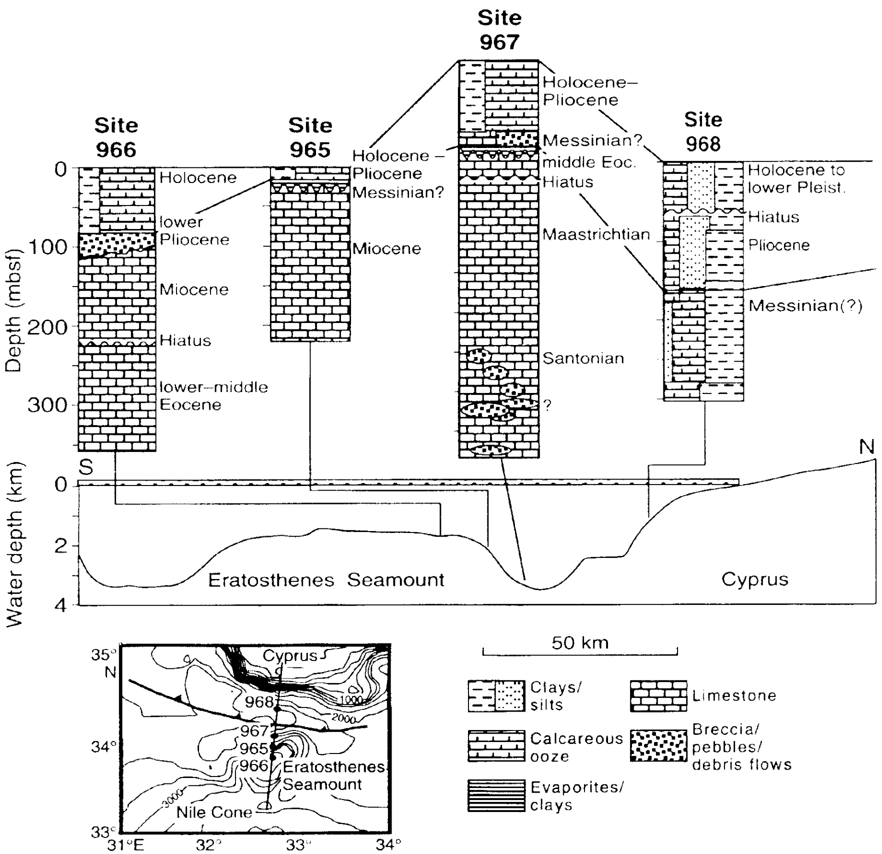


Fig. 4. Summary of the sequences recovered from the Eratosthenes Seamount drilled during Leg 160 (see text for explanation).

carbonate deposition and little terrigenous sediment or redeposited carbonates. A possible explanation of the mixed faunas is that extensive reworking took place on a submerged carbonate platform.

After the Late Eocene–Early Oligocene there was a hiatus; Eratosthenes was then tectonically uplifted at least 1 km, based on palaeodepth estimates, followed by deposition of shallow-water carbonates. Similar carbonates were deposited at the two most southerly sites (Sites 965 and 966). The limestones are provisionally dated as Miocene, based on a benthic foraminiferal assemblage (I. Premoli-Silva, pers. comm. 1995). These limestones record alternations of relatively high- and relatively low-energy settings, typical of lagoonal and near-reef environments. Similar Miocene shallow-water and reef-related carbonates are known in other areas of the Eastern Mediterranean including Israel, southern Turkey and Cyprus (e.g. Flecker *et al.* 1995; Follows & Robertson 1990; Follows *et al.* 1996).

At the northernmost of the three Eratosthenes sites (Site 967), Upper Cretaceous–Middle Eocene pelagic carbonates are overlain by Messinian fine-grained sediments, up to several tens of metres thick. These sediments were only recognized and dated during post-cruise studies (S. Spezzaferri, pers. comm. 1996). This interval includes ostracods (i.e. *Cyprideis pannonica*, *Ammonia tepida*, *A. Beccarii*) and some other shallow-water benthic foraminifera (including *Elphidium* sp.). These

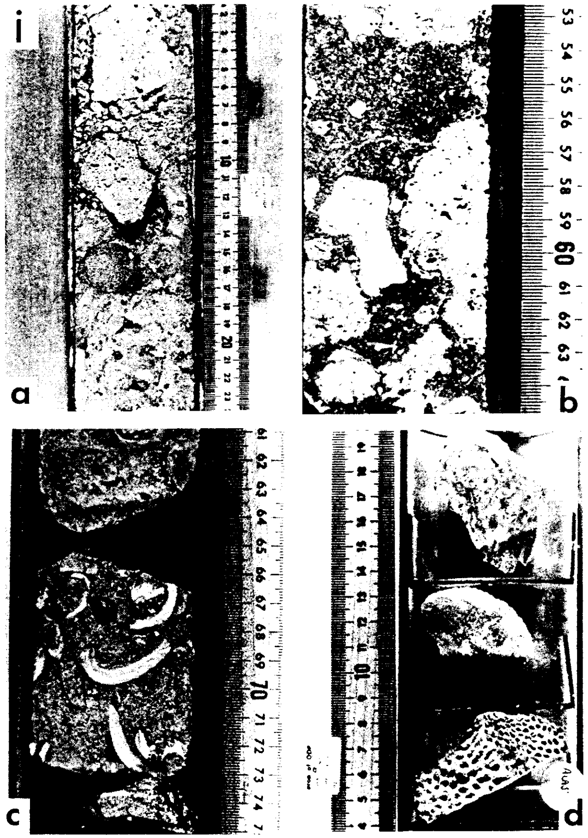


Fig. 5. Photographs of cores from sites S to N across the Eratosthenes platform and on the Cyprus margin (all photos taken by A. H. F. Robertson). **(i)** Crest of the Eratosthenes platform (Site 966). **(a)** Early Pliocene matrix-supported breccias, Hole 966X, Core 3H, Section 1, 2–24 cm. **(b)** Calcareous algal oncolites, Hole 966R, Core 8H, Section 1, 53–65 cm. **(c)** Large bivalves in a bioclastic matrix, Hole 966R, Core 10R, Section 2, 61–75 cm. **(d)** Fragments of bioclastic limestone and coral (lower), Hole 966R, Core 12R, Section 1, 4–20 cm. (b–d are Early Miocene? in age).

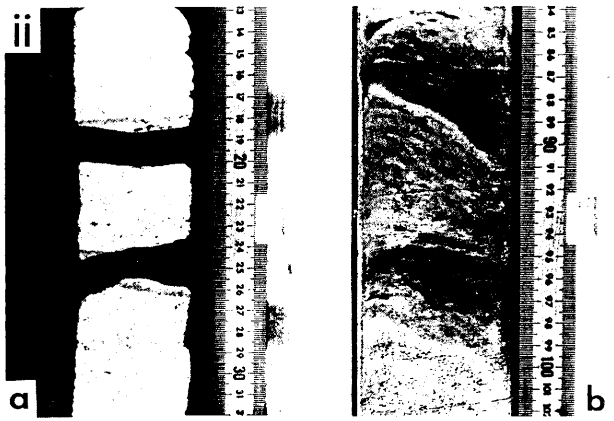


Fig. 5. (cont.) **(ii)** Upper northern flanks of Eratosthenes platform (Site 965). **(a)** Coarse bioclastic limestone composed of shallow-water bioclasts, Hole 955R, Core 20R, Section 1, 13–32 cm (Miocene?). **(b)** Slumped Early Pliocene deep-sea mud, Hole 955H, Core 2H, Section 3, 84–102 cm.

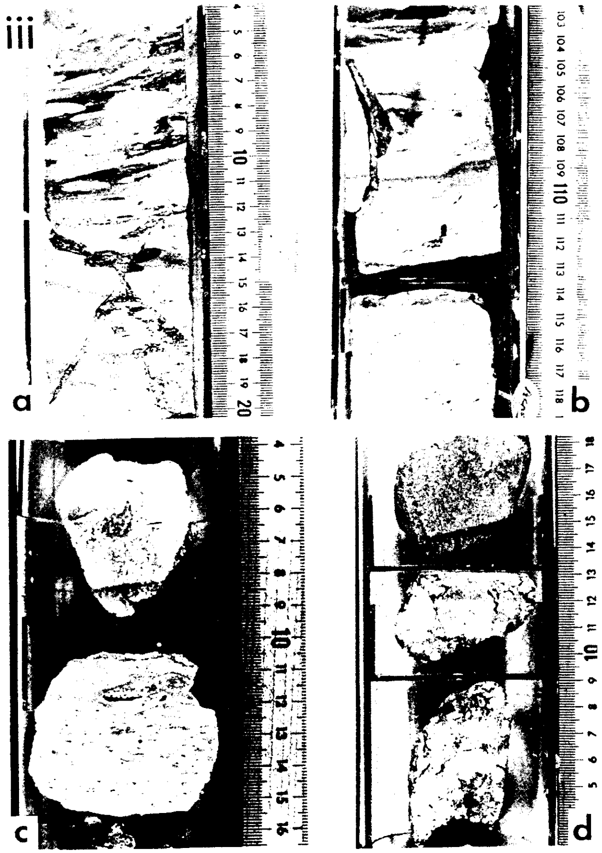


Fig. 5. (cont.) **(iii)** Lower northern flanks of Eratosthenes platform (Site 967). **(a)** Reworked pelagic carbonate (upper), with an infilled neptunian fissure (lower). Hole 967E, Core 6R, Section 3, 4–20 cm. **(b)** Normal faults in pelagic limestone, Hole 967E, Core 14R, Section 1, 103–118 cm. **(c)** Laminated shallow-water carbonate of mid-Cretaceous? age, Hole 967E, Core 41R Section 1, 5–16 cm. **(d)** Tectonically brecciated limestone near the maximum depth drilled (upper two pieces), Hole 967E, Core 46R, Section 1, 3–18 cm.

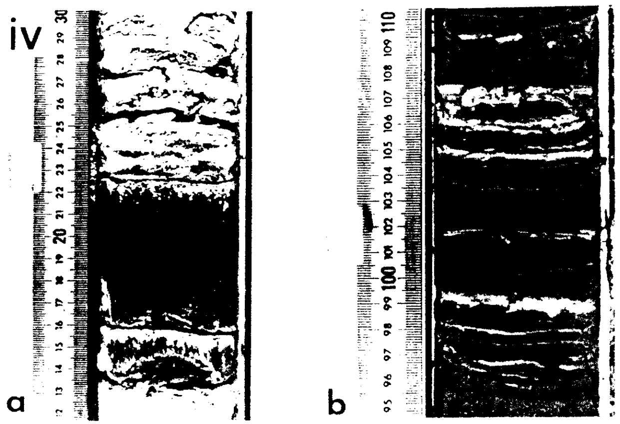
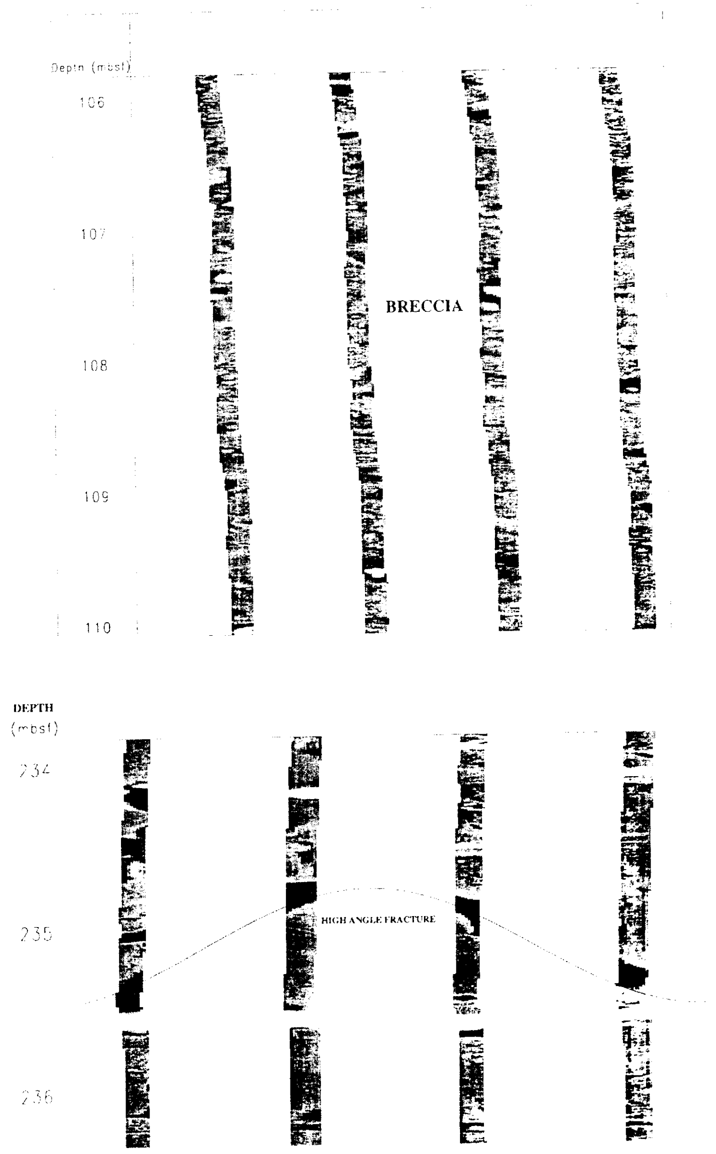


Fig. 5. (cont.) **(iv)** Lower Cyprus slope. **(a)** Detrital sand-sized gypsum (white) within dark silty clays; Hole 967B, Core 25X, core catcher, 12–30 cm. **(b)** Laminated calcareous muds without coeval biota, pale layers are detrital fine-grained gypsum, Hole 968A, Core 26X, Section 2, 95–110 cm.



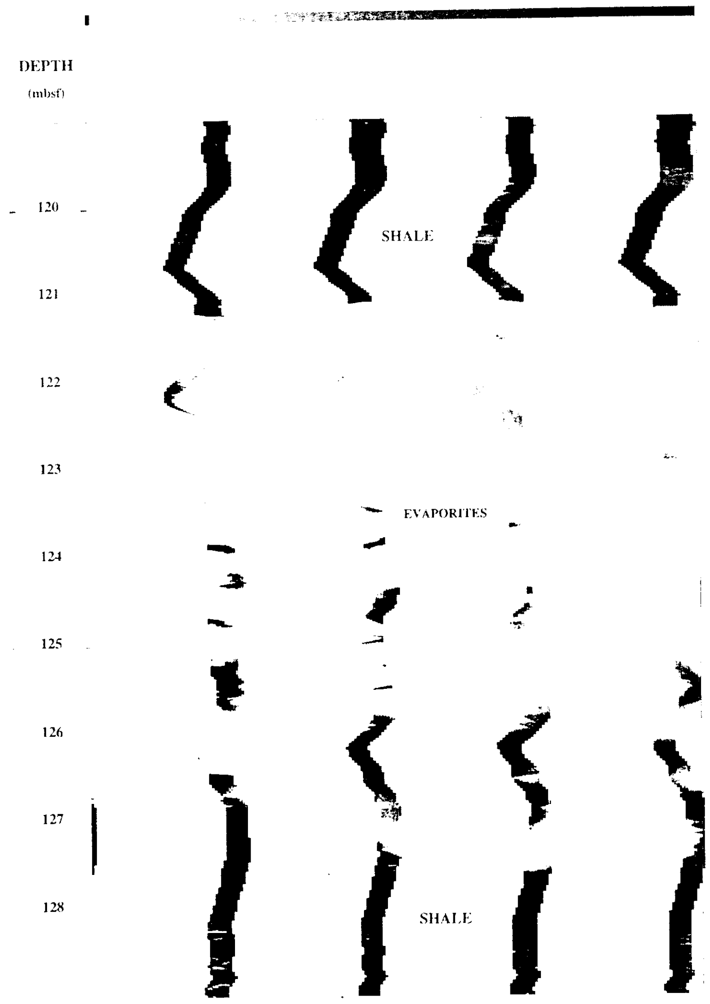


Fig. 6. Formation MicroScanner (FMS) images. **(a)** FMS image of Breccia Unit at Site 966. The 'lumpy' appearance of the record is interpreted to indicate the presence of clasts. The pale lenses are interpreted as limestone clasts, while the grey lenses are mainly hemipelagic sediments. **(b)** High-angle fault at Site 967. High-angle faults observed in the cores are of extensional type. **(c)** Evidence for the presence of evaporites (i.e. gypsum) at Site 967, that were not recovered. Note the distinctive bright image, in contrast to the darker, more argillaceous, sediments above and below. See text for explanation (M.-J. Jurado, unpublished data).

forms are mixed with reworked Eocene, mid-Miocene and, rarely, Cretaceous planktonic foraminifera. The extent of reworking decreases upwards (i.e. in part of Cores 14H, 15H and 16H). The brackish 'lago-mare' Messinian facies then pass upwards, without any observable hiatus, into fine-grained, deep-water sediments of Early Pliocene age. Reworked microfossils of Middle Eocene, Oligocene and Miocene–Early Pliocene age are present within pelagic carbonates at the base of the Early Pliocene succession. The history of this site during the mid-Tertiary is thus debatable. One possibility is that Miocene shallow-water carbonates were deposited, as at Sites 965 and 966, and were later eroded. Another is that Miocene shallow-water carbonates were never deposited there, but that pelagic deposition took place instead, followed by removal of most of these sediments. Perhaps the northernmost Eratosthenes site was located on a carbonate slope, where only reduced pelagic deposition took place in Eocene to Early Pliocene time, combined with extensive reworking of pelagic biota.

Messinian

The Mediterranean underwent its well-known salinity crisis in the latest Miocene, as documented during DSDP Legs 13 and 42 (Hsü *et al.* 1973, 1978). Layers of evaporite, up to several kilometres thick, are inferred to exist beneath the deep Mediterranean basin, based mainly on recognition of a clear 'M' reflector on seismic profiles (Ryan *et al.* 1971; Ross & Uchupi 1977; Woodside 1977; Chaumillon & Mascle 1995). The 'M' reflector pinches out upslope on the south and southwest flanks of the Eratosthenes platform. The top of the platform was therefore above the level of the surrounding Mediterranean deep basin during the Messinian, although the flanks may have remained largely submerged. A prominent reflector, thought to be an erosion surface, was noted at the base of the inferred Pliocene sequence, based on site survey studies (Limonov *et al.* 1994).

Drilling during Leg 160 confirmed that no thick evaporites are present on the Eratosthenes platform (Site 966), or on its northern flank (Sites 965 and 967; Fig. 3). The Messinian is thin, or absent, in the Eratosthenes plateau area. However, at Site 965, several metres of reddish clays were recovered at the boundary between overlying sediments that contain Early Pliocene nannofossils and underlying shallow-water limestones. These clays contain a small fauna of ostracods of possible Messinian to Early Pliocene age, together with dolomite, aragonite and swelling clays. Also, at Site 967, near the base of an interval of muddy sediments that contains only reworked microfossils, an interval several metres thick (not recovered) was identified on geophysical borehole log records as gypsum (e.g. Fig. 6a). Evidence comes from greatly increased levels of porewater sulphate at this level and from geochemical logs. During the Messinian, the Eratosthenes platform formed a topographically raised area, marked by erosion and/or local accumulation of gypsum and ferruginous muds, possibly in small lagoons and/or lakes.

The sedimentary and tectonic history of the Cyprus margin was expected to be quite different from that of the Eratosthenes platform, as these two areas were located on opposing plates. Drilling at Site 968, near the foot of the slope of the Cyprus margin, did reveal such a contrast. Beneath a Plio-Pleistocene succession, more than 200 m of argillaceous sediments were recovered, interbedded with calcareous turbidites. The microfossils on the Cyprus margin are entirely reworked, but include abundant brackish-water ostracods and the benthic foraminifer *Ammonia tepida*. Other clues to the depositional setting include the presence of abundant clay minerals (e.g. smectites) and kaolinite, together with scattered dolomite. Several thin layers of detrital selenitic gypsum sands were also recovered, together with thin layers (5 cm) of fine-grained alabastrine gypsum within clay. Lithoclasts of pelagic chalk and basalt and other constituents within abundant turbidites at Site 968 were derived from the Troodos ophiolite and its sedimentary cover in southern Cyprus (e.g. the Miocene Pakhna Formation; Robertson *et al.* 1991*b*). The turbidites are inferred to have accumulated in a large lake or inland sea of variable salinity. In general, lacustrine conditions are known to have prevailed widely in the late Messinian, especially in the Mediterranean (Hsü *et al.* 1978) and the circum-Black Sea region (Steininger & Rögl 1984). Site 968 was possibly located at the northern edge of a large hypersaline basin, within an existing subduction trench (*c.* 25 km wide), between Eratosthenes and Cyprus. Such trench sediments were possibly subducted in the Plio-Quaternary, explaining why there is now no evidence (based on seismic data) that thick evaporites were ever present between Cyprus and the Eratosthenes platform.

In summary, sediments of inferred Messinian age on the Eratosthenes platform (Sites 965, 967, 968) are thin or absent, whereas a thick (i.e. hundreds of metres) succession of probable Late Miocene lacustrine to hypersaline facies (i.e. the 'lago-mare' facies) is present at Site 968. This confirms a contrast between Cyprus located on the Eurasian plate and Eratosthenes on the Africa plate.

Early Pliocene

Drilling at all of the sites documents refilling of the Mediterranean at the end of the Messinian desiccation crisis (Hsü *et al.* 1978). However, conditions varied at individual locations. At Site 965, on the upper slope of the seamount, a thin (6 m) inferred Messinian interval contains rare, poorly preserved nannofossils of Late Miocene-Early Pliocene age (3.5–6 Ma). There are also possible palaeosols within an interval of reddish and brownish sticky clays. In this vicinity, the base of the Pliocene is marked by a sharply defined, flat seismic reflector, consistent with the presence of a sharp lithology contrast between Miocene limestone below and the weakly consolidated Pliocene fine-grained sediments above. A similar well-defined reflector is present at Site 967 to the north, where the interval between the Early Pliocene and Middle Eocene includes scattered clasts of chalk and limestone and, as noted earlier, reworked foraminifera of Eocene, Oligocene and Lower Miocene age. This is in addition to long-ranging forms that span Late Miocene, and/or Early Pliocene times. A source of both well-lithified and unlithified carbonates must thus have existed in the vicinity of Site 967.

About 65 m of interbedded nannofossil muds and matrix-supported breccias (i.e. debris flows) were recovered at the southernmost of the Eratosthenes sites (Site 966, Fig. 3) as also confirmed by Formation MicroScanner (FMS) data (Fig. 6b). In this area, the seismic character of the unconformity at the base of the Pliocene succession is much less distinct than in adjacent parts of the platform. Records were studied in four adjacent holes, allowing detailed comparisons. The matrix-supported breccias mainly formed by mass-flow processes in a tectonically unstable deep-sea setting. A similar, but less pronounced history of tectonic instability, with erosion of limestone and redeposition of clasts in a deep-marine setting, is documented at Site 965. It is clear that such tectonic instability and faulting were active at, and probably prior to, 4.5 Ma (i.e. Early Pliocene). Deposition reflects both the effects of initial tectonically triggered subsidence of the Eratosthenes platform and rapid sea-level rise at the end of the Messinian.

An entirely different Miocene–Pliocene transition is documented at the base of the Cyprus slope at Site 968, where the upward transition to the Early Pliocene is marked by an incoming of age-diagnostic nannofossils and planktonic foraminifera. Deposition of calcareous turbidites, derived from Cyprus, continued with no obvious break. Site 968 was already located below eustatic sea level during the Messinian salinity crisis; deep-marine sedimentation then ensued in the Early Pliocene with no observable break in deposition.

Pliocene–Pleistocene

At each of the four sites, the Plio-Pleistocene sequence records deep-marine accumulation. The Eratosthenes platform and its flanks were then at water depths ranging from 700 to 2900 m. The lowest part of the Early Pliocene succession already contains bathyal pelagic microfossils. Further deepening took place after the Late Pliocene, at least at Site 967, as benthic foraminifera there indicate marked upward deepening. Thin steel-grey mud turbidites in the uppermost part of the succession at the base of the Eratosthenes Seamount slope (Site 967) were deposited from dilute gravity flows containing mica, biotite and other minerals, probably derived from the Nile.

The Eratosthenes platform experienced tectonic disturbance during Late Pliocene–Pleistocene time. A hiatus of a maximum of 0.5 Ma exists within the Late Pliocene–Early Pleistocene time interval at Sites 965 and 967 on the Eratosthenes slope. At Site 966, extremely slow sedimentation rates ($1–2$ m Ma^{-1}) suggest that a depositional hiatus may be present in the early Pleistocene, although no micropalaeontological zones are missing. The hiatuses could reflect deformation of the Eratosthenes plateau area, as suggested by the evidence of low-angle discordances and folding observable on high-resolution deep-tow seismic records (Limonov *et al.* 1994). The probable cause of this deformation is faulting of underlying pre-Pliocene–Pleistocene rocks.

Evidence of thrusting and break-up of Eratosthenes

Interpretation of seismic data indicates the presence of a small ridge at the base of the lower slope of the Eratosthenes Seamount at Site 967. This ridge is underlain by a northward-dipping fault zone (i.e. a reverse fault, or thrust). Prior to Leg 160 it was hypothesized that this ridge is in the process of tectonic detachment from the Eratosthenes Seamount (Limonov *et al.* 1994; Robertson *et al.* 1994, 1995*b*; Fig. 7). An objective of drilling at Site 967 was to test if there is any evidence of such a zone of reverse faulting. Indeed, it was hoped to drill through a décollement zone at a depth of *c.* 550 m. In the event, drilling penetrated to the maximum permitted depth (600 m), but did not reach a décollement. This was probably because previous depth estimates did not take account of the presence of thick limestones with relatively high seismic velocities, that made the reflector appear shallower than in reality. However, drilling terminated in a unit of tectonically brecciated limestones (based on core observations), suggestive of proximity to a major fault. Faults observed in the overlying cores of Eocene and Upper Cretaceous limestone exhibit mainly normal offsets as supported by FMS data (Fig. 6c). FMS log data (M. J. Jurado pers. comm. 1996) suggest that numerous zones of deformation and brecciation are present. Accordingly, it seems likely that Eratosthenes at Site 967 experienced a complex history of both extensional and compressional deformation which still requires clarification.

Although a décollement was not actually penetrated, the history of thrust-disruption of the base of the northerly Eratosthenes platform slope can be inferred from seismic evidence. Faulting must be relatively recent, as Plio-Pleistocene sediments that form the uplifted ridge at the base of the slope are clearly seen to be deformed on seismic profiles. Also, the ridge has a small sedimentary

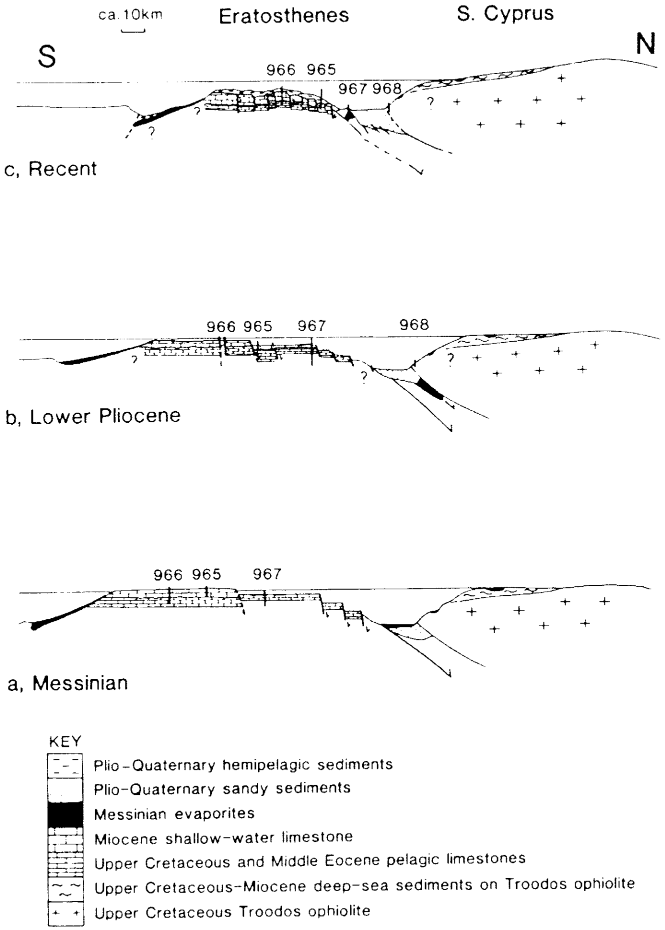


Fig. 7. Tectonic–sedimentary history of the northern Eratosthenes platform shown as a series of time slices. Note the role of extensional faulting of the platform margin and the inferred thrusting at the base of the lower slope.

basin ponded against it to the south. This basin is also well imaged on deep-tow high-resolution seismic profiles (Limonov *et al.* 1994) and can be seen to be deformed by numerous upright folds, with estimated wavelengths of only a few metres. The folds are interpreted to result from shortening of the sedimentary basin fill, associated with contemporaneous movement on the upthrust ridge to the south. Reverse faults are also imaged directly to the south, on the lower slope of the Eratosthenes Seamount.

Significance of Eratosthenes drilling for on-land accretionary processes

The Eratosthenes drilling sheds light on fundamental processes associated with the early stages of continental collision leading to the formation of mountain belts. By the time mountains begin to emerge, collisional processes are already well advanced and thus the early stages must be explored beneath the sea. Converging continental plates may not be linear and, where present,

promontories and embayments may influence the timing and nature of collision in different areas (Dewey 1980). In addition, rifted continental slivers or oceanic edifices may be accreted prior to suturing of large continental plates. The arrival of an oceanic seamount at a trench has already been shown to involve subsidence and break-up of a volcanic edifice, in the case of the Daisha Seamount in the Japan trench (Le Pichon *et al.* 1987; Fig. 8). However, the Eratosthenes drilling instead investigated the collision of a carbonate platform with a convergent margin. This platform is assumed to be underlain by continental crust, based mainly on geophysical evidence (Makris *et al.* 1983). The results suggest that the platform underwent strong flexural break-up and collapse as it approached and then entered the trench (Fig. 9). For both Daisha and Eratosthenes, break-up was largely achieved by high-angle normal faulting. Post-cruise work is continuing to model the collisional history of the Eratosthenes platform.

The drilling results also help with the general problem of preservation of continental fragments and carbonate platforms within on-land accretionary terrains (e.g. Tethys, or the Palaeozoic Caledonian–Appalachian belt). In the case of the Daisha Seamount it appears that the bulk of the volcanic edifice is being consumed within the trench (Fig. 8). In future, little trace of its existence may remain, other than a disrupted forearc and the

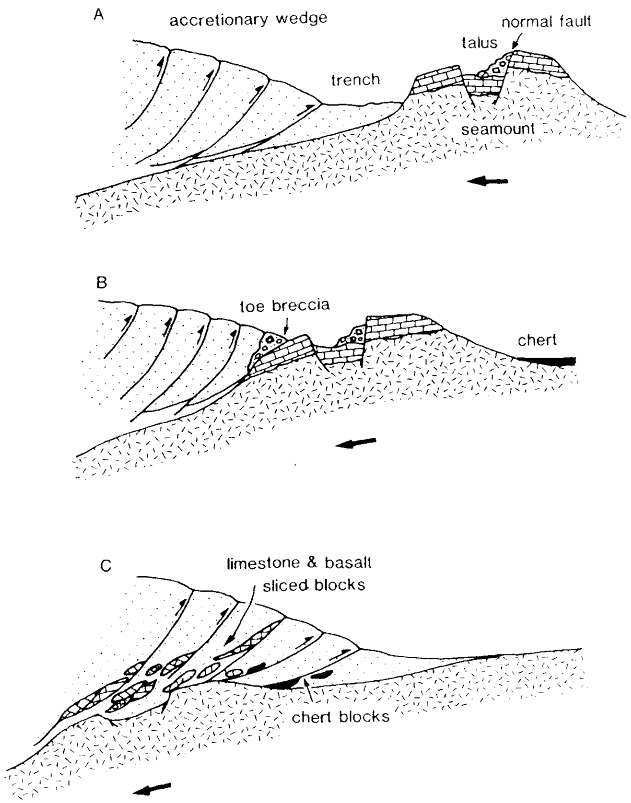


Fig. 8. Model showing processes active when an oceanic seamount arrives at a trench. The seamount undergoes large-scale normal faulting, shedding large volumes of basalt and sediment-derived clastics, often as debris flows. The bulk of the seamount is subducted while fragments are incorporated into an accretionary prism as detached blocks and debris flows (i.e. 'olistostromes'. Similarities and differences with the Eratosthenes–Cyprus trench collision are discussed in the text. From Taira *et al.* (1989); drawing courtesy of E. Pickett.

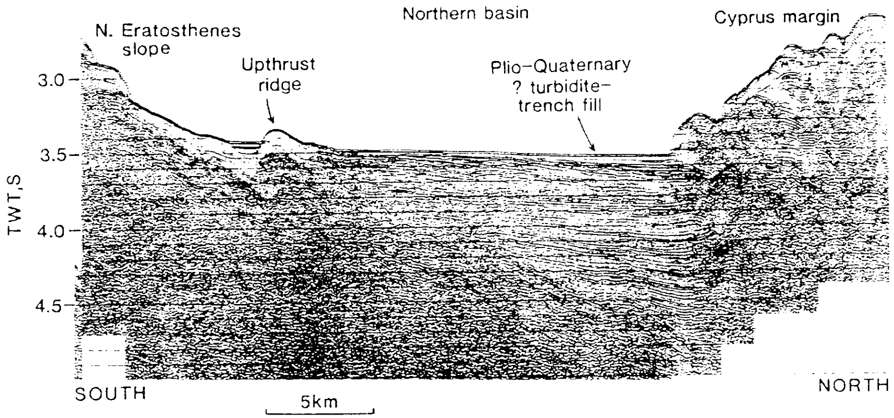


Fig. 9. Single-channel seismic profile from the northern margin of the Eratosthenes platform to the base of the southern Cyprus slope. TREDMAR Line 120. The Eratosthenes platform is breaking up and being thrust beneath southern Cyprus, with a sediment-filled trench above. Note the prominent raised ridge at the base of the northern slope. This folded Pleistocene sediments and appears to be currently active. The raised feature is interpreted as a thrust culmination above a blind thrust, related to detachment of a sliver of Eratosthenes limestones related to subduction and collision.

presence of volcanic–sedimentary debris flows and detached blocks incorporated into an accretionary prism. This debris would have a high chance of ultimate preservation in the stratigraphical record and can be regarded as recent equivalents of widespread 'olistostromes' (i.e. debris flows) found in many on-land accretionary terrains, including those in Japan. The fate of Eratosthenes would seem, similarly, to involve underthrusting and deep burial beneath the over-riding plate. The upper plate is represented by southern Cyprus, including the Troodos ophiolite. However, seismic and drill results at Site 967 from the foot of the northern slope of the Eratosthenes platform indicate that detachment of a sliver of the Eratosthenes carbonate platform above an active thrust is currently taking place (Fig. 10). If this process continues, in the future the main part of the Eratosthenes platform could be subducted, while at least one crustal sliver (*c*. 1 km thick) may be accreted and thus have a high preservation potential. Such a preserved slice (e.g. at Site 967) would comprise a basement of brecciated limestone above a thrust fault, then a *c*. 400 m thick slice of pelagic carbonates, overlain by a hemipelagic succession (with sapropels) and then terrigenous turbidites.

Similar crustal fragments have been preserved on land by processes of subduction/accretion and are widely exposed in the Tethyan orogenic belt (e.g. Robertson 1993, 1994; Figs 11 and 12). Such units include accreted carbonate platform fragments, e.g. Upper Permian–early Mesozoic, in older (i.e. Palaeotethyan) Tethyan terrains in northern Turkey and equivalents in western Turkey. Similar units in the Greek area were accreted in the mid-Mesozoic (e.g. from the Pindos Ocean of northern Greece). Accretion of similar units also took place in the Late Cretaceous–Early Tertiary in both the Greek and southern Turkish areas (e.g. Antalya Complex).

Such accretion of small thrust slices is, however, not a mechanism to emplace large carbonate platforms on the scale of many kilometres across and kilometres thick. Examples of such carbonate platforms in the Tethyan orogenic collage include the Parnassus carbonate platform in Greece and the Bey Dağları carbonate platform in southwest Turkey (e.g. Robertson *et al.* 1991*a*). Carbonate platforms on this scale were perhaps too large to be accreted as discrete thrust slices, but were instead preserved by other means. One possibility involves oceanward relocation of the subduction zone, as in a number of SW Pacific examples (Weissel *et al.* 1982). Another possibility is suggested by site survey results for the Eratosthenes platform. The southern margin of Eratosthenes is apparently being thrust beneath the Levantine Basin to the south (Limonov *et al.* 1994; Fig. 3). Africa–Eurasia convergence is thus now beginning to be accommodated by both northward and southward underthrusting of the Eratosthenes platform. Thus, Eratosthenes may not in future be thrust far beneath

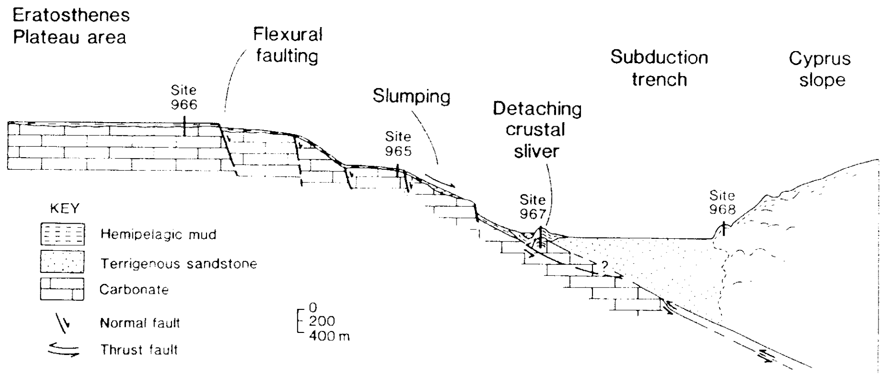


Fig. 10. Tectonic interpretation of processes affecting the northern margin of the Eratosthenes platform. These are mainly flexural normal faulting related to impingement with the subduction trench to the north, and thrust detachment of a sliver of Eratosthenes limestone at the base of the northern slope.

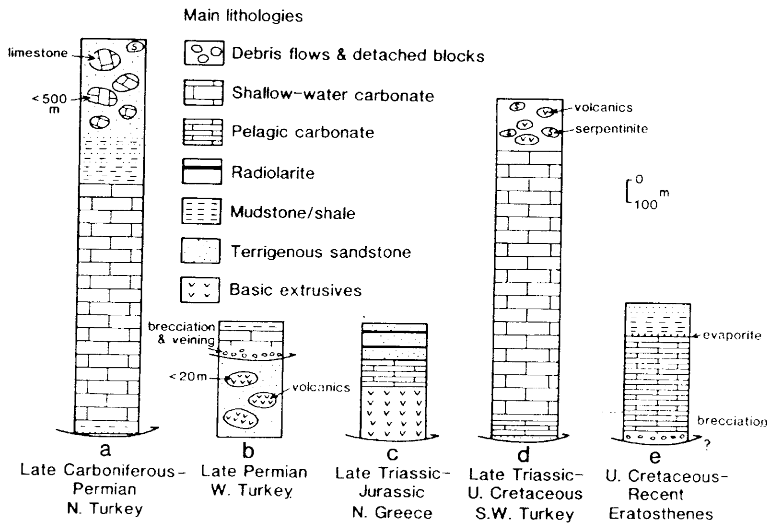


Fig. 11. Logs of limestone-dominated crust. (a–d) Slivers in melange terrains of Turkey and Greece: (**a**) Late Carboniferous–Late Permian thrust slice within an accretionary complex, Central Pontides, northern Turkey (Kargı unit); (**b**) Late Permian–Triassic thrust slice of limestone with a terrigenous basement, Çal unit, Karakaya Complex, W Turkey; (**c**) disrupted thrust slice of basalt overlain by limestones and the deep-water sediments, Alopetra unit within the Avdella Melange, Pindos Mtns, NW Greece; (**d**) large limestone thrust slice within sutured deep-sea and oceanic material, Sutçuler unit, SE part of the Antalya Complex, SW Turkey. (**e**) Eratosthenes unit at Site 967 for comparison. It is assumed that the succession is floored by a thrust fault, as in Fig. 7. All but (c) are interpreted as carbonate platforms within an open oceanic area that were emplaced by subduction and accretion; (c) represents limestone constructed on a volcanic seamount. At least (c) and (d) originated near a rifted continental margin, as inferred for Eratosthenes (e). All of these units experience obduction related to subduction–accretion processes. Data sources in Robertson *et al.* (1991, 1996).

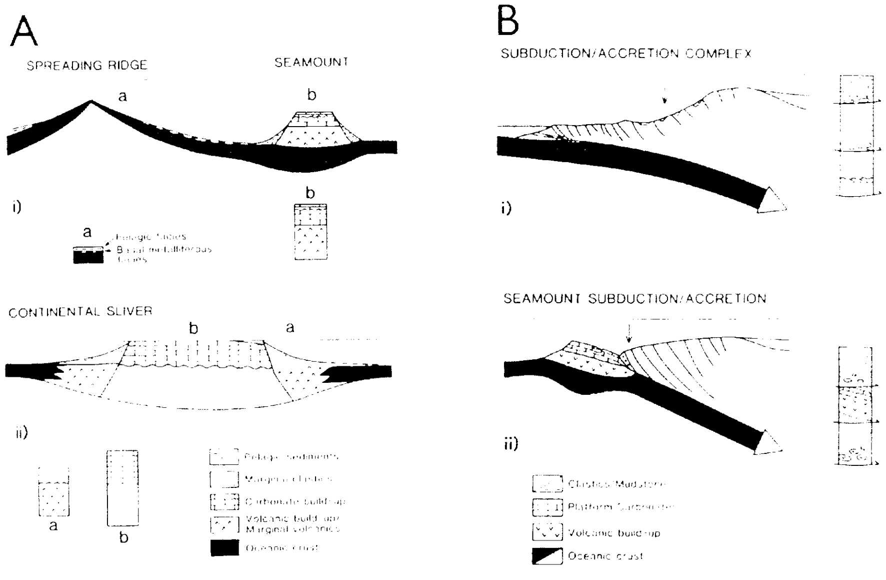


Fig. 12. Tectonic facies models: (**A**) (i) volcanic seamount of axis of spreading ridge; (ii) rifted off continental fragment; (**B**) (i) simple accretionary prism; (ii) accretion of a carbonate platform. Both continental fragments and volcanic seamounts were accreted in the Tethyan suture zone. Eratosthenes is interpreted as an accreted continental sliver.

Cyprus (and metamorphosed), but may instead remain at a high structural level between the plates, where it could later be exhumed and eroded.

Role of flexure-induced subsidence

The collision of the Eratosthenes platform can be compared with the development of foredeeps where thrust units are emplaced onto continental crust (e.g. Beaumont 1981; Stockmal *et al.* 1986). The Eratosthenes platform is interpreted as having evolved into a foredeep related to collision with the Cyprus active margin. The upward passage from shallow-water carbonates to deep-water hemipelagic and terrigenous sediments can be compared with that observed on land in many accreted carbonate platform slices. These include most of the examples of accreted units described earlier (Fig. 11). In addition, a similar trend from shallow- to deep-water sediments is seen in a number of Tethyan continental margins (e.g. in Oman: Robertson 1987) and in other areas (e.g. S Appalachians: Whiting & Thomas 1994), related to thrust and nappe emplacement. Preliminary calculations suggest that the Eratosthenes platform can be modelled in terms of an exponential increase in subsidence rate with time during the Plio-Pleistocene (B.M. Whiting pers. comm. 1996). Subsidence was accompanied by important normal faulting as observed in seismic profiles (Limonov *et al.* 1994), and in cores (Emeis *et al.* 1996; Kopf & Flecker 1996). Indeed, the Eratosthenes crust did not deform according to a simple flexural model (e.g. Beaumont 1981), but underwent major normal faulting during subsidence. This coeval faulting could reflect reactivation of pre-existing zones of structural weakness within the Eratosthenes platform.

Significance for ophiolite obduction

Modes of ophiolite emplacement have long been enigmatic. One favoured model involves the collision of oceanic crust above a subduction zone with a passive continental margin. A modern example is the collision of the North Australian margin with the Banda arc (Harris 1991); another is the emplacement of the Taitao ophiolite, south Chile (Le Moigne *et al.* 1993). In the Eastern Mediterranean and Middle Eastern regions most of the large ophiolites are inferred, mainly based on geochemical evidence, to have formed above

intraoceanic subduction zones (e.g. Jurassic Pindos ophiolite, N Greece; U Cretaceous Semail ophiolite, Oman (Pearce *et al.* 1984)). These ophiolites were emplaced when an above-subduction-zone ophiolite collided with a Tethyan passive margin, either the main margin of Gondwana (e.g. in Oman) or a small rifted continental fragment (e.g. Pelagonian zone, N Greece). The significance of the Eratosthenes results is that they document a Tethyan ophiolite actually in the process of being emplaced onto continental crust. Most of the other Upper Cretaceous ophiolites which formed in the southerly Neotethys (e.g. Hatay, Baer-Bassit, Oman) were emplaced onto the Arabian passive margin (i.e. Gondwana) in the latest Cretaceous and were transgressed by clastic sediments and then shallow-water carbonates. However, the Troodos ophiolite retains an unbroken sedimentary cover from the time of genesis of the oceanic crust in the Upper Cretaceous until the Lower Miocene (Robertson 1990). The Troodos ophiolite remained within a remnant of the Neotethyan Ocean during the Tertiary. It was then strongly uplifted in the Plio-Pleistocene, with most of the uplift taking place in the Late Pliocene to mid-Pleistocene (Poole & Robertson 1992). This uplift was broadly coeval with collapse of the Eratosthenes platform and it is inferred that the two events are related. The first sign of break-up of the Eratosthenes platform is dated as Early Pliocene, suggesting the existence of a several million year time gap before evidence of strong uplift of southern Cyprus (i.e. Upper Pliocene). However, there is evidence of rapid subsidence of Eratosthenes in the Upper Pliocene to lower Pleistocene, based on microfossils (S. Spezzaferri, pers. comm., 1995), coeval with rapid

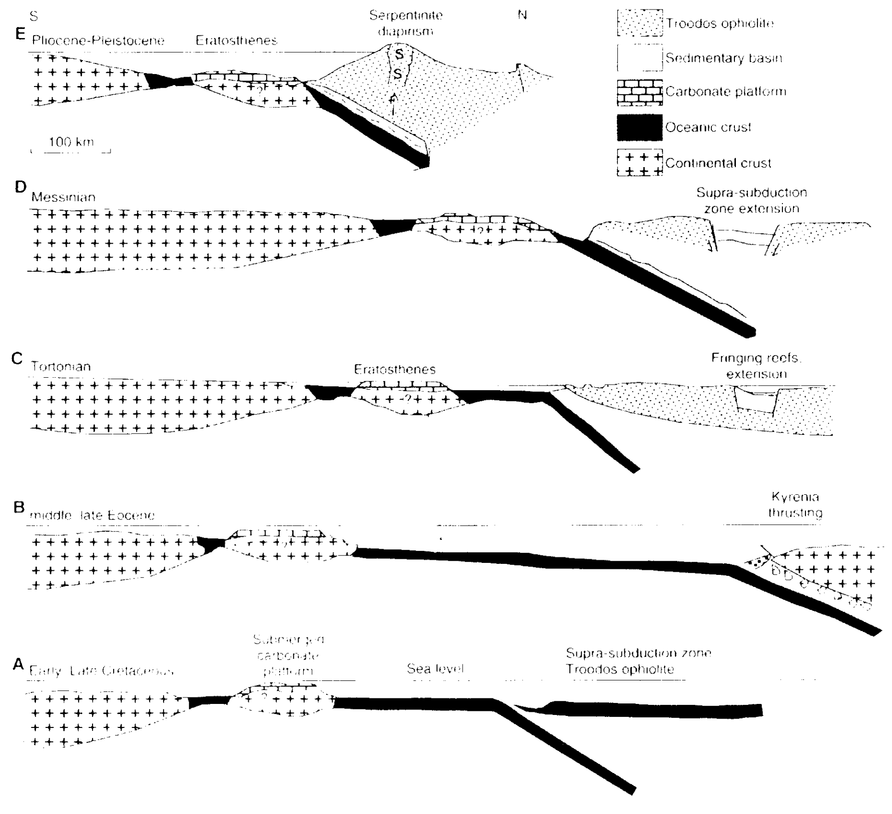


Fig. 13. Plate tectonic model for the evolution of the Eratosthenes platform in relation to Cyprus (see text for explanation).

uplift of the Troodos ophiolite. The collision of the Eratosthenes platform with southern Cyprus along the Cyprus active margin is identified as a major driving force in the emplacement of the Troodos ophiolite, with implications for other examples in the geological record.

In summary, drilling of the Eratosthenes carbonate platform has shed important light on processes of the initial stages of collision of the opposing African and Eurasian plates; it has also helped explain how carbonate platform fragments of different scales could be preserved in accretionary complexes on land, similar to examples from Mediterranean Tethyan terrains. Our working tectonic hypothesis is shown in Fig. 13.

Mud volcanism on the Mediterranean Ridge

There might seem to be little link between mud volcanism and carbonate platform collisional processes. However, early-stage collisional processes do provide a link. The structures drilled, the Milano and Napoli mud volcanoes, form part of a well-defined field of mud structures (Olympi Field) located on the northern part of the Mediterranean Ridge (Cita *et al.* 1989, 1994*a,b*; Cita & Camerlenghi 1990; Camerlenghi *et al.* 1992, 1995; Premoli-Silva *et al.* 1996; Staffini *et al.* 1993; Limanov *et al.* 1994, 1995; Fig. 14). The Mediterranean Ridge is a mud-dominated accretionary complex that was constructed in the later Tertiary, related to northward subduction of southern Neotethyan oceanic crust bordering the North African plate (Le Pichon & Angelier 1979; Le Pichon *et al.* 1982). During the Mesozoic, a number of such strands of Neotethyan Ocean existed in this area, separated by microcontinents rifted from the north Gondwana margin (e.g. Adria, also know as Apulia). Together with Eratosthenes, the Mediterranean Ridge is sited within the most southerly of these Neotethyan oceanic strands. Other former oceanic basins further north in the Greek area include the Pindos and Vardar zones. Related to convergence of the African and Eurasian plates, the more northerly of these oceanic basins completely closed by Early Tertiary time (i.e. Eocene–Oligocene), such that further Africa–Eurasia convergence could be taken up only within the most southerly Neotethyan oceanic basin. Northward subduction within this basin then gave rise to the Mediterranean Ridge accretionary complex and its eastwards extension, the Cyprus active margin. Onset of subduction and the beginning of growth of the Mediterranean Ridge accretionary complex probably took place around Late Oligocene time (e.g. Kastens 1991; Meulenkamp *et al.* 1994), and subduction and accretion were well advanced by the Late Miocene (Fig. 15).

Understanding of the Mediterranean Ridge has been retarded by the existence of seismically impenetrable Messinian evaporites ('M' reflector). However, recent geophysical studies shed new light on its structure and geological history (i.e. Kastens *et al.* 1992; De Voogd *et al.* 1992; Truffert *et al.* 1993; Dickmann *et al.* 1995; Mascle *et al.* 1995; Reston *et al.* 1995; Chaumillon & Mascle 1995). It is now clear that the Mediterranean Ridge accretionary complex is unusually low and broad compared to most subduction complexes. One factor may be that during the Plio-Pleistocene the trench lay adjacent to a mainly submerged continental margin to the north (i.e. Aegean Sea), and thus only limited volumes of coarse clastic sediment reached the trench (e.g. from Crete). On the other hand, some sand probably reached the trench from North Africa, much as today. In addition, a large amount of evaporite was probably precipitated in subduction trench, ridge and associated forearc basin settings during the Messinian desiccation crisis. Evaporites within the trench were later subducted or accreted, reducing the strength of the wedge and allowing it to spread out laterally above a gently dipping subduction zone.

By the Late Pliocene or Early Pleistocene, the Mediterranean Ridge began to collide with a large promontory (Cyrenaica) of the North African plate (Fig. 14), causing the toe of the accretionary complex to be uplifted. Accretionary wedges are continuously maintained in mechanical equilibrium (Platt 1990). Maintenance of a 'critical taper' was achieved by initiating crustal thickening via

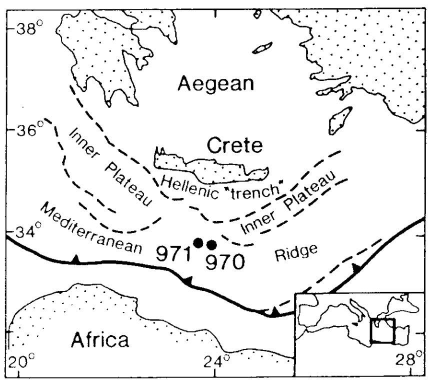


Fig. 14. Tectonic setting of the mud volcanoes drilled during Leg 160.

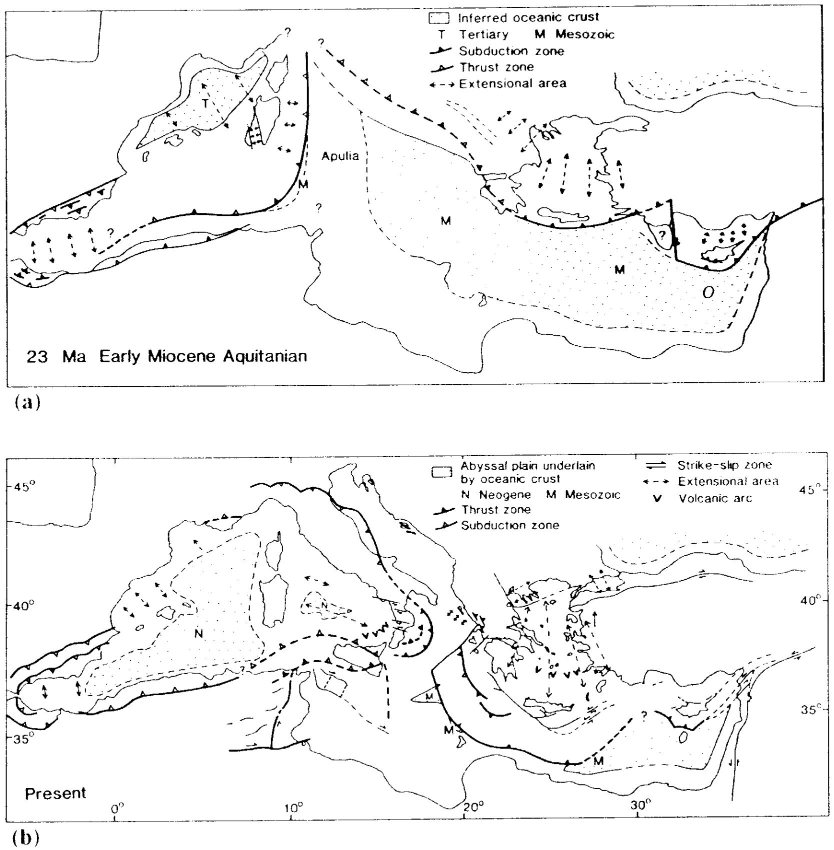


Fig. 15. Plate tectonic maps showing the setting of the Mediterranean Ridge accretionary prism in: (**a**) Early Miocene; (**b**) Present. Modified from Robertson & Grasso (1995).

backthrusting of the northern margin of the Mediterranean Ridge accretionary complex. In addition, backthrusting is known to affect accretionary wedges undergoing steady-state subduction/accretion, unrelated to collision (Brown & Westbrook 1988). One probable effect of regional collision with the African margin to the south is that the northern part of the Mediterranean Ridge accretionary complex was thrust northwards over a backstop of continental crust to the north. This led to overpressuring within muddy sediments of mainly Neogene to Plio-Pleistocene age. The presence of Messinian evaporites may also have helped retain such overpressured fluids.

Drilling during Leg 160 was designed to define the internal anatomy, age and mode of mud volcanism. The two examples selected, the Milano and Napoli mud volcanoes, were already seismically well-imaged and were known to show contrasting morphologies, and possibly illustrated different stages of development, with one, Napoli, being currently active, in contrast to Milano. The drill sites aimed to constrain crest, inner flank and outer flank settings. Specifically, drilling of the crestal areas aimed to shed light on alternative extrusive (i.e. as mud-debris flows) versus intrusive (i.e. as semi-solid 'protrusions') origins (Limonov *et al.* 1994; Camerlenghi *et al.* 1995). Drilling of the flanks would reveal evidence of volcanic upbuilding, while it was hoped to reach pre-volcanic deep-sea sediments on the outer flanks and thus date the age of mud volcano initiation. Details of the main features of the two mud volcanoes drilled are given below (Figs 16 and 17).

Milano mud volcano

Nannofossil oozes, nannofossil clays and sapropels (i.e. organic-matter-rich muds) of early late Pleistocene age were cored at an outermost hole, beyond the mud volcano (Hole 970B). These sediments are interbedded with poorly consolidated, thin-to medium-bedded sands and silts, presumably shed from the mud volcano. Some intervals are tilted, with small normal and reverse faults. A hole in the outer flank area (Hole 970A) revealed alternations of clast-rich, mud-supported sediments ('mud breccias') and normal hemipelagic sediments. Using the FMS the lowest interval recorded there (but not cored) was identified as matrix-supported conglomerate (i.e. mud breccia). The lowest interval actually recovered is pelagic sediment, dated 1.75 Ma. This is overlain by mud-debris flows and coarse-grained turbidites, in which the FMS clearly images numerous clasts (<5 cm to 55 cm in diameter). Above comes a thin interval of pelagic sediment, dated as *c.* 1–1.5 Ma. This, in turn, is overlain by a thick, clast-rich, mud-supported sedimentary interval with local thin sapropels (also detected with FMS) and, finally, by an uppermost pelagic interval (<1 m), dated as <0.26 Ma. By contrast, two holes on the inner flank (Hole 970C) and on the crest (Hole 970D) of the Milano mud volcano recovered gaseous muddy, silty and sandy sediments.

Napoli mud volcano

A succession on the outer flank (Hole 971A) begins with normal hemipelagic sediments and sapropels

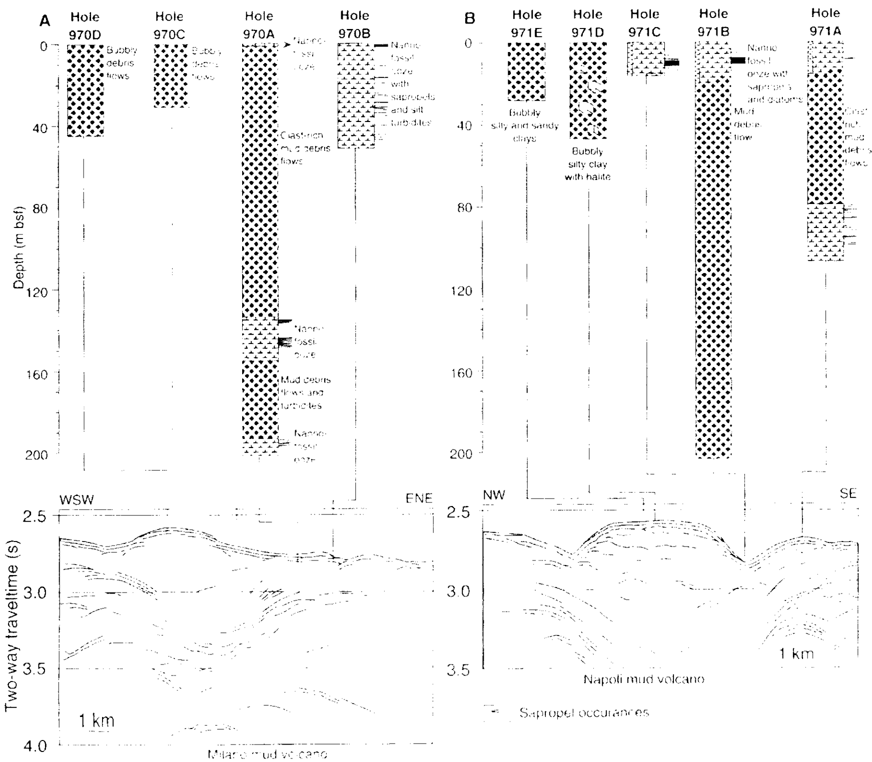


Fig. 16. Summary of the lithostratigraphy of the Milano (**A**) and Napoli (**B**) mud volcanoes drilled during Leg 160. The seismic reflectors visible within the two mud volcanoes are shown below. Note the presence of inward-dipping reflectors beneath both flanks of the Napoli and Milano structures. See text for explanation.

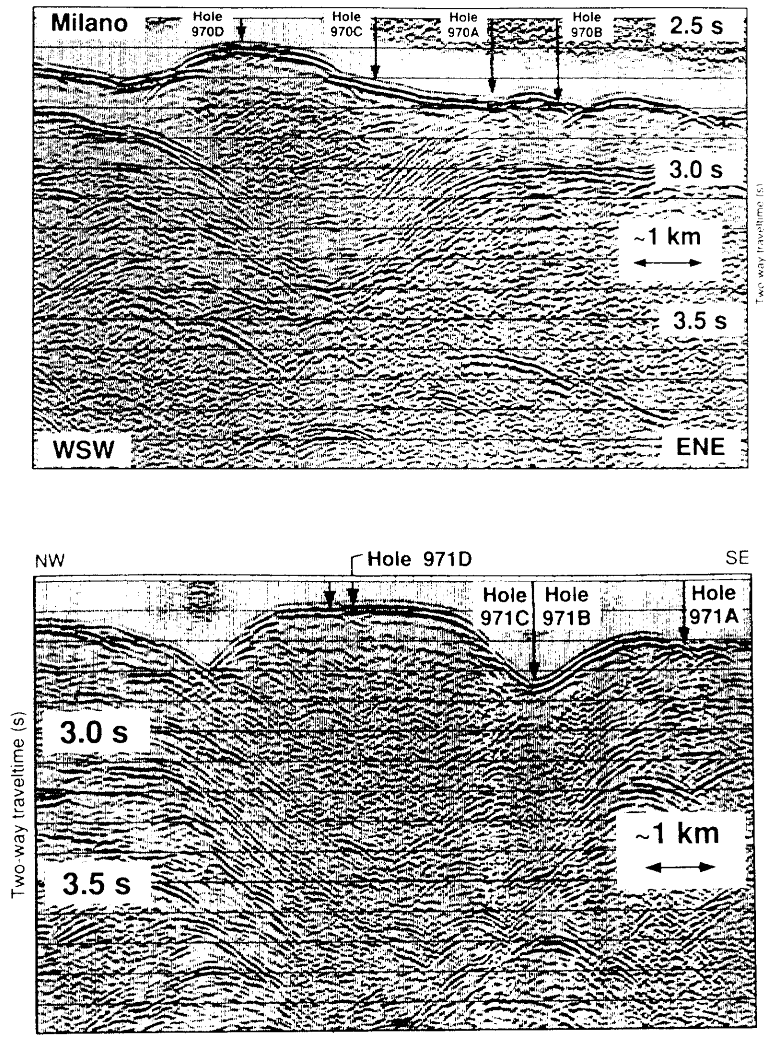


Fig. 17. Seismic profiles of the Milano and Napoli mud volcanoes based on site survey work during Leg 160. (**a**) Milano; (**b**) Napoli.

dated 0.46–1.5 Ma (i.e. within the large *Gephyrocapsa* zone). This interval is followed by clast-rich, matrix-supported sediments, in which the clasts are mainly calcareous and range from several millimetres to a few centimetres in size. The succession ends with a *c.* 20 m succession of nannofossil ooze, nannofossil clay and turbidites, dated as middle late Pleistocene to Middle Pliocene (<1.5 Ma). A thick unit of matrix-supported, clast-rich muddy sediments was next recovered on the inner flank (Hole 971B) and dated as between 0.26 and 0.46 Ma. Intervals with scattered clasts (<5 cm) alternate with more homogeneous silty clay. Downhole logs (especially natural gamma and resistivity) reveal layers that might correspond to relatively silty to sandy intervals. Overlying this are hemipelagic sediments, including sapropels. Hole 971C was drilled at the same location as Hole 971B, revealing an expanded sequence that probably resulted from redeposition of fine-grained sediment from the crestal area of the mud volcano into a surrounding moat-like depression. On the crest of the Napoli mud volcano (Hole 971D) gaseous silty clay was recovered, with scattered small (<5 cm) clasts of mudstone and siltstone. Angular to subrounded clasts of coarsely crystalline halite (up to 3 cm diameter) were noted within thin, silty layers, together with a few subrounded halite-cemented mudstone clasts (<5 cm diameter). The matrix is significantly finer at the crest of the Napoli mud volcano, than at Milano (Flecker & Kopf 1996). Finally, bubbly clays and silts with thin (several centimetres), more sandy layers were recovered at another crestal site (Hole 971E), together with a few small (<3 cm) clasts of mudstone and fine-grained carbonate. Rare nannofossils of Pleistocene age are present in the upper part of the section, and reworked Miocene nannofossils are common throughout.

Sediment clast and matrix types

Well-consolidated, matrix-supported, clast-rich muddy sediments dominate the flanks of both mud volcanoes (Fig. 18). These are the well-known 'mud breccias' of Cita *et al.* (1981). The matrix ranges from silty clay to rare sandy silt, and includes nannofossils, foraminifera, clay, quartz and rock fragments. The matrix-supported texture is supported by FMS data (Fig. 19). Nannofossils and planktonic foraminifer assemblages within the matrix are dominantly of Middle Miocene age. However, Eocene, Oligocene and Middle Miocene nannofossils are also present and may be reworked. In addition, Pleistocene microfossils are present in the matrix of the Napoli mud volcano. Clasts vary from mainly subangular to subrounded, and are less commonly angular or rounded. Lithologies include poorly consolidated sandstone and siltstone, weakly to well-consolidated calcareous claystone and mudstone, together with calcite- (or locally quartz-) cemented sandstone and siltstone. Sandstone clasts are mainly of plutonic igneous and metamorphic origin, and were probably mainly derived from North Africa, although a source in Crete cannot be ruled out. There are also shallow-water carbonate clasts with calcareous algae, polyzoans and reworked pelagic carbonate. The clasts in both volcanoes contain the following biota: (i) nannofossils and planktonic foraminifera of Lower–Middle Miocene (i.e. Burdigalian–Langhian) age; (ii) mixed nannofossil and planktonic foraminifer assemblages of Middle Miocene, Oligocene and Eocene ages, together with Cretaceous nannofossils; and (iii) brackish-water-type ostracods of Late Messinian–Early Pliocene age in the Milano mud volcano.

Fig. 18. Photographs of cores of the Milano mud volcano (photos: ODP). **(a)** Massive clast-rich mud. Note the small angular claystone clasts (upper) and the larger pale (sandstone) clasts (lower). Drilling disturbance has occurred in the vicinity of the large, hard clasts. 960A, 14X, 1, 30–0 cm. **(b)** Typical clast-rich mud. Clasts include sandstone (pale), micritic limestone (medium grey) and claystone (dark). Note also the hemipelagic mud (upper). 970A-15X-1, 0–30 cm. The clast-rich muds are interpreted as extrusive debris flows rather than intrusive bodies, as in some earlier interpretations. Hole 967E, Core 46R, Section 1, 0–20 cm.

Geochemical processes

The presence of clathrates (i.e. methane hydrates) was inferred in the crest of the Milano mud volcano based on the evidence of abnormally low porewater

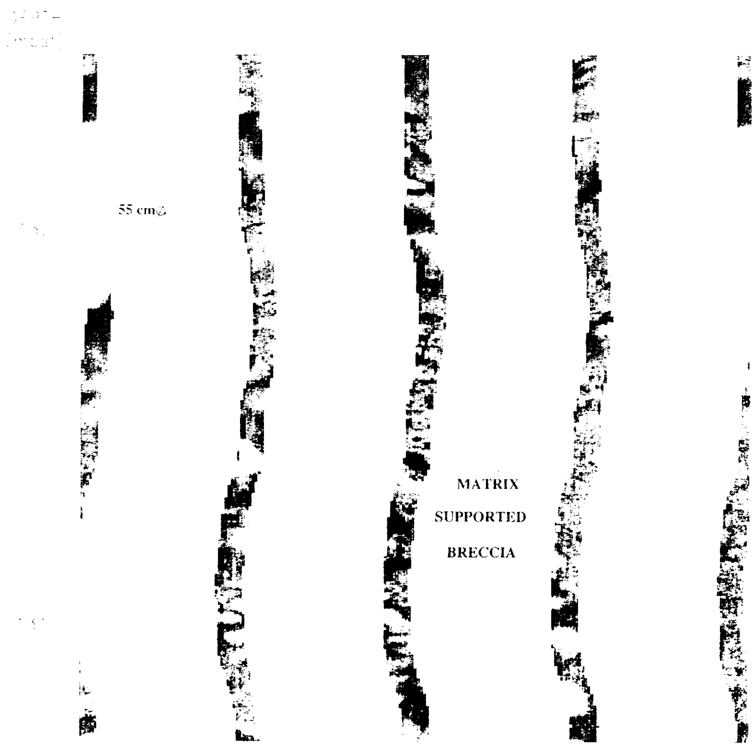


Fig. 19. Formation MicroScanner (FMS) image of typical 'mud breccias' from Hole 970A. The pale lenses correlate with lithified sandstone and limestone clasts, while the darker material is mainly matrix and small argillaceous clasts. See text for explanation (M. J. Jurado, unpublished data).

salinities (Holes 970C and 970D). These low values are probably due to the decomposition of clathrates that took place immediately after core recovery. In addition, oxygen-isotopically heavy ($\delta^{18}O$) porewaters indicate clathrate decomposition at deeper levels (G. De Lange, pers. comm. 1996). The absence of methane hydrates in the crest of the Napoli mud volcano could reflect the existence of higher pore-fluid temperatures and salinities (up to 300 g kg^{-1}) that acted to suppress clathrate formation. Low levels of sulphate in Hole 970D could relate to intense bacterial sulphate reduction in an anoxic environment. Pure methane is abundant as gas bubbles in the uppermost 30 m below the crest of the Milano mud volcano (Hole 970D), but methane concentrations drop sharply below this, consistent with the formation of methane hydrate at relatively shallow depths. In accordance with this, levels of higher hydrocarbons relative to methane abruptly increase below the clathrate zone.

Hydrocarbon gas is abundant in the Napoli mud volcano, where methane/ethane ratios vary from 10 to 40 overall and remain constant with depth, but vary significantly from hole to hole (Holes 971A, B, D and E). In contrast to the Milano mud volcano, clathrate was not detected. The gas in the Napoli mud volcano also contains several higher hydrocarbons (up to hexane) that are currently being identified. Porewaters from the crestal holes are saturated with respect to halite. There are marked local variations in potassium content suggesting that brine of more than one source may be present (i.e. in the lower part of Hole 971A). Very high alkalinity throughout (*c.* 80 mmol l^{-1} in Holes 971D and 971E) probably reflects microbial consumption of methane. Sulphate decreases sharply downward in Hole 971B, probably owing to high rates of bacterial sulphate reduction. A single temperature measurement of 16.1°C was obtained in Hole 971D at 45 m below sea floor, which is 2°C above normal bottom-water temperatures. Under these conditions, hydrocarbon gases may continuously flow to the surface of the Napoli mud volcano rather than being trapped as clathrates.

Processes of mud volcanism

The lowest known interval of 'mud breccias' (i.e. seen using FMS) relates to a relatively early stage of eruption above inferred Messinian evaporites and thin (i.e. tens of metres) sediments of Pliocene? age (Fig. 20). At Milano, this was followed by deposition of a distinctive clastic interval composed of debris flows and turbidites, and then by more quiescent extrusion of large volumes of multiple debris flows that interfinger with surrounding deep-sea sediments to build up the mud volcano cone. Facies transitions, as seen at Napoli, favour non-intrusive processes of mud volcano construction.

The mud volcanism involved detachment of lithified clasts derived from an underlying sedimentary succession of at least partly Miocene age. The depth range of derivation remains poorly constrained, but preliminary petrographic and clay mineralogical evidence does not indicate very deep burial (i.e. more than anchizonal) conditions. One possibility is that the matrix was derived from near the décollement of the downgoing plate, estimated at a depth of 5–7 km (Camerlenghi *et al.* 1995). This décollement apparently cuts through Miocene sediments, based on recent high-resolution seismic data (Chaumillon & Mascle 1995). More probably, most or all of the clasts were derived from shallower depths, within the accretionary wedge (i.e. <3 km). The driving force was possibly related to backthrusting against a backstop of rigid Cretan crust to the north. Such backthrusting could have resulted in tectonic disruption and formation of new pathways for escape of overpressured materials to the surface. Mud volcanism could have been initiated in this model when an overlying seal, where present, of impermeable Messinian evaporite was broken. Elsewhere, faulting alone may have been sufficient to trigger expulsion of overpressured fluids.

Significance of mud volcano drilling

Mud volcanoes and related mud diapirs are known in a wide variety of settings world-wide and have been the subject of numerous publications in the international literature in the last decade or so (e.g. Brown & Westbrook 1988). Many examples are unrelated to subduction (e.g. Alboran Sea in the W Mediterranean and Black Sea (Henry *et al.* 1990; Limonov *et al.* 1994)). Mud volcanoes in accretionary settings have commonly been seismically imaged, and exposed counterparts on land are often composed of muddy debris flows (Barber *et al.* 1986). However, drilling of the Milano and Napoli mud volcanoes has offered the first opportunity to characterize the internal anatomy of submarine mud volcanoes in detail and determine their age and period of activity. The discovery that both the Milano and Napoli mud volcanoes are >1 Ma old is a surprising and important result. Once initiated, mud volcanoes are capable of remaining episodically active for geologically significant periods of time. Post-cruise work and companion studies are continuing to elucidate the intriguing nature of mud volcanism on the Mediterranean Ridge. However, at present it seems likely that a number of specific factors acted in concert to promote mud volcanism (Figs 21 and 22). These were: (i) shallow northward subduction (5–7 km) giving rise to overpressured mud (Camerlenghi *et al.* 1995); (ii) structural control of previously accreted material; (iii) the local presence of Messinian evaporites to help seal fluids; and (iv) backthrusting to provide zones of fluid escape.

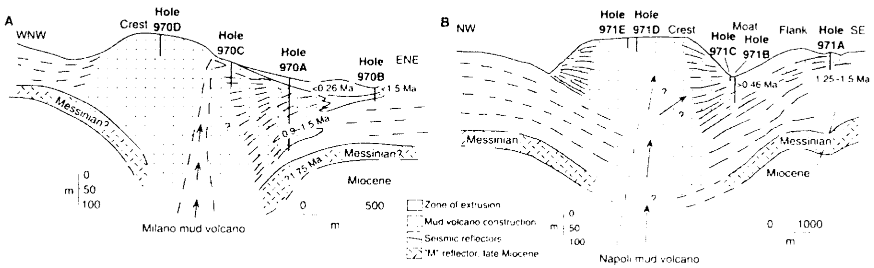


Fig. 20. Interpretation of the anatomy of (A) the Milano and (B) the Napoli mud volcanos. Clast-rich mud-debris flows were intruded from depth and were then extruded on the sea floor building up mud volcano edifices. Peripheral subsidence appears to have taken place to form a moat, with an infilling of multiple debris flows.

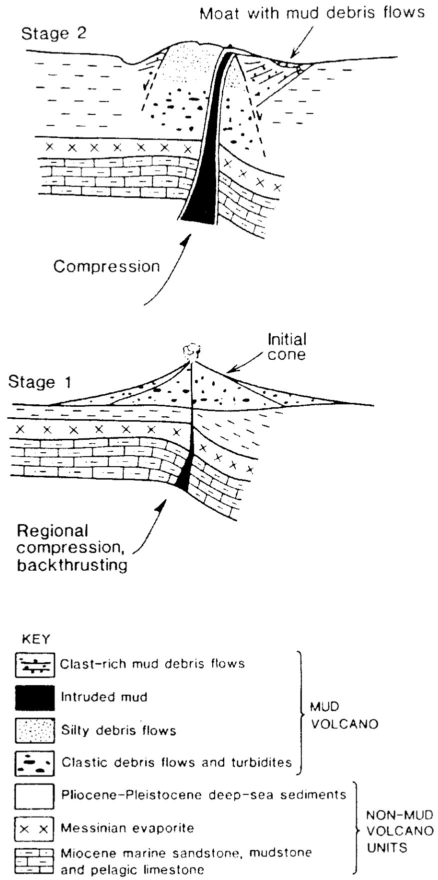


Fig. 21. Model for development of mud volcanism at the sites drilled. Mud volcanism was initiated when collision-related backthrusting increased *in situ* fluid pressure beneath an impermeable layer of Messinian evaporite. Once punctured, mud volcanism remained active for more than 1 Ma. Stage 1: early explosive phase builds up a clastic cone. Stage 2: collapse to form a moat which progressively fills with multiple debris flows. The detailed structural setting, however, remains unclear as collection of high-resolution seismic data is hampered by the presence of salt.

Conclusions from Leg 160 tectonic drilling

Drilling during ODP Leg 160 in the Eastern Mediterranean has successfully shed light on fundamental tectonic processes related to the early stages of convergence and collision of lithospheric plates.

Eratosthenes platform

The Eratosthenes platform south of Cyprus is confirmed to be in the process of incipient collision with the Cyprus active margin to the north. The platform is inferred to be a continental fragment rifted from the northern margin of the North African plate (i.e. Gondwana) in early Mesozoic time. By the mid-Cretaceous, Eratosthenes formed a shallow-water carbonate platform. Similar shallow-water carbonates are exposed in the Levant to the east. In common with the Levantine platform, the Eratosthenes carbonate platform subsided in the Late Cretaceous and was overlain by bathyal pelagic carbonate. It escaped tectonic disruption in the latest Cretaceous, associated with ophiolite emplacement in areas to the north, including Cyprus and Turkey. Eratosthenes was then still in a southerly position adjacent to the North African passive margin. Eratosthenes was tectonically uplifted by the Early Miocene to become a shallow-water carbonate platform. This uplift could relate to the initial effects of northward subduction. During the Messinian Mediterranean-wide desiccation crisis Eratosthenes was emergent, with local palaeosol development, while the flanks may have remained submerged. In the Early Pliocene it was then submerged to bathyal depths, accompanied by deposition of localized matrix-supported debris flows. The platform was later overlain by deep-water hemipelagic muds, including sapropels: subsidence then accelerated in the Upper Pliocene–Pleistocene. This subsidence is seen as the result of collision with the Cyprus active margin to the north.

A sliver of the Eratosthenes crust is in the process of thrust detachment near the base of the northern slope of the platform. Its existence provides a mechanism for the mode of accretion of comparable platform slivers within on-land melange terrains, e.g. in Greece and Turkey. Collapse of the Eratosthenes platform in Early Pliocene–Pleistocene time was broadly coeval with the main phase of surface uplift of the Troodos ophiolite in the Late Pliocene to mid-Pleistocene. The two events are seen as intimately related to collision of the African and Eurasian plates, and associated with final emplacement of the Troodos ophiolite.

Milano and Napoli mud volcanoes

Drilling of the Milano and Napoli mud volcanoes on the Mediterranean Ridge south of Crete has shed

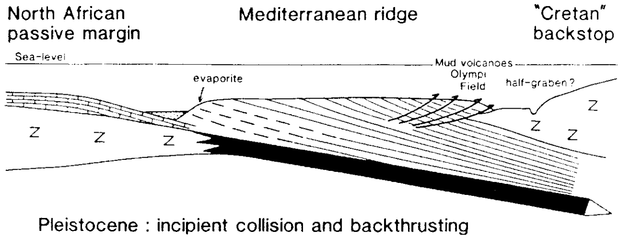


Fig. 22. Sketch of the inferred setting of mud volcanism on the Mediterranean Ridge accretionary complex, related to backthrusting.

light on the timing and processes of mud volcanism in accretionary settings. Both mud volcanoes are dominated by clast-rich, mud-matrix sediments, interpreted as multiple mud-debris flows. Drilling supported interpretatious made during the TREDMAR Site Survey Cruise (Limonov *et al.* 1994). The 'mud breccias' are similar to the origin of some debris flows associated with mud volcanoes on land (e.g. in Indonesia). Secondly, the presence of *in situ* hemipelagic sediments, both beneath the flanks of the mud volcano and interbedded with the mud-debris flows, shows that both mud volcanoes are >1 Ma old or older. Thus, individual mud volcanoes may remain active over geologically significant periods of time. The mud volcanoes developed above a shallow northward-dipping subduction zone in proximity to a zone of backthrusting along the northern part of the Mediterranean Ridge accretionary complex, adjacent to a rigid backstop of Cretan continental crust to the north. Backthrusting is also known to take place within open-ocean accretionary complexes undergoing steady-state subduction (e.g. Barbados). In the case of the Mediterranean Ridge, backthrusting was a consequence of maintaining mechanical equilibrium (i.e. the critical taper), following onset of collision of the Mediterranean Ridge accretionary complex with a promontory of the North African continental margin to the south. The backthrust zone may have provided egress for overpressured materials originating from within the accretionary prism.

We thank the captain, the crew and the marine technicians for outstanding support of RV *JOIDES Resolution* during Leg 160. The drilling could not have taken place without the essential Site Survey data collected during a number of cruises over a decade or so.

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