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Evidence of Collisional Processes Associated with Ophiolite Obduction in the Eastern Mediterranean: Results from Ocean Drilling Program Leg 160

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Figure 1. JOIDES Resolution at Marseilles, France, prior to departing on Leg 160.

ABSTRACT

Recent drilling in the eastern Mediterranean Sea south of Cyprus has revealed important insights into fundamental tectonic processes associated with continental collision and ophiolite emplacement. A transect of four sites was drilled across the Africa-Eurasia plate boundary. The results show that the African plate, represented by the Eratosthenes Seamount, underwent rapid subsidence and related faulting in Pliocene-Pleistocene time. The driving force was tectonic loading by the Eurasian plate. In this area the leading edge is represented by the Troodos ophiolite. The breakup and subsidence history of the Eratosthenes Seamount, as revealed by drilling during Leg 160, is clearly linked with the emplacement of the Troodos ophiolite. This underwent strong surface uplift during active tectonic emplacement, associated with collision of the seamount with the Cyprus margin.

INTRODUCTION

Many ophiolites were emplaced long ago by processes that are no longer active (e.g., the Upper Cretaceous Oman ophiolite). However, the Troodos is an example of an ophiolite that is undergoing active emplacement today, in an area that is easily accessible and geologically well known. Much of the evidence for this emplacement is recorded beneath the sea to the south of Cyprus, along the boundary between the African and Eurasian plates. This area was a target of drilling during Leg 160 in March and April 1995 (Figs. 1 and 2).

The eastern Mediterranean Sea (Fig. 3) is a remnant of the Mesozoic Tethys ocean (Dercourt et al., 1993). Different areas record various stages of Tethys closure, ranging from fully collisional settings on land to the east to areas of incipient collision on the Mediterranean Ridge in the west (Cita and Camerlenghi, 1990). One such area of incipient collision includes the Eratosthenes Seamount, south of Cyprus. Previous geophysical studies (Woodside, 1977, 1991; Krasheninnikov et al., 1994) suggest that the Eratosthenes Seamount is a fragment of continental (or transitional-type) crust that is undergoing subsidence and breakup in a zone of incipient collision between the African and Eurasian plates (Robertson, 1990; Kempler, 1993; Limonov et al., 1994; Robertson et al., 1994, 1995).

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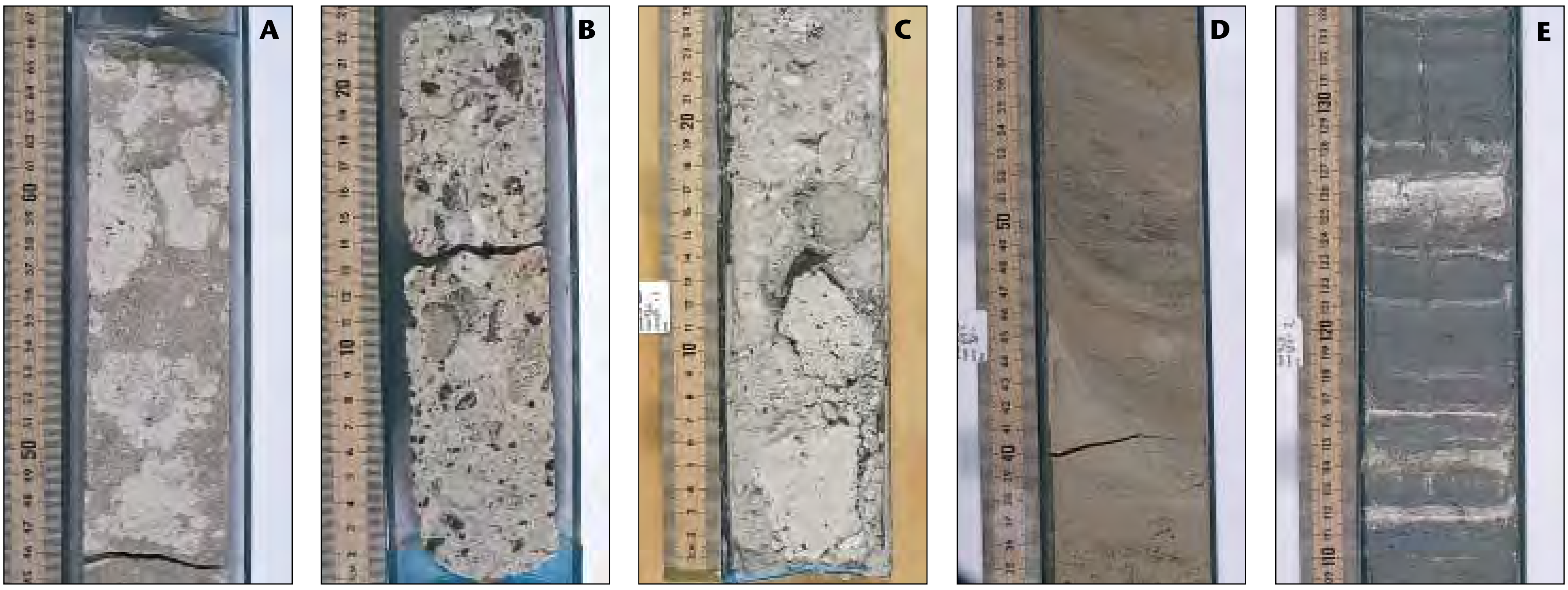

Figure 2. Core photographs illustrating stages in the tectonic-sedimentary evolution of the Eratosthenes Seamount and the adjacent Cyprus margin. A: Oncolites (algal balls) that accumulated on a shallow-water carbonate platform in Miocene time (Site 966, Core 17R, Section 1, 45–65 cm). B: Limestone (Miocene?) composed of various types of clasts, reflecting current reworking in a shallow-water shelf setting (Site 966, Core 13R, Section 1, 1–21 cm). C: Debris flow composed of clasts of altered shallow-water limestone in a matrix of muddy nannofossil ooze of early Pliocene age (Site 966, Core 8H, Section 1, 1-23 cm). D: Clast-rich nannofossil ooze of Pliocene age showing slumping and color banding. The slumping is related to collapse of the Eratosthenes Seamount (Site 965, Core 3H, Section 3, 35–58 cm). E: Calcareous silty mud with detrital gypsum of Messinian(?) age, possibly deposited in a saline lake located at the foot of the Cyprus slope (Site 968, Core 25X, Section 2, 108–132 cm).

Obduction *continued from p. 213*

This hypothesis could be tested by drilling a transect of relatively shallow holes (most <300 m) across the Africa-Eurasia plate boundary. One hole was drilled on the northern part of the seamount plateau (Site 966), one on the upper northern slopes (Site 965), one on a small high at the base of the northern slope of the seamount (Site 967), and one on the lower slope of the Cyprus margin to the north (Site 968; Fig. 4, inset).

In this article we summarize the new information gained by drilling, and we demonstrate how this can be used to test a model of collisional processes and ophiolite obduction that is of general importance. The details of the recovery at the individual sites are recorded elsewhere (Emeis, Robertson, Richter, et al., 1995).

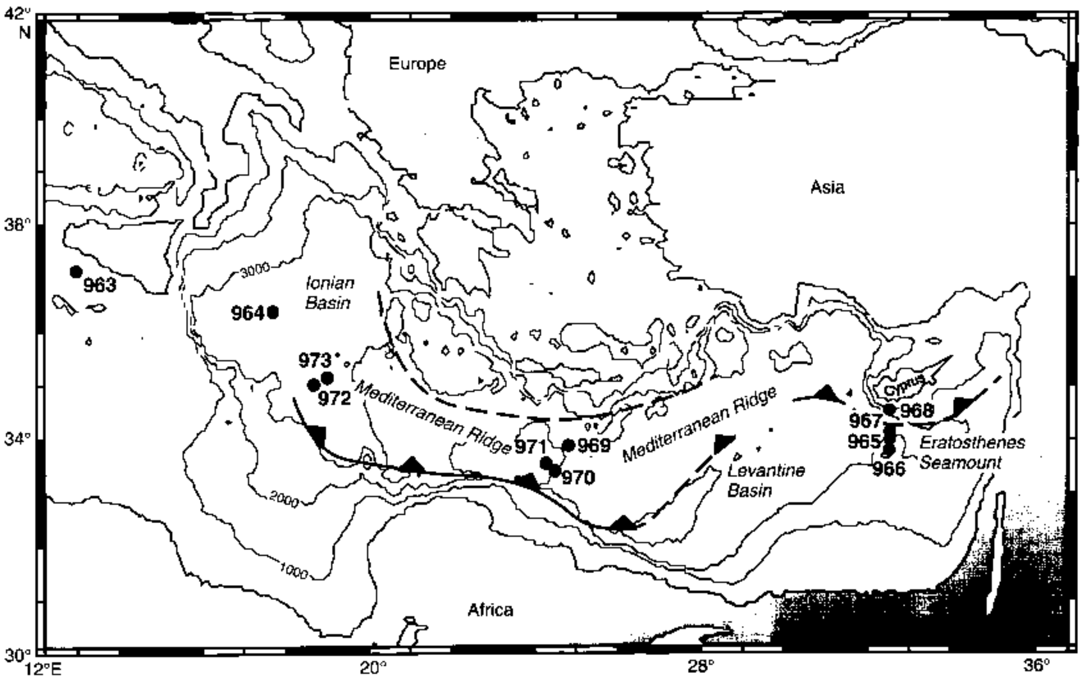

Figure 3. Outline map of the Mediterranean showing the main tectonic features and the locations of the sites drilled during Leg 160. This article deals only with the transect of sites drilled between Cyprus and the Eratosthenes Seamount (Sites 965, 966, 967, and 968). The line with teeth marks the deformation front between the African and Eurasian plates.

SUMMARY OF DRILLING RESULTS

The nature of the basement of the Eratosthenes Seamount is unknown, but it might represent transitional crust of a rifted passive margin. The presence of mafic igneous intrusions at depth is suggested by the existence of a strong magnetic anomaly beneath the seamount and adjacent seafloor areas (Woodside, 1977, 1991). The oldest sediments recovered during Leg 160 are undated shallow-water carbonates that underlie Upper Cretaceous pelagic carbonates at Site 967 (Fig. 4). In the pre–Upper Cretaceous, the Eratosthenes Seamount formed part of a carbonate platform, as widely exposed around the eastern Mediterranean (e.g., in southern Turkey and the Levant). Overlying pelagic carbonates, of Upper Cretaceous and middle Eocene age at Site 967 and of exclusively middle Eocene age at Site 966, indicate accumulation in a quiet deep-water (bathyal) setting. The absence of gravity input (e.g., turbidites) within the Upper Cretaceous and middle Eocene pelagic sediments is consistent with deposition on a submerged platform or promontory, isolated from terrigenous input. The Eratosthenes Seamount area was probably then still located well to the south of areas of Tethys that experienced ophiolite emplacement and active margin deformation in the latest Cretaceous (Campanian-Maastrichtian; Şengör and Yilmaz, 1981).

Middle Eocene pelagic carbonate accumulation was followed by shallow-water carbonate deposition. The carbonates accumulated in a near-reef, platform setting and are dated as early Miocene at Site 967, on the basis of benthic foraminifera (I. Premoli-Silva, 1995, personal commun.). Water depths must have decreased by more than several hundred meters between the middle Eocene and the Miocene, which implies that surface tectonic uplift of the Eratosthenes Seamount must have taken place, in addition to the effects of any eustatic sea-level change. This uplift is not likely to have been collision-induced, because the subsequent Miocene shallow-water deposition took place under relatively tectonically stable conditions, but it could instead reflect tectonic movements related to an earlier history of subduction. Regional and local evidence (e.g., in Cyprus and Crete) suggests that the present-day Africa-Eurasia plate boundary was already in existence in the eastern Mediterranean by the Miocene (Dewey and Şengör, 1979; Şengör et al., 1985; Robertson et al., 1991; Meulenkamp et al., 1994).

During the Messinian salinity crisis, shallow-water marine deposition on the Eratosthenes Seamount gave way to erosion and/or local accumulation of gypsum and ferruginous muds in small marginal lagoons and/or lakes, as recorded at Sites 965 and 967 (Fig. 5). By contrast, a much thicker (~150 m) succession of inferred Messinian age was deposited at Site 968 on the lower Cyprus slope. This was probably deposited in a large lake or inland sea, well below eustatic sea level. The existence of Messinian lakes was previously inferred in the western Mediterranean Tyrrhenian Sea (Kastens, Mascle, et al., 1990).

Distinctive matrix-supported breccias occur between underlying shallow-water carbonates and overlying nannofossil oozes of early Pliocene age at Site 966. They formed by mainly mass-flow processes during the early Pliocene (pre–4.5 Ma). The source of many of the clasts was a shallow-water limestone, similar to the underlying succession. Pliocene accumulation took place in a relatively deep-marine setting (more than several hundred meters), based on microfossils in the matrix. Erosion of the limestones that are redeposited as clasts in the lower Pliocene might have been subaerial, subaqueous, or both, but there is little evidence of clast rounding via sedimentary transport. A tectonic fabric present within several clasts could suggest derivation from a faulted rock (e.g., an erosional fault scarp). The presence of nannofossil mud clasts also indicates that deep-marine sediments were reworked in an unstable slope setting.

The Pliocene-Pleistocene successions at each site are composed of nannofossil oozes interbedded with calcareous muds, numerous sapropels, and minor volcanic ash. The Eratosthenes Seamount sites (Sites 965, 966, and 967) are now at water depths ranging from 700 to 2900 m. These differences in water depth are the result of differential subsidence of the seamount area. Much of this subsidence took place relatively rapidly. The early Pliocene sediments accumulated in deep water, without evidence of a gradual upward transition from shallow-water conditions. Benthic foraminifers indicate a further deepening after the late Pliocene, at least at Site 967.

TECTONIC MODEL OF COLLISION AND OPHIOLITE EMPLACEMENT

The new information obtained by drilling can be used to test and substantiate a model of incipient collision and ophiolite emplacement. The tectonic model to be tested maintains that, following a more than 85 m.y. evolution

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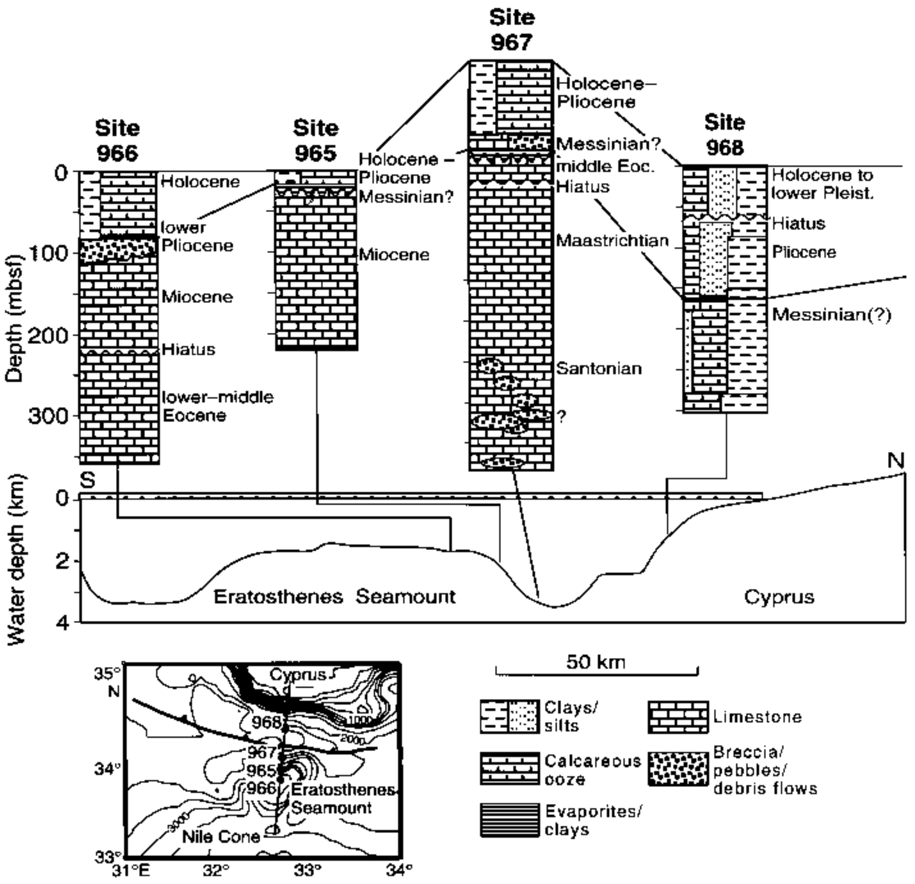


Figure 4. Summary of the successions drilled on the Eratosthenes Seamount and lower slope of the Cyprus margin. Lower left: Simplified bathymetry of the transect area.

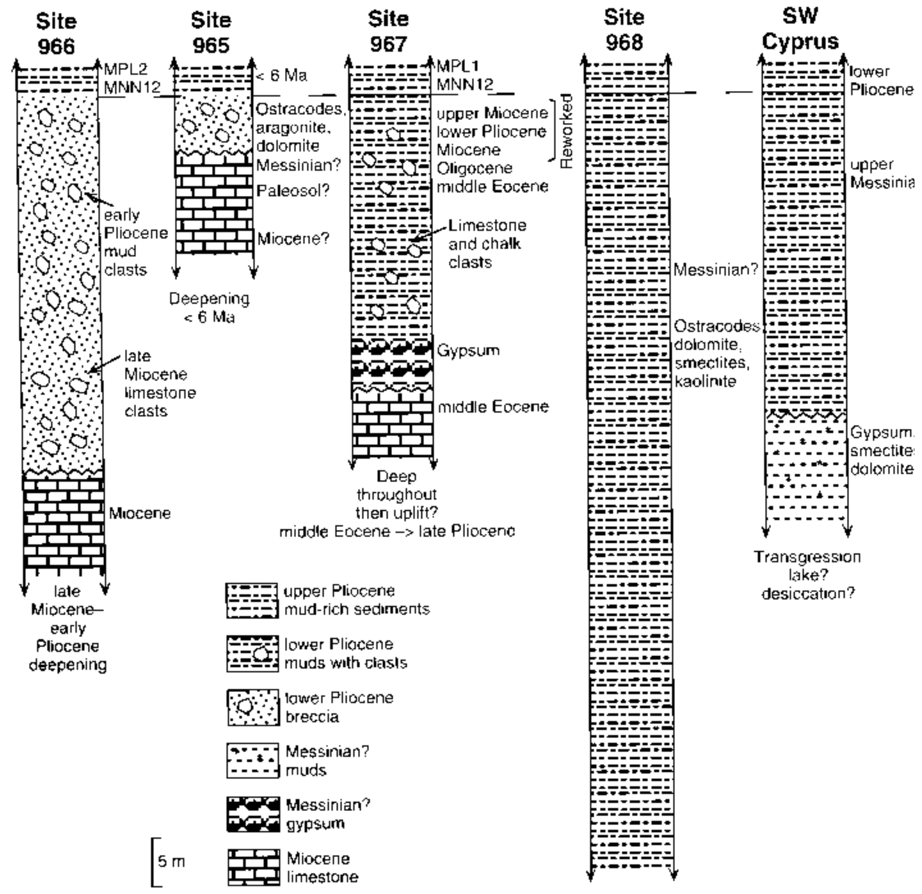


Figure 5. Logs summarizing only (from south to north) the mainly Messinian and lower Pliocene intervals of successions recovered during Leg 160. Southwest Cyprus is added for comparison (Orszag-Sperber and Elion, 1989). Rapid subsidence of the Eratosthenes Seamount took place during the early Pliocene, associated with mass wasting and fault activity (Sites 966, 965, 967). Site 968 on the lower Cyprus slope and onshore Cyprus, however, documents a contrasting sedimentary and tectonic history (see text).

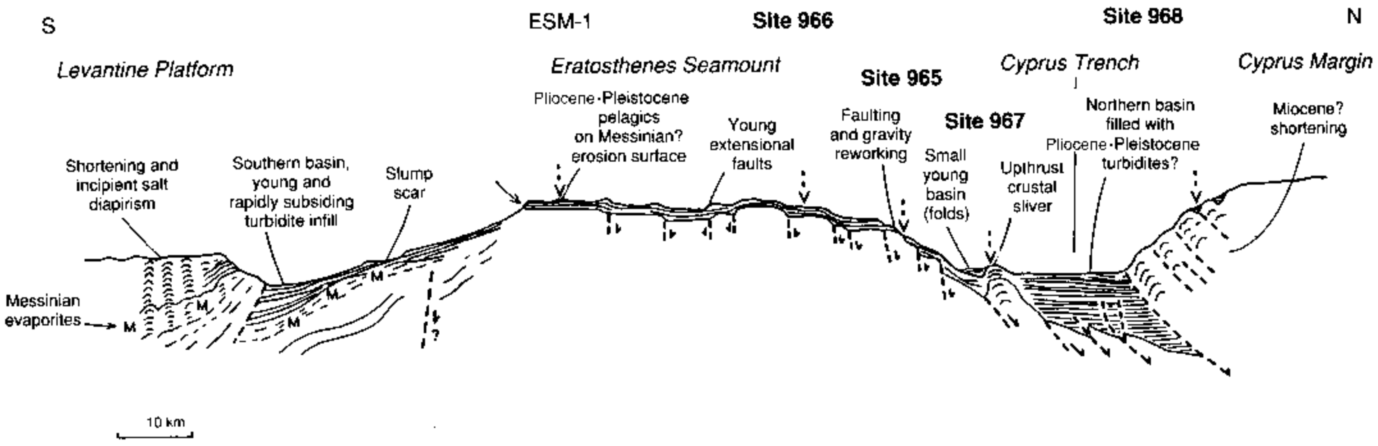


Figure 6. Tectonic model of collision and ophiolite emplacement prior to Leg 160 drilling (Limonov et al., 1994; Robertson et al., 1994, 1995). The Eratosthenes Seamount is being thrust beneath the Troodos ophiolite to the north. The seamount plateau area is undergoing load-induced extensional faulting. There is a transition from extensional tectonics in the south to shortening in the north. This model was tested and substantiated during Leg 160. In addition, the interpretation of the seismic profiles suggests that the Eratosthenes Seamount is also being thrust beneath the Levantine platform to the south, an aspect that was not investigated during Leg 160.

Figure 7. Plate tectonic model of the evolution of the Eratosthenes Seamount in relation to Cyprus. A: The Troodos ophiolite formed possibly above an earlier north-dipping subduction zone. The Eratosthenes Seamount is shown as a rifted marginal continental fragment of the North African plate. B: The northern plate was strongly deformed in middle to late Eocene time, while Eratosthenes was unaffected. C: Northward subduction in the Miocene was reflected in supra–subduction zone extension in Cyprus. Eratosthenes was uplifted and overlain by shallow-water carbonates. D: Eratosthenes was emergent during the Messinian salinity crisis, and initial collision with Cyprus possibly began. E: The Eratosthenes Seamount was thrust beneath the Troodos ophiolite, triggering surface uplift and relative southward displacement, accompanied by serpentinite diapirism.

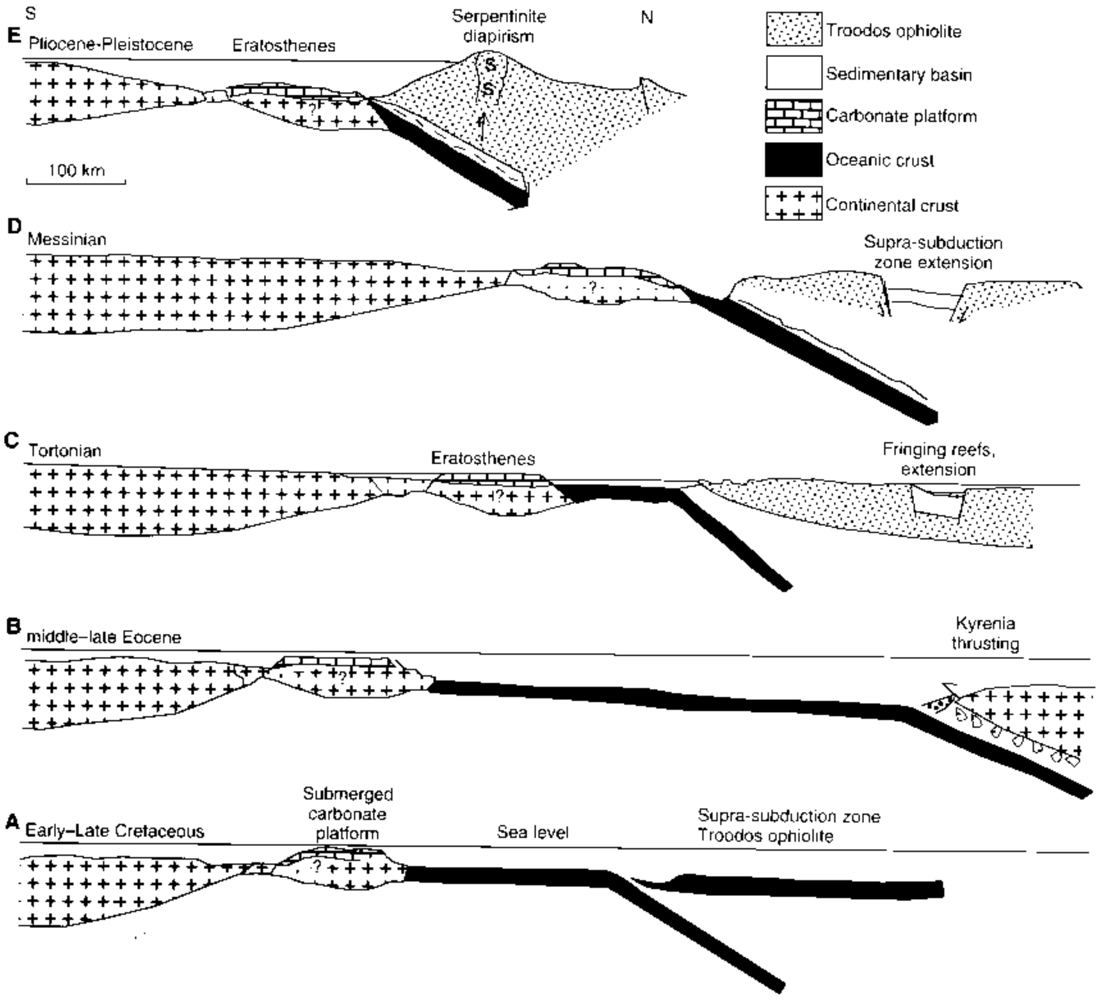
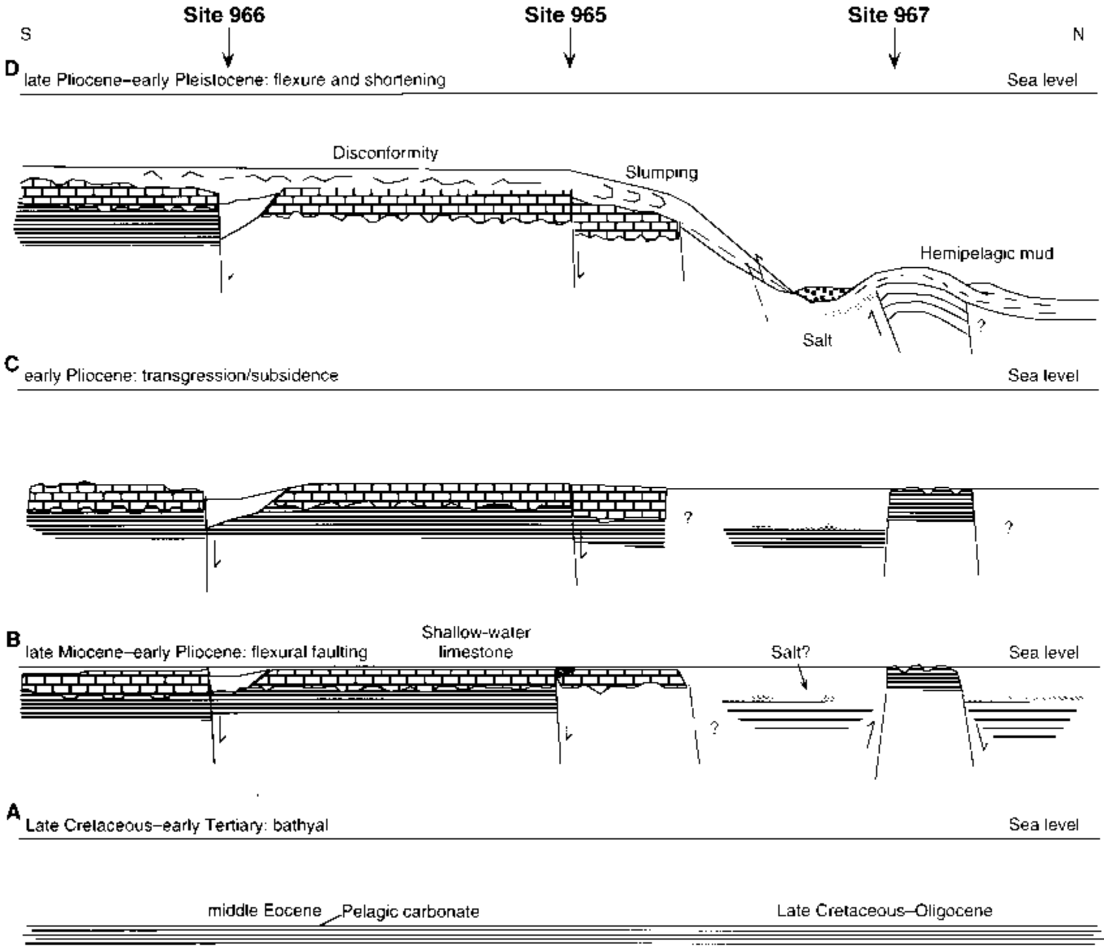


Figure 8. Inferred tectonic history of the northern margin of the Eratosthenes Seamount. A: A stable bathyal carbonate-depositing setting. B: Flexurally induced faulting related to onset of collision and the start of southward ophiolite emplacement, probably during the Messinian salinity crisis. C: Subsidence continued following the end of the Messinian salinity crisis. D: The northern extension of the Eratosthenes Seamount collapsed as a result of flexural loading by the overriding Troodos ophiolite, with a switch to shortening in the north.



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as part of the passive margin of Gondwana, the Eratosthenes Seamount is being thrust beneath the Troodos ophiolite to the north. Related to this collision there is a transition from extensional tectonics and collapse of the Eratosthenes Seamount in the south, to shortening in the north, beginning near the lower northern slope of the Eratosthenes Seamount (Fig. 6; Limonov et al., 1994; Robertson et al., 1994, 1995). The new information gained during Leg 160 largely substantiates this model (Fig. 7).

Evidence of Load-induced Subsidence

The Eratosthenes Seamount is inferred to have collided with the active margin of the Eurasian plate to the north, including Cyprus, resulting in subsidence and collapse of the seamount. An exponential increase in subsidence rate with time would be predicted theoretically, as in the case of foredeeps associated with thrust and nappe emplacement in mountain belts (e.g., Beaumont, 1981; Stockmal et al., 1986; Whiting and Thomas, 1994). The paleontological evidence indicates that rapid subsidence of the Eratosthenes occurred in the early Pliocene, and it may have begun earlier (Fig. 8). In addition, the early Pliocene matrix-supported breccias at Site 966 are indicative of masswasting and accumulation on relatively steep submarine slopes.

Evidence of Related Faulting

Interpretation of seismic data suggests that the northernmost part of the Eratosthenes Seamount is now thrust beneath Cyprus, including the overriding Troodos ophiolite (Limonov et al., 1994; Robertson et al., 1994, 1995). The seamount thus forms the footwall of an overriding thrust load. To what extent did the footwall deform by faulting during load-induced collapse? This is a current question for many on-land foredeep settings (e.g., Alps and Himalayas). If the effects of thrustloading exceeded the flexural rigidity of the crust, then normal faulting would be anticipated. The incoming Eratosthenes slab represents old (Mesozoic or older) crust that would be expected to behave in a relatively rigid manner, on theoretical grounds (Stockmal et al., 1986). Nevertheless, flexurally induced faulting can be facilitated by preexisting zones of structural weakness in crust of any age.

Seismic evidence indicates that the plateau area of the Eratosthenes Seamount is currently tectonically active. A set of roughly east-west-oriented fault zones, up to several hundred meters wide, cuts the uppermost Pliocene-Pleistocene sedimentary strata. Some of these faults exist as large open cracks on the seafloor. Several of the faults on the Eratosthenes Seamount plateau predate accumulation of the Pliocene-Pleistocene deep-sea sequence. These faults are interpreted to represent the result of flexurally induced faulting (Limonov et al., 1994; Robertson et al., 1994, 1995). Seismic data also suggest that a small ridge at the base of the lower northern slope of the Eratosthenes Seamount is underlain by a northward-dipping fault zone (a reverse fault or thrust; Fig. 6). Both this ridge and the adjacent lower slopes of the Eratosthenes Seamount appear to be undergoing tectonic shortening. The ridge is apparently being detached from the downgoing Eratos-

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thenes Seamount and is being accreted to the overriding thrust wedge. The seismic evidence is interpreted to reflect a switch from flexurally induced normal faulting in more distal (i.e., southerly) areas of the footwall, to shortening in areas closer to the overriding thrust load (i.e., more northerly).

Drilling during Leg 160 provided additional evidence in support of the role of faulting in collision-related deformation of the Eratosthenes Seamount, as follows: (1) Evidence of predominantly extensional faulting is present in the Upper Cretaceous and middle Eocene sequences drilled at Site 967, and to a lesser extent in the middle Eocene sequences recovered at Site 966. For example, numerous small normal faults are present within well-cemented limestone. Unfortunately, the timing of fault movement cannot be determined. (2) Extensional faulting was probably active in generating the highly immature matrix-supported breccias of early Pliocene age at Site 966. (3) At Site 965, Pliocene-Pleistocene nannofossil muds and oozes show evidence of widespread slumping and reworking as debris flows that may have been triggered by faulting. This area today forms part of the steep upper slopes of the Eratosthenes Seamount and is bounded by large normal faults; these faults may have had an earlier history of movement that was reflected in sediment instability. (4) Fine-grained mud turbidites in the upper part of the sequence at Site 966 may reflect tectonically induced redeposition from within the plateau area. In addition, drilling at Site 967 penetrated 700 m into the small compression-induced basement ridge mentioned above. The recovered section ends with a tectonic breccia that is mainly composed of limestone. Geophysical logs (e.g., Formation MicroScanner) suggest that numerous zones of deformation and brecciation are present within the Upper Cretaceous and middle Eocene intervals at Site 967. At present, it seems likely that Site 967 had a complex tectonic history that may have involved, first, flexure-related extensional faulting resulting from thrust loading of the Eratosthenes Seamount, and then large-scale compressional deformation and local surface uplift related to underthrusting beneath the overriding slab.

Link with Ophiolite Emplacement

Load-induced collapse and underthrusting of the Eratosthenes Seamount was generally synchronous with emplacement of the Troodos ophiolite (Fig. 9). The collapse and underthrusting of the footwall represented by the Eratosthenes Seamount took place from early Pliocene (or late Miocene?) to Pleistocene time, whereas the main uplift of the Troodos ophiolite occurred in the late Pliocene and Pleistocene (McCallum and Robertson, 1990; Poole and Robertson, 1992). The two events are clearly inextricably linked. However, in detail, strong surface uplift of the Troodos ophiolite appears to have been delayed up to several million years after collapse of the Eratosthenes Seamount began. This could reflect a time delay during which sufficient crustal thickening took place at depth to promote buoyant uplift of the overriding ophiolite. However, it seems unlikely that uplift of the Troodos ophiolite was driven by collisional processes alone. Modeling of gravity data has revealed that the Troodos ophiolite has a deep-rooted serpentinite core (Gass and Masson-Smith, 1963). Moores and Vine (1971) related the uplift of the Troodos ophiolite to the effects of diapiric protrusion of serpentinite. Ultramafic rocks of the lower levels of the ophiolite sequence were hydrated and rose diapirically, uplifting the ophiolite. It is now known that this event took place in the context of collisional deformation within a large area of the eastern Mediterranean (e.g., the Kyrenia Range of northern Cyprus and onshore southern Turkey). In summary, documentation during Leg 160 of the breakup and subsidence of the Eratosthenes Seamount as a result of collision between the African and Eurasian plates clearly links these events with emplacement and uplift of the Troodos ophiolite.

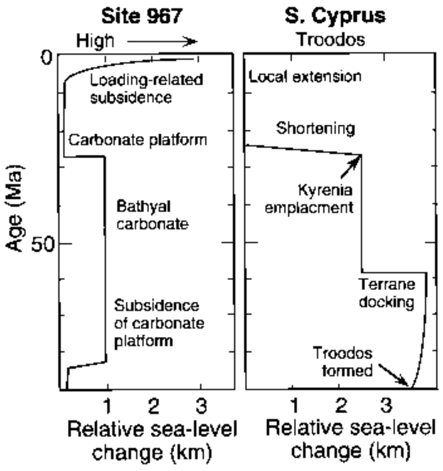

Figure 9. Indication of relative sea-level change through time. A: Site 967 on the Eratosthenes Seamount. B: Southern Cyprus (data from Robertson et al., 1991). The timing and extent of relative sea-level change differs, reflecting locations on different plates until the Pliocene-Pleistocene, when the Eratosthenes Seamount and the Troodos ophiolite began to collide.

CONCLUSIONS

Drilling during Leg 160 indicates that one of the world's most accessible and best documented ophiolites is in the process of active tectonic emplacement. This active emplacement is accompanied by loading and collapse of the footwall, represented by the Eratosthenes Seamount to the south of Cyprus. This collapse is accompanied by widespread extensional faulting that developed in response to crustal flexure ahead of the advancing thrust load. The collapse and ophiolite obduction are taking place in a zone of incipient collision between the African and Eurasian plates. The tectonic processes documented during Leg 160 may thus help us to understand tectonic processes associated with ophiolite obduction and the early stages of collision in many other mountain belts.

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GSA International Division Seeks Funds

Pinar O. Yilmaz
President, International Division

Although few in numbers, GSA International Division members are an active group. The division is cosponsoring Theme Session 2, Geology and Tectonics of the Caribbean Region, at the GSA Annual Meeting in New Orleans. The session is on Tuesday, November 7. We believe that this kind of international exchange of ideas broadens our knowledge and gives us new insight into geoscientific problems. Travel costs for speakers from the Caribbean are funded by the International Division, the GSA Foundation, and Exxon Production Research Company.

Because it is relatively new and still small, the International Division has not yet reached a level of funding that would give it access to matching funds from the GSA Foundation. Therefore, the Division is requesting contributions, to supplement the dues paid by its members. These contributions will be used as part of the funding for symposiums at GSA annual meetings, to pay travel costs for non–North American speakers. All contributors will be listed in the symposium flyers. See the accompanying coupon, or contact Pinar Yilmaz at (713) 423-7465, fax 713-423-7719.

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Boulder, CO 80301
(303) 447-2020

International Division Award Fund

☐ Enclosed is my contribution in the amount of $__________ for the International Division Award Fund.

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