Images may show start of European-African plate collision

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Aspects of the initial stages of a collision between European and African plates may have been documented in a geophysical survey of the central Mediterranean Ridge (MR) conducted last year. The idea of an incipient collision was first suggested by Finetti [1976], and details of the seafloor and tectonic deformation along the MR, revealed for the first time in the survey, seem to point in that direction.

A unique opportunity may therefore exist for studying the beginnings of such a collision—between the passive margin of a major plate (Africa) acting as a continental indenter against the active margin of another plate (Europe). More wide angle data, deep penetrating multichannel seismic data, and drilling data are crucial to better assess the nature and the architecture of the underlying lithosphere, the styles of sedimentary deformation, and the consequences on fluid releases. Such data will make it possible to establish, or reject, a geodynamic collision model.

The ridge is a large accretionary prism between Africa and southern Europe (Figures 1a and 1b), and the research was known as the Mediterranean Accretionary Prism (Prismed II) survey. The data so far demonstrate clear differences in seafloor morphology and elevation and a strong contrast in structures and sedimentary architecture of the MR east and west of ~24°0'E (Figure 1b). The region to the east has an average water depth of 2400 m, and its outer domain consists of an eastward widening folded belt cross cut by a conjugated faults system (Figure 2).

The region to the west involves the possible incipient collision of the plates. It lies just north of the Cyrenaica promontory on the African continental margin and has an average water depth of just 1700 m. Undulating structural trends were observed there that approximately parallel the southern MR front along the African slope more than 60 km away (Figure 2). It is these observations that suggest that the western part of the MR is being affected by the onset of a collision between the Cyrenaica-Africa continental margin (acting as an indenter) to the south and the underlying thinned edge of the Cretan margin to the north.

The data also illustrate a widespread occurrence of mud volcanoes and mud flows, particularly along the northern MR border (Figure 2). These features are not randomly distributed but appear closely related to backthrusting, transcurrent faulting, and regional backstop widening.

Prismed II was designed to investigate, with full bathymetric coverage, areas that were thought to represent different structural settings and major sedimentary and tectonic processes that compete to imprint and shape the seafloor of the eastern Mediterranean. The survey was conducted in February 1998 aboard the R/V *l'Atalante*, an Institut Francais de la Recherche pour l'Exploitation de la Mer (IFREMER) ship.

In three dimensions, as well as in plan shaded views and on acoustic imagery (Figures 1b, 2, and 3), the surveyed area clearly shows several major provinces, well characterized by distinct bathymetric features and trends, and contrasted backscatter signatures. Seismic data also show strongly contrasted structures. There are three recognizable main domains: the African continental slope to the south, the southern Crete margin and bordering trench system to the north, and the MR in the middle.

The Mediterranean Ridge

From both bathymetry and backscatter intensity, several morphostructural domains characterize the seafloor and subbottom of the MR. An outer domain corresponds to a progressively eastward developing folded belt, marked by elongated zones of alternatively high and weak backscatter clearly correlatable with seafloor features detected on bathymetry (Figures 2 and 3). This domain is disconnected from the Libyan margin by narrow, almost linear, northwest-southeast oriented deeps.

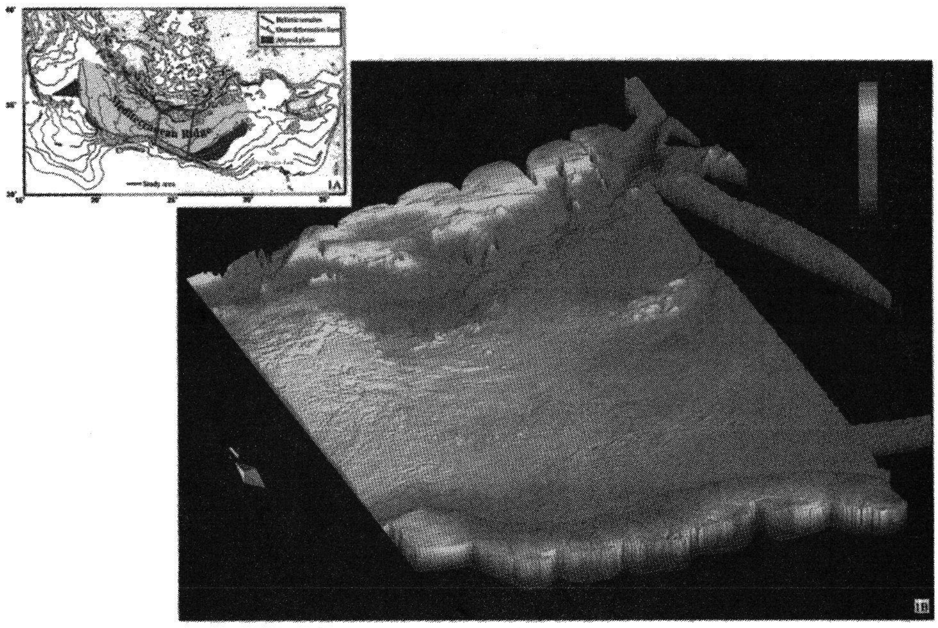

Fig. 1. a) Location of the surveyed area in a general geodynamic framework of the eastern Mediterranean Sea. b) A three-dimensional perspective view of the surveyed area, between the Libyan continental slope to the south and the southern Crete margin to the north. The area covers a surface of approximately 50,000 km^2. Original color image appears at the back of this volume.

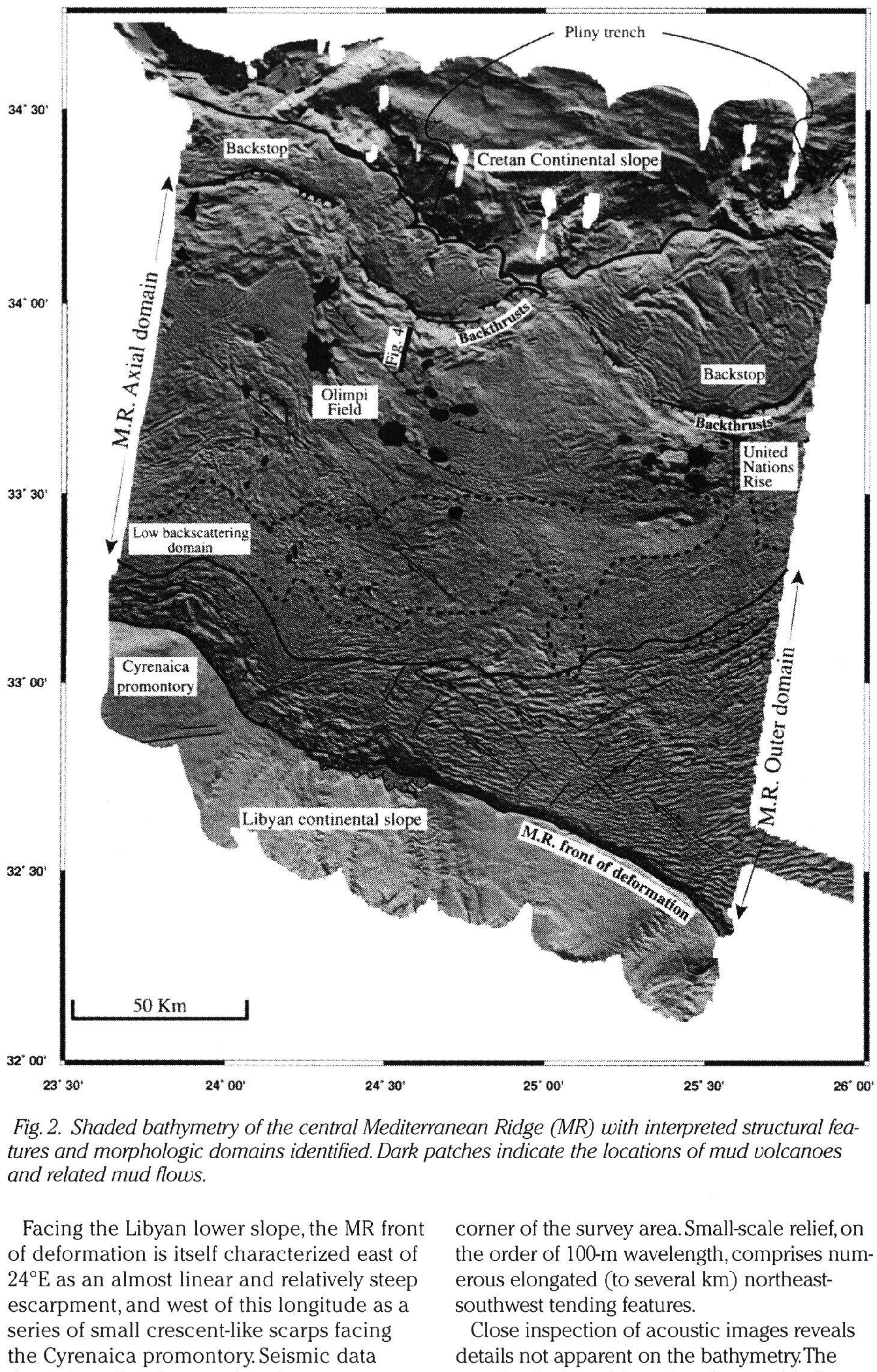

Fig. 2. Shaded bathymetry of the central Mediterranean Ridge (MR) with interpreted structural features and morphologic domains identified. Dark patches indicate the locations of mud volcanoes and related mud flows.

Facing the Libyan lower slope, the MR front of deformation is itself characterized east of 24°E as an almost linear and relatively steep escarpment, and west of this longitude as a series of small crescent-like scarps facing the Cyrenaica promontory. Seismic data show these last features forming a narrow belt of stacked thrusts and accompanying small piggyback basins with frontal sedimentary slumps [*Chaumillon and Mascle*, 1997]. Just north of this area the seafloor surface of the outer MR displays important bathymetric trend variabilities and forms irregular, curved trends, the more pronounced of which appear to closely follow the curvature of the nearby southern African continental slope (Figure 2).

The outer domain widens from a few kilometers, at 24°E, to about 80 km in the southeastern corner of the survey area. Small-scale relief, on the order of 100-m wavelength, comprises numerous elongated (to several km) northeast-southwest tending features.

Close inspection of acoustic images reveals details not apparent on the bathymetry. The most intriguing of these is a dense grid of conjugate lineaments cross cutting most of the eastern, triangular, outer domain (Figure 2). These seem to be a dense network of faults of very low relief, and our hypothesis is that their strong acoustic backscatter may result from fluid release and related development of scattered carbonate crusts along the fault paths. The fold system, which evidently affects Messinian deposits, shows a progressive eastward increase in amplitude and wavelength as a direct consequence of an increasing thickening of the recent sedimentary cover as indicated from previous multichannel seismic data [*Chaumillon and Mascle*, 1997].

The various important contrasts in the morphological characteristics of the axial domain east and west of 24°E include the following. To the east, the seafloor is a very gentle surface with only small and subdued features. To the west, besides being significantly shallower, the seafloor is rougher and more complex, and includes elongated and curved features as well as north-south structural trends.

Incipient Collision Reflected

Most of the bathymetric features of the western outer domain appear to partly reflect trend variations detected along the southern MR front and along the African slope more than 60 km away. Running north-south along longitude 24°10'E are a series of en echelon features, which seem to be indicative of a dextral transcurrent motion.

Taken together then, these observations imply that the central MR west of this longitude reflects an incipient collision characterized by increasing sedimentary deformation and probable crustal faulting, formed by indentation of the Cyrenaica promontory. In this view, the structures mapped east of 24°E would be chiefly the result of oblique convergence active on a thick pile of pre-Messinian, evaporite bearing Messinian and Pliocene to Quaternary sediments [*Chaumillon and Mascle*, 1997].

Most of the southern part of the axial domain is nearly homogenous acoustically, with the exception of scattered patches and higher backscatter trends that can be correlated with bathymetric features (Figure 3). On seismic data this region is seen as an almost reflection-free area, with the exception of narrow tectonic corridors (thrusts and wrench zones).

This intriguing observation, the absence of any significant relief (with the exception of a belt of potential small mud cones), and very weak backscatter remain difficult to understand. Either deformation is concentrated into narrow tectonic corridors or, more speculatively, the sedimentary pile, being strongly compressed, may be releasing a large amount of fluids which, in turn, might tend to homogenize subbottom acoustic reflection. Perhaps both are the case.

The northern edge of the axial domain is characterized by large-scale, crescent-like relief expressed in a series of elongated basins and bordering highs (Figures 2 and 3). This relief is similar to features seen in the western branch of the MR [*Lallemant et al.*, 1994] and is believed, from both morphology and seismic data, to delineate a general backthrusting of the MR against its probable backstop domain.

Bordering Continental Margins

To the south of the studied area, the African continental slope appears, on seismic data, as

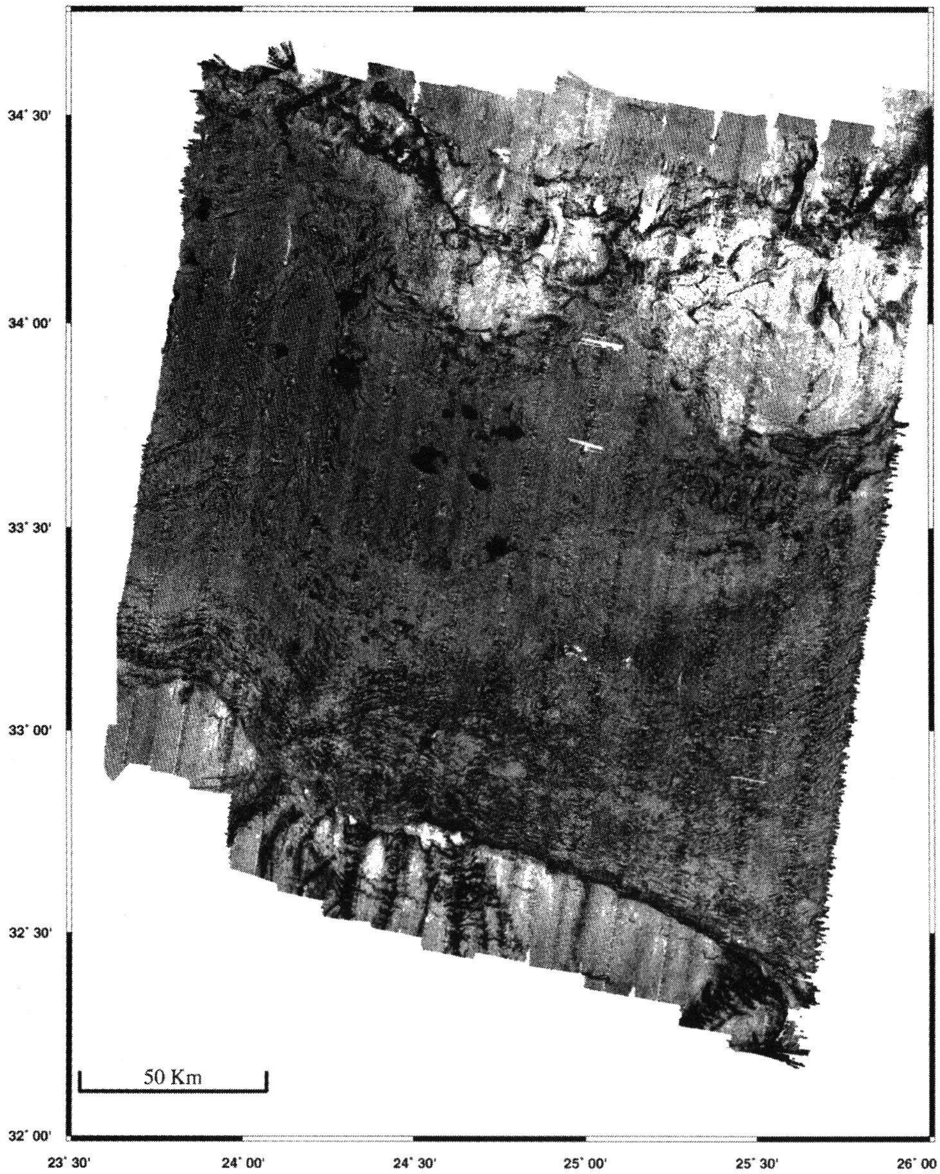

Fig. 3. Backscatter image of the surveyed area. Darker shades indicate higher backscatter. The mud volcano fields are seen as areas of very high backscatter in the northern part of the otherwise weak backscattering axial domain of the Mediterranean Ridge.

a thick wedge of subhorizontal units, either slightly tilted toward the south, west of 24°E, or gently inclined northward elsewhere. In many areas, and particularly in the southeastern corner, these units may be distinguished northward to a distance up to 30 km beneath the overriding deformed wedge of MR sediments. Just east of 24°E, where the margin is offset toward the north by more than 50 km in an almost north-south direction (Figure 1b), the slope is cut by deep canyons. In this area, which corresponds to the eastern submerged border of the Cyrenaica promontory, evidence of recent northeast-southwest trending faulting (underlined on Figure 2) can be detected, chiefly on acoustic imagery, over more than 20 km.

The Cretan continental slope, at the northern end of our survey, is formed by a series of high-standing massive blocks bounded by fault-controlled steep cliffs, and slope basins. North-south slope directions are common, especially along massive promontories that divide the southern bounding Pliny trench into a series of narrow depressions (Figure 2). The main morphological trends are, however, similar to those of the Pliny trench. In most of the survey area, this deep trench defines the base of the steep Crete island continental slope, with a series of deep, almost disconnected, en echelon troughs along a general northeast-southwest trend.

West of 24°30'E, however, the Pliny trench progressively vanishes to be replaced by shallower and very narrow depressions oriented roughly northwest-southeast between the base of the continental slope and deep, poorly reflective areas made of gentle relief slightly inclined northward. This last region is broken either by local important relief (in the western area) or by an irregular pattern of isolated depressions (Figure 2) and contains a relatively thick recent cover above a reflector similar to that of the Messinian (M reflector of Ryan et al. [1973]).

Like Lallemant et al. [1994] and the Innovative Mediterranean Ridge Seismic Experiment Working Group [1998], we believe the crust of this last domain may be made of a relatively thin superposition of former alpine tectonic napes and might constitute a thin continental backstop, progressively deforming and tilting northward. As a consequence, the post-Miocene cover of this area might be gliding northward using the underlying Messinian evaporites as a decollement level. This may explain its morphological features, such as apparent flow structures and extensional fissures and the slightly curved and gentle slope segments facing the disconnected deep troughs that constitute the Hellenic-Pliny trench system.

Seismic data are of little help to better define the geological structure of Pliny trench and associated troughs. They do not show evidence of thick sediment infill nor of typical Messinian units. We are inclined therefore to interpret the trench as a very young feature that has developed as a kind of active transform crustal boundary between a thick and rigid pile of tectonic units related to the previous alpine orogen and a southern, thinner, continental backstop of the Mediterranean ridge.

Both the African and Cretan continental margin segments, as well as the probable backstop just north of the MR, are rather weak backscatter zones (Figure 3). Areas of steep slopes are exceptions to this general observation—for example, where canyons cut across the African slope or the rugged relief of the upper Cretan margin.

Mud Volcanoes

The northern sector of the MR axial domain contains numerous subcircular features several kilometers in diameter and a few hundred meters in elevation. These are concentrated mostly in two regions, which exhibit very high backscatter. Comparison with bathymetric data indicate that these high backscatter images correspond to mud volcanoes and their mud flows that have previously been identified as the Olimpi mud volcano field [*Camerlenghi et al.*, 1992] and the United Nations field [*Limonov et al.*, 1999] (Figures 2 and 3).

Our data indicate a more widespread occurrence of mud volcanoes in these regions than previously known. Moreover, our results demonstrate that mud volcanoes are not randomly distributed. The majority occur, as suggested prior to the survey [*Robertson et al.*, 1996], in close relationship with backthrusting. For example, Figure 4 shows the genetic relationship between the plane of one of these backthrusts and one of the newly discovered mud volcanoes.

Our data show, however, that the two main fields (Olimpi and United Nations) are lo-

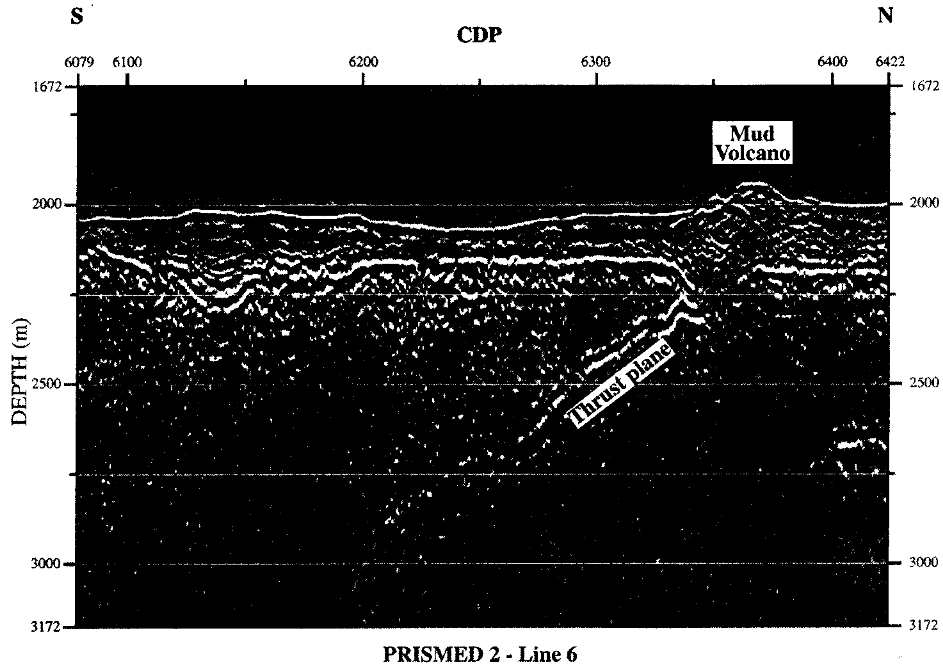

Fig. 4. Processed seismic line (see location in Figure 2) across the Mediterranean Ridge backthrust area showing the genetic relationship between mud volcano and inferred thrust plane.

cated just where the inferred backstop extends farther to the south. This suggests a regional increase of mud and fluids being forced upward to the seafloor as a consequence of increasing internal pressure in the MR. The acoustic images also suggest that emplacement of some mud volcanoes, such as the ones delineating a north-south trend along longitude 24°E, might be related to mechanisms other than backthrusting, such as transcurrent faulting.

In this case mud volcanoes are seen in the bathymetry not as cones, but rather as irregular and subdued hills. In the acoustic imagery they are seen as irregular patches of high backscatter up to 15 km in breadth, with variable degrees of backscatter intensity. As did Volgin and Woodside [1996], we interpret such backscatter variability as a consequence of superposition of successive mud flow events, the latest flow being characterized by highest backscatter.

Bathymetry, Backscatter Images Mapped

During the Prismed II survey the seafloor bathymetry and backscatter images were mapped at 10 knots (approximately 18.5 km/h) using a multibeam system with 162 beams, providing 150° angular coverage, which typically provided swath coverage of ~15 km by an average water depth of 2200 m. The bathymetric data resolved seafloor details of horizontal and vertical scales as small as 20 m. Backscatter data can image features at approximately half that size. Following processing both onboard and in laboratory, using recently developed software CARAIBES from IFREMER, the backscatter data (Figure 3) was correlated with the bathymetry to assist in the subdivision and interpretation of various contrasting terrains.

The seismic system included two GI 75 airguns with a total volume of about 2.45 liters and a firing rate of 10 s and a six-channel streamer, all towed at 7 m depth. The data were filtered with a band pass of 10/15-120/150 Hz. The seismic data were processed onboard. Continuous 3.5 Khz profiling, gravity, and magnetic measurements were also collected. All systems were operated by an IFREMER-Genavir technical team.

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Authors

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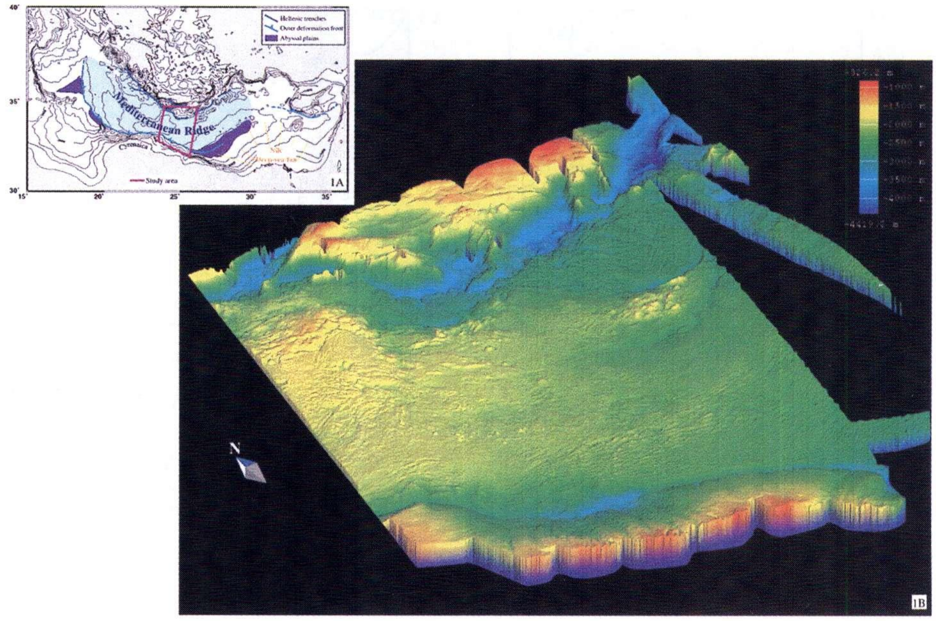

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