OCEAN DRILLING PROGRAM

LEG 161 SCIENTIFIC PROSPECTUS

MEDITERRANEAN SEA II - THE WESTERN MEDITERRANEAN

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This Scientific Prospectus is based on pre-cruise JOIDES panel discussions. The operational plans within reflect JOIDES Planning Committee and thematic panel priorities. During the course of the cruise, actual site operations may indicate to the Co-Chief Scientists and the Operations Superintendent that it would be scientifically or operationally advantageous to amend the plan detailed in this prospectus. It should be understood that any proposed changes to the plan presented here are contingent upon approval of the Director of the Ocean Drilling Program in consultation with the Planning Committee and the Pollution Prevention and Safety Panel.

ABSTRACT

Leg 161 represents the second in a two-leg program to investigate (1) the tectonic history of the Mediterranean Sea and (2) the origin of sapropels, laminated organic-rich layers deposited in the Eastern Mediterranean Basin. Leg 161 will focus upon the tectonic evolution of the Alboran Sea, a typical "Mediterranean backarc basin," and the paleoceanography of the Western Mediterranean.

The cause of the extension in basins such as the Alboran Sea Basin, and the rapid evolution of a collisional zone into superimposed regions of extension and adjacent contraction, has not yet been adequately explained, and the Alboran basin presents an ideal situation to investigate competing hypotheses. The Neogene extensional basin beneath the Alboran Sea developed behind an arc-shaped mountain belt and is located on the site of a late Cretaceous/Paleogene orogen generated from collisional stacking. The region straddles the boundary between the European and African plates which converged during the Neogene; the basin thus formed in an overall environment of plate convergence. During the Miocene, the migration of the arcuate mountain front may have been nearly coeval with extension in the inner part of the arc that resulted in crustal attenuation and basinal spreading on the Alboran Domain. The basin formed from early Miocene onward, whereas, outside the arc, the thrusting processes continued.

Three proposed sites (Alb-2, Alb-3A, and Alb-4A) and corresponding alternate sites (Alb-2A, Alb-2B, Alb-3, and Alb-4) have been chosen to determine the origin and tectonic evolution of the basin. Petro-structural and petrological studies, of the predicted-metamorphic basement rocks on a structural high in the Western Alboran Basin (proposed site Alb-2) will help to determine the history of convergent tectonism, and to which particular crustal domain, or units within those domains, the basement belongs. Combining drill results regarding the timing of later tilting and uplift of the basement high in the Western Alboran Basin (proposed site Alb-2), and the syn-rift and post-rift subsidence in the Eastern Alboran Basin (proposed site Alb-4A), with seismic and commercial well data will allow us to determine the magnitude of the extension and the relative proportions of syn-rift to post-rift subsidence in the basin. The nature of the postulated late Miocene to Holocene contractional reorganization that produced folding, strike-slip faulting, block rotation, and pull-apart-type structures in the basin will be tested by drilling in the Eastern and Southern Alboran Sea (proposed sites Alb-3A and Alb-4A).

The transect of Leg 160 and Leg 161 sites across the entire Mediterranean will be drilled during Leg 160 and Leg 161 to determine the history of water- mass circulation and the influence of monsoon-driven atmospheric forcing on Mediterranean climate. This Mediterranean-wide drilling program is needed to establish a database that will allow synoptical mapping of hydrographic and climatic conditions throughout the Mediterranean. Leg 160 will core the easternmost sites of sapropel formation in the Mediterranean Sea (proposed sites MedSap-2, -3, and -4), and Leg 161 will concentrate on sampling the westernmost occurrence of sapropels and areas in the western part of the basin, where no sapropels formed. The primary paleoceanographic goal of Leg 161 is to document the history of water-mass circulation and hydrographic variability in the Western Mediterranean as a function of climate change and atmospheric forcing back to Pliocene/Miocene times. High-resolution geochemical and sedimentological profiles are needed at the different drill sites to determine hydrographic and geochemical gradients between the Eastern and Western Mediterranean, from which potential flow patterns and geochemical balances between the eastern and western basins will be inferred. This will eventually enable us to decipher the Mediterranean-wide hydrographic changes, which must have occurred during times of sapropel formation in the east.

INTRODUCTION

Extensional Basins in Collisional Settings: the Scientific Problem

Much of the Mediterranean region is underlain by Neogene extensional basins that are located on the sites of Late Cretaceous to Paleogene orogens generated by collisional stacking (Fig. 1). These basins are surrounded by highly arcuate thrust belts that were active before and during the extension that formed the basins. The basins are in some ways analogous to the marginal basins of the Western Pacific and Western Atlantic oceans, which formed by extension in island arc/trench systems, but they differ in several important respects: the basins are smaller, mostly floored by extended continental crust, and, in several cases, are surrounded by predominantly intra-continental convergent arcs. These attributes characterize the so-called "Mediterranean backarc basins" (Horvath and Berckhemer, 1982). The Aegean and southern Tyrrhenian basins are marginal basins that they lie above clearly defined subduction zones and behind an active island arc (the Aeolian and Hellenic arcs). In fact, the Tyrrhenian Basin may be locally floored by quasi-oceanic crust (Kastens et al., 1987). The evolution of the North Balearic Basin may also have been analogous to Western Pacific backarc basins: it is generally accepted that the Paleogene-Neogene extension of the North Balearic Basin (Ligurian Sea), the anti-clockwise rotation of Sardinia, and the subduction of residual Mesozoic Tethyan oceanic crust beneath the island occurred contemporaneously. In contrast, the northern Tyrrhenian Sea, the Pannonian Basin, and the Alboran Sea, show no clear geophysical evidence to support subduction of oceanic lithosphere during the period of extension in the basin. There are significant variations in the directions of extension in the basins and in the direction of relative convergence in the surrounding arcs, and they show no clear or direct relationship to the overall relative motion of the African and Eurasian plates that bound these systems. There is no general agreement about the causes of extension in the basins, and the rapid evolution of a collision zone into superimposed regions of extension, adjacent contraction and arc migration has not yet been adequately explained.

As far as the origin of the basins is concerned, some authors have emphasized the role of anomalous mantle diapirism, the extensional locus of the basin being static (Van Bemmelen, 1972; Weijermars, 1985; Wezel, 1985), whereas others consider that basin extension is contemporaneous with the subduction, similar to the Western Pacific backarc model (Biju-Duval et al., 1978; Rehault et al., 1985; Dercourt et al., 1986; Malinverno and Ryan, 1986; Kastens et al., 1987). Removal and detachment of the thickened mantle lithosphere during the last episode of convergence have been invoked to explain the lithospheric thinning superimposed on the collision zone, either by delamination (Bird, 1979) or by convection (Houseman et al., 1981). To explain the origin of extensional basins that postdate and are superimposed on continental collision sutures, Channel and Mareschal (1989) suggest that the rapid evolution of the collision suture into a zone of rifting, and the development of closely juxtaposed regions of compression and extension, can be explained by a mechanism that involves collision-induced delamination ("subduction") of continental mantle lithosphere. Their models for the Tyrrhenian Basin-Calabrian Arc show that asymmetric lithospheric thickening generates asymmetrical flow in the underlying mantle, and extension and contraction in contiguous regions.

The Alboran Sea Basin is a clear-cut, well-defined, and well-studied example of a Mediterranean backarc basin where these competing hypotheses can be fully investigated. Several conflicting hypotheses for the origin of the Alboran Sea have been the subject of various papers. However, most of them are poorly supported by data regarding extensional mechanisms, kinematics that produced the Betic-Rif orogen crustal attenuation, and the formation of the Alboran Basin. Below, we briefly discuss the two, most accepted, hypotheses that best fit the structural organization of the region.

Platt and Vissers (1989) suggest that convective removal of a thickened lithospheric root could explain the formation of the Alboran extensional basin, on the site of a former collisional orogen (Fig. 2A). In this hypothesis, the thickened ridge above, with no supporting lithospheric root below, is not supported isostatically, and thus the ridge begins to collapse, forcing thrust sheets outward and resulting in radial emplacement of thrust nappes around the Alboran Sea Basin. After this, the lithosphere would thermally subside, creating the Alboran Basin. In this model, extension drives the peripheral compressive events, and Alboran Basin rifting predates peripheral collision.

García-Dueñas et al. (1992) and Comas et al. (in press, a) envisage a different scenario for the origin of the Alboran Basin-Gibraltar Arc, based on the concept of asymmetric delamination of the lithospheric mantle (Channel and Mareschal, 1989). This asymmetric delamination produced not radial but preferential migration of the arcuate mountain front (Gibraltar Arc) to the west-southwest (Fig. 2B). This hypothesis suggests that the westward progression of the mountain front (with thickened crust) obliterated a thinned crust at 30-20 Ma, and that the collision between the mountain front and the adjacent continental margins (Maghrebian and South Iberian) to form the Gibraltar Arc occurred at 21 Ma (Fig. 2B, A to B). When asymmetric delamination (caused by adjacent regions of different lithospheric thickness) became active, crustal thinning in the "backarc" region started. Later (by 16 Ma), the extension propagated west-southwest and reached the Gibraltar Arc (extension superimposed on a former contraction), and the contraction propagated outward toward the paleomargins (Fig. 2B, B to C). This hypothesis relates the initial crustal thinning in the Alboran Basin and the preferential westward migration of the Gibraltar Arc (between 21 and 16 Ma) with the origin of the South Balearic basin. From 16 to 7 Ma, preferential westward migration of the locus of extension resulted in additional crustal thinning in the Alboran Sea region (Fig. 2B, C to D). Therefore, rifting in the Alboran Basin would entirely postdate collision.

The tectonically oriented sites to be drilled during Leg 161 in the Alboran Sea (Fig. 1) will shed light on an important current problem in understanding convergent plate boundaries, which is the development of extensional basins on collisional orogens. Furthermore, the continental rift system that led to the development of the Alboran Basin provides an opportunity to examine variation in the brittle/ductile deformation of the lithosphere, the variable role of magmatism in rifting processes, and the role of the upper mantle in crustal modification and lithospheric evolution. This basin, as a part of the Mediterranean Sea, can be considered a "natural laboratory " where collisional processes can be investigated. Leg 161 results in the Alboran Sea will have immediate implications in establishing models to explain the origin and evolution of the Western Mediterranean, as well as other "Mediterranean-type" backarc basins observed around the world. As the processes discussed above operate to some extent independently of surrounding plate tectonics, it is vital to the development of a truly global tectonic theory to improve our understanding of their nature and causes.

Paleoceanography and Depositional History During Formation of Sapropels in the Mediterranean

Numerous studies have revealed the existence of laminated organic-rich "sapropel" layers both in sediment cores from the deep Mediterranean and in outcrops on land in the Mediterranean region (Fig. 3; for a comprehensive review see Hilgen, 1991). Even after three decades of research it is not clear what constituted the driving force behind formation of the sapropels. Traditional models postulate that sapropels accumulated under stagnant, anoxic conditions because lack of oxygen would greatly enhance preservation of organic carbon at the seafloor (e.g., Ryan, Hsü et al., 1973; Hsü, Montadert, et al., 1978; Kullenberg, 1952; Olausson, 1961). This model is supported by the absence of benthic foraminifers in most sapropels, and by faunal and isotopic indicators of stable water-mass stratification and restricted deep ventilation during sapropel formation (Williams et al., 1978; Thunell et al., 1984; Vergnaud-Grazzini et al., 1986). Further support for the anoxia hypothesis is derived from the existence of organic-rich deposits in the Bannock and Tyro basins, in which anoxic and hypersaline bottom waters prevail (Jongsma et al., 1983; De Lange and ten Haven, 1983; Cita et al., 1985; Parisi et al., 1987). Yet, it appears that early Holocene sapropel formation in the Black Sea, the "type" euxinic basin usually referred to by those favoring the stagnation/anoxia hypothesis, occurred under well-oxygenated conditions, which are inferred from inorganic oxygen tracers (Calvert, 1990). A systematic reevaluation of published data suggests that organic carbon levels in marine sediments are primarily a function of sediment texture, dilution, and carbon flux, rather than of water-column oxygen levels (Pedersen and Calvert, 1990). Isotopic and geochemical tracers point to a predominantly marine origin for the sapropel organic carbon (Sutherland et al., 1984; Smith et al., 1986; ten Haven et al., 1987) and imply that the formation of sapropels was probably promoted by enhanced rates of marine productivity.

Several models have been put forward to explain how higher productivity levels in the otherwise oligotrophic Mediterranean could have been brought about. It has been postulated, for instance, that enhanced volumes of freshwater input during deglacial meltwater surges and/or monsoon-controlled river floodings would have reversed the Mediterranean circulation toward an anti-estuarine system (Fig. 4) (Sarmiento et al., 1988; Lohmann and Pride, 1989; Thunell and Williams, 1989). If true, the Mediterranean would have imported nutrients via an inflow of nutrient-enriched subthermocline waters from the Atlantic, which would have upwelled in the Eastern Mediterranean and stimulated biological productivity there. Biological productivity may have also been enhanced in response to the development of chlorophyll maxima at the base of the euphotic zone (Rohling and Gieskes, 1989; D. Castradori, unpubl. research) as the pycnocline shoaled during times of enhanced water-mass stratification. Salient maxima of dinosterols and long-chain alkenones that are associated with some sapropels (Smith et al., 1986; ten Haven et al., 1987) were used to infer that coccolithophorid and dinoflagellate productivity was high during sapropel formation, thus also pointing to the potential importance of primary productivity for the formation of the Mediterranean sapropels. These new studies are now calling attention to biological productivity combined with distinctive changes in physical water-mass circulation as important controls of the formation of organic-rich, sapropelic deposits.

The temporal pattern of sapropel occurrence during the past provides some clues about the causes of sapropel formation. Sapropel formation is not linked in a simple fashion to global environmental patterns, e.g., glacial-interglacial climate cycles (Fig. 5A). Apparently, sapropels formed during full glacial stages, full interglacial stages, and during interstadial stages (e.g., Vergnaud-Grazzini et al., 1977; Cita et al., 1977). A more systematic correlation has been obtained between the distribution of sapropels and maxima of the so-called orbital insolation monsoon index (Fig. 5B) (Rossignol-Strick, 1983). This correlation suggests that sapropels primarily formed during times of intensified Indian Ocean summer monsoons. During these periods continental humidity in tropical-subtropical East Africa was enhanced, which ultimately led to strongly increased freshwater discharge by the Nile. Simultaneously, atmospheric depressions along the northern borderlands would have been more active, leading to stronger rainfalls over the Eastern Mediterranean (Rohling and Hilgen, 1991). Conceivably, this would have resulted in periodic reversals of flow patterns between the Eastern and Western Mediterranean, which would have caused the Eastern Mediterranean to become a nutrient trap, thereby increasing the oxygen demand and resulting in episodic anoxia (Sarmiento et al., 1988). Thus it seems that redistributing freshwater between the Eastern and Western Mediterranean basins could have been an important mechanism to precondition the Eastern Mediterranean toward the formation of sapropels.

We must obtain continuous sedimentary records extending back to the Miocene to evaluate the importance of monsoon-driven atmospheric anomalies on the paleoceanographic history of the Western Mediterranean. Numerical simulations that are constrained by paleoclimatic data indicate that monsoons as strong as those today occurred only after 7 to 8 Ma, when the Himalayas and the Tibetan Plateau had risen to about half their modern elevation (Prell and Kutzbach, 1992).

Multi-proxy records along an east-west transect across the entire Mediterranean are needed to evaluate the influence of the various factors of anoxia, productivity, and hydrography on the formation of sapropels. Such a transect will allow synoptical mapping of the hydrographic and climatic conditions throughout the Mediterranean both at sites in the eastern basin where sapropels formed as well as at sites in the western basin where sapropels did not form. Six drill sites have been chosen along an east-west transect across the Mediterranean to accomplish this goal. Leg 160 will drill the easternmost sites (proposed sites MedSap-2B, -3, and -4). Leg 161 will drill the western sites (proposed sites MedSap-5, -6A, and Alb-2 [MedSap-7B]) to document the Miocene to Holocene paleoceanographic evolution of the Western Mediterranean. Sediments recovered at proposed sites Alb-4A and Alb-3A will also address these paleoceanographic objectives.

BACKGROUND

Alboran Sea

The Alboran Sea forms the westernmost part of the Mediterranean, and is about 400 km long and 200 km wide (Fig. 6). It is surrounded to the north, west, and south by the Betic (Southern Spain) and Rif (Morocco) compressional mountain chains, which connect around the Gibraltar Arc. The system as a whole is bounded to the north and south by the Iberian and African continental forelands, and to the east and west by the oceanic Balearic Basin and the Atlantic Ocean.

Plate-motion studies by Dewey et al. (1989) suggest that this part of the Africa/Eurasian plate boundary experienced about 200 km of roughly north-south convergence between middle

Oligocene and late Miocene time, followed by about 50 km of west-northwest-directed oblique convergence in late Miocene to Holocene time. The Alboran Basin therefore formed in an overall collisional environment of plate convergence. This convergent history is not directly reflected in the kinematics either of the surrounding mountain chains or of the extension in the Alboran Basin.

Two-dimensional modeling that combines heat-flow, crustal structure, and topographic data, shows a dramatic decrease in lithospheric thickness from 60-80 km in the Western Alboran Basin to 30-40 km in the Eastern Alboran Basin. The crustal thickness also decreases from about 14 km in the West Alboran Basin to less than 11.5 km in the easternmost Alboran Sea (Torné and Banda, 1992; Polyak et al., in press). Commercial wells and DSDP Site 121 established that the crust (basement) in those locations is made up of metamorphic rock of the Alboran Crustal Domain (Internal Zones), which is exposed in the surrounding Betic and Rifean mountain chains (Jurado and Comas, 1992). This crustal domain represents disrupted and extended fragments of a convergent orogenic belt (Figs. 6 and 7) that evolved during Late Cretaceous to early Miocene time (Balanyá and García-Dueñas, 1987, 1988; De Jong, 1991; Monié et al., 1991). Pre-Miocene convergence caused substantial crustal thickening, accompanied by high-pressure, low-temperature metamorphism (Bakker et al., 1989; Goffé et al., 1989). The remains of this orogen, which underwent Miocene extension, probably also underlies much of the Alboran Sea, and therefore, sampling basement is a high priority of the Leg 161 drilling program. Onshore, extensional detachment systems and fault-bounded sedimentary basins of Miocene age are superimposed upon the continental collision structures (Galindo et al., 1989; García-Dueñas and Balanyá, 1991; Platt and Vissers, 1989; García-Dueñas et al., 1992). This Miocene extensional phase was accompanied by a distinctive low-pressure, high-temperature metamorphic event (Zeck et al., 1992). Crustal thinning over much of the region (both on- and offshore) likely resulted from this phase of extension.

Both the Iberian and Maghrebian continental margins and the Flysch Trough units (Fig. 6) (Betic-Rifean External Zones) exhibit continued crustal shortening during the Miocene. This crustal shortening on Iberian and African continental margins that surround the Alboran Domain occurred contemporaneously with crustal extension of the Alboran Domain itself. Shortening began in the basal Aquitanian (early Miocene), apparently almost coevally with the beginning of extension in the internal parts of the system, and continued into the late Miocene. Shortening directions vary from northwest in the Betic Cordillera (Banks and Warburton, 1991), to west in the Gibraltar Arc region

(Balanyá and García-Dueñas, 1987, 1988), to west-southwest in the Rif (Frizon de Lamotte, 1987). From the whole region, we can postulate that during the early to middle Miocene, the migration of the arcuate mountain front was nearly coeval with the extension in the inner part of the arc that resulted in crustal attenuation and basinal spreading on the Alboran Domain. In such a way, the Alboran Basin formed from early Miocene onward, whereas outside the arc thrusting processes continued. Schematic true-scale sections across the Alboran Sea and adjacent mountain belts (Figs. 7A and 7B) illustrate the position of the basin in a convergent orogenic setting.

The Alboran Sea has a complex morphology, with several sub-basins, ridges, banks, and platforms (Fig. 8). Miocene to Holocene sediments, 1-7 km thick (Comas et al., 1992; Jurado and Comas, 1992), occur in the various sub-basins (Fig. 9). One of the ridges, the Alboran Ridge, is locally emergent, forming the small island of Alborán, with exposures of volcanic rock. The structure of the Alboran Basin (Fig. 6) results from superimposed tectonic stages in basin evolution (Comas et al., 1992, 1993). Earlier structures correspond to extensional grabens of several rifting episodes (from earliest Burdigalian? to early Tortonian?). Magmatic events and mud diapirism were related to this rifting. Later structures testify to a post-rift, north-south contraction, involving folding and strike-slip faulting (e.g., de Larouzière et al., 1988; Mauffret et al., 1987; Woodside and Maldonado, 1992), resulting in the present-day seafloor morphology. The last faulting episode took place by the early Pliocene(?) and produced Pliocene-Quaternary basin subsidence. This episode is believed to have influenced the location of the present-day coastline. Aeromagnetic anomaly maps (Galdeano et al., 1974) suggest a pattern of volcanic ridges within the basin. In fact, late Serravalian to Pliocene volcanics of various alkaline and calcalkaline types (Bellon et al., 1983; Hernández et al., 1987) are exposed onshore and have been found offshore (Comas et al., 1992). These characteristics are consistent with an origin of the basin by rifting, extension, and subsidence during the Neogene.

Circulation and Water-Mass Distribution in the Mediterranean Sea

The primary paleoceanographic goal of Leg 161 will be to determine the hydrographic development in the Western Mediterranean during periods of sapropel formation in the east. Water-mass circulation in the Western Mediterranean is dominated by inflowing Atlantic waters at the surface and by intermediate-depth and deep waters being advected from the Eastern Mediterranean through the Sicily Channel and forming regionally in the Western Mediterranean. The driving force for this circulation pattern is the water-mass deficit of the Mediterranean due to the excess of evaporation over freshwater supply and, on seasonal time scales, mesoscale meteorologic forcing (Bethoux, 1980; Parrilla and Kinder, 1987; Hopkins, 1988; Millot, 1991). The strategy for Leg 161 is not to resolve the paleoceanographic evolution of water-mass circulation in the Western Mediterranean in detail. The geochemical and sedimentological profiles to be established rather will be used to determine the general hydrographic domain of its surface waters before they enter the Eastern Mediterranean, and of its deeper waters, which in part are derived from the eastern basin. These data are needed to determine how the Western Mediterranean contributed to the hydrographic environment that led to the formation of sapropels in the east, and whether or not circulation reversals between the Eastern and Western Mediterranean occurred during periods of sapropel formation.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1. To better understand the dynamics, kinematics, and deformation of the continental lithosphere, particularly in regard to (a) the development of extensional basins on collisional orogens, (b) the dynamics of the collapse of collisional ridges resulting in extensional basins surrounded by arc-shaped orogenic belts, and (c) collisional processes.

2. To investigate the nature of the crust, to develop a lithospheric model for the observed rifting system, and to establish (a) models for Miocene rifting, particularly to constrain the nature of the basement and the geometry of rifting, (b) the magnitude and timing of extensional faulting, (c) the nature of syn-rift vs. post-rift subsidence and the pattern of total tectonic subsidence, and (d) the timing and role of volcanism during extension.

3. To investigate post-rift deformation, in particular (a) late Miocene to Holocene contractive reorganization, (b) the transition to recent strike-slip tectonics, (c) the role of volcanism, and (d) recent basin collapse.

4. To determine the sedimentary sequence and document the amplification of the global isotopic signal, to determine the late Miocene desiccation of the Mediterranean basins, and to calibrate the sea-level signal.

5. To determine the paleoceanographic evolution of the Western Mediterranean from the Pliocene to Holocene. This will provide the database to determine inter-basin hydrographic and biogeochemical gradients between the Western and Eastern Mediterranean.

High-resolution sampling of complete sequences (triple APC coring) will be necessary to address objectives 4 and 5 at all sites. Where possible, we will triple APC core to obtain complete sequences for high-resolution sampling of laminated intervals and take whole rounds for organic analyses. However, these samples may be taken from sites with only one hole.

Specific Tectonic Objectives and Methodology

Leg 161 drilling cannot directly resolve arguments about the kinematics of deformation of the lithosphere, or the dynamics of the process by which the Alboran Basin formed. However, we will systematically test the response of the crust to both compressional and extensional forces by obtaining cores that can provide accurate information on the stratigraphic record, basin geometry, timing and nature of deformation, rates of subsidence, and nature of the basin floor, to test the predictions of some of the competing genetic hypotheses. It is critical that drilling results are integrated with geological and geophysical data from the Alboran Basin itself and the surrounding orogenic belt (the Betic and Rif chains).

Nature of the Basement

Only by sampling the basement of the basin can we establish to what extent its development was controlled by the preexistence of a collisional orogen. Petro-structural and petrological studies, metamorphic fabrics, PTT (pressure-temperature-time) paths, and radiometric ages of the predicted metamorphic basement rocks on a structural high in the Western Alboran Basin (proposed site Alb-2 or Alb-2A) will help to determine the history of convergent tectonism and the basement affinity to a particular crustal domain, or units within those domains.

Rifting System and Rifting Processes - Lithospheric Model

Drilling Western Alboran Basin basement at proposed site Alb-2 or Alb-2A will provide data that can be used to assess the geometry of middle Miocene rifting. If the continental floor of the basin has been greatly extended, metamorphic rocks may have been exhumed from considerable depth within the crust along normal faults. The nature of the basement rocks recovered will allow us to determine if the basement belongs to the hanging wall of the detachment systems cropping out on land or to the exhumed footwall (Fig. 2A vs. Fig. 2B). It will also allow us to determine if the rifting geometry can explain the absence of lower crust in the orogen, as is suggested from refraction data. By combining onshore data on the extensional detachment system with drilling results on subsidence patterns at this residual high, we will determine the degree of upper crustal asymmetry. The pressure-temperature histories of basement rocks at these sites will reveal the rate and thermal history of the extension (Buck et al., 1988; Ruppel et al., 1988; Voorhoeve and Houseman, 1988) beneath the Alboran Sea.

Recovery of the sedimentary sequences that fill the basin is essential to provide good stratigraphic control on extensional structures identified on seismic lines and to determine if the timing of extension was strictly coeval with development of compressional structures on surrounding chains.

Drilling results regarding the timing of later tilting and uplift of the basement high in the Western Alboran (proposed site Alb-2 or Alb-2A), as well as syn-rift and post-rift subsidence in the Eastern Alboran (proposed site Alb-4 or Alb-4A), combined with existing seismic and commercial well data, can constrain the magnitude of the extension and the relative proportions of syn-rift to post-rift subsidence in the basin. These results will allow us to interpret the subsidence data in terms of various rifting or other types of thermal models. Back-stripping of biostratigraphic data from commercial wells (Watts et al., 1994) provides estimates of crustal thickness and can be compared to present-day estimates based on seismic and gravity anomaly data. By comparing the calculated and observed thicknesses, we should be able to determine the initial thermal structure and elevation and/or processes that modified the crust since rifting. Comparison with back-stripped subsidence curves computed for onshore Betic Neogene basins (Cloething et al., 1992) will quantify the extension for the Miocene Alboran Basin as a whole.

If volcanic or volcaniclastic rocks are encountered between the postulated syn-rift sediments at proposed site Alb-4 or Alb-4A, we can learn about the role of volcanism during extension. Results from commercial well and seismic data imply that volcanic and volcano-sedimentary rocks are intercalated with middle Miocene to Pliocene sediments in the basin fill. The age and chemistry of these sediments and rocks will provide direct constraints on the thermal and structural evolution of the underlying mantle (Lachenbruch and Morgan, 1990; Latin and White, 1990; White and McKenzie, 1989).

Post-Rift Deformation: Later Stages of Structural Reorganization and Present-Day Tectonics of the Basin

Tectonic objectives also focus on the extent of the continuing deformation in the basin during the post-Messinian subsidence phase (proposed sites Alb-3A and Alb-4A), as well as related volcanism. Recent models for the extensional collapse of collisional orogens (England and Houseman, 1989) suggest that the tectonic style is closely related to the potential energy of the system, and hence to surface elevation. The opportunity to compare data from the elevated onshore part of the basin and the offshore part on the Alboran Ridge (proposed site Alb-3A) offers unique possibilities in this respect. The nature of the postulated late Miocene to Holocene contractional reorganization that produced folding, strike-slip faulting, block rotation, and pull-apart-type structures in the basin will be tested by drilling in the Eastern and Southern Alboran Sea. Paleomagnetic data will be used for these purposes. We expect to measure heat flow and the present stress field at each of the Leg 161 sites to determine the present-day tectonics of the basin.

Specific Paleoceanographic Objectives and Methodology

Amplification of the Global Isotopic Signal, Late Miocene Desiccation , and Calibration of the Sea-Level Signal

The Alboran Sea is presently one of the key oceanographic gateways. Over the 132-m-deep Gibraltar sill, a surface-water mass flows into the Mediterranean from the Atlantic and a deep-water mass exits from the Mediterranean as a dense saline flow that is detectable as one of the principal intermediate-water masses in much of the North Atlantic. The earlier connections between the Atlantic and the Mediterranean and, before that, with the Tethys, have been controlled by the tectonic evolution of this region and the Alboran Sea may not have been a direct gateway until after the Messinian isolation of the Mediterranean (Adams et al., 1977). Comparative studies of the development of Atlantic and Mediterranean water masses represent one of the prime targets still to be addressed by paleoceanographers (Kennett, 1982). This and other important paleoceanographic objectives from sedimentary sequences will be addressed at all drill sites.

Apart from ODP Leg 107 in the Tyrrhenian Sea, no hydraulic piston coring has been carried out in the Mediterranean. All of the sites proposed in the Alboran Sea are in present-day pelagic or hemipelagic settings and will provide an integrated high-resolution stratigraphic record for the Pliocene-Pleistocene. Vergnaud Grazzini and Pierre (1991) have drawn attention to the amplification of the isotope record in the enclosed Mediterranean through studies of surface piston cores from the Alboran Sea. The reason for this amplification is that evaporation exceeds precipitation and water-mass exchange with the open ocean is restricted, since the gateway through the Strait of Gibraltar is narrow enough to limit the rate of inflow and outflow. Apparently, the amplitude of climatic signals increases to the east, where evaporation is strongest (Thunell and Williams, 1989). If during times of sapropel formation, a brackish surface layer existed in the Eastern Mediterranean, the east-west gradient of paleoceanographic proxies, which monitor surface-water conditions, should be decreased (e.g., Williams et al., 1978; Vergnaud-Grazzini et al., 1986). It is therefore essential for the sapropel program to develop detailed paleoenvironmental records at the Western and Eastern Mediterranean drill sites to map the development of hydrographic gradients back to the Pliocene. The most promising candidates are the quantitative analysis of planktonic foraminiferal and calcareous nannofossil assemblages, which are sensitive to changes in hydrographic conditions and nutrient concentrations (Thunell et al., 1984; Rohling and Gieskes, 1989; D. Castradori, unpubl. research). The evolution of the amplified climate signal since the onset of Northern Hemisphere glaciation will be targeted during Leg 161 drilling in the Western Mediterranean.

DSDP Legs 13 and 42A addressed the phenomenon of the late Miocene desiccation of the Mediterranean basins (Ryan, Hsü, et al., 1973; Hsü, Montadert, et al., 1978). Key sites in the confirmation of the deep-water desiccation hypothesis were DSDP Sites 372 on the Menorca Rise and DSDP Sites 375 and 376 on the Flores Rise, west of Cyprus, which penetrated the feather edge of the Messinian evaporite sequence (Hsü et al., 1977). Cover recovery at the onset of evaporite conditions and at the Miocene/Pliocene boundary was crucial to the debate. Further recovery of undisturbed material (APC coring) over these intervals at other locations within the Mediterranean is needed to allow more detailed studies of these important paleoceanographic boundaries. The Alboran drill sites will penetrate the Messinian erosional unconformity (M) of the feather edges of the upper Messinian sequences, ensuring that the upper evaporitic and Main Salt sequences are avoided, offering prime sites for continuation of these paleoceanographic studies.

The extensive suite of MCS and high-resolution SCS profiles that we have available in this area has allowed detailed mapping of reflectors throughout the Alboran sub-basins and onto the thick sequences of the margins. A seismic stratigraphy has been established for the margin sequences (Fig. 9) (Comas et al., 1992; Jurado and Comas, 1992; Maldonado et al., 1992) that sometimes appears to be linked to Cenozoic sea-level change, despite the changing tectonic picture within this region. The Alboran drill sites allow calibration of this regional data set and potentially can contribute to the debate over tectonic vs. sea-level effects on seismic stratigraphy. Detailed sedimentological studies of the reflector transitions are planned as a subsidiary objective of this study.

Much of the paleoceanographic work will depend on detailed continuous chronostratigraphic control, which will be provided by biostratigraphic, paleomagnetic, tephrochronologic, and oxygen isotopic data. Bio- and magnetostratigraphic analyses can be carried out for integration with the oxygen-isotope record and then can be refined by the suite of core-logging techniques now available to shipboard scientists. As part of the shore-based program, spectral analysis in conjunction with orbital tuning will be an essential tool to determine possible external forcing mechanisms on the Mediterranean paleoceanography. For instance, orbital forcing of atmospheric anomalies that determine the freshwater flux to the Mediterranean should occur primarily at the orbital precessional frequency band ($v={}^{1}/_{23}$ k.y.) (Hilgen, 1991). For the Western Mediterranean, a strong overprint of high-latitude signals is anticipated, which are advected with the inflowing North Atlantic surface waters. Here, enhanced variance at the orbital obliquity frequency band ($v={}^{1}/_{41}$ k.y.) may be expected. Along the trans-Mediterranean drilling transect, which will be drilled during Legs 160 and 161, the proxy records will be used to monitor the influence of the Atlantic vs. the Mediterranean climate signal as one moves from the Western to the Eastern Mediterranean. This will eventually enable us to decipher the Mediterranean-wide hydrographic changes that must have occurred during times of sapropel formation.

PROPOSED DRILL SITES AND DRILLING PLAN/STRATEGY

The following section provides the drilling plan for Leg 161 in chronological sequence in which the sites will be occupied.

Proposed Site MedSap-5, Tyrrhenian Sea

Proposed site MedSap-5 reoccupies ODP Leg 107, Site 652, in the Tyrrhenian Sea on the lower Sardinian margin (Table 1; Fig. 10). It is located on a small tilted block between the Central Fault and de Marchi Seamount overlain with pre-rift, syn-rift, and post-rift sedimentary units (Fig. 10). Site 652 penetrated 684 m of Messinian through Pleistocene sediments and recovered 8 sapropels (Kastens et al., 1987). The sedimentary units will consist of calcareous muds and marly nannofossil oozes with scattered mudstone intervals and volcanic ash layers (Fig. 11). This is the westernmost location where sapropels have been recovered. Discontinuous recovery and rotary (RCB) drilling at Site 652 requires that we reoccupy this site to use APC/XCB technology to obtain continuous and undisturbed cores for the sapropel program and other paleoceanographic studies. At this site, the upper 200 m of sediments will be cored to provide a complete Pliocene-Pleistocene section. Triple APC holes will be cored to refusal, from where the rest of the sequence will be cored with double XCB tools down to 200 m. The standard three logging suites will be carried out, including formation microscanner (FMS), geochemical tool string, and quad combo. We also propose to run magnetic susceptibility logs, should the tool be available.

Proposed Site MedSap-6A, Menorca Rise

Proposed site MedSap-6A is on the Menorca Rise at 2369 m water depth (Table 1; Fig. 12). This site was chosen to monitor "mean hydrographies " of the Western Mediterranean. Different water masses originating from the Alboran and Balearen seas blend in this region before flowing into the Eastern Mediterranean. SCS profiles at this site reach the M Reflector (also called Y Reflector), representing the top of Miocene sediments (Fig. 13). A gravity core was taken at the position of this site (Tyro core MT 15) and retrieved 9.5 m of pelagic sediments, which reveal a succession of warm interglacial faunas at the top 1.5 mbsf transgressing to cold glacial faunas down to 8 mbsf, and back to warm interglacial faunas at about 9 mbsf. Thus, core MT 15 monitors the last full interglacial-glacial-interglacial climatic cycle. According to this preliminary stratigraphy, the core covers the past 125,000 yr, with sedimentation rates of about 7-cm/k.y. Triple APC holes will be cored to refusal, from where the rest of the sequence will be cored with double XCB tools down to 350 m. The standard three logging suites will be run, including FMS, geochemical tool string, and quad combo. We also propose to run magnetic susceptibility logs, should the tool be available.

The drill sites proposed above must fulfill the four essential requirements of stratigraphic continuity, high stratigraphic resolution, long stratigraphic range (as sapropels did form under very different global climatic settings), and optimum areal coverage. To ensure highest quality information on the depositional environment during sapropel formation, sampling density of the sapropel layers, as well as the "normal" sediments immediately below and above the sapropels, must be on scales of centimeters to millimeters. Such high sampling resolution is essential for determining the factors that have led to the formation of the sapropels and that have helped in maintaining an environment favorable for the formation of sapropels over time scales of 10^2 to 10^3 years.

Triple APC/XCB coring is necessary to achieve the paleoceanographic goals of Leg 161, but the final decision on the APC/XCB coring will be made based on the quality of the sediments retrieved. Downhole logging at all sites and shipboard logging of all cores is essential to derive highest possible intra-hole correlation ("composite depth scale ") and site-to-site correlation along the trans-Mediterranean drilling transect across the Western and Eastern Mediterranean.

Proposed Site Alb-2, Western Alboran Basin

Proposed site Alb-2 has been selected to address the paleoceanographic objectives of the sapropel program in the westernmost Mediterranean as well as Alboran Basin tectonic objectives. The location of proposed site Alb-2 allows it to monitor the Atlantic-Mediterranean exchange of water masses. Alternates to this site for paleoceanographic objectives are proposed sites Alb-2A, Alb-2B, and MedSap-7B.

Proposed site Alb-2 is located in the Western Alboran Basin (Figs. 6, 8, and 14), on a structural basement high, which corresponds to the same high that was drilled at DSDP Site 121. This structural high is believed to be a middle Miocene horst of the continental basement of the basin and has an irregular west-facing, fault-controlled escarpment that is roughly parallel to the axis of the main early to middle Miocene graben in the Western Alboran Sea. The drilling plan at proposed site Alb-2 (Table 1; Figs. 15 and 16) is to penetrate through the sediment column for sapropel and paleoceanographic objectives and to sample the uppermost 200 m of metamorphic basement for tectonic objectives. The sediment sequence will be recovered by triple APC coring to refusal, from where the rest of the sequence will be double XCB cored down to the top of the basement at

640 mbsf. One of the XCB holes will be logged using the standard three logging suites (FMS, geochemical tool string, and quad combo). We also propose to run magnetic susceptibility logs and use the borehole televiewer (BHTV), should these tools be available. A reentry cone with casing as necessary, possibly to basement, will be set at a new hole. The sediment column will be washed and the basement will be sampled down to 200 m using one or more RCB bits. Three standard logging suites will be used to log the basement hole plus magnetic susceptibility tools and the BHTV.

Should the sediment and/or basement objective not be met at proposed site Alb-2, alternate site Alb-2A will be drilled (Figs. 14, 16, and 17). Drilling the basement at proposed site Alb-2 remains our highest drilling priority and will help to constrain current geodynamic models for the origin of the basin.

Metamorphic complexes, affected by Miocene extension, are thought to underlie the Alboran Sea. Because the nature of these metamorphic complexes is well known, petro-structural and petrological studies (metamorphic fabrics, PTT path, and radiometric ages) of the predicted metamorphic basement samples will establish their affinity to a particular crustal domain, or units within those domains. As known from on-land data, elements of four pre-Miocene crustal domains occur in the Gibraltar Arc, (1) the South Iberian continental margin, (2) the Maghrebian continental margin, (3) the Flysch Trough, and (4) the Alboran Crustal Domain. (Fig. 6). Prevailing hypotheses suggest that the basement of the Alboran Basin is formed by the Alboran Domain, itself composed of a polyphase thrust stack that includes three nappe complexes, labeled (in ascending order) Nevado-Filabrides, Alpujarrides, and Malaguides. The Alpine metamorphic facies in the Alpujarrides and Nevado-Filabrides show evolution from high P/low T to low P/high T conditions, while the Malaguides have undergone very low grade Alpine metamorphism. Sampling the basement will determine if these basement rocks belong to the hanging wall of the detachment systems cropping out on land or to the exhumed footwall. Consequently, drilling results will tie to on-land structural data and will help to discriminate between models for lithospheric rifting (Fig. 2A vs. 2B) based on the following reasoning:

1. The hypothesis from Figure 2A predicts that the basement rocks at proposed sites Alb-2 or Alb-2A will correspond to the middle or upper part of the Alpujarride complex or to the Malaguide complex, i.e., to the upper tectonic elements of the pre-Miocene stacking of the Alboran Crustal

Domain. According this hypothesis, we will drill in the hanging wall of the predicted westward-dipping main extensional detachment (Fig. 7A).

2. Alternatively, Figure 2B implies that the basement of the Alboran Sea Basin will correspond to the footwall of the extensional detachments. If this is the case, the basement sampled at proposed site Alb-2 will correspond to the lower complexes of the metamorphic nappe of the Alboran Crustal Domain, i.e., rocks from the lowermost units of the Alpujarride complex either from the Nevado-Filabride complex or even-lower unknown units (Fig. 7B).

At proposed sites Alb-2 or Alb-2A , we will not penetrate the lower Miocene sedimentary units in the basin (Comas et al., 1992; Jurado and Comas, 1992). These earlier sediments have already been penetrated in commercial wells along the Spanish (Fig. 9) and Moroccan margins and therefore already provide information regarding the early subsidence history of the basin that will be used to complement Leg 161 drilling results.

The sedimentary sequence to be drilled corresponds to about 640 m of Pliocene-Pleistocene sediments upon the Messinian M unconformity. An interval of conglomerate or breccias is expected to be encountered at the sediment/basement boundary.

MCS line 75-334, shown in Figure 16, crosses all proposed sites in the Western Alboran Basin.

Proposed Site Alb-4A, Eastern Alboran Basin

Proposed site Alb-4A, and its proposed alternate site, Alb-4, are located in the Eastern Alboran Basin (Figs. 6, 8, and 18). They are situated on small graben structures to the north of the Yusuf Ridge and Basin in the East Alboran Sea, and to the east of a northeast-southwest-trending strike-slip fault system. The drilling plan (Table 1; Fig. 19) is to single APC/XCB core to refusal, then to log this hole using the standard three logging suites plus magnetic susceptibility tools (if available). Then we will RCB core to penetrate and sample the sedimentary sequence to total depth (1200 mbsf at proposed site Alb-4A and 900 mbsf at alternate site Alb-4) and log this interval. If a bit change is required and time is available, a free-fall funnel (FFF) may be deployed.

According to our data, the Eastern Alboran Basin does not seem to have the same structural pattern as the Western Alboran Basin. This region is underlain by northwest-southeast- or east-westtrending basement ridges and basins, with thinner and probably younger sedimentary fill and a relative lack of extensional structures.

The tectonic objective at proposed site Alb-4A, and its alternate Alb-4, is to sample the "syn-rift " and "post-rift " sediments to understand the subsidence history of the Eastern Alboran Basin as compared to that of the Western Alboran Basin. Comparing the subsidence history from both regions will have strong implications on constraining the tectonic model and structural evolution for the whole Alboran Sea Basin. Additionally, it is important to calibrate the sediment-fill stratigraphy and seismic units in this region where there has been no prior drilling. Because the Western and the Eastern Alboran basins are separated by structural highs, it is not possible to correlate the sedimentary fill between both basins from seismic profile data.

These sites were selected because they show a lower sequence of tilted, hummocky reflectors with several internal unconformities. This sequence may represent the earliest sediments that infilled the graben and therefore may be "syn-rift" sediments. The tilted sequence is overlain by "passive" Pliocene-Quaternary sediments. Our main objective is to penetrate and sample the unconformity, which lies at about 650 mbsf and separates syn- and post-rift sequences, and continue to total depth to sample "syn-rift" sediments to obtain data about the age and nature of the internal unconformities and on the relative proportions of syn-rift to post-rift subsidence and total subsidence. In addition, proposed site Alb-4A drilling results will permit more accurate seismic correlation with the South Balearic Basin.

New migrated seismic reflection profiles indicate that the basement cannot be clearly identified. It appears that, at this site, there could be a substantial sedimentary section beneath the upper syn-rift units. Therefore, basement sampling may be feasible. However, basement highs around this site, have been sampled by submersible dives (CYANALBORAN Cruise, 1994). The dive samples from the acoustic basement in both the northern escarpments of the Mansour Seamount and the Yusuf Basin (Fig. 8) yield volcanic rocks (Comas et al., in press, b)

Proposed Site Alb-3A, Southern Alboran Basin

Proposed site Alb-3A, and its alternate proposed site, Alb-3, are located in the Southern Alboran Basin (Figs. 6, 8, and 20) and are situated on the southern flank of the Alboran Ridge where existing MCS and single channel seismic reflection profile data indicate a zone of deformation during, and following, deposition of the sediments. The deformation is expressed as a series of folds near the base of the ridge. On the southern ridge flank, there is evidence that the deformed zone (5 km wide) extends laterally for up to 50 km. Both deformation and tilting appear to be relatively recent. The southern flank of the ridge aligns with the Jebha Fault and, therefore, may form part of a major sinistral strike-slip fault system across the Alboran Sea.

The drilling plan is to single APC/XCB core to refusal, then to log using the standard three logging suites plus magnetic susceptibility tools and the BHTV (if available). After that, we will RCB core to penetrate and sample the sedimentary sequence to total depth (600 mbsf at proposed site Alb-3A and 300 mbsf at alternate site Alb-3), plus log this interval. If a bit change is required and time is available, an FFF may be deployed.

Proposed site Alb-3A (Table 1; Fig. 21) is planned to penetrate the main intra-Pliocene unconformity at this site, lying at about 600 mbsf (0.65 sec twt). At the proposed alternate site Alb-3 (Table 2; Fig. 22), our main objective is also to penetrate the intra-Pliocene unconformity that lies at about 300 mbsf (0.3 sec twt) which overlies an 860-m-thick section of folded and tilted sediment, estimated to be as old as earliest Pliocene. The objectives at these sites are to calibrate the recent stratigraphy of the southern part of the Alboran Basin, and to time the later tilting and uplift of the Alboran Ridge and the associated folds and strike-slip faulting. Comparison between recent folding and strike-slip faulting on land (elevated onshore parts) and the offshore deformation, which occurred contemporaneously with the Pliocene to Holocene subsidence, will allow us to constrain the later stage of contractional reorganization of the basin.

The acoustic basement of the southern flank of the Alboran Ridge was recently sampled by submersible diving (CYANALBORAN Cruise, 1994), and all samples recovered are volcanic rocks.

Proposed Alternate Site Alb-2A

Proposed alternate site Alb-2A is 4 km southwest of proposed primary site Alb-2 and is on the same structural basement high as Alb-2 (Fig. 14). The drilling plan (Table 2; Figs. 16 and 17) and scientific objectives for alternate site Alb-2A are the same as for proposed site Alb-2, but, depending on time, an FFF might be deployed instead of the reentry cone. Maximum penetration at this proposed site is 820 m.

Proposed Alternate Site Alb-2B

Proposed alternate site Alb-2B is located on a seismic line where lower Pliocene sediments correspond to an acoustically transparent seismic facies that presumably indicates pelagic sediments (Fig. 14). This transparent seismic facies is not present at proposed sites Alb-2 and Alb-2A due to a middle Pliocene hiatus. Basement will not be reached at alternate site Alb-2B (Table 2; Fig. 23). If time is available at the end of the cruise, alternate site Alb-2B will be occupied to recover the transparent acoustic facies and to splice it into the records obtained at proposed site Alb-2 or alternate site Alb-2A to obtain a complete Pliocene-Quaternary sequence for the western Alboran Basin. The drilling plan for alternate site Alb-2B includes single APC/XCB coring to refusal and logging using the three standard logging suites (FMS, geochemical tool, quad combo). An FFF will be deployed if the transparent acoustic layer has not been reached before XCB refusal, and drilling will continue using RCB tools to a maximum depth of 1000 m.

Proposed Alternate Site Alb-3

Proposed alternate site Alb-3 is 7.6 nmi west of proposed site Alb-3A (Figs. 8 and 20). The drilling plan and scientific objective (Table 2; Fig. 22) are the same as for proposed site Alb-3A.

Proposed Alternate Site Alb-4

Proposed alternate site Alb-4 is 12 nmi north-northwest of proposed site Alb-4A (Figs. 8 and 18). The drilling plan and scientific objective (Table 2; Fig. 19) are the same as for proposed site Alb-4A.

Proposed Alternate Site MedSap-7B

For the sapropel program, MedSap-7B is an alternate to proposed site Alb-2. MedSap-7B re-occupies old DSDP Site 121 in the western Alboran Sea at 1163 m water depth (Table 2; Fig. 24). Site 121 was drilled in an area with an acoustically conformable, stratified upper sediment cover underlain by a less coherent facies that downlaps to the south onto an undulating unit that overlies basement (Fig. 24). Site 121 penetrated through 690 m of Pliocene-Pleistocene sediments with a rich and diverse foraminiferal fauna (Fig. 25). An acoustic unconformity has been stratigraphically mapped as a hiatus between the lower Pliocene and the upper Miocene. This site will be drilled to a sub-bottom depth of 690 m to obtain a Pliocene-Pleistocene sequence. The drilling plan includes triple APC/double XCB coring to refusal; if necessary, RCB coring will be used to total penetration depth. The standard three logging suites (FMS, geochemical tool string, and quad combo) will be used; we also propose to run magnetic susceptibility logs and use the BHTV, should both tools be available.

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TABLE 1 - PRIMARY SITE TIME ESTIMATES

Proposed Site	Position	Water Depth (m)	Penetration (mbsf)	Drilling Operations (days)	Downhole Measurements (type)	Downhole Measurements (days)	Transit Time (days)
Transit - Napoli to MedSap-5							0.37
MedSap-5	40°21.3'N 12°08.6'E	3466	200	3.63	Q, Gc, F, GHMT*, T, Co	1.09	
Transit - MedSap-5 to MedSap-6A							1.57
MedSap-6A	38°53.9'N 4°30.5'E	2369	350	5.05	Q, Gc, F, GHMT*, T, Co	1.01	
Transit - MedSap-6A to Alb-2							1.61
Alb-2	36°12.367'N 4°18.870'W	1080	840 sediments = 640 m basement = 200 m	15.38	Q, Gc, F, GHMT*, BHTV*, T, Co	2.58	
Transit - Alb-2 to Alb-4A							0.46
Alb-4A	36°02.068'N 1°57.036'W	1930	1200	9.23	Q, Gc, F, GHMT*, BHTV*, T, Co	3.53	
Transit - Alb-4A to Alb-3A							0.25
Alb-3A	35°42.306'N 3°12.163'W	1036	600	2.61	Q, Gc, F, GHMT*, BHTV*, T, Co	1.39	
Transit - Alb-3A to Leith							8.15
Total				35.9		9.6	12.41
Total days at sea = 57.91							

Q = quad combo log, Gc = geochemical log, F = FMS log, GHMT = GHMT/magnetic susceptibility log (* if available), BHTV = Borehole televiewer log (* if available), T = ADARA/WSTP temperature measurements, Co = APC core orientation

TABLE 2 - ALTERNATE SITE TIME ESTIMATES

Alternate Site	Position	Water Depth (m)	Penetration (mbsf)	Drilling Operations (days)	Downhole Measurements (type)	Downhole Measurements (days)	Transit Time (days)
Alb-2A	36°10.824'N 4°20.214'W	1095	820 sediments = 620 m basement = 200 m	14.9	Q, Gc, F, GHMT*, BHTV*, T, Co	2.1	17
Alb-2B	36°19.247'N 4°14.026'W	717	1000	5.83	Q, Gc, F, GHMT*, T, Co	2.75	8.58
Alb-3	35°43.123'N 3°21.824'W	967	300	1.39	Q, Gc, F, GHMT*, BHTV*, T, Co	1.18	2.57
Alb-4	36°13.777'N 2°03.268'W	1900	900	6.12	Q, Gc, F, GHMT*, BHTV*, T, Co	2.79	8.91
MedSap-7B	36°09.7'N 4°22.4'W	1163	690	9.56	Q, Gc, F, GHMT*, T, Co	1.28	10.84

Q = quad combo log, Gc = geochemical log, F = FMS log, GHMT = GHMT/magnetic susceptibility log (* if available), BHTV = Borehole televiewer log (* if available), T = ADARA/WSTP temperature measurements, Co = APC core orientation

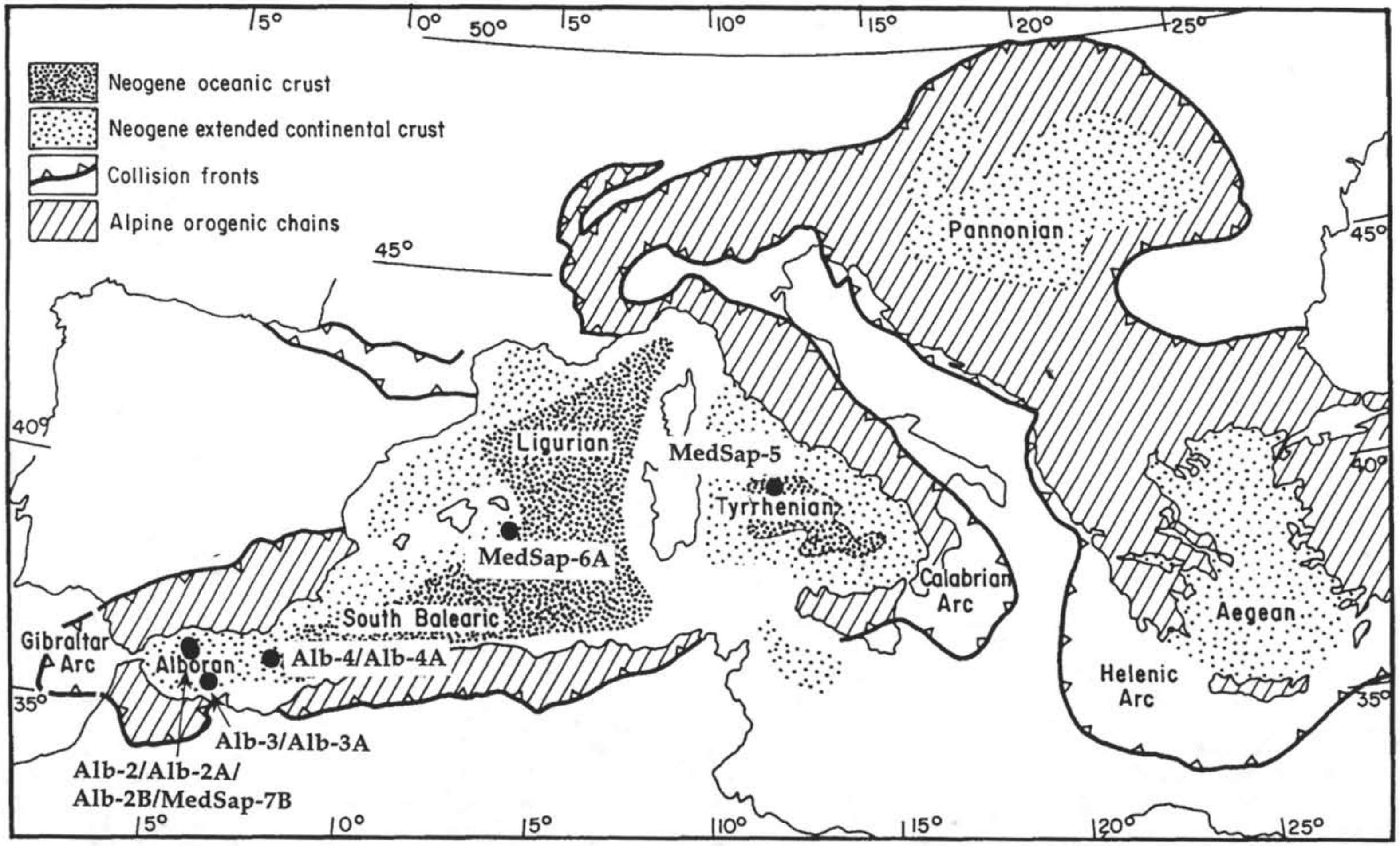

Figure 1. Tectonic map of Mediterranean basins and mountains belts. Leg 161 proposed sites are shown.

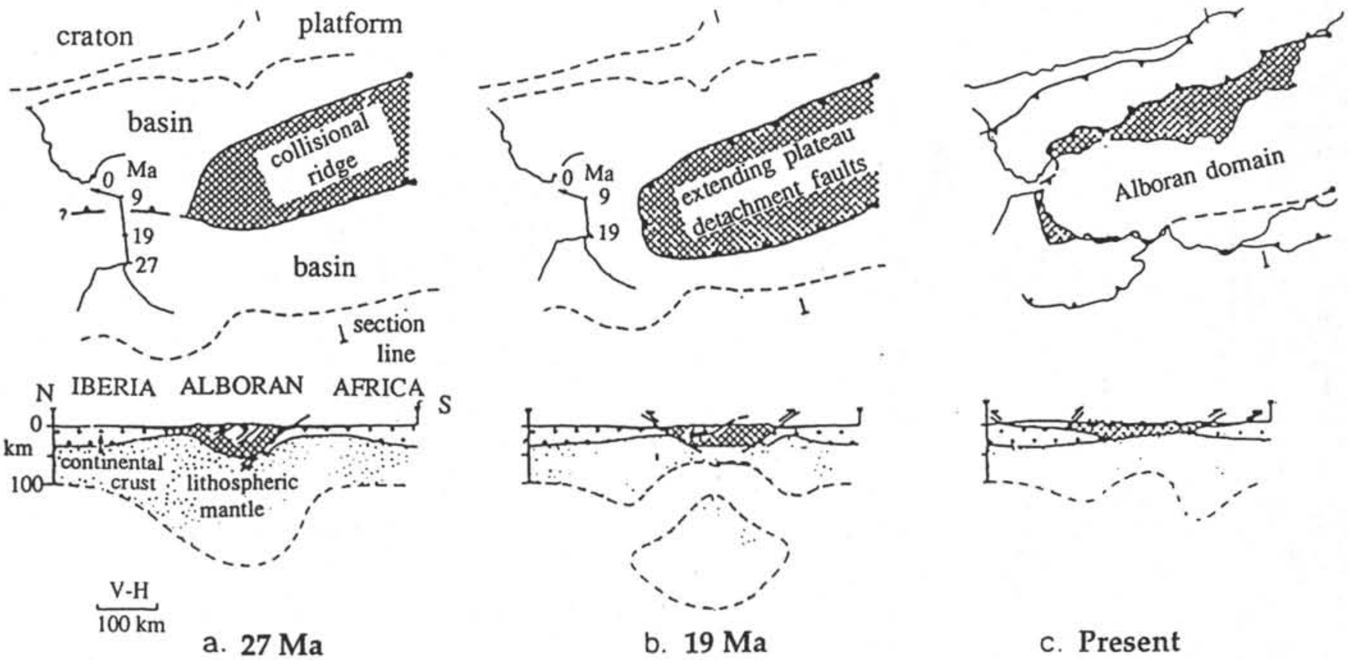

Figure 2A. Tectonic evolution of Alboran region, as hypothesized by Platt and Vissers (1989).

a) Late Oligocene (27 Ma): Collisional ridge with thickened lithospheric root formed by Late Cretaceous-Paleogene convergence. Map (above) shows coastlines around Gibraltar and Tangiers for reference, and plate motion vectors for Africa relative to Europe from 27 Ma to present (after Dewey et al., 1989). Basins were probably underlain by thin continental crust.

b) Burdigalian (19 Ma): Convective removal of lithospheric root has caused uplift, increase in potential energy of collisional ridge, and extension. Extension is accommodated by crustal shortening around margins, producing the external Betic-Rif thrust belts. High-T peridotite emplaced at the base of the crust.

c) Extending Alboran Domain (present) has been emplaced onto surrounding continental margins; center subsides as lithosphere thickens by cooling and continued slow convergence.

Note: Crustal volume is conserved in these figures, but cross-sectional area is not, because of radial pattern of motion.

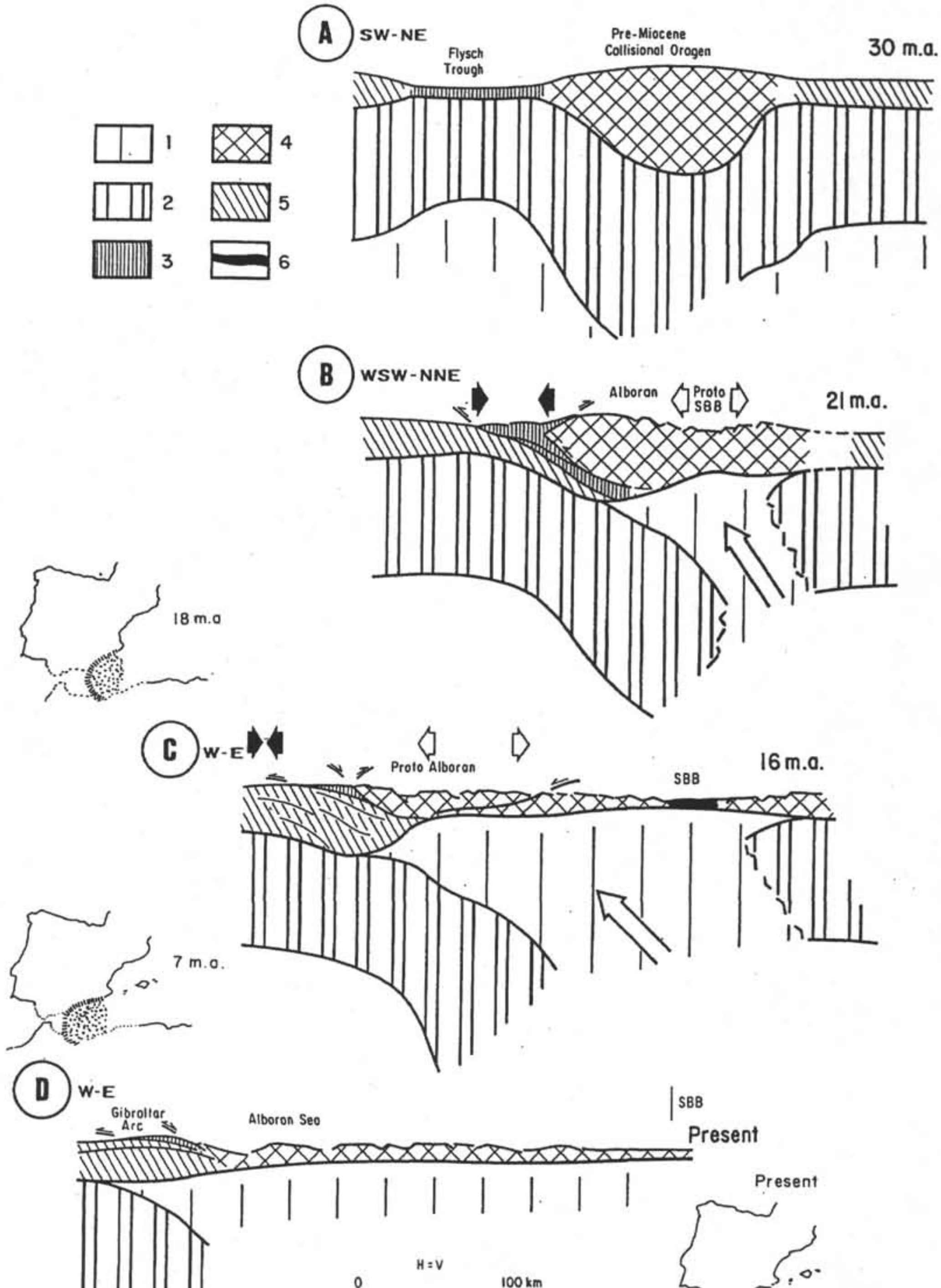

Figure 2B. Hypothesis for the origin of the Alboran Basin, considering the case of initial asymmetric lithospheric thickness (offset) in the collisional orogen and then subsequent "delamination" of the lithosphere. Note that this model implies that the onset of extension on the Alboran Basin itself postdates the Miocene continental collision, which conditioned the Gibraltar Arc (B), and that the locus of the extension migrated (from the South Balearic to the "proto " Alboran Basin) contemporaneously with outwardly vergent thrust-belt development (B to C).

1 - Low-density mantle. 2 - Lithospheric mantle. 3 - Flysch Trough. 4 - Alboran Crustal Domain. 5 - South Iberian/Maghrebian continental margins. 6 - Oceanic or very thin anomalous crust. SBB - South Balearic Basin. Proposed position for the Gibraltar Arc front at 18 and 7 Ma is shown. Note change of orientation from section A to D (from Comas et al., in press, a).

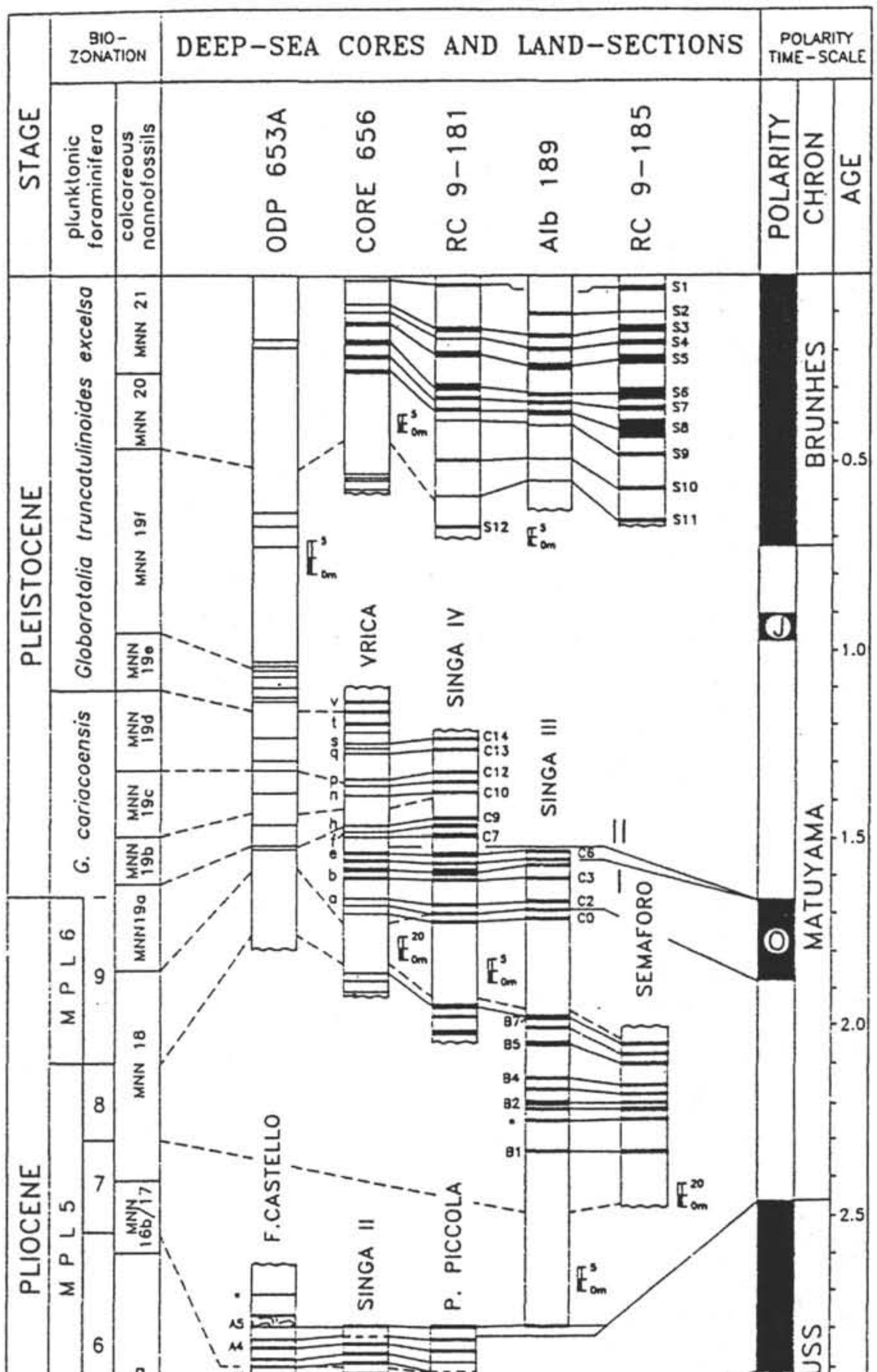

Figure 3. Late Pliocene to Pleistocene distribution of sapropels in land-based sections and in sediment cores from the Mediterranean (from Hilgen, 1991).

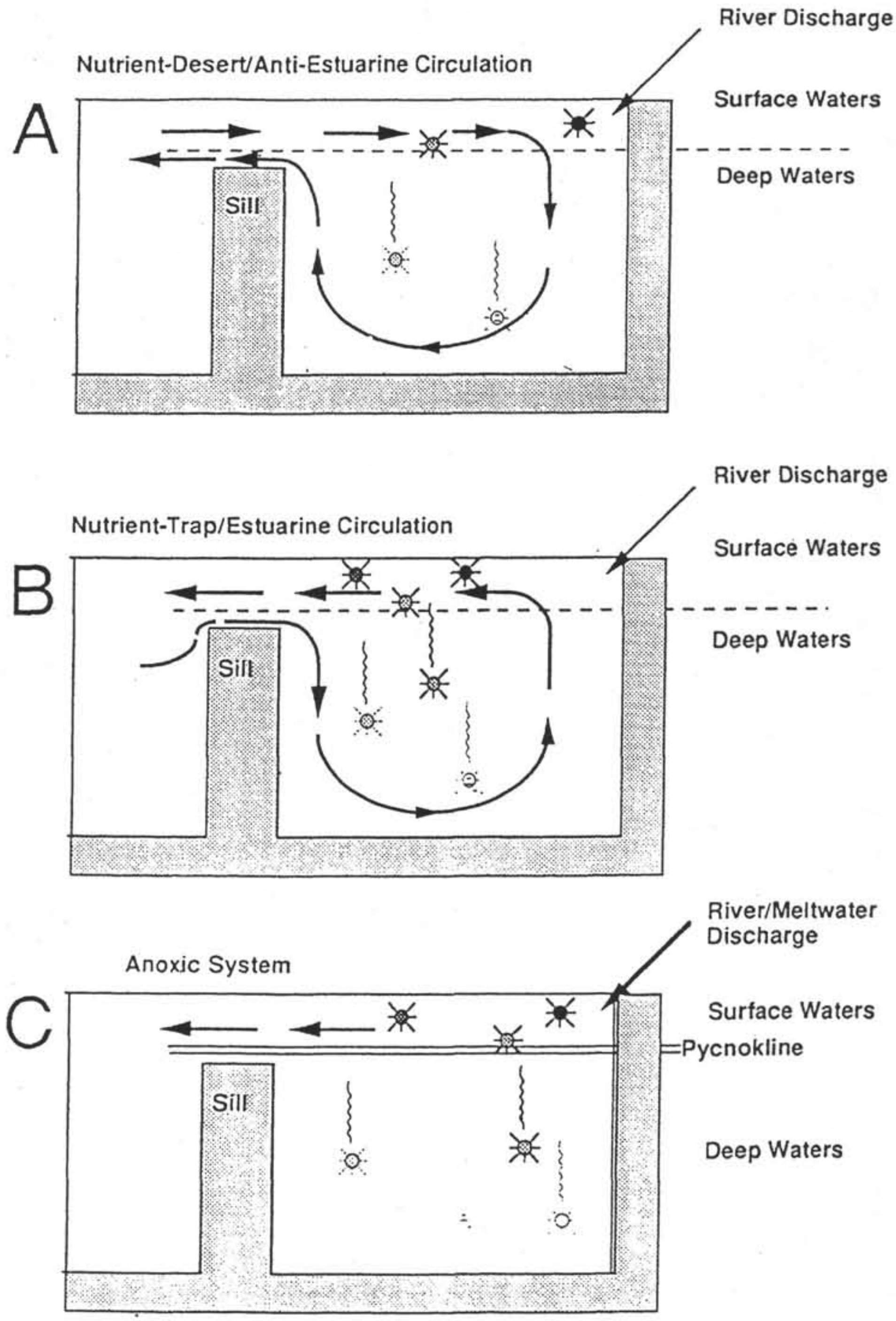

Figure 4. Schematic diagrams showing modern and hypothetical past circulation patterns of the Mediterranean Sea.

(A) Modern anti-estuarine system. (B) Estuarine system (e.g., Sarmiento et al., 1988).
(C) Stagnant "anoxic" system (e.g., Olausson, 1961).

Scenarios (B) and (C) would have promoted the formation of sapropels through either enhanced preservation of organic carbon due to bottom-water anoxia or through enhanced rates of biological productivity in the surface waters, which would have led to increased fluxes of organic carbon to the seafloor.

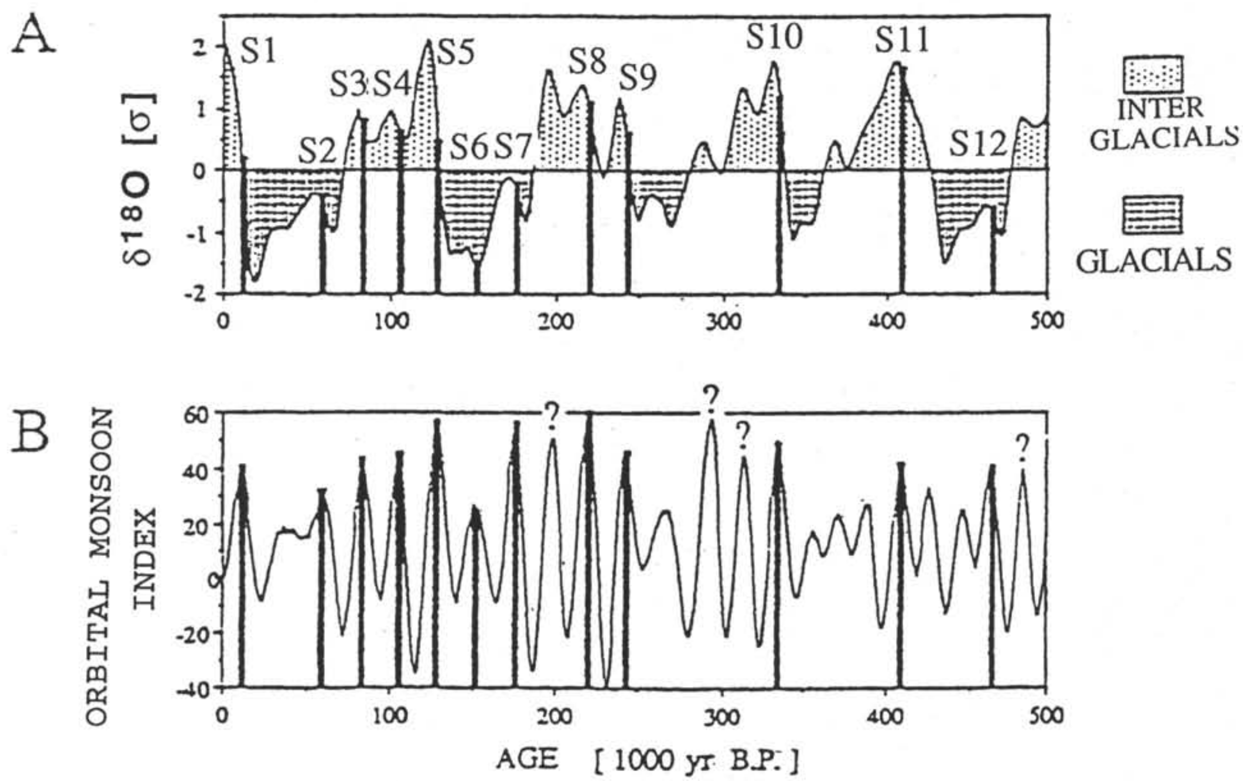

Figure 5. Distribution of Eastern Mediterranean sapropels as a function of (A) global climate and (B) the orbital monsoon index *sensu* Rossignol-Strick (1983).

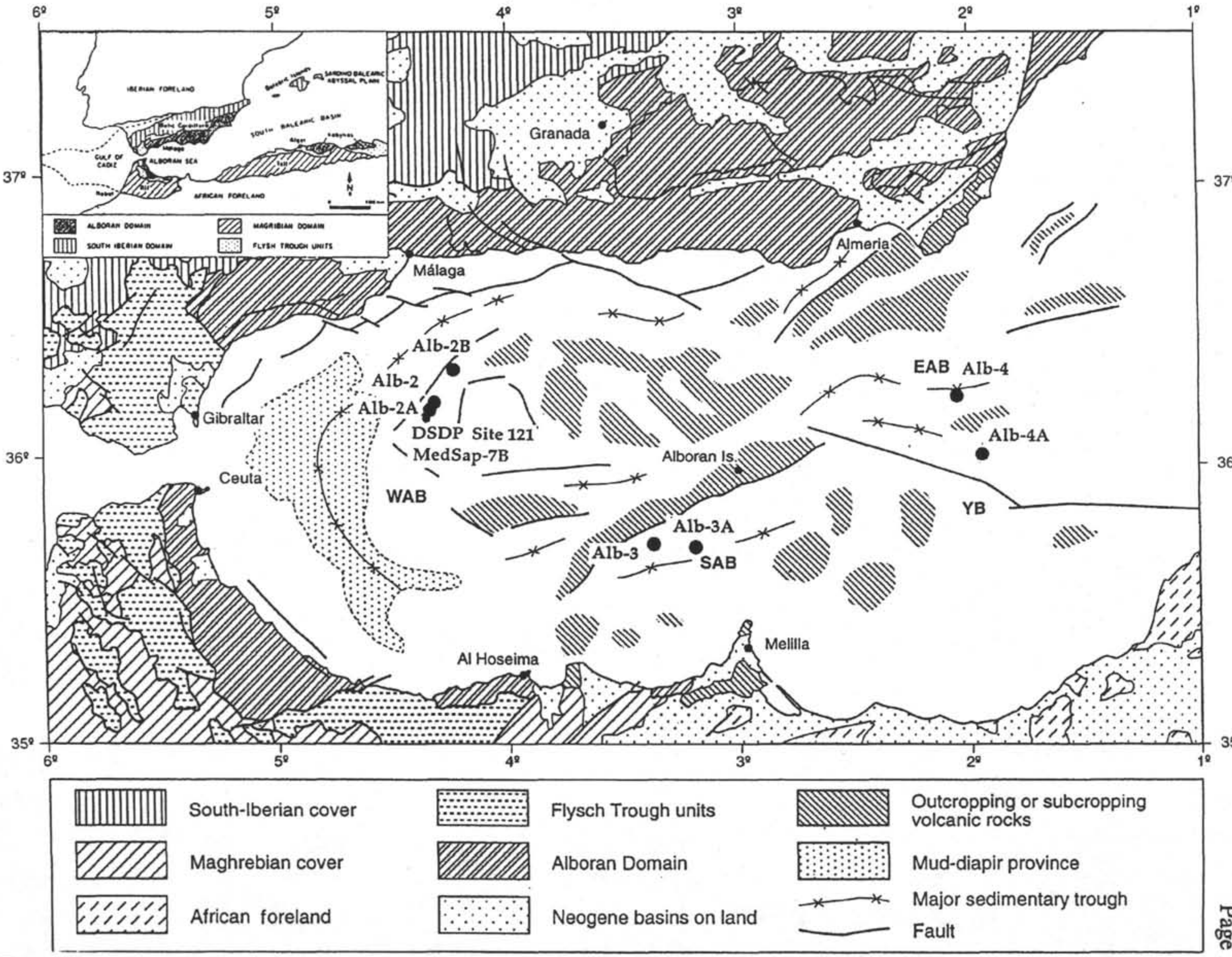

Figure 6. Structural sketch of the Alboran Sea based on interpretation of MCS profiles and the surrounding Betic and Rif Chains (from Comas et al., 1993). Leg 161 drill sites and DSDP Site 121 are shown. Inset - Map showing the Alpine chains surrounding the Alboran Sea and the general tectonic subdivision of crustal domains (from Balanyá and García-Dueñas, 1987). Onshore distribution of this domains indicates that the continental basement beneath the Alboran Sea belongs to the Alboran Crustal Domain.

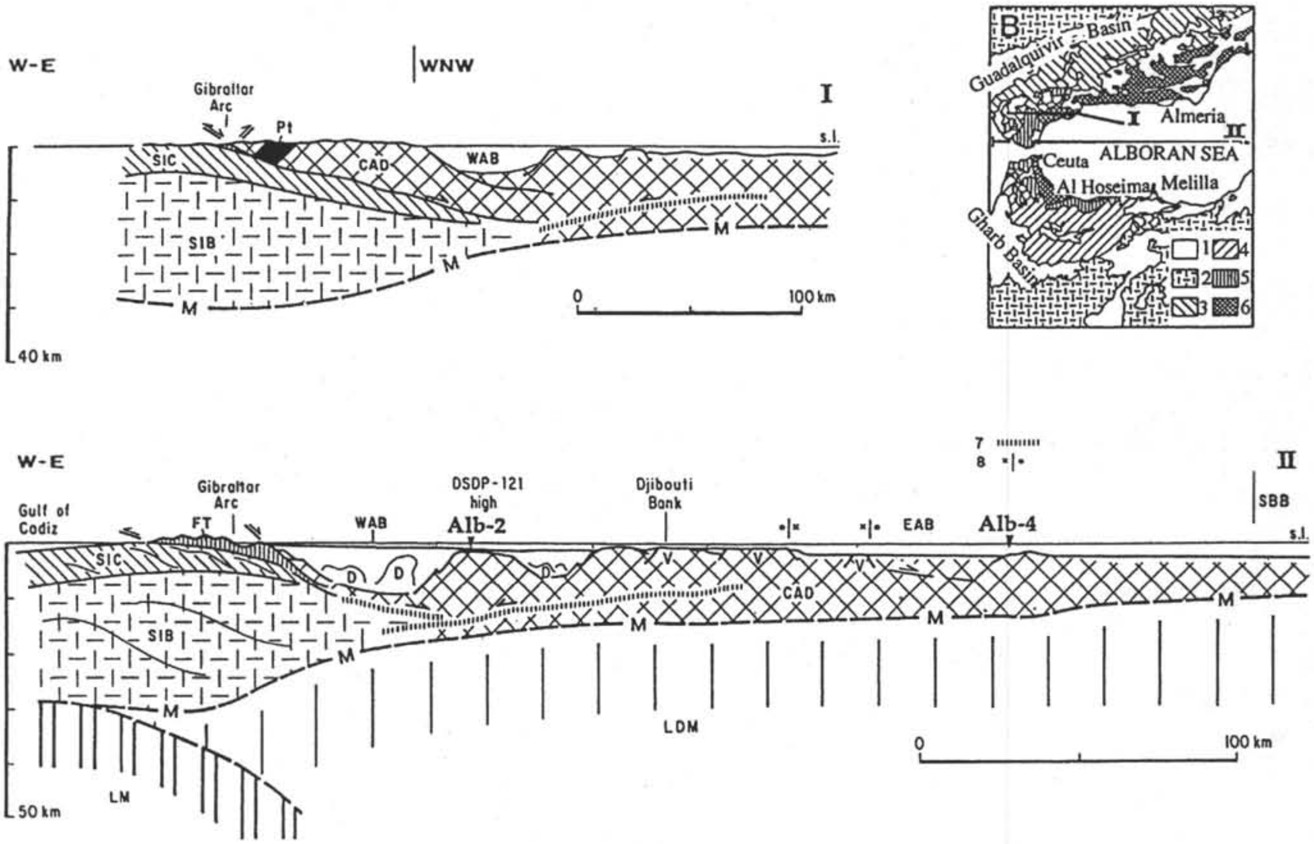

Figure 7A. Schematic true-scale sections across the Gibraltar Arc and the Alboran Sea Basin to illustrate the large-scale east-west structure of the basin and its location on a convergent orogenic setting. Crustal thickness from Banda and Ansorge (1980) and supposed position of ductile extensional detachments (7) within the CAD.

CAD - Crustal Alboran Domain. D - Mud diapirs. FT - Flysch Trough units.
LM - Lithosphere Mantle. LMD - Low-density mantle. M - Moho. Pt - Ronda peridotites.
SIC - South Iberian paleomargin cover. SIB - South Iberian paleomargin basement.
V - Volcanics superimposed on the CAD. SBB- South Balearic Basin.
WAB - Western Alboran Basin.

Proposed drill site locations (Alb-2 and Alb-4) are shown in Section II.

Inset - Structural map of chains surrounding the Alboran Sea.

1 - Miocene to Holocene sediments. 2 - South-Iberian and Maghrebian paleomargin basements.
3 - South Iberian paleomargin cover. 4 - Maghrebian paleomargin cover. 5 - Flysch Trough Units.
6 - Crustal Alboran Domain. 7 - Ductile extensional detachments. 8 - Strike-slip faults.

According to this section, the basement beneath the Alboran Sea would correspond to the hanging wall of a major crustal extensional detachment. Note that the slab of Ronda peridotites are also placed on the hanging wall of the extensional detachment (García-Dueñas et al., 1992; Comas et al., 1993). Note that this cross section is the same as cross section D in Figure 2B.

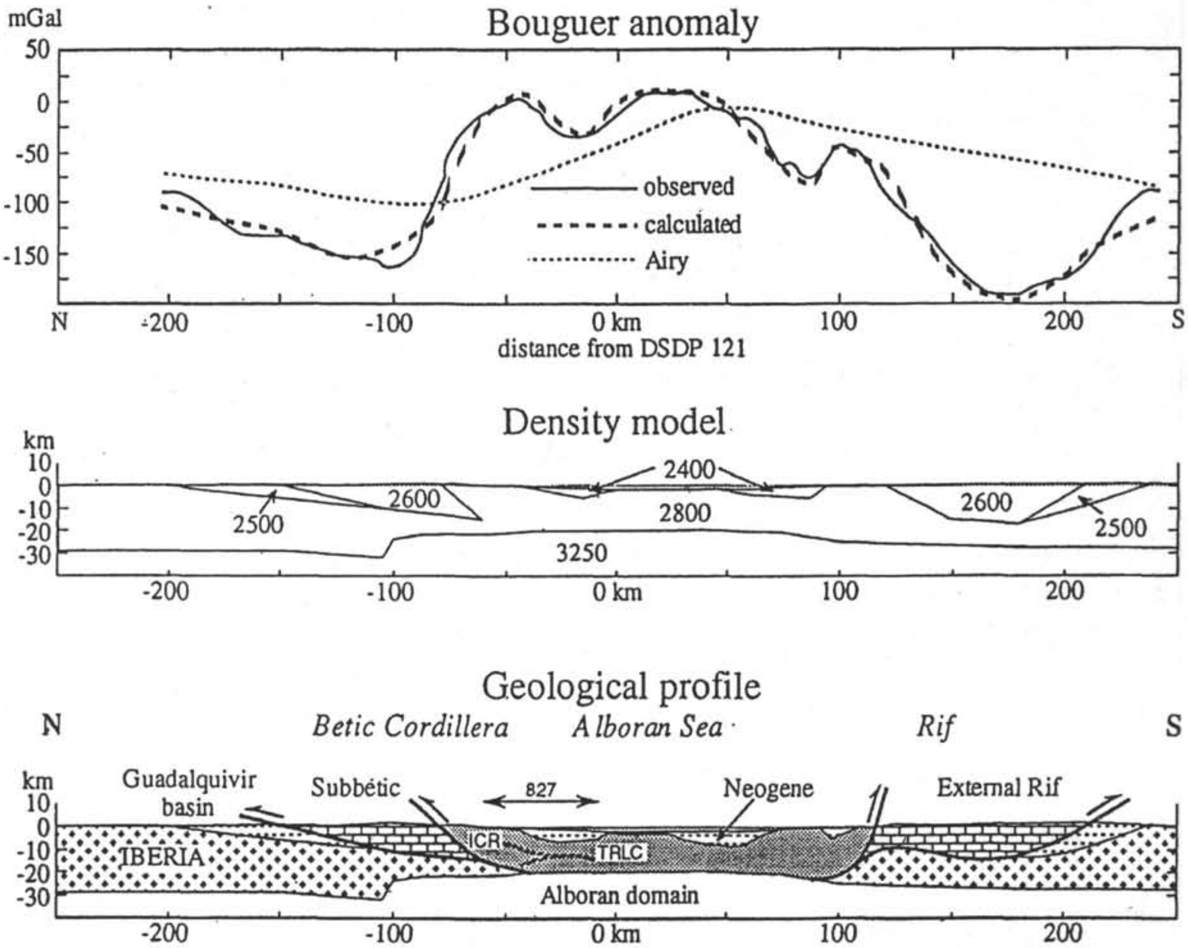

Figure 7B. Bouguer anomaly and schematic true-scale section across the Alboran Sea Basin and adjacent mountain belts.

Upper profile - Bouguer anomaly, calculated anomaly based on the density model shown (middle [kg-3]), and calculated anomaly assuming the basin is in Air-type isostatic equilibrium.

Middle profile - Density model with the assumed densities in kgm-3.

Lower profile - Geological cross section to illustrate the large-scale north-south structure of the basin and its position in a convergent orogenic setting. Deep reflectors ICR (intracrustal reflector) and TRLC (top of reflective lower crust) recognized on seismic line Conrad 827 (arrowed segment) are interpreted as a continuation of the detachment faults onshore (from Watts et al., 1994).

Note that, as known from onshore data, the movement directions on thrusts and extensional detachments have a strong westerly component, oblique to the line of section.

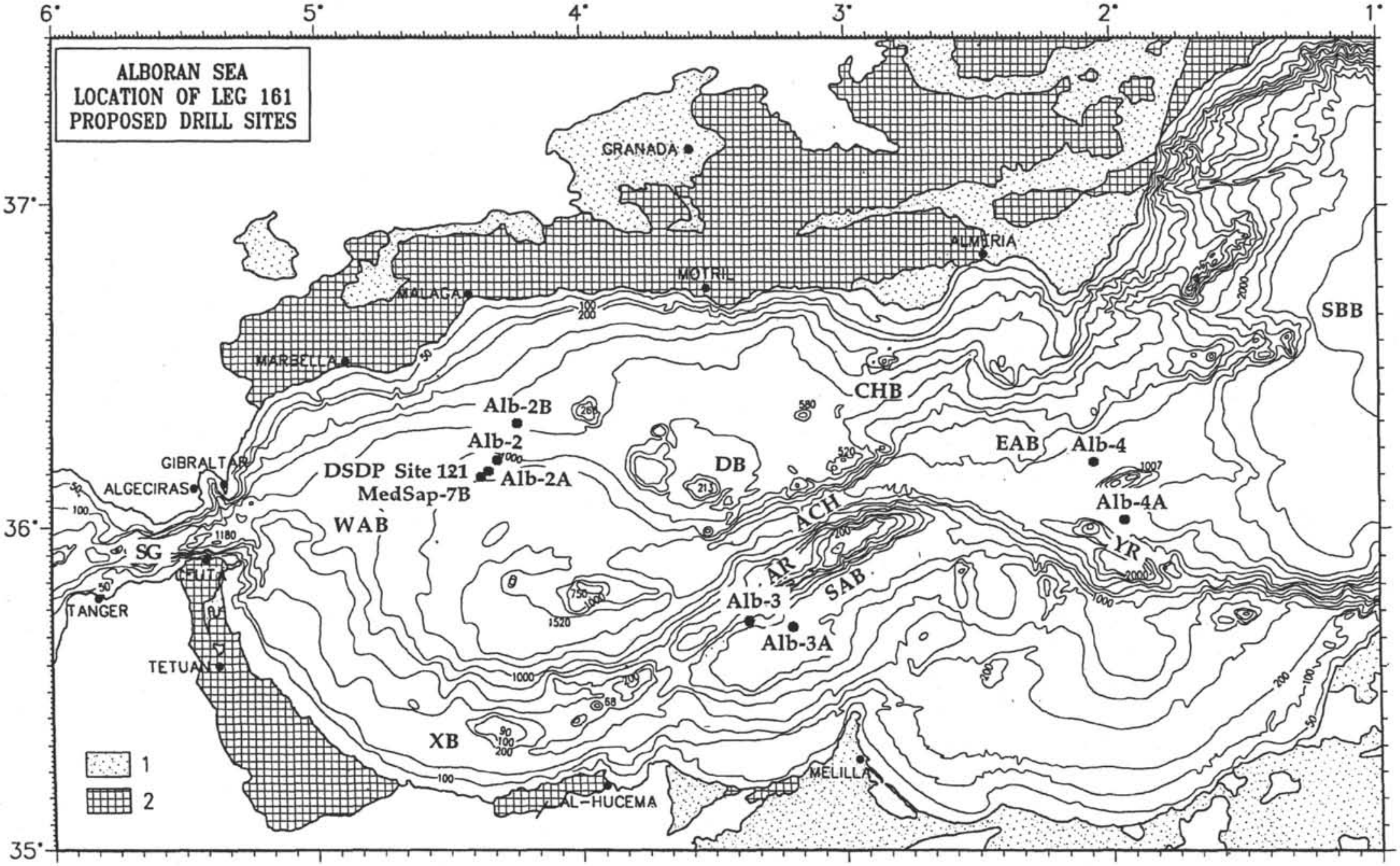

Figure 8. Bathymetric map of the Alboran Sea showing Leg 161 sites. Contour lines in meters.

Onshore: 1 - Miocene marine sediments. 2 - Alboran Domain.
ACH - Alboran Channel. AR - Alboran Ridge. CHB - Chella Bank. DB - Djibuti Bank. EAB - Eastern Alboran Basin.

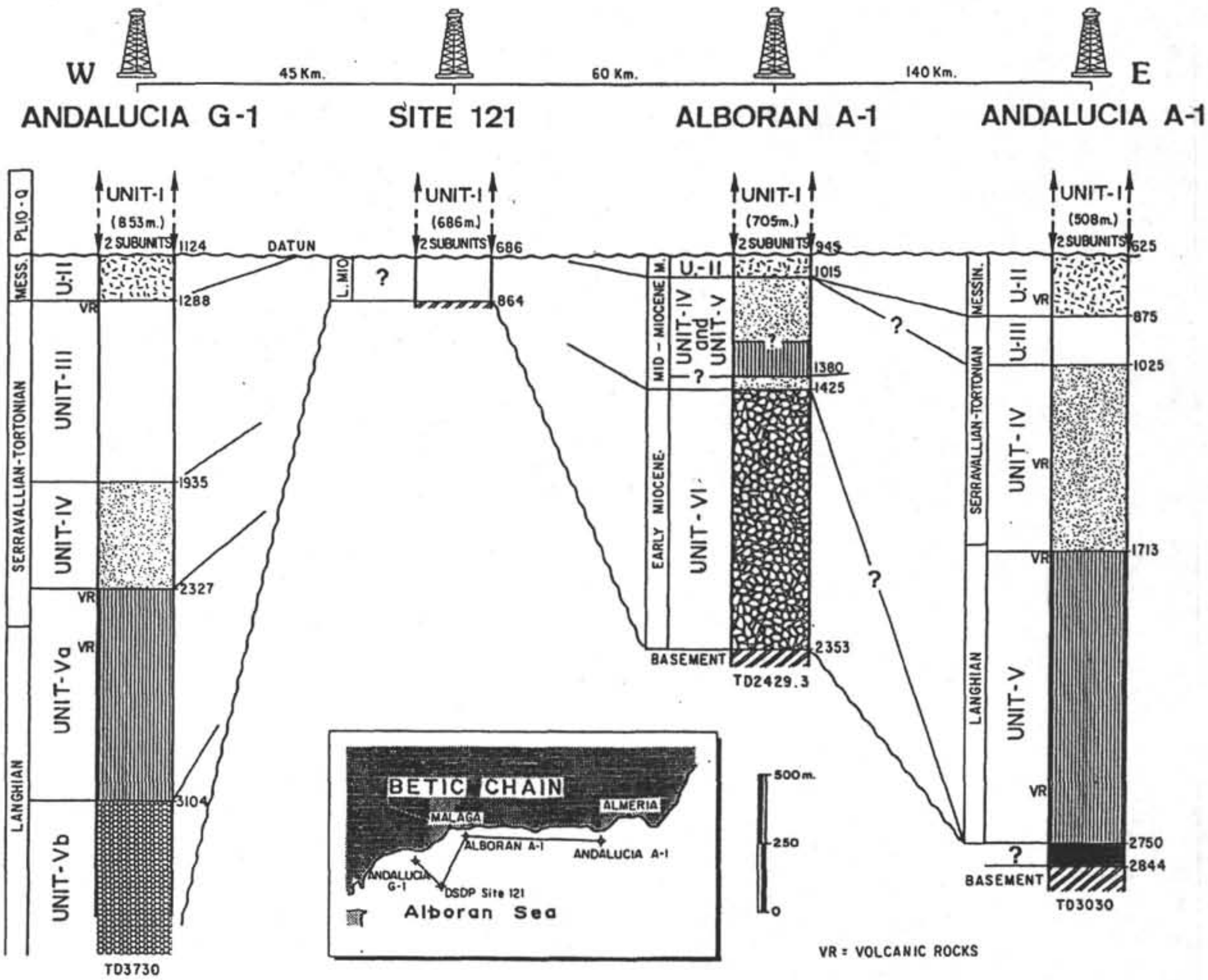

Figure 9. Sedimentary cover on the northern Alboran Sea. An attempt at correlation between commercial wells on the Spanish continental shelf and DSDP Site 121, based on MCS and logging data (from Comas et al., 1992, and Jurado and Comas, 1992).

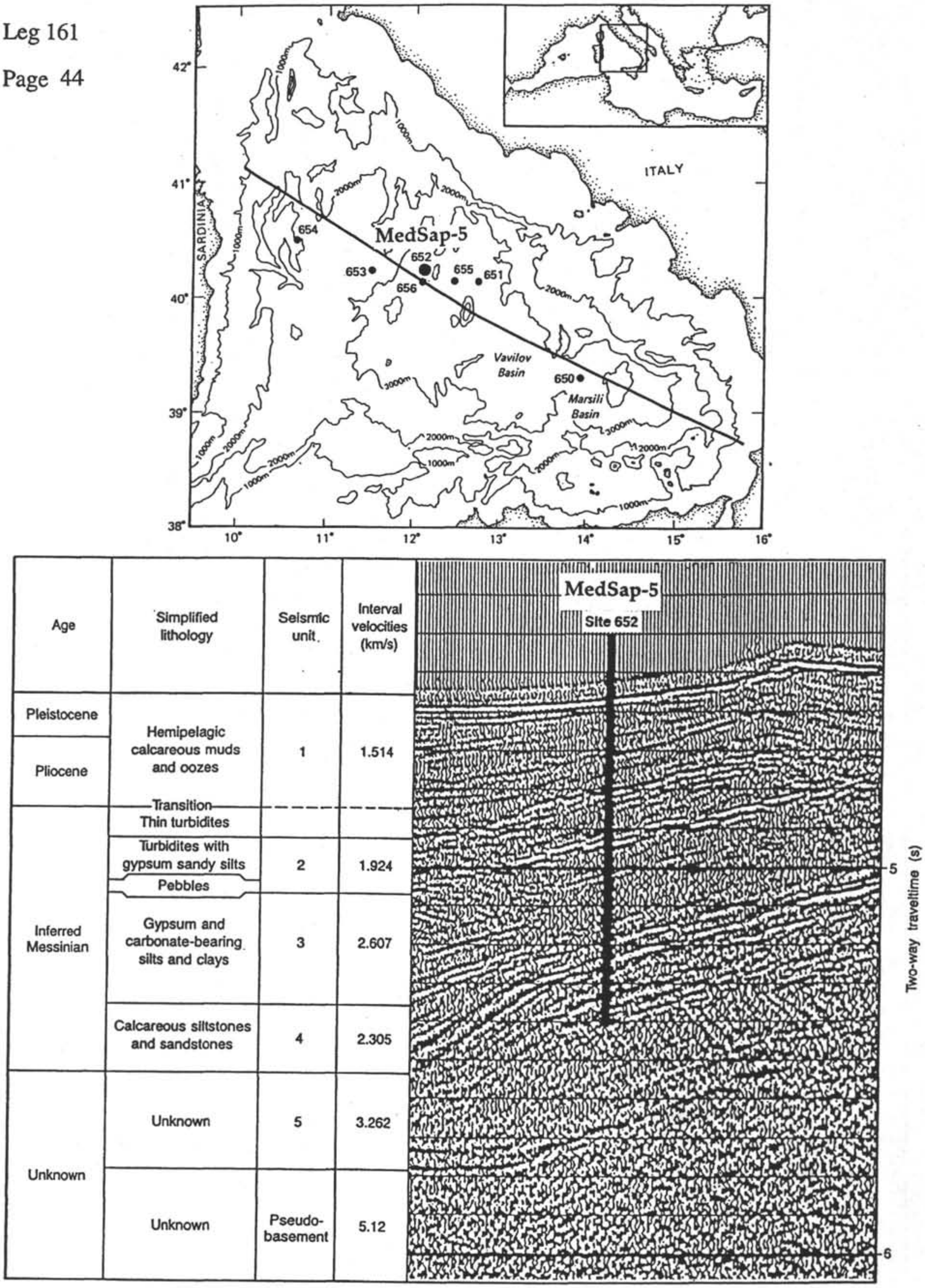

Figure 10. Proposed site MedSap-5 in the Tyrrhenian Sea. MedSap-5 reoccupies ODP Site 652. The lower panel shows seismic units at Site 652, including correlation with interval velocities, main lithologic units, and time scale (from Kastens et al., 1987).

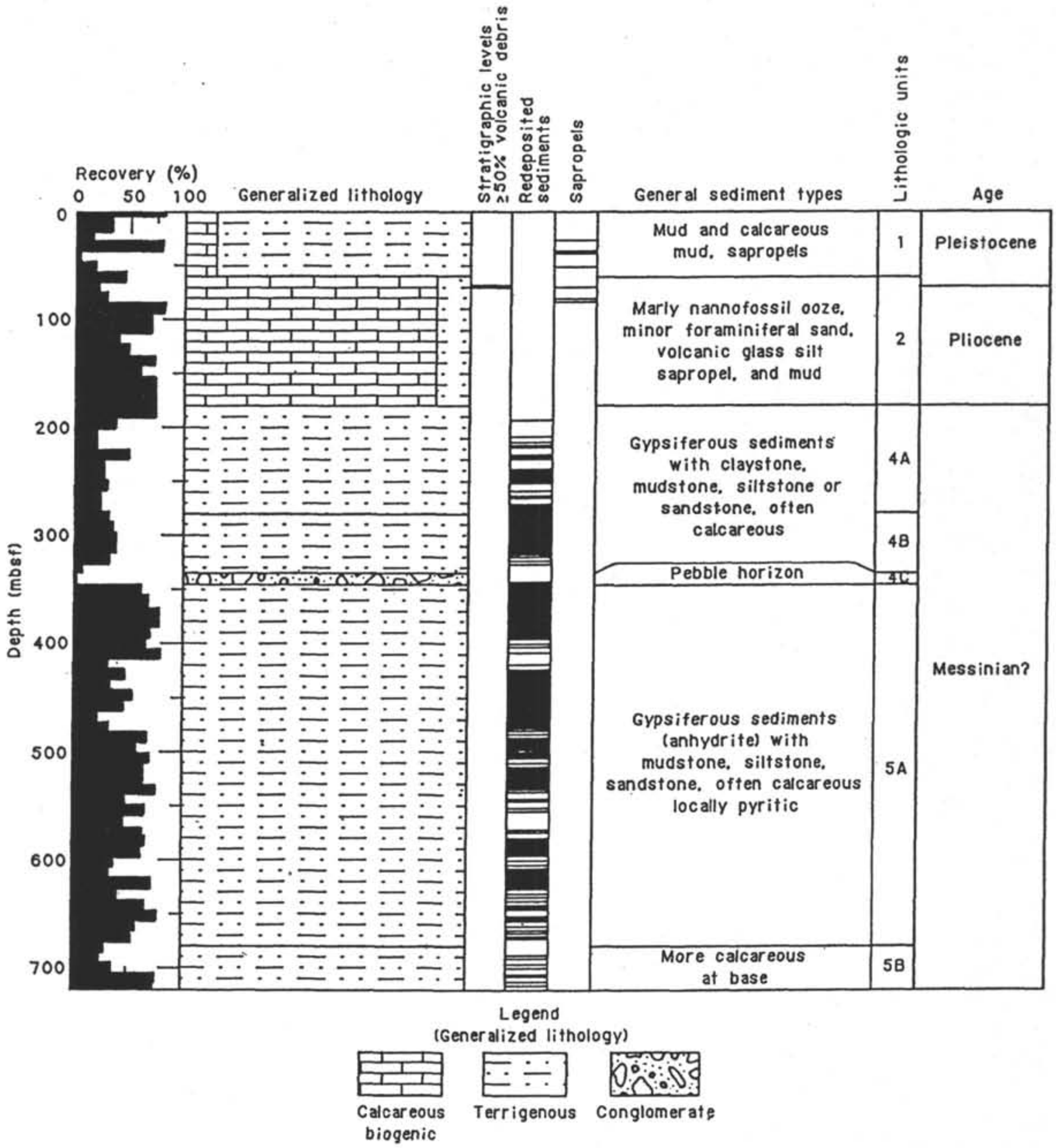

Figure 11. Lithology at ODP Site 652, showing stratigraphic units and sediments to be recovered at proposed site MedSap-5. MedSap-5 will be drilled to a sub-bottom depth of 188 m.

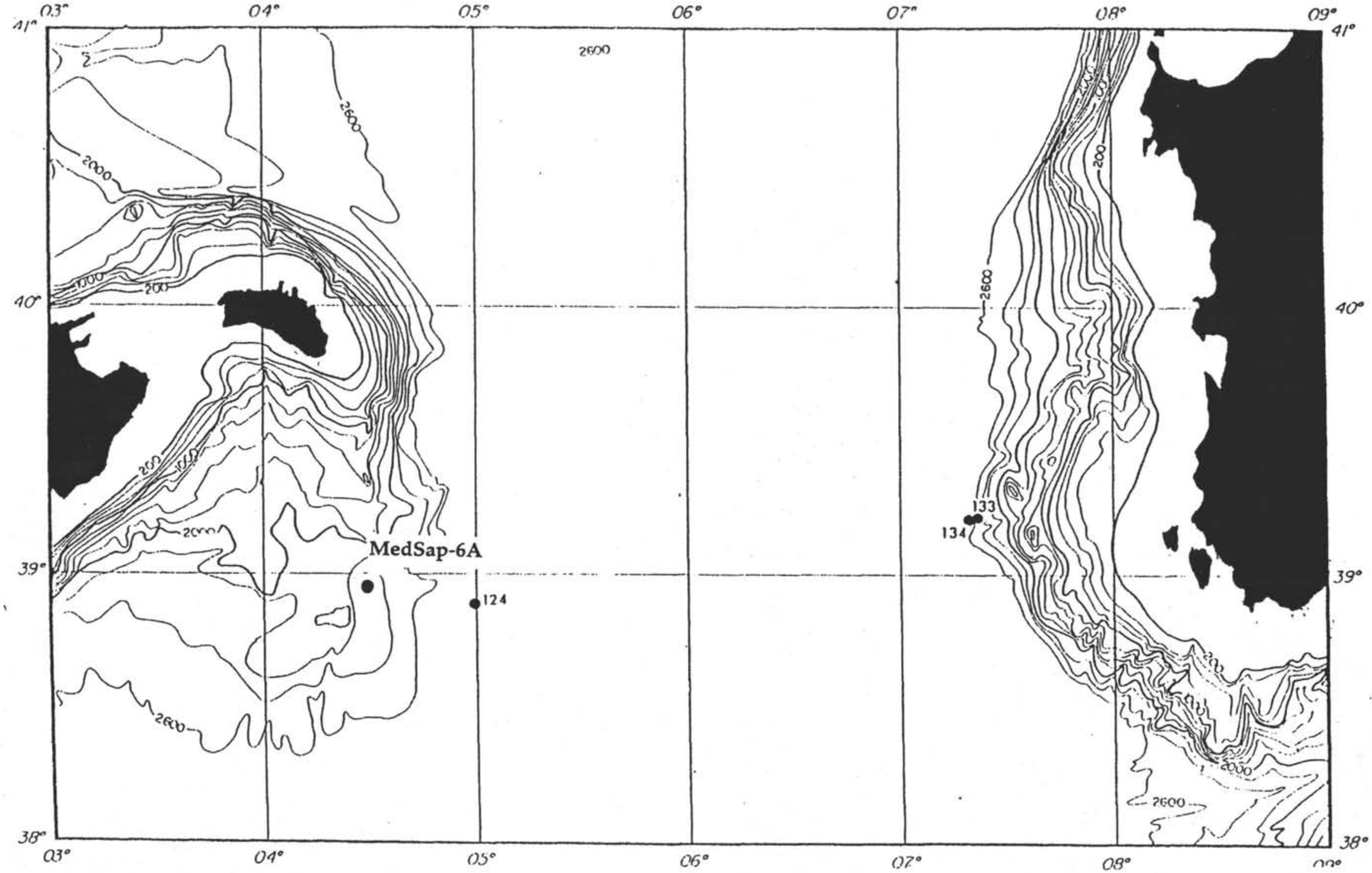

Figure 12. Proposed site MedSap-6 on the southeastern flank of the Menorca Rise.

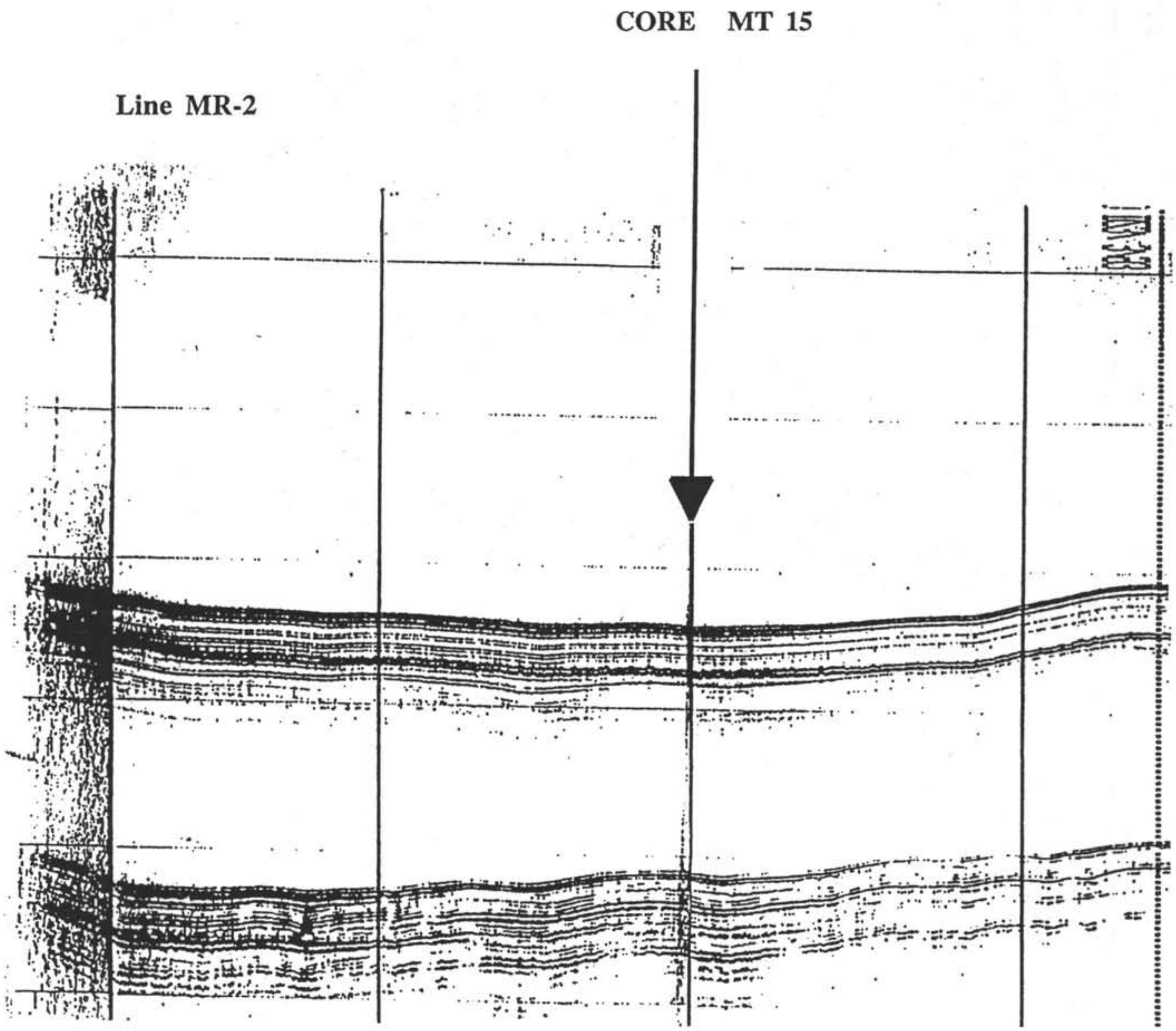

Figure 13. Single-channel air-gun (45-in.^{3}) profile across the position of proposed site MedSap-6 on the Menorca Rise. A 9.5-m-long gravity core (MT 15), retrieved at this position, covers the past interglacial-glacial-interglacial cycle.

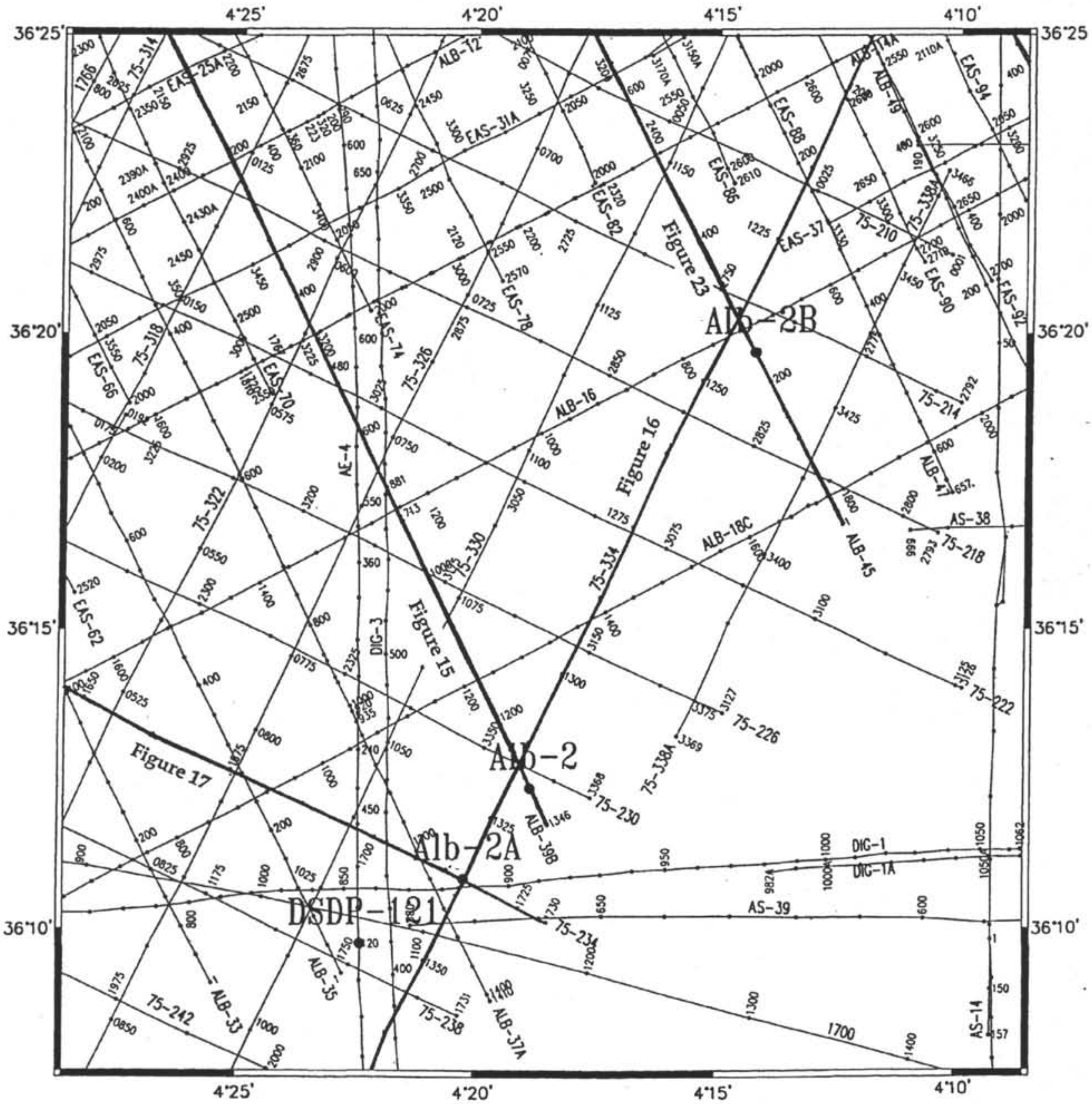

Figure 14. Shotpoint base map around proposed sites Alb-2, Alb-2A, Alb-2B, and DSDP Site 121.

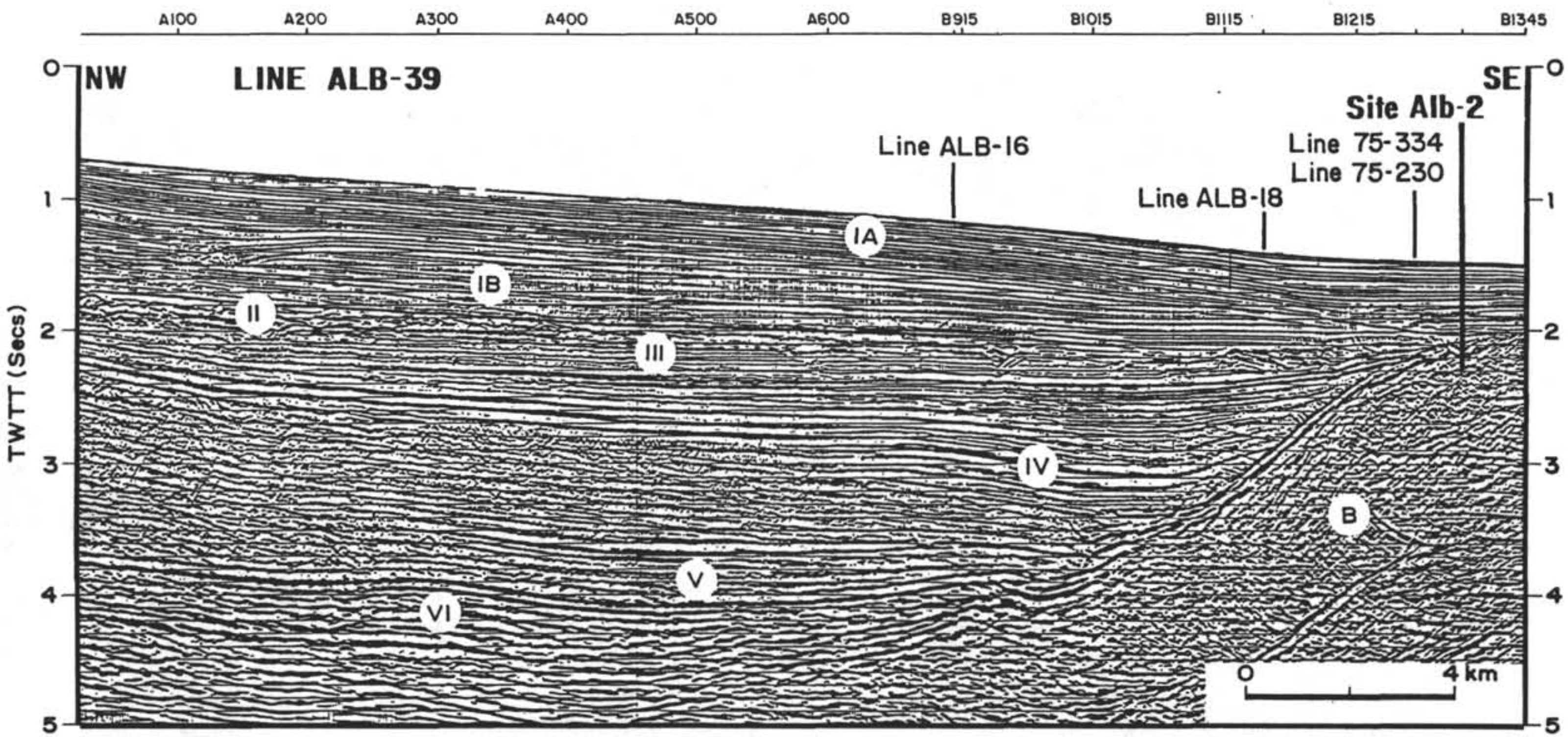

Figure 15. Proposed site Alb-2 on MCS line ALB-39 (dip-line). Cross point with line 75-334 (in Fig. 16) is shown. Numbers for seismostratigraphic units from Figure 9. B - basement. Line position shown in Figure 14.

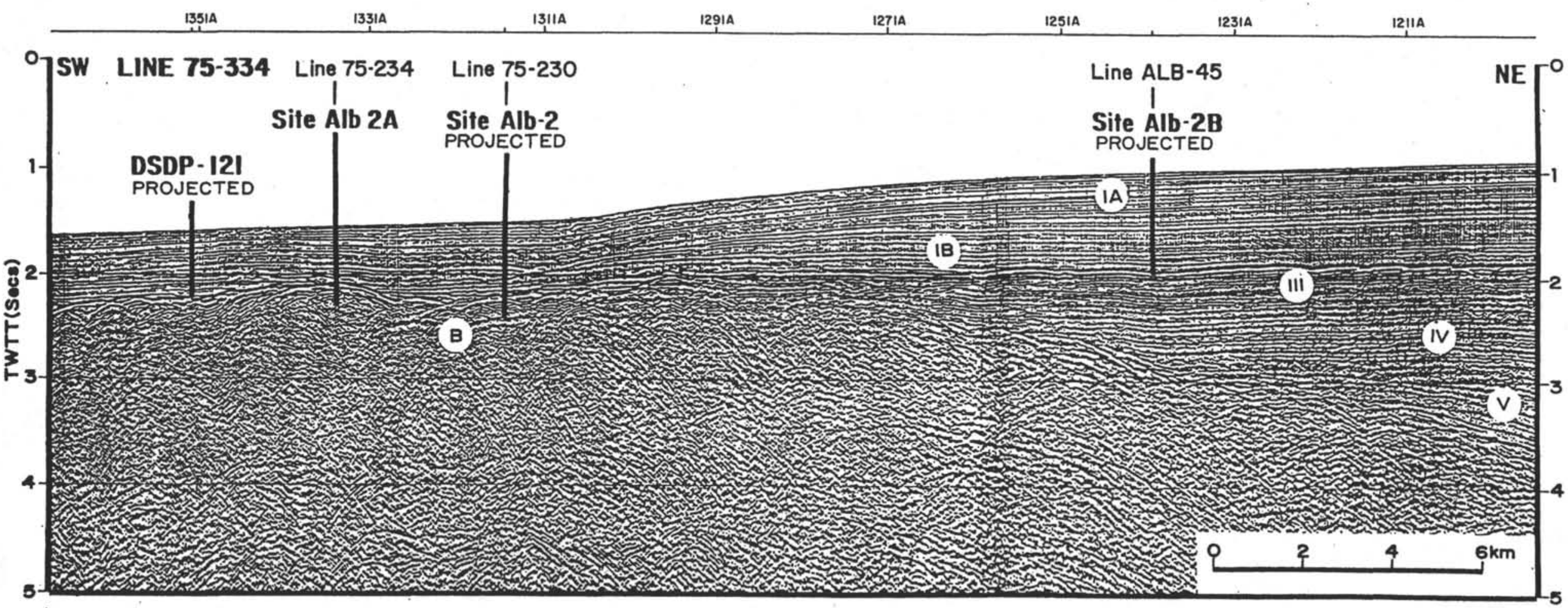

Figure 16. Proposed sites Alb-2, Alb-2A, and Alb-2B and DSDP Site 121 on MCS filtered stack line 75-334 (direction line) and cross point with lines 75-234 (in Fig. 17) and ALB-45 (in Fig. 23). Numbers for seismostratigraphic units from Figure 9. B - basement. Line position shown in Figure 14.

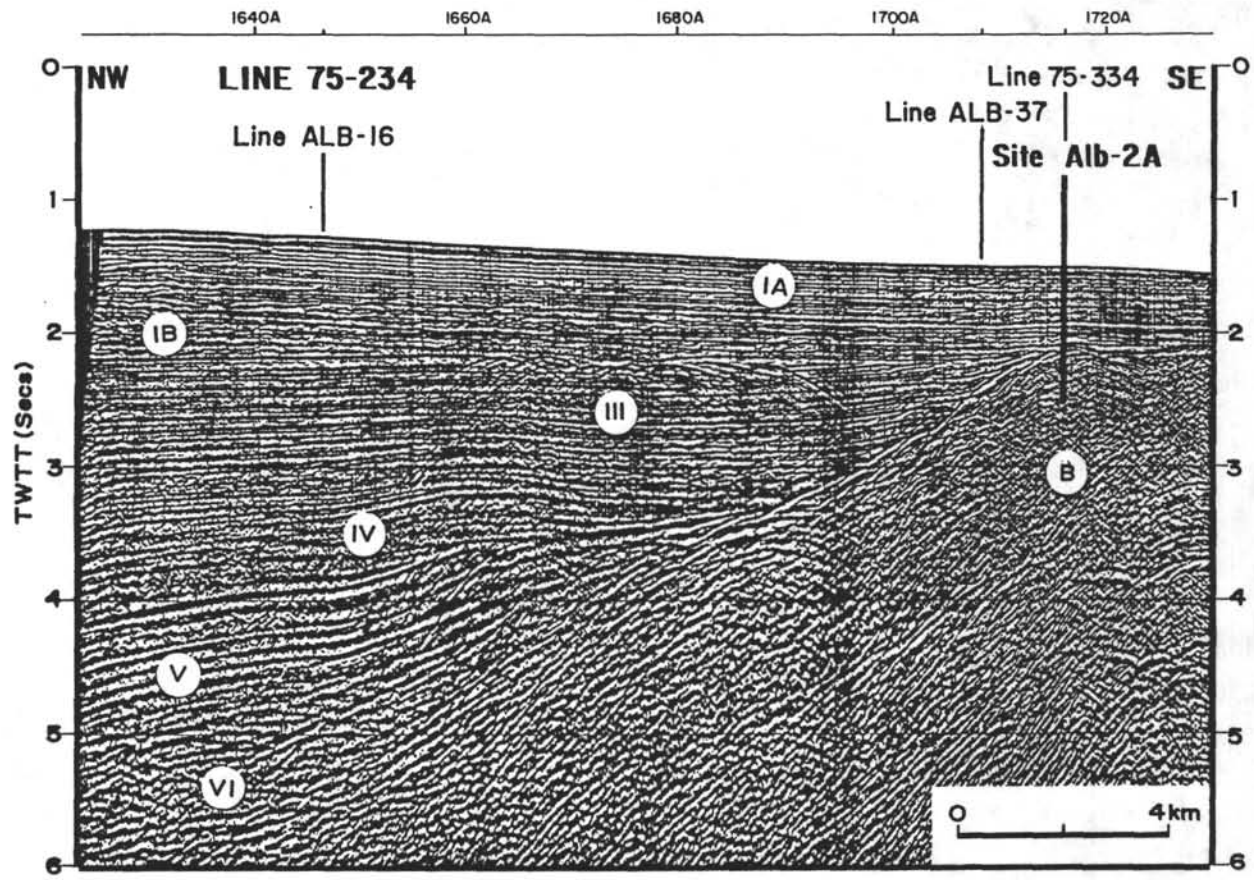

Figure 17. Proposed alternate site Alb-2A on MCS line 75-234 (dip line) and cross point with line 75-334 (in Fig. 16). Numbers for seismostratigraphic units from Figure 9. B - basement. Line position shown in Figure 14.

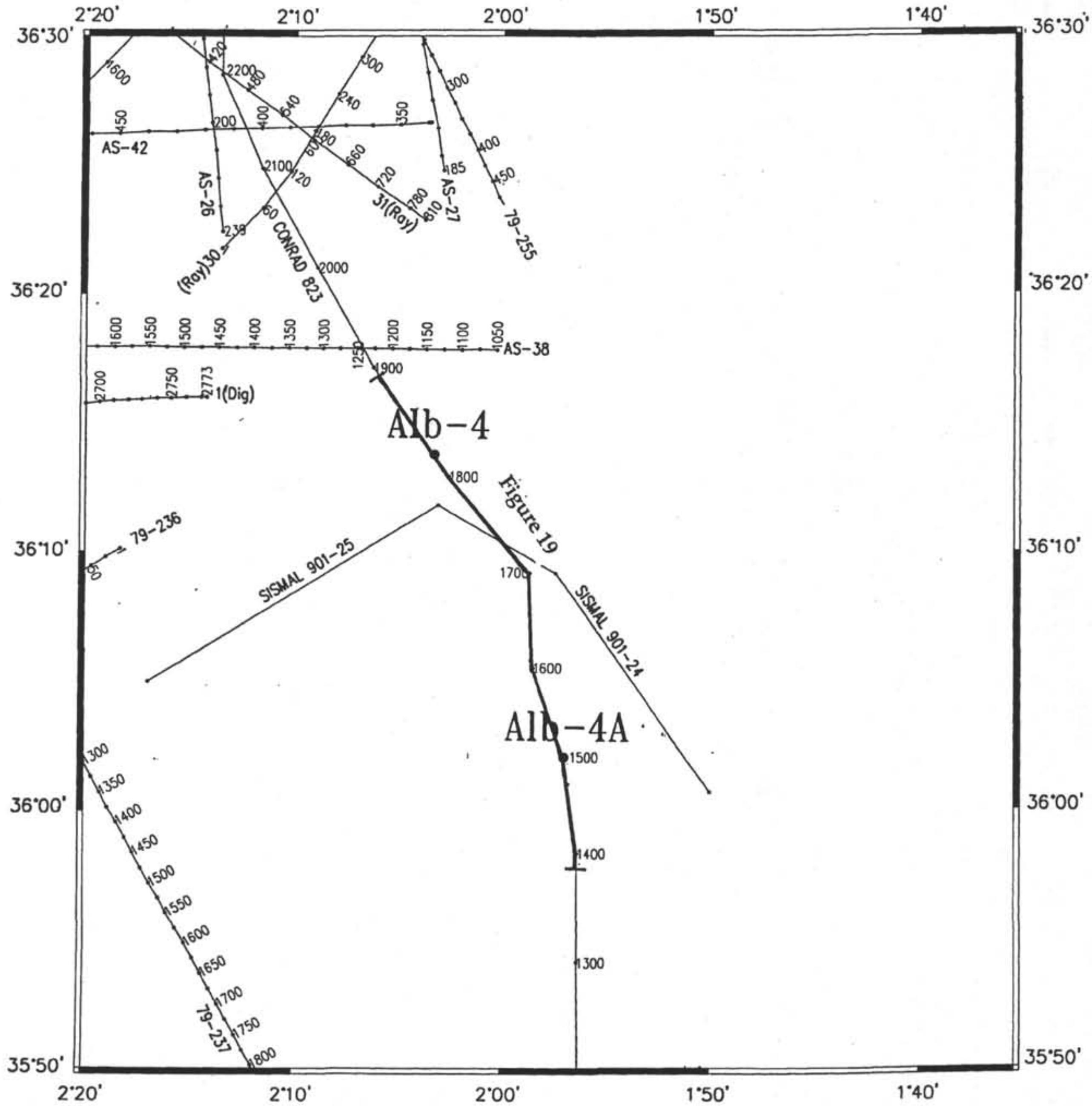

Figure 18. Shotpoint base map around proposed sites Alb-4 and Alb-4A.

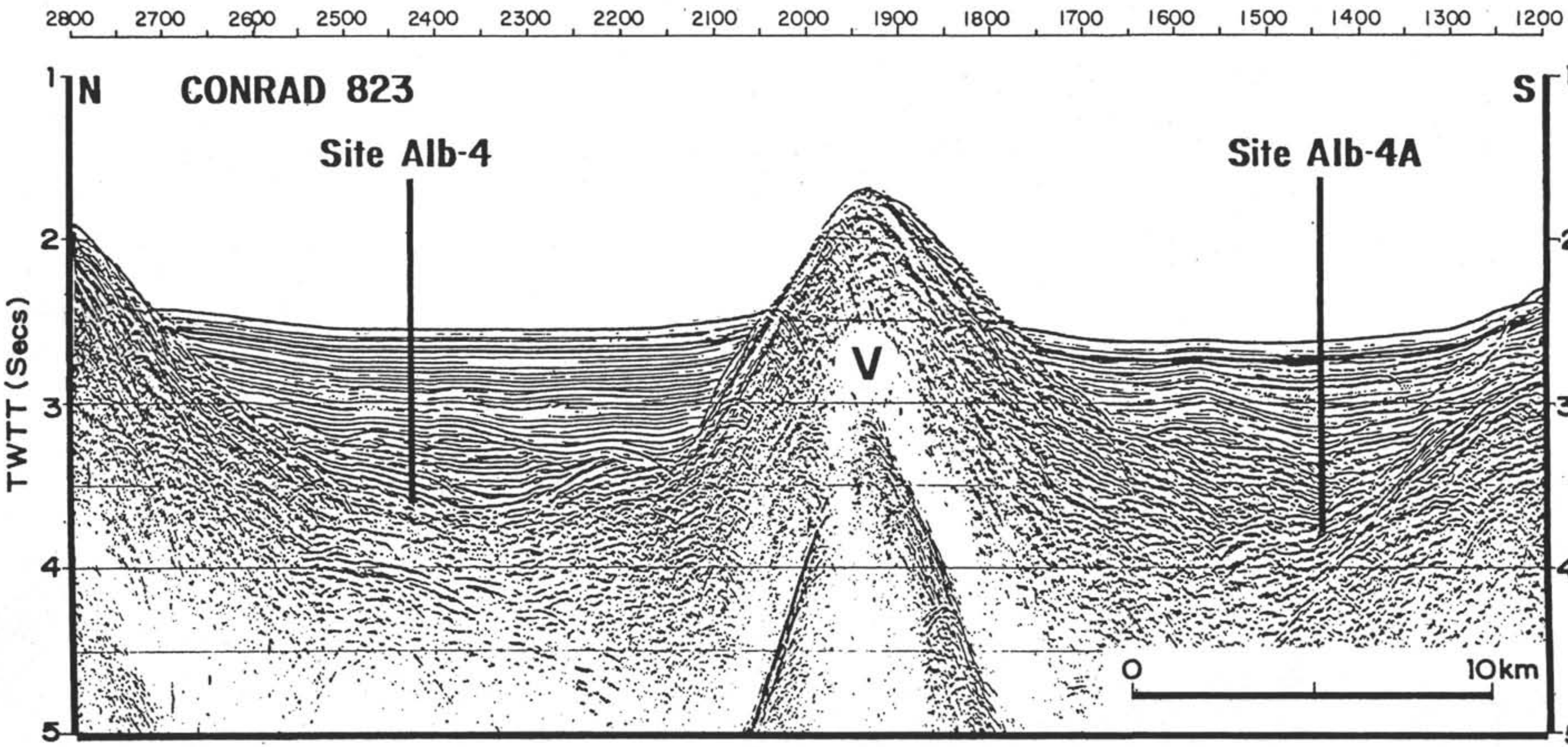

Figure 19. Proposed sites Alb-4 and Alb-4A on MCS line Conrad 823 (dip line). V - volcanic basement. Line position shown in Figure 18.

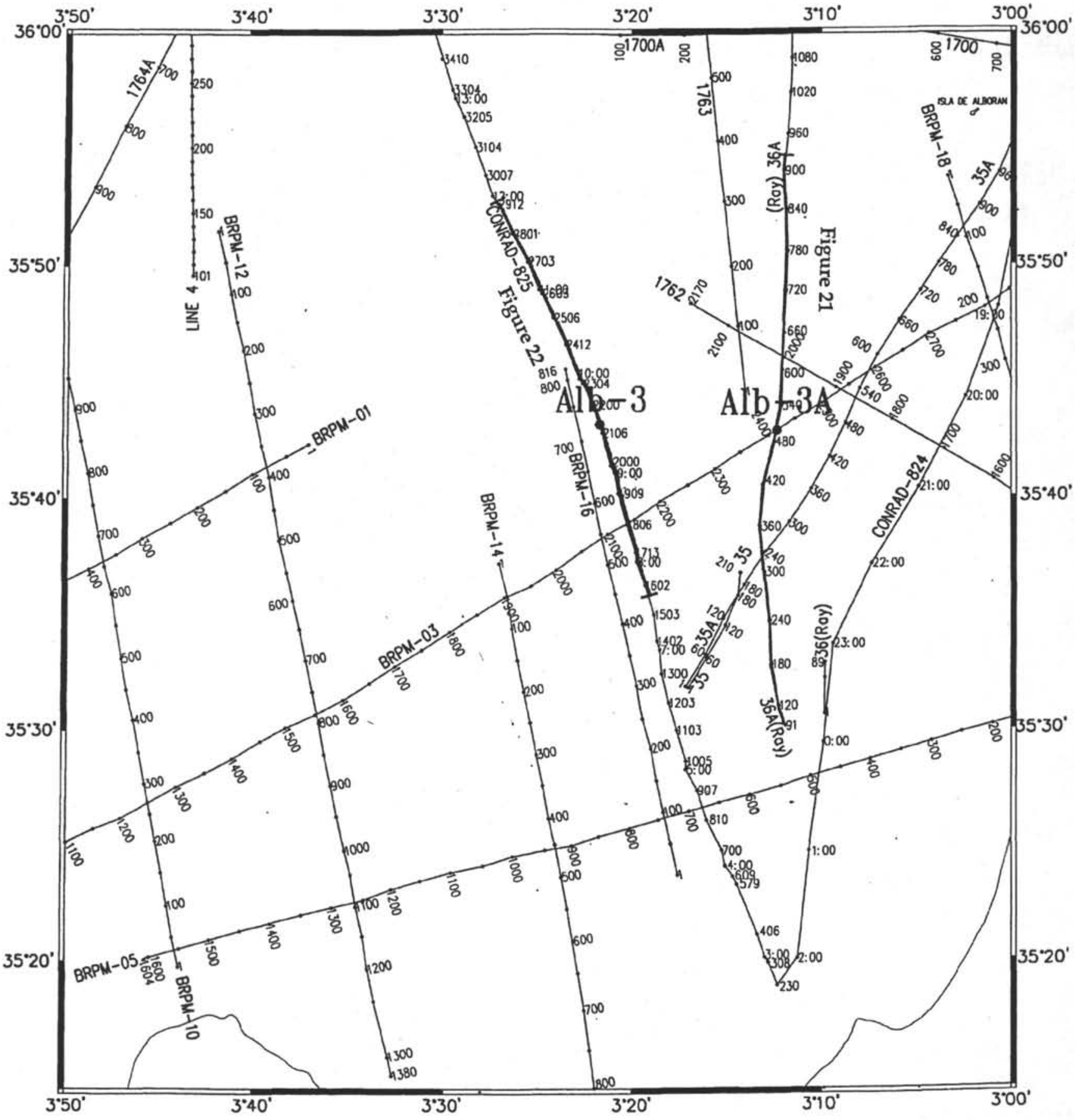

Figure 20. Shotpoint base map around proposed sites Alb-3 and Alb-3A.

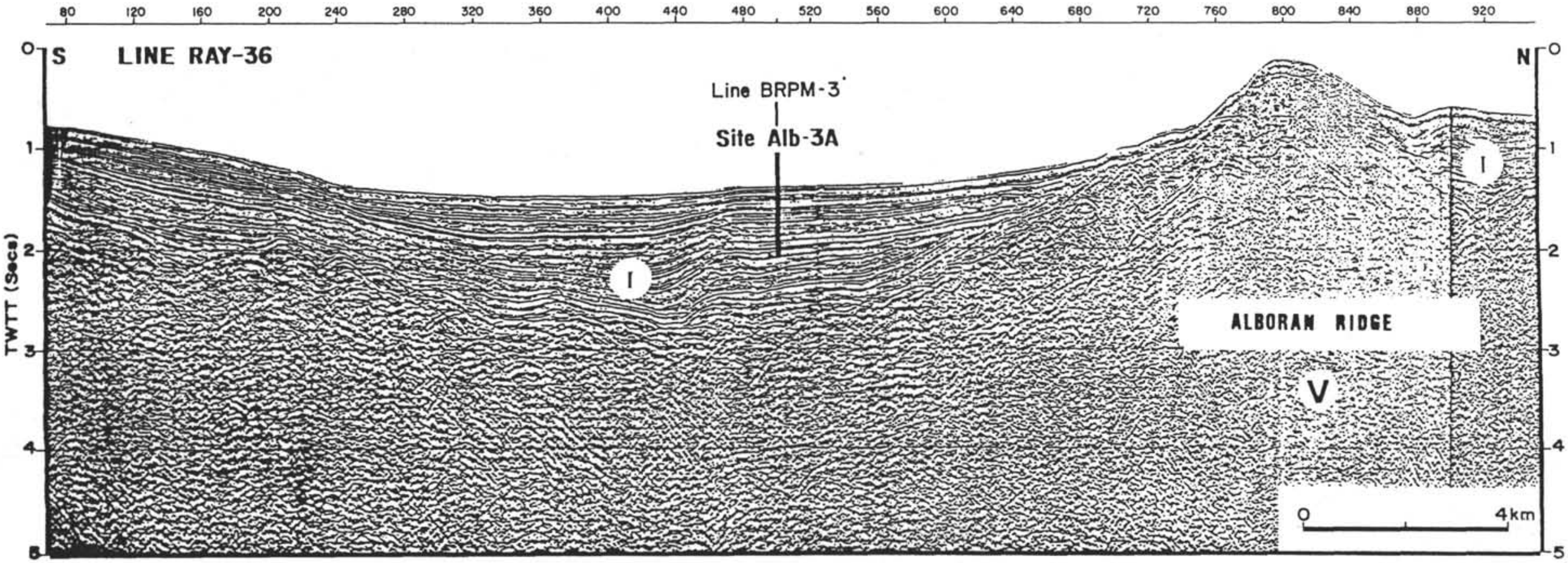

Figure 21. Proposed site Alb-3A on MCS line RAY 36 (dip line). Note cross point with line BRPM-3. Numbers for seismo-stratigraphic units from Figure 9. V - volcanic basement. Line position shown in Figure 20.

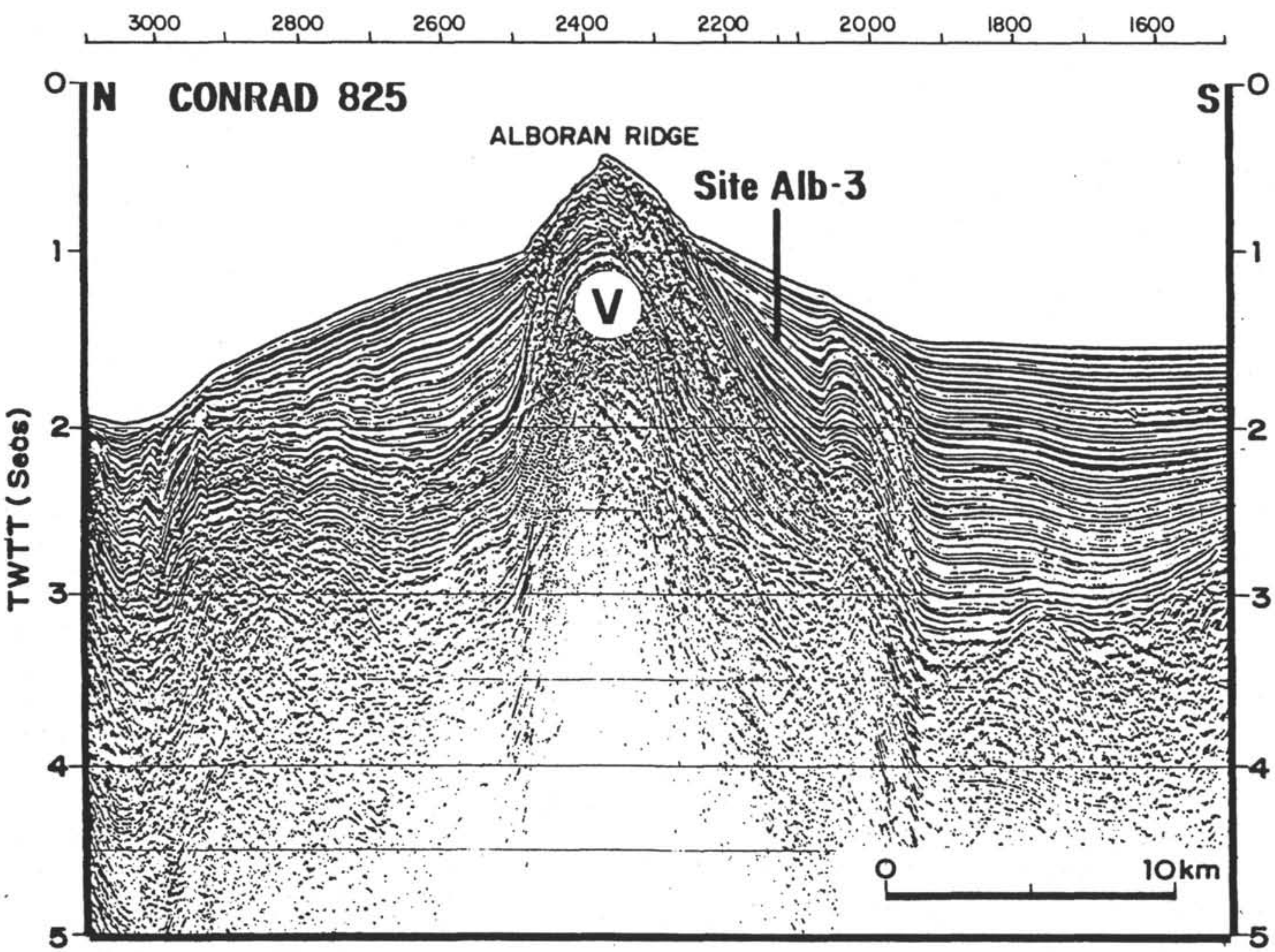

Figure 22. Proposed alternate site Alb-3 on MCS Conrad line 825, showing a folded and faulted sequence on the southern flank of the Alboran Ridge. V - volcanic basement. Line position shown in Figure 20.

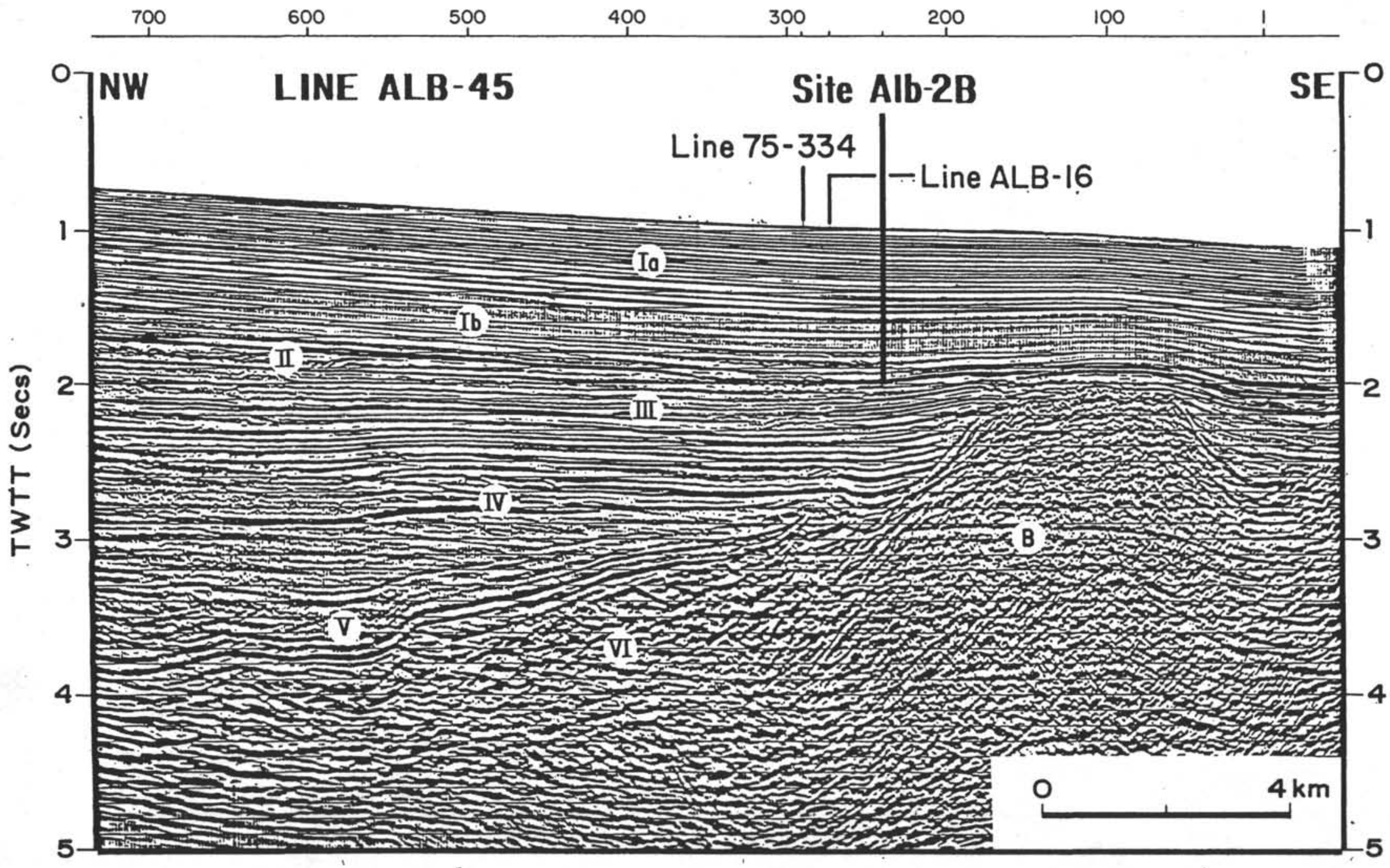

Figure 23. Proposed alternate site Alb-2B on MCS line ALB-45 (dip line). Note cross points with lines 75-334 and ALB-16. If necessary, proposed site MedSap-7B will be combined Alb-2A or Alb-2 which are both about 8 km to the northeast (see Fig. 8). Line position shown in Figure 14.

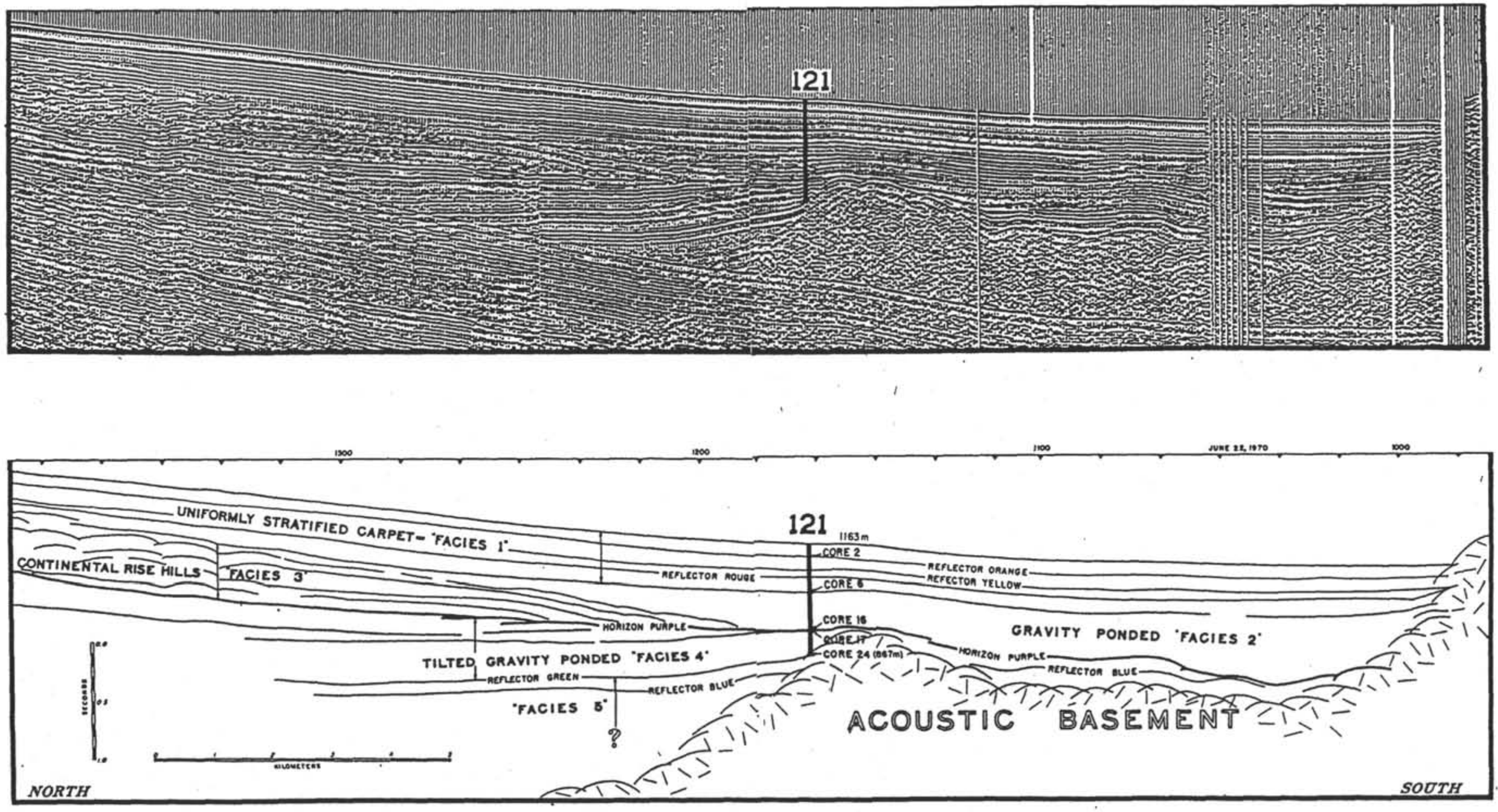

Figure 24. Proposed alternate site MedSap-7B is located at the same position as DSDP Site 121.

Top - Seismic reflection profile (Flexotir) across DSDP Site 121 in the western Alboran Sea. Vertical exaggeration is 2:1.

Bottom - Schematic interpretation of the seismic profile. The marked angular unconformity is shown as "Horizon Purple"; the non-coherent basal reflection unit is taken as acoustic basement (from Ryan, Hsü, et al., 1973).

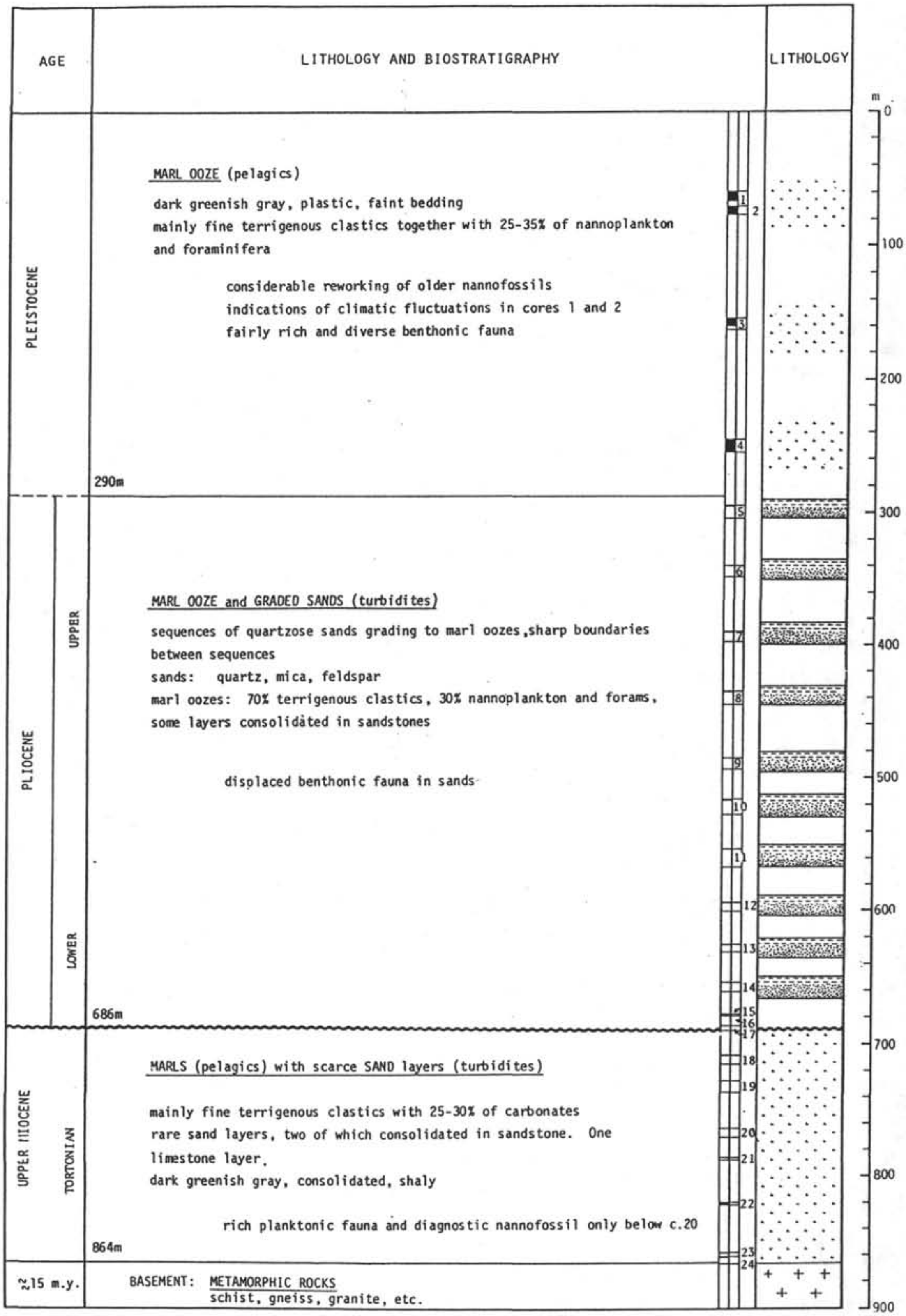

Figure 25. Lithology and stratigraphy expected at proposed alternate site MedSap-7B in the western Alboran Sea (from Ryan, Hsü, et al., 1973). MedSap-7B will be drilled to a sub-bottom depth of 690 m.

Site: MedSap-5 (reoccupation of ODP Leg 107, Site 652)
Priority: 1
Position: 40°21.3'N, 12°08.6'E
Water Depth: 3466 m
Sediment Thickness: >700 m (188 m Pliocene and Messinian)
Total Penetration: 200 m
Seismic Coverage: MCS line ST01, SP 4250 (Figure 10)

Objectives: This site represents the westernmost documented occurrence of sapropels and represents a tie-point for the east-west correlation.

Drilling Program: Triple APC to refusal, then double XCB to 200 m.

Logging and Downhole Operations: FMS, geochemical, quad combo, GHMT/magnetic susceptibility if time available, ADARA/WSTP temperature measurements, and core orientation.

Nature of Rock Anticipated: Calcareous muds and oozes, and sapropels; scattered volcanic ash layers and turbidites.

Site: MedSap-6A

Priority: 1

Position: 38°53.9'N, 4°30.5'E

Water Depth: 2369 m

Sediment Thickness: >350 m

Total Penetration: 350 m

Seismic Coverage: Tyro MR1/MR6 and SCS Bannock BAL09/BAL15 (Figure 13)

Objectives: To study the evolution of surface and intermediate water masses in the Western Mediterranean at times of sapropel deposition in the Eastern Mediterranean. This site represents the central tie-point in the Western Mediterranean.

Drilling Program: Triple APC to refusal and then double XCB to 350 m, where M Reflector represents the top of the Messinian sediments.

Logging and Downhole Operations: FMS, geochemical, quad combo, GHMT/magnetic susceptibility if time available, ADARA/WSTP temperature measurements, and core orientation.

Nature of Rock Anticipated: Calcareous muds and oozes, and sapropels; scattered volcanic ash layers and turbidites.

Site: Alb-2
Priority: 1
Position: 36°12.367'N, 4°18.870'W
Water Depth: 1080 m
Sediment Thickness: 640 m
Total Penetration: 840 m (640 m of sediments and minimum 200 m basement)
Seismic Coverage: MCS line ALB-39, SP 1295 (Figures 14 and 15)

Objectives: To penetrate and sample the basement at the DSDP Site 121 high. To conduct petrologic studies on basement rocks (PTT path, radiometric ages on metamorphic rocks) to reveal the rate and thermal history of extension. To determine rifting geometry. To discriminate between proposed models for the origin of the Alboran Sea. The paleoceanographic objectives include assessment of the mechanism of sapropel formation in the westernmost Mediterranean.

Drilling Program: Triple APC and then double XCB to the top of basement at 640 mbsf. Log deeper XCB hole. Set reentry cone, possibly to basement, at new hole. Wash sediment and sample basement to 200 m using one or more RCB bits. Log basement.

Logging and Downhole Operations: FMS, geochemical, quad combo, GHMT/magnetic susceptibility and BHTV if time available, ADARA/WSTP temperature measurements, and core orientation.

Nature of Rock Anticipated: Sediments - poorly cemented TB turbidites, marly oozes, pelagic marls, siltstones/sandstones, basal conglomerate or minor carbonates (?). Basement - metamorphic rocks, schists, quartz schists, and quartzite veins.

Site: Alb-4A

Priority: 1

Position: 36°2.068'N, 1°57.036'W

Water Depth: 1930 m

Sediment Thickness: 1775-1800 m

Total Penetration: 1200 m

Seismic Coverage: LDGO MCS line 823, CDP 1443 (Figures 18 and 19)

Objectives: To penetrate the sedimentary sequence in a graben structure in the East Alboran Basin. To determine the post-rift, syn-rift vs. total subsidence in the East Alboran Sea. To calibrate the sediment fill stratigraphy. Structural features into sedimentary sequence.

Drilling Program: Single APC/XCB to refusal, log, then RCB to penetrate sedimentary sequence to total depth and log. If a bit change is required and time is available, an FFF may be deployed.

Logging and Downhole Operations: FMS, geochemical, quad combo, GHMT/magnetic susceptibility and BHTV if time available, ADARA/WSTP temperature measurements, and core orientation.

Nature of Rock Anticipated: Oozes, clay, sand, silt, marl, TB turbidites, pelagic facies, and some conglomerate interbedding. Volcaniclastic/volcanic levels.

Site: Alb-3A
Priority: 2
Position: 35°42.306'N, 3°12.163'W
Water Depth: 1036 m
Sediment Thickness: 1500 m
Total Penetration: 600 m
Seismic Coverage: MCS line RAY-36, SP 501 (Figures 20 and 21)

Objectives: To penetrate the major intra-Pliocene (?) unconformity in a zone of compressional deformation on the south flank of the Alboran Ridge near the depocenter of the Southern Alboran Basin. To calibrate post-Messinian stratigraphy. To constrain the timing of latest uplift of the Alboran Ridge and associated folding. Structural features into sedimentary sequence.

Drilling Program: Single APC/XCB to refusal, log, then RCB to penetrate sedimentary sequence to total depth and log. If a bit change is required and time is available, an FFF may be deployed.

Logging and Downhole Operations: FMS, geochemical, quad combo, GHMT/magnetic susceptibility and BHTV if time available, ADARA/WSTP temperature measurements, and core orientation.

Nature of Rock Anticipated: Oozes, clay, silt, marl, TB turbidites (clay, silt, sand), and volcaniclastic levels.

Site: Alb-2A

Priority: Alternate

Position: 36°10.824'N, 4°20.214'W

Water Depth: 1095 m

Sediment Thickness: 620 m

Total Penetration: 820 m (620 m of sediments and 200 m basement)

Seismic Coverage: MCS line 75-234, SP 1716 (Figures 14, 16, and 17)

Objectives: To penetrate and sample the basement at the DSDP Site 121 high. To conduct petrologic studies on basement rocks (PTT path, radiometric ages on metamorphic rocks) to reveal the rate and thermal history of extension. To determine rifting geometry. To discriminate between proposed models for the origin of the Alboran Sea.

Drilling Program: Triple APC and then double XCB to the top of basement at 640 mbsf. Log deeper XCB hole. Set reentry cone or deploy FFF, possibly to basement, at new hole. Wash sediment and sample basement to 200 m using one or more RCB bits. Log basement.

Logging and Downhole Operations: FMS, geochemical, quad combo, GHMT/magnetic susceptibility and BHTV if time available, ADARA/WSTP temperature measurements, and core orientation.

Nature of Rock Anticipated: Sediments - poorly cemented TB turbidites, marly oozes, pelagic marls, siltstones/sandstones, basal conglomerate or minor carbonates (?). Basement - metamorphic rocks, schists, quartz schists, and quartzite veins.

Site: Alb-2B
Priority: Alternate
Position: 36°19.247'N, 4°14.026'W
Water Depth: 717 m
Sediment Thickness: 2000 m
Total Penetration: 1000 m
Seismic Coverage: MCS line ALB-45, SP 240 (Figures 14 and 23)

Objectives: To study gateway circulation between the Atlantic and the Mediterranean. To reconstruct the paleoceanographic exchange and monitor the effects of tectonic/sea-level changes since the Pliocene.

Drilling Program: Single APC/XCB to refusal and log. Deploy FFF if transparent acoustic layer not reached before XCB refusal, then RCB.

Logging and Downhole Operations: FMS, geochemical, quad combo, GHMT/magnetic susceptibility if time available, ADARA/WSTP temperature measurements, and core orientation.

Nature of Rock Anticipated: Calcareous muds and oozes and sand/silt/clay turbidite interlayers. Possible basal conglomerate.

Site: Alb-3
Priority: Alternate
Position: 35°43.123'N, 3°21.824'W
Water Depth: 967 m
Sediment Thickness: 860 m
Total Penetration: 300 m
Seismic Coverage: *R.D. Conrad* LDGO MCS line 825, SP 2129 (Figures 20 and 22)

Objectives: To penetrate the major intra-Pliocene (?) unconformity in a zone of compressional deformation on the south flank of the Alboran Ridge near the depocenter of the Southern Alboran Basin. To calibrate post-Messinian stratigraphy. To constrain the timing of latest uplift of the Alboran Ridge and associated folding. Structural features into sedimentary sequence.

Drilling Program: Single APC/XCB to refusal, log, then RCB to penetrate sedimentary sequence to total depth and log. If a bit change is required and time is available, an FFF may be deployed.

Logging and Downhole Operations: FMS, geochemical, quad combo, GHMT/magnetic susceptibility and BHTV if time available, ADARA/WSTP temperature measurements, and core orientation.

Nature of Rock Anticipated: Oozes, clay, silt, marl, TB turbidites (clay, silt, sand), and volcaniclastic levels.

Site: Alb-4
Priority: Alternate
Position: 36°13.777'N, 2°3.268'W
Water Depth: 1900 m
Sediment Thickness: 1775-1800 m
Total Penetration: 900 m
Seismic Coverage: LDGO MCS line 823, CDP 2424 (Figures 18 and 19)

Objectives: To penetrate the sedimentary sequence in a graben structure in the East Alboran Basin. To determine the post-rift, syn-rift vs. total subsidence in the East Alboran Sea. To calibrate the sediment fill stratigraphy. Structural features into sedimentary sequence.

Drilling Program: Single APC/XCB to refusal, log, then RCB to penetrate sedimentary sequence to total depth and log. If a bit change is required and time is available, an FFF may be deployed.

Logging and Downhole Operations: FMS, geochemical, quad combo, GHMT/magnetic susceptibility and BHTV if time available, ADARA/WSTP temperature measurements, and core orientation.

Nature of Rock Anticipated: Oozes, clay, sand, silt, marl, TB turbidites, pelagic facies, and some conglomerate interbedding. Volcaniclastic/volcanic levels.

Site: MedSap-7B (reoccupation of DSDP Leg 13 Site 121)

Priority: Alternate

Position: 36°09.7'N, 4°22.4'W

Water Depth: 1163 m

Sediment Thickness: 860 m

Total Penetration: 690 m

Seismic Coverage: DSDP Site 121 site survey package (Figure 24)

Objectives: To study gateway circulation between the Atlantic and the Mediterranean. To reconstruct the paleoceanographic exchange and monitor the effects of tectonic/sea-level changes since the Pliocene.

Drilling Program: Triple APC/double XCB, then RCB to total penetration if necessary. Log.

Logging and Downhole Operations: FMS, geochemical, quad combo, GHMT/magnetic susceptibility and BHTV if time available, ADARA/WSTP temperature measurements, and core orientation.

Nature of Rock Anticipated: Calcareous muds and oozes and sandy turbiditic interlayers.

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