1 - Introduction

The CIESM Marine Geosciences Committee, chaired since June 1998 by Jean Mascle – Géosciences Azur, Observatoire océanologique, Villefranche-sur-mer – has decided, following a policy promoted by CIESM, to organize a new series of focused workshops. Three topics have been selected; they concern (1) Scientific Drilling Prospects in the Mediterranean Sea and adjacent areas, (2) the African continental margins of the Mediterranean Sea, and (3) the major deltaic systems in the Mediterranean and Black seas.

This report results from the first workshop, dedicated to "Mediterranean Scientific Drilling Prospectives", held in Granada, on June 10-12 1999.

The workshop, which was locally organized by Pr. M. Comas – Instituto Andaluz de Ciencias de la Tierra, CSIC/Granada University – has allowed 24 scientists to give presentations and participate to high quality discussions. Among the participants, from France, Germany, Greece, Israel, Italy, the Netherlands, Romania, Spain, Switzerland, Tunisia, Turkey and United-Kingdom, 12 of them have already being involved in Scientific Drilling Operations in the Mediterranean Sea, including 5 former co-chiefs of Ocean Drilling Program Legs, in the area.

Several of these scientists belong to ODP - related International Committees, or panels, and one participant is strongly involved in the International Continental Drilling Program (ICDP). We were aiming thus to create strong scientific links between Continental and Marine Scientific Drilling (ICDP and ODP).

2 - Workshop scopes and organisation

The goals of the workshop were multiple:

- to better inform participants (and thus national Communities) on the current state and functioning of, both, ODP (the only active program in Ocean Scientific Drilling) and ICDP;
- to provide an overview of already existing proposals and of drilling interests;
- to organize discussions in order to tentatively focus, or help to focus, on realistic proposals of common interest;
- to provide a report volume (this volume) to better advertise the international community of major scientific issues (and good supporting proposals), to be addressed to the Mediterranean Sea and surroundings.

To achieve these goals, the workshop was organized in two folds: formal presentations and discussions.

Presentations have been made by all participants. They have concerned, either what we may call mature, and/or already existing, scientific drilling proposals, or presentation of scientific problems that can be addressed by drilling. Each presentation (between 15-25 mn) was followed by questions and open discussions.

Discussion - On the afternoon of the second day the participants of the workshop splited into two groups for more advanced discussions, and to better identify and focus potential major issues to be addressed by drilling: the two groups, chaired by A. Robertson and K. Emeis, respectively, were dealing with Earth Interior processes and External processes, recorded in the sedimentary cover and rocks of the Mediterranean and Black Sea basins and margins.

Syntheses of group discussions are provided here in order to help to better understand what are some of the global basic questions to be addressed in this specific area. It is hoped that the CIESM report will thus greatly help to better define priority research topics that could be solved by Scientific Drilling.

Due to the relatively restricted numbers of participants (to be more efficient and to facilitate exchange between scientists), the report conclusions do not necessarily reflect all potential research topics to be solved by Scientific Drilling; we, nevertheless, believe it constitutes a good introduction and a valuable support for further Scientific Drilling in the Mediterranean and Black seas.

3 - Information on scientific drilling in the Mediterranean (A. Robertson)

a - Ocean Drilling Program

The current phase of scientific ocean drilling (Ocean Drilling Program) will continue until autumn 2003, scientifically directed by the Long Range Plan, which highlights potential "Earth processes" related to the earth's interior and exterior. Currently, two complete proposals (under review) aim to drill in the Mediterranean during the present phase: Droz *et al.,* "Western Mediterranean deep-sea fans", and Kopf *et al.,* "Mediterranean backstop". Any further proposals will need to be submitted to ODP in the near future (as complete proposals) if they are to stand a realistic chance of being seriously considered for drilling by the end of 2003. A number of proposals have recently been submitted to drill in the N-Atlantic region and thus there is a realistic chance that the *Joides Resolution* will return to the Atlantic during the 2002/2003 time window.

b - IODP International Ocean Drilling Program

After five years of discussion, the Japanese have now committed to build (and fund) a new drill ship with riser/B.O.P. potential. This ship is scheduled to come into service in 2006 and will initially be able to drill up to ~5 km in water depth of <2.5 km. The ship is expected to focus on drilling the seismogenic zone off Japan for the first few years, but could then move to other areas. It is, therefore, worth beginning planning for future riser-ship drilling in the Mediterranean (*e.g.* Mediterranean Ridge and/or Corinth Graben).

c - Future non-riser ship ?

The recent COMPLEX meeting in Vancouver (June 1999) demonstrated a major international demand for continued deployment of a *Joides Resolution*-type non-riser ship, largely to work on "climatic change" projects that require relatively short (<1000m) high resolution cores (using hydraulic piston cover) from many regions of the world ocean. A national proposal is likely to be put to the US National Science Foundation to fund a future non-riser vessel, which might come into service at the end of the present ODP phase (2004), or later. The greater the scientific demand, the greater the chance of having a future non-riser ship. The Mediterranean community should thus aim to submit future targets for non-riser Mediterranean drilling in the near future as preliminary proposals.

d - Alternative platforms ?

The COMPLEX meeting also demonstrated a strong demand for alternative platforms, *e.g.* Ice Barge to drill in the Arctic, industry rig to drill on continental shelves (in relatively shallow water). Partnerships with industry and e.g. the International Continental Drilling Program (ICDP) are envisaged. Possibilities for future drilling using "alternative platforms" are thus worth considering (*e.g.* Corinth rift project).

e - European role in future scientific drilling

At Brussels in March 1999 European countries agreed to collaborate with a view to contributing to future International Scientific Ocean Drilling (IODP). There is now a need to move forward with some urgency to ensure Europe maximizes the benefits of future participation.

f - Scientific themes of future ocean drilling

The COMPLEX meeting, Vancouver, emphasized the role of integrated "Earth System Science". Key topics are likely to include: climate, biosphere (deep), gas hydrates (carbon cycle), catastrophic events (*e.g.* slides), Solid Earth System (subduction "factory", spreading "factory", flumes and volatiles), mantle dynamics. Only world-class problems will be drilled.

4 - EARTH'S INTERIOR GROUP : MAIN CONCLUSIONS (Coordinator : A. Robertson)

The group identified the "subduction factory" and "collisional processes" as related over-arching themes, in the length of the existing ODP Long Range plan, and the aims of future International Scientific drilling, as proposed at the COMPLEX meeting (Vancouver, 1999).

a - Subduction factory/collisional processes

The Eastern Mediterranean is the world's ideal location for study of fundamental processes of progressive and diachronous continental collision (*e.g.* fluid flow, mass transfer). The primary target is the Mediterranean Ridge accretionary prism.

i) Backstop Proposal

A full proposal (see Kopf *et al.,* this volume) now exists (submitted spring 1999) to investigate sediment/fluid mass transport in the "backstop" area of the central part of the Mediterranean Ridge (South of Crete). The rear-part of the prism is fundamental to understanding the "subduction factory" but has never been studied by scientific drilling anywhere. This proposal also aims to study processes of tectonic exhumation operating in the proximal forearc region (behind the "backstop"), and is relevant to proposed continental drilling (ICDP) on Crete (see Papanikolaou *et al.*, this volume). During the Workshop it was decided to integrate Deep Biosphere objectives with this proposal (see MacKenzie, this volume).

ii) Collisional transect

A long-term aim is to complete a N-S transect across the Central Mediterranean Ridge. Data obtained during the recent PRISMED-2 cruise (see Mascle *et al.*, this volume) provide the basis of a planned new preliminary proposal to focus on the timing and processes of incipient continental collision and related fluid flow (Mascle *et al.*, in prep.).

iii) Subduction/accretion transect

In addition, data provided by the (EU-supported) IMMERSE Project (R. von Huene *et al.*) and earlier Italian cruises provide the basis for a study of the western segment of the Mediterranean Ridge accretionary complex (Della Vedova *et al.*, this volume). Collision is only, at most, incipient in the western segment and, thus, this area provides a window into more "steady state" accretionary processes. A preliminary proposal is being prepared (Della Vedova *et al.*).

iv) Collisional processes

The easternmost segment of the African-Eurasian plate boundary in the Eastern Mediterranean Sea is an excellent area for the study of progressive (diachronous) collisional processes in an area where a large accretionary wedge is not preserved. Proposed drilling targets build on successful results of drilling of the Eratosthenes Seamount (ODP Leg 160) and the recent PRISMED-2 cruise. A number of potential drilling targets along the leading edge of the Eurasian margin (upper plate) provide windows into different states of incipient continental collision (see Mart, this volume; Woodside, this volume), as follows:

- Florence Rise (West of Cyprus), culmination of steady-state subduction;
- Anaximander Seamounts, collisional disruption of a promontory in the over-riding plate;
- Rhodes Basin, rapid flexural ? collapse related to collision (foreland basin ?);
- Hecataeus Plateau, submerged ophiolitic forearc.

There is also interest in drilling deeper in the Eratosthenes Seamount with a view to testing the hypotheses of rift-related magmatic rocks as the source of the associated magnetic anomaly. A preliminary proposal is in progress, which would, however, need to be supported by additional site survey data (Mart, Woodside, and Robertson).

b - Rifting processes

Back-arc areas provide an excellent opportunity to study fundamental processes of crustal extension, fluid flow and related seismicity. A major European project is currently devoted to multi-disciplinary study of the Corinth graben. Drilling on land (south margin) is planned to investigate shallow (<3 km) extensional fault related processes. However, a deep hole will eventually be needed in the centre of the Corinth Graben to penetrate deeper levels (~6 km) of the Corinth extensional detachment system. This work might be carried out by a future IODP riser ship or by an "alternative platform" (i.e. oil industry drilling rig). It is planned to submit a preliminary proposal on deep drilling of the Corinth graben in the near future.

c - Transform (strike-slip processes)

The Tunisian segment of the North African continental margin records a N-S part of the overall E-W, rifted North African continental margin. The Tunisian margin experienced multiple stages of oblique rifting (transtensional) during Mesozoic times, and N-Tunisia has experienced oblique collision with the in-coming Eurasian plate. A large amount of hydrocarbon industry data exists for the Tunisian shelf and is readily available. A preliminary proposal may be submitted to study strike-slip related processes along the Tunisian margin (see Bedir, this volume).

d - Post-collisional processes (orogenic collapse)

After collision, orogens commonly undergo collapse, the "central" suture, for reasons that are poorly understood, but include "roll back" of the downgoing slab; deep delamination and detachment of the dense lower crust. Much progress was made on study of the timing and thermal history of orogenic collapse by drilling in the Alboran Sea during Leg 161. Further work on this topic is in progress in the S-Balearic Basin and adjacent areas, and this may lead, in due course, to a preliminary proposal to ODP.

In summary, the current studies of "Earth's Interior" drilling topics in the Mediterranean are as follows:

- Mediterranean Backstop, Kopf, Mascle, Robertson *et al.* - complete proposal, under revision;
- Mediterranean Collisional Transect, Mascle *et al.* - preliminary proposal in preparation;
- Mediterranean Subduction Transect, Della Vedova *et al.* - preliminary proposal in preparation;
- Easternmost Mediterranean Collisional, Mart, Woodside, Robertson - preliminary proposal in preparation.

Each of these drill topics/targets is of global significance and highlights societal relevance (i.e. seismic hazard) and integration with local geology (ICDP).

5 - EARTH'S EXTERNAL PROCESSES GROUP : MAIN CONCLUSIONS (Coordinator: K. Emeis)

a - Stratigraphy, climate evolution, and sea level variations

The setting of the Mediterranean Sea and the adjacent Black Sea with respect to climatic zones and influences by high- and low-latitude climatic processes offers a wide range of drilling targets to address questions of sea-level change, stratigraphy, and climate evolution. The Nile River monitors precipitation in equatorial regions and is regulated by the monsoon system. The history of glaciation in high-latitude northern continental areas is mirrored in Black Sea sediments fed by large river systems, and the evolution of climate in the Western Mediterranean Sea, which is influenced by climate in the Atlantic Ocean, is recorded in the fans of rivers that drain into the Western Mediterranean Sea. Climatic and hydrographic changes in the Mediterranean catchment have resulted in a pronounced cyclicity of sedimentary deposits since the basal Pliocene (Lourens *et al.*, 1996) and beyond to at least the Serravallian (Hilgen *et al.*, 1997). These cycles have been used successfully to establish high-resolution stratigraphies by tuning proxy records to orbital cycles. Stratigraphic studies on land outcrops and in cores drilled during ODP Legs 160 and 161 show that first-order patterns of sapropels and their occurrence through time on land and in the marine records are similar in the Pliocene to the Holocene (Kroon *et al.*, 1998; Lourens *et al.*, 1998; Sprovieri *et al.*, 1998). Most are even isochronous in the temporal resolution afforded by tuning the sapropel occurrences to insolation curves (Hilgen, 1991; Lourens *et al.*, 1996). Similar studies on cyclic peat and lignite deposits on land in the Northern Mediterranean borderlands (*e.g.*, Mommersteeg *et al.*, 199; van Vugt *et al.*, 1997) suggest that combined drilling efforts on land and at sea may be able to perform detailed climate reconstructions in a variety of climate settings that are all mirrored in discrete deposits of the Mediterranean Sea. Some of these possible targets have been identified during the CIESM workshop.

i) Evolution of the Nile deep-sea fan as an indicator of low-latitude climate evolution

The intensity of the African Monsoon, which channels moisture from the South Atlantic into the Nile catchment area, is dependent on several variables, among them the geographical position of the meteorological equator (or ITCZ) and trade wind intensity in the southern hemisphere (Rossignol-Strick, 1985). The basic, low-latitude mechanism leading to sapropels in the Eastern Mediterranean Sea has been in operation at least since the basal Pliocene (Emeis and Sakamoto, 1998), and may have been operational during the Messinian and older times (Ryan and Hsü, 1973). Since approximately 2.6 Ma, this basic, low-latitude signal has modulated by a high-latitude influence since the onset of NH glaciation, and increasingly so after bi-polar glaciation has become firmly established (Emeis *et al.*, submitted).

Drilling on the Nile fan, which has recently been mapped and investigated by acoustic methods, may shed light on the history of the African Monsoon, on the role of tectonic uplift in the East African region, and on the influence of southern hemisphere climate on Nile runoff. In conjunction with studies on deep-sea fans in the Western Mediterranean Sea and on the evolution of sedimentary deposits in the Black Sea region proposed by workshop participants – and described in the following abstracts: 1. Climate change and sedimentation in the Black Sea Region in response to Pleistocene climatic cycles, proposal by Flood *et al.,* presented by N. Panin; 2. Turbidite systems in the Western Mediterranean Sea : contribution of sedimentary facies to understand turbidite system growth and to evaluate turbidite system models, Alonso *et al.,* and 3. Sand-rich *versus* mud-rich turbidite systems at intermediate latitudes: stratigraphic response to sea-level changes, Droz *et al.* –, climatic influences and sea-level influences on fan evolution in the Mediterranean region can be separated. An added benefit of drilling the Nile Cone is the expected good stratigraphic control, because Pleistocene sapropel events are recorded in sediments on the Nile Fan (Calvert *et al.*, 1992); the stratigraphic control afforded by the sapropels may be expected to extend into the Messinian in the deltaic sediment pile.

ii) Records of high-resolution climatic variability

Sediments in the Eastern Mediterranean are known to provide ideal archives of global paleoclimatic continental and marine signals. This is partly due to :

- the highly sensitive nature of this semi-enclosed basin regarding climatic change, and
- the distinct differences in rock/soil type and climatic/weathering history of surrounding continental areas (provenance of terrigenous detritus).

<u>*Semi-enclosed basin*</u>

The rather restricted circulation in the Mediterranean basin results not only in a delicate oxygen balance, but also in a bottom water formation that is very sensitive to global climatic variations. This is probably one of the reasons why Mediterranean sediments resemble Cretaceous sediments from periods of possibly restricted circulation, as they contain regular intervals that are extremely enriched in organic matter. This cyclicity is governed by astronomical parameters and serves as a perfect time-marker for Mediterranean Miocene to recent sediments. Such cyclicity permits an unprecedented comparison of samples in identical time-slices but from different locations.

<u>*Provenance of terrigenous detritus*</u>

There exists a large variety of continental characteristics not only in geological signature but also in vegetation and climatic zones in the circum-Mediterranean realm. This fact allows detecting subtle changes in Global paleoclimatic conditions in this area, using geochemical, petrological/mineralogical, and palynological proxies.

As a consequence, climatic variations are accurately recorded in the sedimentary record not only by giving variations in typical marine but also in continentally derived signals. The Monsoonal index is strongly associated with the paleoclimatic conditions in the circum Eastern Mediterranean areas, i.e., Sahara/Africa, Middle East, and Southern Europe. This association is clearly reflected in sediments as a ~ 21/23 kyr precession-controlled cycle : during wet climatic periods organic-rich sediment (sapropel) is deposited containing strong river and marine productivity signals, whereas during dry climatic periods organic-lean oxygenated sediments are deposited containing high dust input signals. The various types and ages of continental rock surrounding the Eastern Mediterranean facilitate establishing provenance studies of dust and riverine material using a suite of major, minor, and radiotracer elements.

The Eastern Mediterranean, therefore, is an ideal area to study land-sea interactions of global paleoclimatic variations, in particular as this area is influenced and preserved paleoclimatic signals from the mid to high latitude northern borderlands to the low latitude monsoon influenced southern borderlands. Owing to the extreme sensitivity of these borderlands to subtle climatic changes, the Eastern Mediterranean is a potential treasure for paleoclimatic research, especially at locations with high sedimentation rates.

Paleoclimatic studies with a time resolution of better than a few 100 years, are hampered in the Eastern Mediterranean due to the relatively low sedimentation rates (2-4 cm/kyr) of sites studied thus far (*e.g.* Emeis *et al.*, 1998; ODP Leg 160). Recently, a few sites were found in key areas with sedimentation rates of 10-20 cm/kyr. All these sites are located in areas of potential major changes in paleo-bottom-water formation, i.e., the Adriatic and Southern Aegean Sea, or with major changes in climatically controlled freshwater influx (Nile plume). The preliminary study of the former sediments for the last 10 kyrs indicates an unprecedented time resolution, and the accurate detection of rather abrupt major changes in climatic (continental/marine?) conditions.

The major advantages for such high sedimentation rate sites are :

- limited or no oxidation and consequent preservation of several labile climatic proxies (*e.g.*, organic carbon, dino-cysts, pollen, biomarkers);
- less severe effects of bioturbation;
- higher time resolution permitting the detection of abrupt relatively rapid climatic changes (potentially Heinrich or Dansgaard-Oeschger type events).

Leg 160 has resulted in a wealth of scientific paleoclimatic results in particular for organic-rich intervals. The oxic intervals in between are nearly barren in organic matter, contain almost no dinocysts, pollen, and organic biomarkers. Though perhaps originally present, the great majority of the organic climatic markers has been destroyed in the oxic intervals and conclusions are solely based on the occurrence of such proxies in the remaining organic-rich intervals. This considerably limits the potential interpretation of these records. In the above mentioned high sedimentation rate sites it will not only be possible to study these proxies in non-sapropelic intervals, but also to detect timescale events that are much shorter than the 21-23 kyrs periodicity of orbital cycles. Heinrich-type events have been found amongst others in Atlantic and N-Indian Ocean sediments, and possibly in the Alboran Sea. It seems therefore likely that these rapid climatic events will also have been recorded in this environment that is sensitive to climatic changes. The excellent time control from Recent to Miocene or beyond for the high sedimentation rate sites in the eastern Mediterranean would permit not only the detection of such events, but also the establishment of their exact timing beyond 14C ages down to at least the Miocene (if present), and their relation to the astronomical cyclicity.

b - The Deep Biosphere : questions that can be addressed in the Mediterranean Sea

In the early to mid-1990's, geomicrobiologists working with samples recovered from drill holes cored by the Ocean Drilling Program (ODP) discovered that bacteria are not only present at much greater depths (>750 meters) beneath the deep seafloor than was previously thought, but they actually thrive there in colossal numbers (Parkes *et al.*, 1994). This exciting discovery has led to a major new initiative within ODP to study the deep sub-seafloor biosphere. The extent of this major biosphere and the nature of the "extremophiles" living there are essentially unknown. Ocean drilling offers the potential to probe this unexplored world of the deep sub-seafloor, which represents a unique habitat that couples biosphere/geosphere cycles. Exploring down to the base of the deep sub-seafloor biosphere will have important societal implications for new biotechnology applications, for better understanding the generation of hydrocarbons and ore deposits, for defining as yet unknown components of the carbon cycle, and for evaluating the origins of life on Earth and elsewhere.

The Mediterranean Sea is an ideal location to undertake drilling campaigns to investigate the deep sub-seafloor biosphere. During the late Neogene, the Mediterranean sedimentary basins were repeatedly the location of peculiar environmental conditions, which led to the deposition of highly organic carbon-rich sediments, known as sapropels. In addition, during the Messinian Salinity Crisis in the Mediterranean, a thick sequence of evaporite sediments was deposited basin-wide with the desiccation of the deepest basins. Beneath the evaporite are older sediments, which also contain high amounts of organic matter. The thick evaporite sequence essentially serves as a cap-rock seal limiting the upward migration of altered organic matter (petroleum) or gases. This trapping effect produces an obvious safety/pollution hazard and has prevented drilling deep into and through the Messinian evaporites. If it were possible to drill through these traps using advanced drilling technology with blowout prevention equipment, an unusual isolated deep biosphere community could be penetrated and sampled.

There are natural windows into this deep, isolated biosphere, inhabitants of which are very likely part of the microbial community in the sediments of so-called mud volcanoes. They mark locations where overpressured mud originating in the deep levels of the accretionary wedge of the Mediterranean Ridge is extruded to the seafloor. These chimneys apparently vent methane and fluids and host gas hydrates in close proximity (<20m) to the seafloor. One might suspect that large methane fluxes through mud volcanoes, as inferred from the large methane anomalies found in the water column on top of the volcanoes, also feed active bacteria colonies at depth . On the other hand, deep originating bacteria, making part of the erupted mud (possibly erupted from below the evaporites), have probably been raised by the mud eruption process to depths drillable by conventional ODP drilling techniques.

On the other hand, the close proximity of microbially viable organic matter in the sapropel layers and the underlying evaporites in relatively young (not deeply buried) sediments is rather unique to the Mediterranean. Where fluids have penetrated the evaporite seal and migrated upward through the overlying Pliocene/Pleistocene sediments, pore water analyses indicate elevated salinity due to the dissolution of the more soluble minerals along their pathway. These fluids are particularly enriched in sulfate ions, which can be used as a terminal electron acceptor to promote anaerobic degradation of the organic matter in the sapropel layers. Thus, the ingredients for an active deep sub-seafloor biosphere are available and easily reached with the drill-string, making the Mediterranean sediments a fertile system in which to explore for the deep sub-seafloor biosphere.

Preliminary microbial studies were undertaken on the recent ODP Legs 160 and 161 with encouraging results. In particular, studies were conducted on the sedimentary sequence from Site 969, which is located in 2202 m deep water in the Eastern Mediterranean and contains approximately 80 sapropel beds (Cragg *et al.*, 1998). The collected data demonstrate that microbial activity occurs with depth throughout the entire 116-m-thick Pliocene/Pleistocene sequence, even in sediment as old as 5 myr. The microbial activity varies within the sequence, with the bacterial counts being higher in the sapropel layers than in the surrounding sediments (Fig. 1).

High sulfur concentrations present in the form of pyrite also reflect this bacterial activity. The total amount of sulfur increases with depth showing that bacterial sulfate reduction does not occur only at shallow depths but continues after deep burial. This continued activity is supported by the flux of sulfate from below, as shown by the pore-water analyses. The sulfate concentration throughout the sequence was always equal to or greater than seawater and increased with depth. This preliminary work indicates that the combination of viable organic matter in the sapropel layers and sustained high sulfate concentrations are essential ingredients for promoting continued bacterial sulfate reduction with burial.

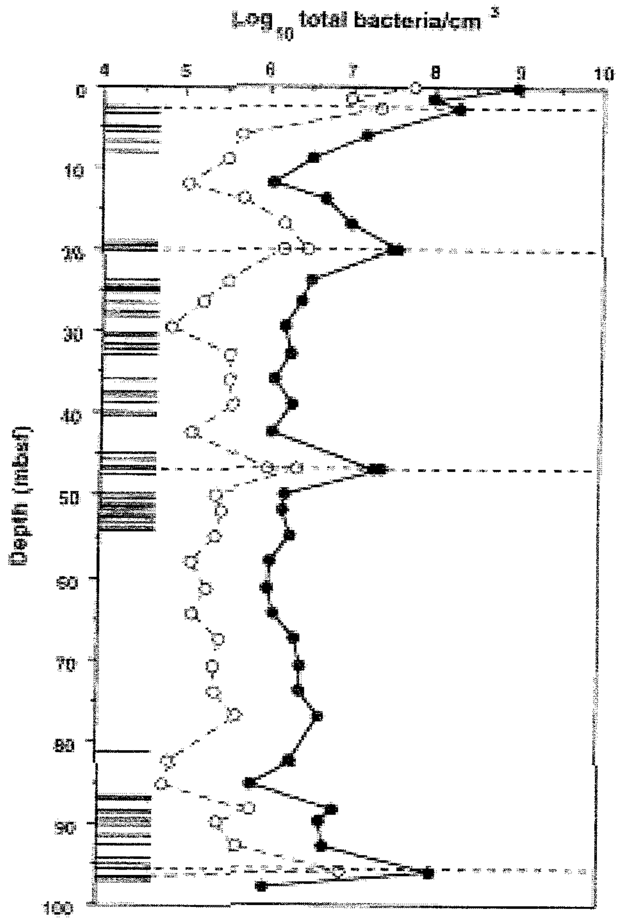

Fig. 1. Depth distribution of total bacteria (solid circles) and dividing/divided cells (open circles) at Hole 969B using the acridine orange direct count (AODC) technique. Average variance for sample enumerations in this data set was 0.012 Log_{10} units. This produced an average 95% confidence limits of 0.251 log_{10} units (range 0.055-0.452). Horizontal lines on the y-axis indicate the presence of sapropels. From Cragg *et al.*, 1998.

Thus, an excellent potential to study the processes governing the deep sub-seafloor biosphere exists in Mediterranean sedimentary deposits. In particular, the regular injection of organic matter into the sediments at frequent intervals to form the sapropel layers provides conditions for controlled experiments in a natural laboratory. The sapropel layers are produced at specific intervals, approximately every 21 to 23 kyr., in response to precession-controlled climate changes. Knowledge of this timing allows for good age control, making it possible to study changes in the microbial community and their organic substrate with depth and determine how such a system evolves with time. Future drilling of the deep sub-seafloor biosphere in the Mediterranean will require a dedicated leg(s) to undertake such experiments and will be possible with the currently available drilling technology. To study the even deeper and potentially more active and more isolated biosphere will require the technical ability to drill in regions which have been previously avoided, such as drilling into the Messinian evaporite sequences and penetrating potential hydrocarbon oil and gas rich zones. Such a program in the Mediterranean must await the arrival of a drill-ship capable of drilling safely in these environments.

(See references in annex. 1)

6 - Concluding remarks and recommendations

Scientific drilling, combined with *in situ* down holes measurements, are crucial to better evaluate, study and understand some of the Earth's Interior and External processes that are particularly well recorded in the Mediterranean Sea and surroundings.

The Granada CIESM workshop was not aimed to select among the different proposals and ideas that were presented and discussed during these three days. Many of them are still in an early stage of preparation and will be upgraded during the coming years. They will be thus ready for post ODP phases of Ocean Drilling (IODP and following programs).

Among the different proposals discussed, two of them have been already submitted to ODP International evaluations. A third one is intending to help to better evaluate seismic hazards that are often, and particularly recently, occurring and strongly damaging the Mediterranean continental borders, particularly in Turkey and Greece.

One of the ODP mature proposals is addressed to specific collisional/convergent setting particularly to the physical state and hydrological conditions of the Mediterranean Ridge backstop, South of Crete.

The workshop participants strongly support its integration with proposed onshore Crete Island Continental Drilling (ICDP) in order to provide a full set of information on upper crustal deformation mechanisms and history (up to the backstop) and thus to obtain a transect normal to an "on collision" plate boundary. Such transect may be, later on, completed by drilling across the collisional accretionary wedge.

The participants have also been very interested by proposals addressed to turbiditic and fans system. It is strongly suggested to upgrade, if possible, the Rhône fan proposal, for example, by increasing the links between stratigraphic studies, high resolutions climatic variabilities and sea level fluctuations. It has been stressed that the Mediterranean Sea and the Black Sea might provide ideal archives for such combined studies due to distinct differences in climatic/weathering history of surrounding continental areas.

Finally, the participants have been quite impressed by what is already known on the deep sub sea floor biosphere, whose importance is only recognized since the early 90's.

The Mediterranean and Black seas appear as particularly good candidates to investigate the deep sub sea floor biosphere and it is therefore strongly recommended to consider such field of investigations in any kind of Scientific Drilling in the area.

We feel this CIESM supported workshop has been a great success. Not only it has allowed to generate discussions and interactions among Earth's Interior or External processes specialists, but it provides this scientific report which can be regarded as a synthesis of what the near future, and future, of any Scientific Drilling in the Mediterranean Sea and surrounding may (or should) be.

In this view, we fully agree with the idea of an integrated drilling concept, designed on a modular basis, with long term planning and coordination between onshore and offshore activities and between Earth's Interior and Earth's External processes proposals8.

Turbidite systems in the Western Mediterranean Sea. Contribution of sedimentary facies to understand turbidite system growth and to evaluate turbidite system models

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Abstract

The Ebro Turbidite System and the Guadalfeo Turbidite System are located respectively in the NW and the SW Mediterranean Sea. The Ebro Turbidite System has developed during the Upper Pliocene and Quaternary, has about 600 ms (twtt) of maximum thickness and covers an area of 3000 km^2. Its main architectural elements include: multiple short canyons, slides and mass flow deposits, channel-levee complexes (erosive-depositional and depositional), interchannel areas, and base-of-slope aprons. The Guadalfeo Turbidite System has developed during the Pliocene and the Quaternary, has about 800 ms (twtt) of maximum thickness, and covers an area of 1000 km^2. It is composed mainly by 10 fanlobes (channel-levee complexes and channelized lobes). The drilling on these turbidite systems has a wide scientific relevance because they offer a good opportunity to understand the growth processes of small, mixed turbidite systems and to improve the existing sedimentary models of turbidite systems located in a semi-enclosed basins.

Introduction

Most of the studies on deep marine areas (distal margins and basins) refer to turbidite systems. The turbidite systems represent volumetrically the most important sediment accumulation on deep marine environments. Studies on turbidite systems provide insights into a variety of down-slope (occasionally also alongslope) processes of transference of sediments from the shelf to the basin, and into the role played by climate, sea-level changes, tectonism, seafloor physiography, and sediment sources on deep marine sedimentation.

The turbidite systems display a great variety of depositional models, with distinct morphologies, internal structures, and facies associations (Shanmugam and Moiola, 1988). Therefore, the recent studies on modern and ancient turbidite depositional systems have mainly concentrated on the understanding of facies and related depositional processes (Mutti and Ricci-Lucchi, 1975; Nardin *et al.*, 1979; Nilsen, 1985), factors controlling turbidite processes and growth of turbidite systems (Normark, 1978; Nelson and Nilsen, 1984; Stow *et al.*, 1983/1984; Pickering *et al.*, 1986; Flood *et al.*, 1997). The Ebro Turbidite System and the Guadalfeo Turbidite System in the Western Mediterranean represent two good examples of turbidite systems where detailed studies of seafloor morphology, stratigraphic architecture, tectonics, sediment sources and sedimentary facies have contributed to understand the development of turbidite systems (Nelson *et al.*, 1983/1984; Alonso *et al.*, 1985; O'Connell *et al.*, 1987; Nelson and Maldonado, 1988; Alonso and Maldonado, 1990; Pérez-Belzuz *et al.*, 1995; Pérez-Belzuz, 1999, in press).

Quantitative studies on turbidite systems refer mainly to sediment supply and geometric parameters. The analysis of sediment supply in turbidite systems has focussed mainly on the quantification of the sediment transfer supplied by external sources, mainly rivers (Curray and Moore, 1971; Allen and Allen, 1990; Wetzel, 1993). This transference is controlled by several factors, such as river basin configuration, available sediment type, river mouth type, and sea-level changes (Moore, 1969; Wetzel, 1993). Quantification of geometric parameters has focussed mainly on determining its external geometry parameters, such as length, width and maximum thickness (Normark, 1970; Nelson and Nilsen, 1984; Barnes and Normark, 1985). Some authors have established a correlation between sediment supply and length in turbidite systems (Wetzel, 1993).

GEOLOGICAL SETTING

The Ebro Turbidite System (NW Mediterranean Sea) and the Guadalfeo Turbidite System (SW Mediterranean Sea-Alboran Sea) are located in quite different tectonic, physiographic and sediment supply settings (Figs. 1 and 2).

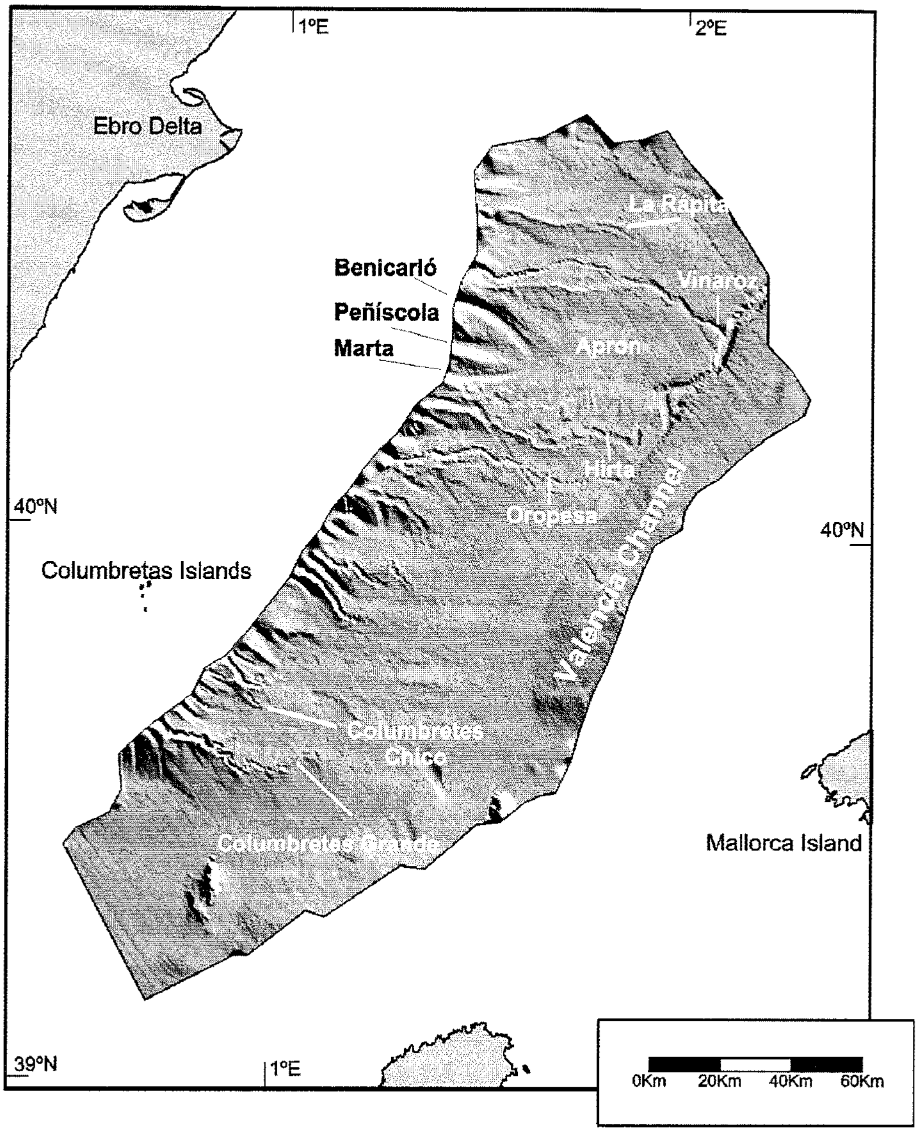

Fig. 1. Shaded mean-depth bathymetric map showing the pathways of the turbidite channels of the Ebro Turbidite System, NW Mediterranean Sea.

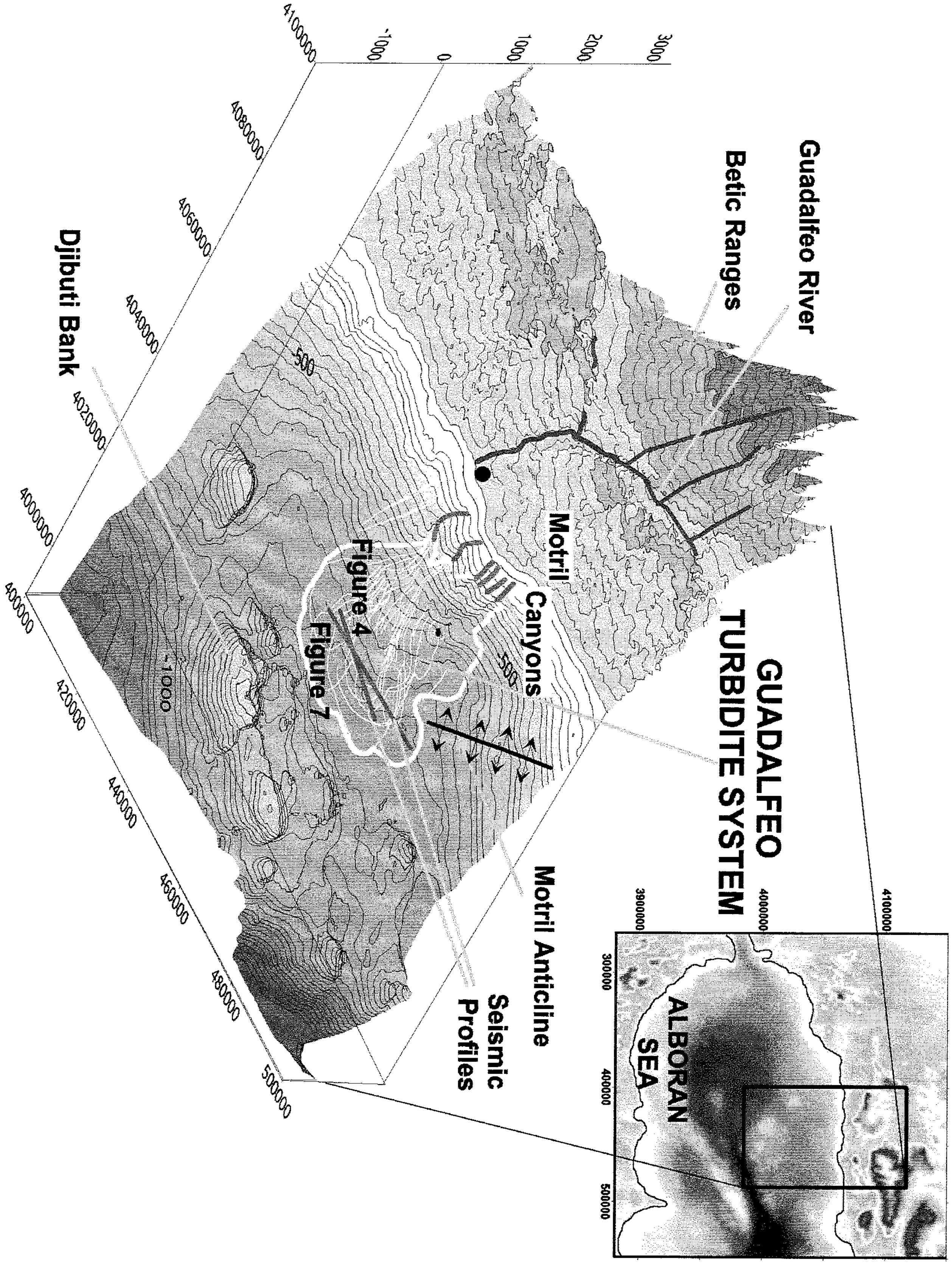

Fig. 2. Schematic 3-D view showing the location of the Guadalfeo Turbidite System. Feeder rivers, canyons, fanlobes and morphological highs (Djibuti Bank, Motril Anticline) are also shown.

The Ebro Turbidite System develops off the Ebro River in a restricted basin located between two landmasses, the Iberian Peninsula and the Balearic Promontory (Fig. 1). It is located on the Iberian passive continental margin, which comprises a wide continental shelf (up to 70 km) and a narrow steep continental slope (10 km). The Ebro Turbidite System develops from the slope to the basin floor of the Valencia Channel, between 300 and 1800 m below sea level, covers a large area of 3000 km^2 and has a length of 62 km (Alonso and Maldonado, 1990). Important sediment supply to this system is derived from the Ebro River with a drainage basin of 84260 km^2, and is fed by multiple submarine point sources represented by at least seven short canyons (Fig. 1). The geological setting can be described as a "Type C basin" based on Mutti and Normark (1987) classification. Type C basins are formed over continental crust, have relatively long-lasting sediment supply, and have a structurally controlled basin configuration and evolution.

The Guadalfeo Turbidite System developed in the North of the Alboran Sea (SW Mediterranean) in a semi-enclosed basin located between the Iberian Peninsula and several submarine volcanic highs. It is built in a tectonically active margin characterized by a very narrow shelf (2-4 km) and slope (10 km) (Fig. 2). This small clastic depositional system (36 km in length) develops at shallow waters (100 to 950 m water depth) and receives sediment mainly from a small river, the Guadalfeo River with a drainage basin of 1350 km^2 and a seasonally variable discharge, and is fed by six submarine canyons showing different sedimentary activity through time.

WHAT ARE THE AVAILABE DATA ?

The Ebro and Guadalfeo Turbidite Systems have particularly been studied by means of a quite complete set of geophysical and shallow-core data. These data have allowed a good knowledge of : A) a very detailed morphology based on side-scan sonar (TOBI) and swath bathymetry (SIMRAD EM-12); B) high and ultra-high resolution stratigraphy and sedimentary architecture determined with single-channel seismic reflection profiling systems (TOPAS system, airgun, sparker) and multichannel systems; and C) recent sedimentary processes established with gravity cores (2 to 10 m length).

WHAT DO WE KNOW FROM THE SEISMIC STRATIGRAPHY ?

In the Ebro continental margin, we divided the post-Messinian into a lower sequence (Pliocene) and upper sequence (Quaternary) following the works of Alonso (1986), and Field and Gardner (1990) (Fig. 3). The base of the lower sequence, represented by the seismic reflector M, is characterized by a well-defined high-amplitude reflector that corresponds to the top of the Messinian evaporite sequence (Ryan, 1973). The lower sequence appears transparent in the sparker profiles, grading upwards to subparallel stratified facies. The stratified facies is commonly interrupted by lenses of transparent facies that are interpreted as channel deposits and aprons formed by mass-transport deposits. Except near the top, where small channel deposits occur, the lower sequence has fewer channels than the upper sequence. The thickness of the lower sequence ranges from more than 1200 m near the slope in the southern area (Field and Gardner, 1990) to about 300 m on the basin floor in the northern area (Alonso, 1986). The boundary between the upper and lower sequences is marked by a strong reflector termed Reflector G. Alonso (1986) mapped this reflector and suggested that it represents a gently seaward dipping surface, except in areas affected by volcanic intrusions and paleochannel relief. The seismic character of the upper sequence varies from the slope to the base of slope. The upper sequence is characterized by stratified facies and is incised by submarine canyons on the slope. Whereas, on the base of slope it is composed of stratified facies but mainly of pinch-and-swell reflectors associated to chaotic and transparent facies. This association represents channel-levee complexes and aprons of mass-transport deposits, and their facies pattern comprises active erosive-depositional channel-levee complexes overlying a series of abandoned depositional channel-levee complexes with floors partially filled in the northern and southern sectors, and base of slope aprons in the central sector. The thickness of upper sequence ranges from 200 to 480 m, and it generally thins to the East.

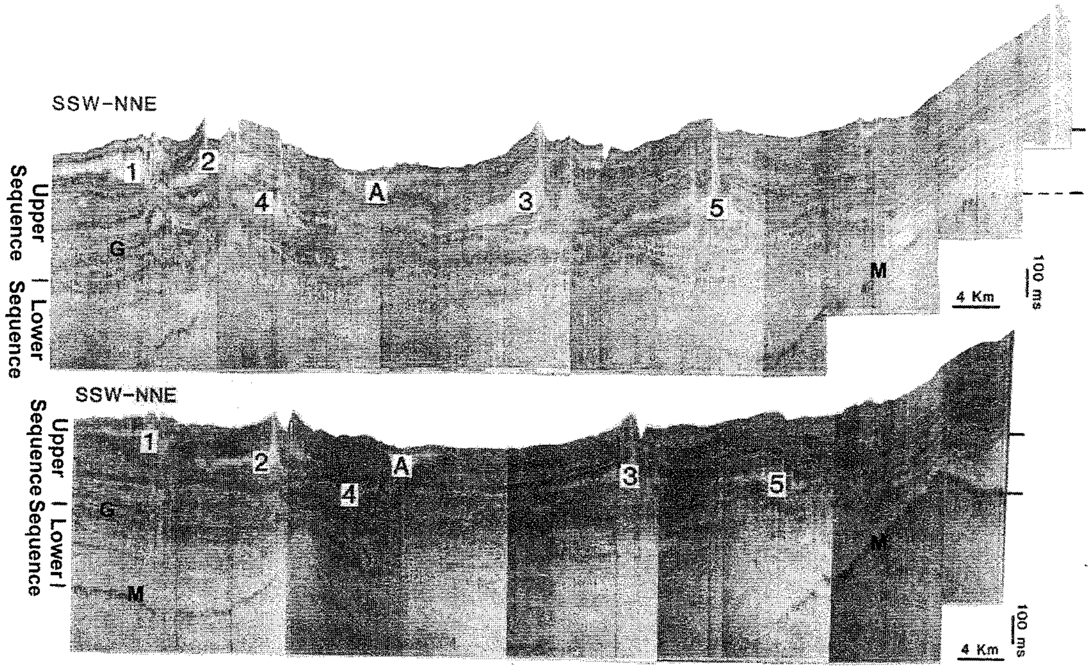

Fig. 3. Selected seismic profiles across the Ebro Turbidite System showing five channel-levee complexes (numbers **1, 2, 3, 4** and **5**) and apron deposits (letter **A**). Legend: **M**, seismic Reflector M of Messinian age; **G**, seismic Reflector G that bounds the lower sequence (Pliocene) and the upper boundary (Quaternary).

Nine lenticular acoustic units of channel-levee complexes were identified within the upper sequence along transverse sections of the base-of-slope (Alonso, 1986; Alonso *et al.*, 1990; Field and Gardner, 1990). These units have been described in detail by Nelson and Maldonado (1988) and Field and Gardner (1990). The lenses increase in number and size upward through the upper sequence (Fig. 3). The floors of the channel-levee complexes generally contain convergent stratified facies with the thickest part of the lenses represented by transparent facies. The bases of the levees are unconformable where the convergent stratified reflectors onlap or downlap. Individual channel-levee complexes are 250-420 ms thick and 5-15 km wide. Each channel-levee complex is an elongated lenticular body that extends downslope from the mouth of a slope canyon (Fig. 3). The thickness of each complex decrease towards the basin and the maximum thickness is always found on the southern levees. The lengths of the channels in the northern sector range from 25 to 52 km, and most of these intersect with the Valencia Channel at about 1700 m water depth (Alonso *et al.*, 1985). In contrast, the average length of the channels in the southern sector is 35 km, and none reaches the Valencia Channel, whose floor is about 1300 m deep in this area (Field and Gardner, 1990).

The Plio-Quaternary seismic stratigraphy of the Guadalfeo Turbidite System has been established by Pérez-Belzuz (1999, in press) who defines two seismic sequences, the lower sequence (Lower Pliocene) and the upper sequence (Upper Pliocene-Quaternary) (Fig. 4). The lower sequence is built above a strong basal unconformity that correlates with the seismic reflector M that is well expressed around the Mediterranean Sea (Hsü *et al.*, 1973; Ryan, 1973; Cita, 1982). The lower sequence, which is composed by a single seismic unit (Pl1), is characterized by discontinuous low-amplitude stratified and semitransparent seismic facies in the high resolution seismic records. This facies grades upwards to continuous and discontinuous high-amplitude stratified and chaotic facies forming lenticular bodies that belong to the first fanlobe identified in the Guadalfeo Turbidite System (fanlobe A). Moreover, multichannel seismic records allow to recognize a large canyon fill body (3 km wide, 500 m thick) in the lower part of this seismic sequence. This means that the Guadalfeo Turbidite System is active since the Lower Pliocene. The initiation of the sedimentary activity of this turbidite system is probably related to the Messinian Salinity Crisis (Upper Miocene). The maximum thickness of the lower sequence (750 ms) is found in the lower slope and base of slope (Pérez-Belzuz, 1999, in press) (Fig. 4).

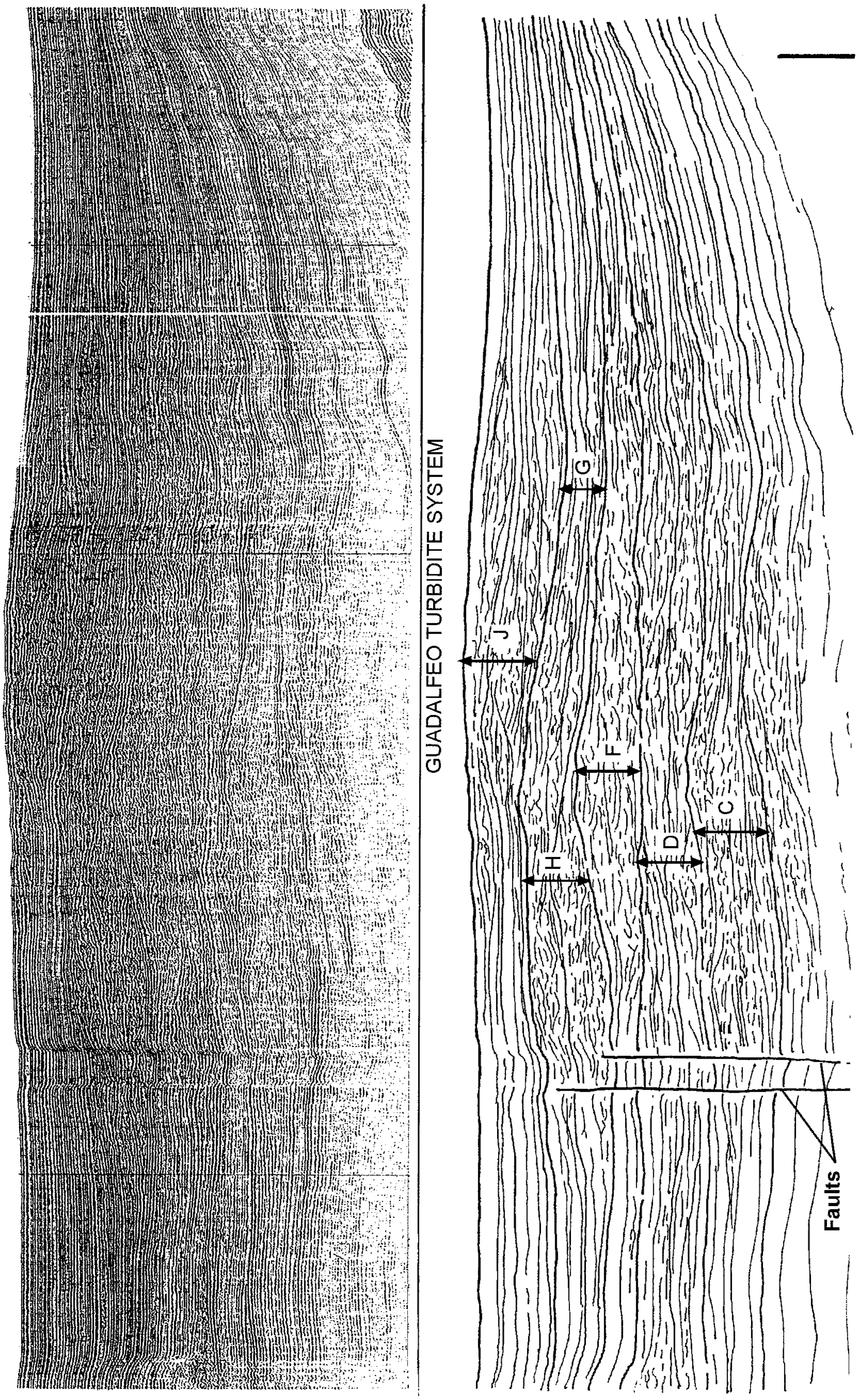

Fig. 4. High resolution seismic profile (air-gun) showing a transverse section of several fanlobes (**C**, **D**, **F**, **G**, **H**, **J**) developed in the Guadalfeo Turbidite System. See location in Figure 2.

The lower boundary of the upper sequence is marked by a high amplitude seismic reflector that can be traced around the entire Alboran Sea (Alonso and Maldonado, 1992; Campillo *et al.*, 1992; Pérez-Belzuz *et al.*, 1995; Estrada *et al.*, 1997; Pérez-Belzuz, 1999, in press). The upper sequence is subdivided in five seismic units (Pl2, Early Upper Pliocene; Pl3, Late Upper Pliocene; Ct1, Early Lower Quaternary; Ct2, Late Lower Quaternary; Ct3, Upper Quaternary) that are limited by distinct unconformities passing basinward to condensed sections (Pérez-Belzuz, 1999, in press). The upper sequence is characterized in the slope by canyon-fill deposits. These deposits comprise chaotic and high-amplitude discontinuous facies, cutting stratified slope facies. In the base of slope and in the Motril Basin, channel-levee complexes and channelized lobes are predominant, although stratified deposits and debris flow deposits are locally identified. The upper sequence reaches a maximum thickness of 800 ms in the base of slope (Fig. 4) (Pérez-Belzuz, 1999, in press).

In the upper sequence nine fanlobes are identified (B, C, D, E, F, G, H, I, J) which are fed by six submarine canyons. These fanlobes that have been built on the slope, base of slope and Motril Basin, and are composed by channel-levee complexes that can evolved basinward into several channelized lobes. Based on submarine sediment sources, two types of fanlobes are distinguished: multiple-source fanlobes (D, G, I) that are fed by several canyons, and point-source fanlobes (B, C, E, F, H, J) that are fed by only a single canyon (Fig. 4). Individual fanlobes are 80-300 ms thick, 13-31 km long, 8-32 km wide and has a volume of 5-65 km^3 (Pérez-Belzuz, 1999, in press).

WHAT DO WE KNOW FROM THE SEDIMENTARY FACIES?

In the Ebro Turbidite System, five facies associations can be defined for the Late Quaternary: (1) channel floor of erosive-depositional channel-levee complex facies; (2) levee of erosive-depositional channel-levee complex facies; (3) depositional channel-levee complex facies; (4) interchannel facies; and (5) apron facies. The channel floor of erosive-depositional channel-levee complex facies (1) consists mainly of massive sands. The levee of erosive-depositional channel-levee complex facies (2) is characterized by turbidite sequences showing Boum's Tc-e, Td-e and Te intervals. The depositional channel-levee complex facies (3) (floor and levee) is characterized by abundant turbidite muds (Te) alternating with thin (< 1 cm thick) turbidite sand-silt layers. The interchannel facies (4) consists predominantly of turbidite and hemipelagic muds, with a low proportion of sand-silt layers. The interchannel facies is differentiated from the levee of erosive-depositional facies (2) on the basis of fewer and thinner sand beds with a less rhythmic distribution. The apron facies (5) is highly variable, with thin beds of turbidite sands, turbidite silts, turbidite muds (Tb-e), and thick, massive, poorly sorted sand layers (<80 cm thick) which show structures indicative of mass deformation. This facies changes systematically from North to South (Figs. 5 and 6).

The recentmost deposits of the Guadalfeo Turbidite System comprise of (1) canyon-fill deposits, (2) channel-levee deposits, (3) channel-lobe transition deposits and (4) channelized-lobe deposits. Canyon-fill deposits (1) are characterized mainly by poorly sorted to well sorted sands and gravels that are arranged in fining-upward sequences (Ta-Tb) bounded by erosional surfaces. Channel-levee deposits (2) are composed by poorly sorted and very poorly sorted silty sands and sandy silts showing mainly Bouma's sequences Tc-e, Td-e and Te. Channel-lobe transition deposits (3) are characterized by very poorly sorted sands and silty sands forming centimetric thick layers and small lenses with erosive lower boundaries. These layers are intercalated with very poorly sorted sandy silts. Channelized lobes (4) are constituted by moderately well sorted massive sands arranged in layers up to 30 cm thick with sharp lower and upper boundaries. These massive sands appear interlayered with turbiditic sandy muds and silty muds (Fig. 7).

WHAT DO WE KNOW FROM THE PRESENT SEA FLOOR FEAUTURES?

The Ebro Turbidite System shows multiple-source slope canyons, which continue, across the continental margin evolving into turbidite channels. The lengths of the channels in the northern area range from 25 to 52 km and most of them intersect the Valencia Channel at about 1700 m water depth. In contrast, the average length of channels in the southern area is about 35 km, and any reaches Valencia Channel whose floor is about 1300 m deep in this area. Their widths range

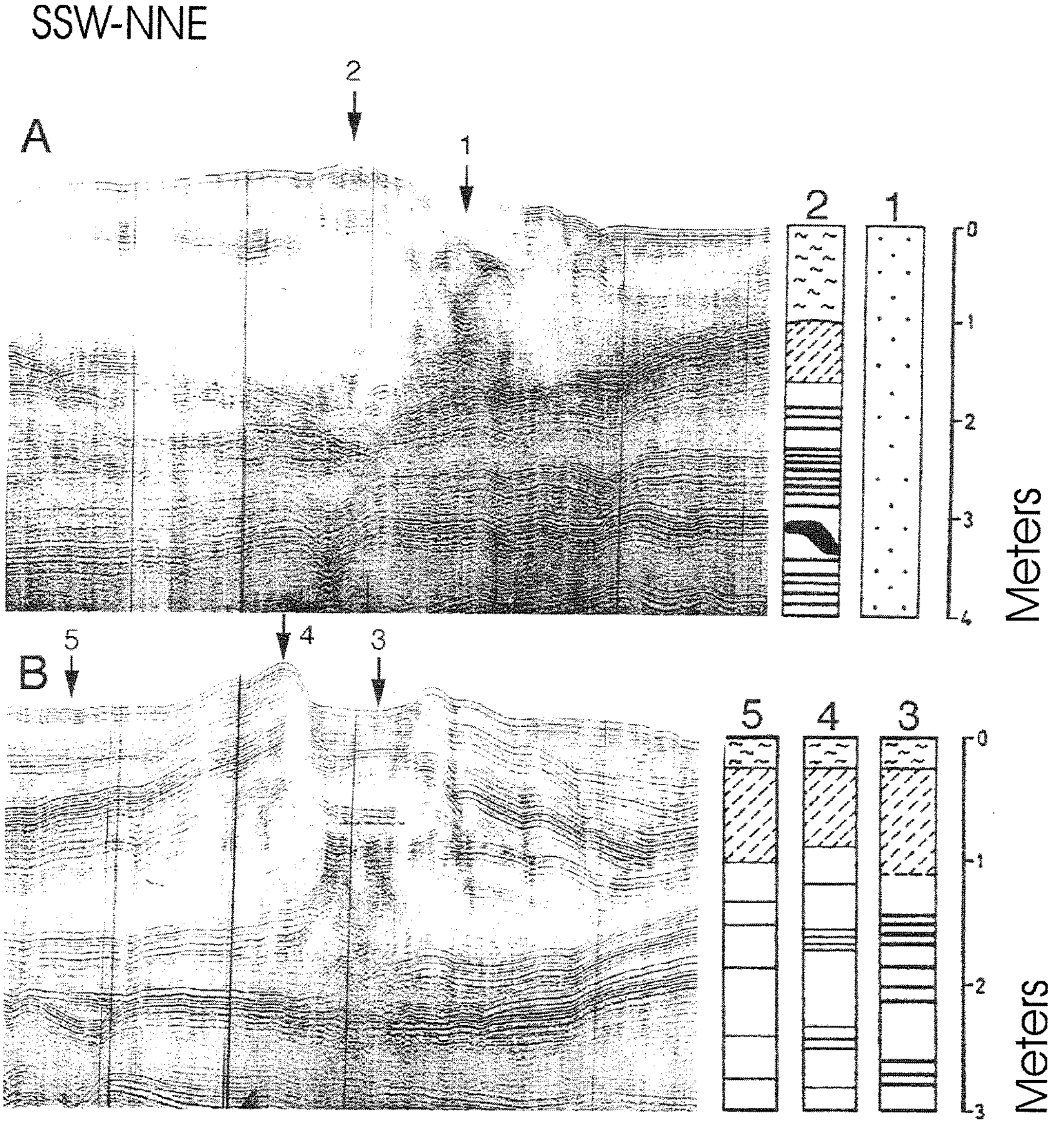

Fig. 5. Characteristics of the sedimentary facies developed in the Ebro Turbidite System: **A**) erosive-depositional channel-levee complex; **B**) depositional channel-levee complex. Numbers with arrows refer to the location of the sediment cores. Legend in Fig. 6.

from 200 to 1200 m and have an intermediate sinuosity (1.25). The channels preferentially develop their right levee (SE margin) and have axial gradients (0.4-1.9°) similar to those channels developed in the upper environment of turbidite systems located in mature passive margins (Damuth and Kumar, 1975).

The morphology of the Guadalfeo Turbidite System shows all the diagnostic elements of this type of clastic depositional systems. This multiple-source turbidite system has six small canyons (max. length 5 km, max. width 2 km, max. depth 200 m) that fed several straight to sinuous submarine channels (max. length 15 km, max. width 1 km, max. depth 60 m) with well-developed levees. Channel relief and levee height decrease towards the distal area of the base of slope and the Motril Basin where small distributary channels (maximum width 400 m, maximum depth 8 m) depicting a dentritic pattern are incised (Pérez-Belzuz, 1999, in press).

WHAT DO WE KNOW FROM THE QUANTITAVE ANALYSIS?

A quantitative analysis has been made in the Guadalfeo Turbidite System focussed in: a) the quantification of volume and rate of sediment supply, and b) the quantification of the main geometric parameters.

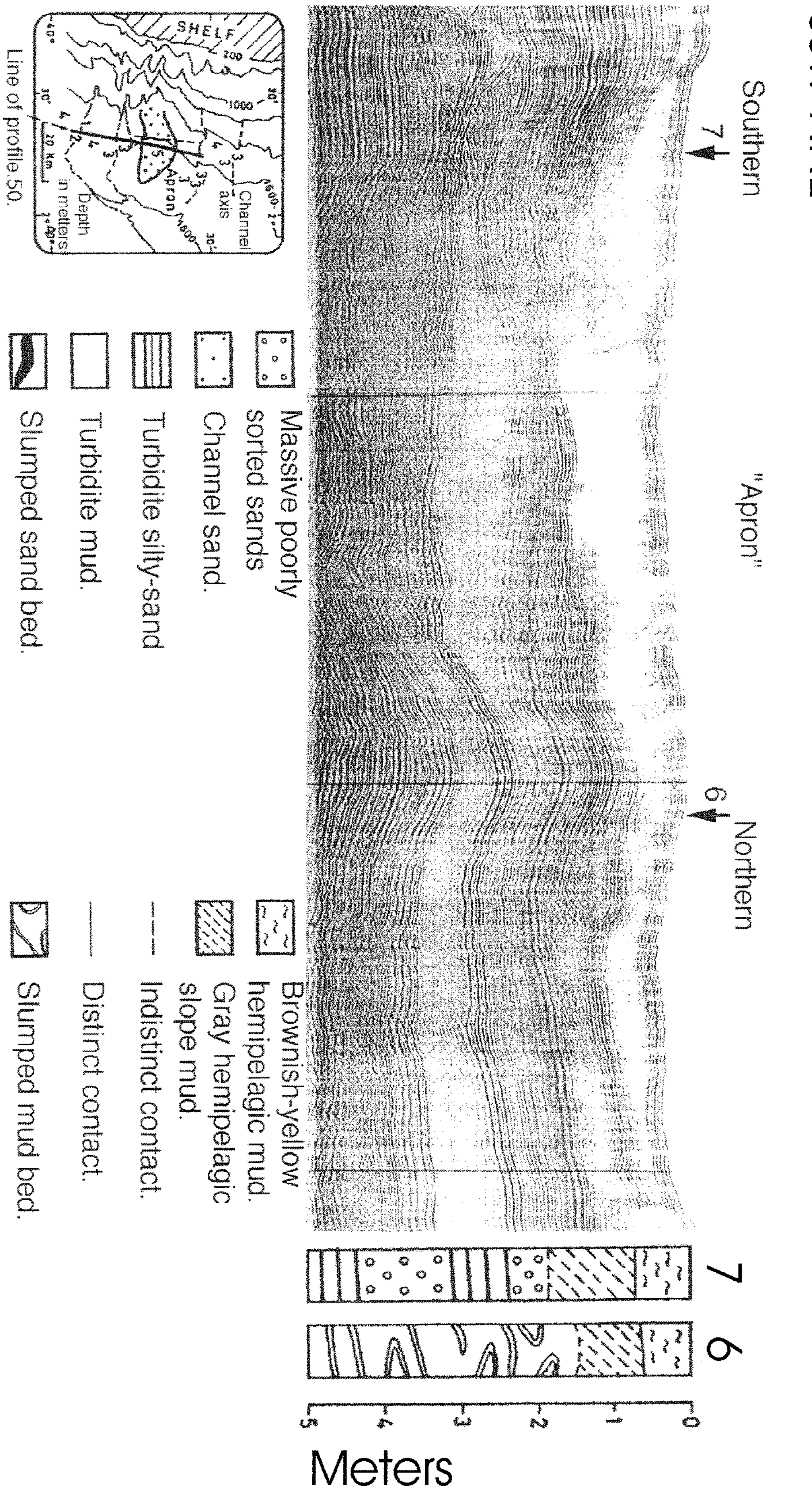

Fig. 6. Characteristics of sedimentary facies of apron deposits in the Ebro Turbidite System. Numbers with arrows refer to the location of the sediment cores.

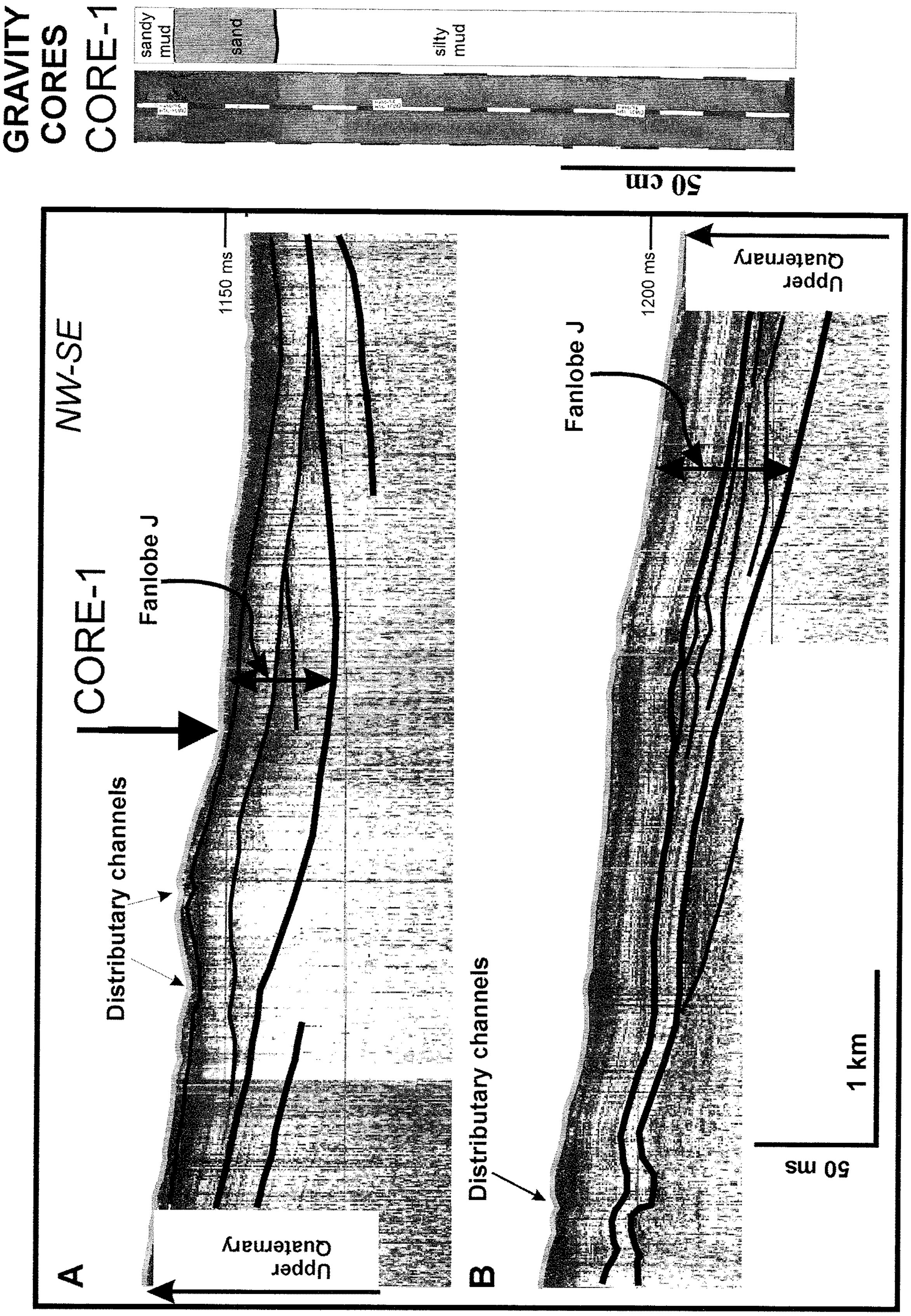

Fig. 7. Ultra-high resolution seismic profile (TOPAS System) showing the distal fanlobe J and gravity core recovered in the Guadalfeo Turbidite System.

The total volume of the Guadalfeo Turbidite System during the Upper Pliocene and the Quaternary (upper sequence) is 488 km^3 and the average rate of sediment supply of this turbidite system during the Upper Pliocene and the Quaternary is 148 km^3/m.y. The quantification of the sediment supply rate corresponding to every seismic unit belonging to the upper sequence (Pl2, Pl3, Ct1, Ct2, Ct3) allows to characterize the evolution of the sediment supply feeding this turbidite system during the Upper Pliocene and the Quaternary. The rate of sediment supply is low in the Early Upper Pliocene (110km^3/m.y.) and increases in the Later Upper Pliocene (190 km^3/m.y.). The rate is again low in the Early Lower Quaternary (111 km^3/m.y.), increasing in the Later Lower Quaternary (195 km^3/m.y.) and finally decreasing in the Upper Quaternary (136 km^3/m.y.) (Pérez-Belzuz, 1999, in press).

A detailed quantification of the sediment supply in the Guadalfeo Turbidite System fanlobes built during the Upper Pliocene and the Quaternary (fanlobes B, C, D, E, F, G, H, I, J) has also been done. The volume of the fanlobes ranges between 5 km^3 (fanlobe E) and 131 km^3 (fanlobe D), and the sediment supply rate between 11 km^3/m.y. (fanlobe E) and 187 km^3/m.y. (fanlobe D). Sedimentation rate shows similar values in all the fanlobes, with a minimum of 15 cm/1000 years (fanlobe D) and a maximum of 28 cm/1000 years (fanlobe E) (Pérez-Belzuz, 1999, in press).

The quantification of the geometric parameters of the Guadalfeo Turbidite System give a length of 36 km, a width of 38 km and an surface of 1000 km^2. The length of Guadalfeo Turbidite System fanlobes is between 13 km (fanlobe E) and 31 km (fanlobe D). The maximum length of fanlobes is limited in the Western sector of the Guadalfeo Turbidite System by a volcanic high (Djibuti Bank) located 31 km away from the apex of the fanlobes, and in the eastern sector of this turbidite system by the Motril Anticline, which is located 18 km from the apex of the fanlobes. The width of the fanlobes varies between 8.5 km (fanlobe E) and 32.5 km (fanlobe D). The surface of the fanlobes is variable with a minimum of 76 km^2 (fanlobe E) and a maximum of 663 km^2 (fanlobe D) (Pérez-Belzuz, 1999, in press).

WHAT DO WE KNOW FROM THE SEDIMENTARY EVOLUTION?

The sedimentary evolution of the Ebro Turbidite System took place during the Plio-Quaternary. The development of submarine canyons occurred mainly in the Late Pliocene and Early Pleistocene, and the deposition of channel-levee complexes and base-of-slope aprons alternating with hemipelagic deposition took place mainly during the Pleistocene. The upbuilding and style of growth of the Ebro Turbidite System resulted from the interplay among the climate and sea-level changes, sediment supply and location of the sedimentary depocenters during the different sea-level stands. During the periods of sea-level fall and lowstand stages, freshwater discharge from the Ebro River increased, large amounts of terrigenous sediment were transported into the heads of the slope canyons and were subsequently carried seaward through their associated active channels, but without developing lobe deposits. As an active channel was abandoned, a new channel-levee complex occupied the adjacent depression; the whole of the complexes indicates a migration from North to South with time. Likewise, during these stages, sediment instability was induced by the steep slopes and rapid sediment accumulation, and subsequently unconfined mass flows and turbidite currents developed the base of slope aprons in the gullied slope terrains of the central sector. The reduced growth of the Ebro Turbidite System occurred during the high sea-level stands, and the predominant process on the distal continental margin was the deposition by hemipelagic settling.

The sedimentary evolution of the Guadalfeo Turbidite System took place during the Plio-Quaternary. The onset of the sedimentary activity of this turbidite system is related to the Messinian Salinity Crisis that caused an important sea-level fall in the Western Mediterranean. This sea-level lowering controlled the incision of an important canyon that was active during the Lower Pliocene. The number of canyons increased up to six during the Upper Pliocene and the Quaternary. The development of fanlobes started during the Lower Pliocene (fanlobe A) becoming more important during the Upper Pliocene (fanlobes B, C and D) and during the Quaternary (fanlobes E, F, G, H, I, J). The sedimentary evolution of fanlobes was controlled by the activity of the submarine canyons that fed point-source and multiple-source fanlobes. Changes in the sedimentary activity of these canyons caused lateral and longitudinal migration of the fanlobes. The lateral shifts are characterized by an overall eastward trend during the Plio-Quaternary, whereas longitudinal migrations are more variable, although a distinct retrogradation occurred during the Upper Quaternary. The upbuilding and the growth patterns of the Guadalfeo Turbidite System were mainly controlled by the tectonic evolution of the surrounding areas, sea-level changes and variations in sediment supply. The change of a distensive tectonic regime to a compressive tectonic regime at the end of the Lower Pliocene increased the uplift of the margin favoring the incision of up to six canyons and the efficient transfer of sediments towards the turbidite system. Sea-level falls and lowstands also controlled a more effective transfer of sediments towards the turbidite system (Pérez-Belzuz , 1999, in press).

CONCLUSIONS

Why the Ebro and the Guadalfeo Turbidite Systems?

Because both examples are small mixed turbidite systems which have not been drilled up to day. Only large muddy turbidite systems such as the Mississippi (Bouma *et al.*, 1986), the Amazon (Flood *et al.*, 1997) and the distal edge of the Indus (Cochran *et al.*, 1989) have already been drilled. Therefore, the drilling proposal of these new and different turbidite systems is relevant, and can provide a significant improvement to what is already known about similar ancient systems.

Because they both represent two good analogues of clastic reservoirs, and the results of the drilling program can help to evaluate the existing depositional models, based on outcrop mapping. The ancient turbidite systems provide only a limited scope for sedimentary processes modelling, and their interpretation lacks of a better knowledge of the original shape of the depositional surfaces.

Because they both are located in well known and geophysical controlled semi-enclosed basins. This makes them suitable to perform quantitative analysis of sediment supply and its variations, and relationships with allocyclic and autocyclic processes. In addition, they offer a good opportunity to understand the growth processes of small turbidite systems, and to improve the existing sedimentary models.

What are the key scientific questions?

The key scientific questions are the followings:

- to characterize the sedimentary facies;
- to perform a quantitative analysis of sediment supply and sedimentation rate changes with time;
- to determine the relationships between sedimentary facies and high and ultra-high resolution seismic facies (data already available);
- to establish a high resolution study of the controlling factors (sediment supply, sea-level, tectonics, and physiography) in the growth of both systems during the same period (Plio-Quaternary, 5.3 my.);
- to establish a correlation between turbidite system stratigraphy and the stratigraphy of the shelf (available information);
- to develop and improve the existing turbidite system models.

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Sand-rich *versus* mud-rich turbidite systems at intermediate latitudes : stratigraphic response to sea level changes : Var fan (Ligurian margin) *vs* Rhône fan (Golfe du Lion), Western Mediterranean an ODP proposal

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This expanded abstract synthesizes the last version of an ODP proposal (n°467) that was submitted prior to the CIESM Workshop on "Mediterranean Scientific Drilling Prospectives". It will be revised to follow recommendations of both ESSEP and the workshop.

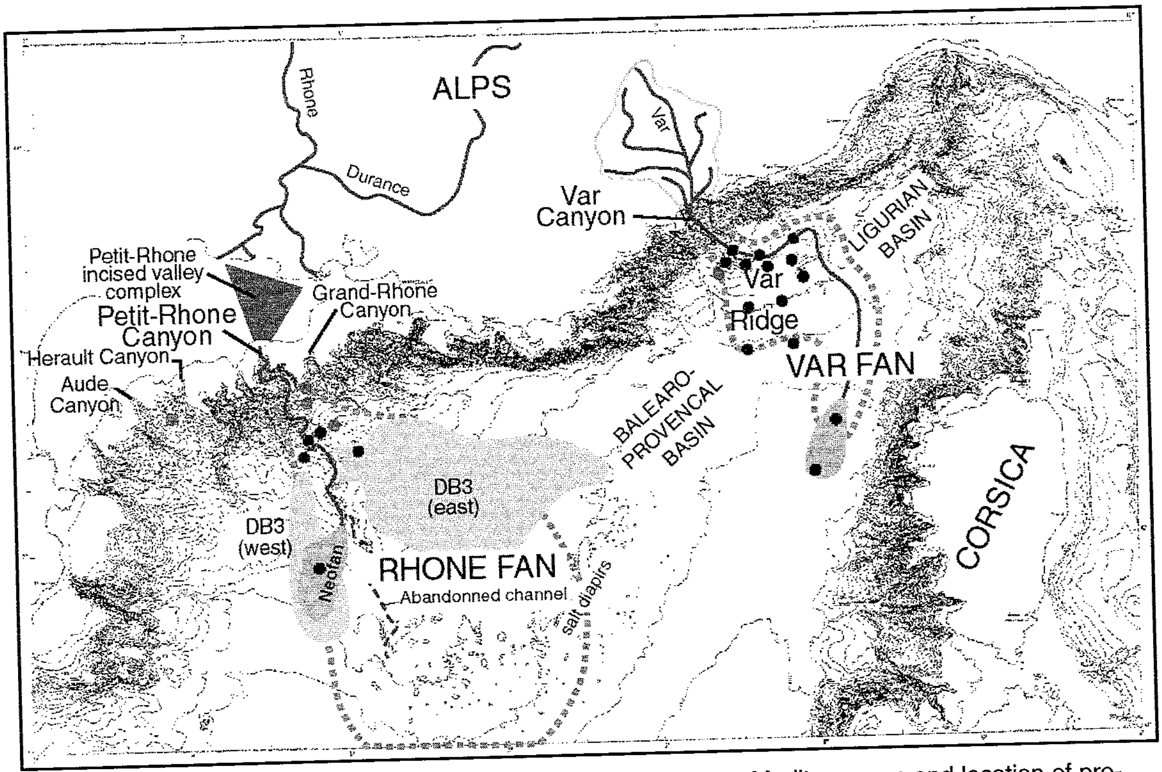
The growth patterns of deep sea fans are strongly influenced by sea-level and climate changes and character of turbidity currents that deposit on them (Normark and Piper, 1991). Results from Leg 155 on the Amazon Fan confirmed the fluctuating sea-level to be the fundamental factor that controls sedimentation in large muddy turbidite systems that are detached from their fluvial source during relative sea-level highstands.

This proposal constitutes the next step for full understanding of factors that primarily control deposition both on the shelf and in basins within deep-sea fans. It contributes towards the effort to test sea-level control on sedimentary architecture by a global coverage in a variety of tectonic, sedimentary, climatic and oceanographic settings advised by the Sea-Level Working Group (SL-WG) and by the Sedimentary and Geochemical Processes Panel (SGPP).

It aims to investigate the stratigraphic response to eustatic changes on siliciclastic passive margins at intermediate latitudes and in the Icehouse stratigraphic interval (Plio/Quaternary) on two end members turbidite systems of the same basin, the large muddy Rhône Fan in the Golfe du Lion and the smaller, sandier and still active Var Fan on the Northern Ligurian Margin of the Western Mediterranean.

WHY DRILLING THE MEDITERRANEAN TURBIDITE SYSTEMS

When compared to other turbidite systems that have been drilled so far, drilling the Mediterranean systems (Fig. 1) offers several advantages that satisfy to the recommendations of



The Rhône and Var deep-sea fans in the framework of the Western Mediterranean and location of proposed ODP drilling sites (grey dots : stratigraphic objectives, 500 to 1500 m bsf; black dots : sedimentological objectives, 100 to 200 m bsf).

SL-WG and SGPP to "*test sea-level control on sedimentary architecture by a global coverage on a variety of*":

- "*tectonic settings*": this proposal concerns two passive margins with contrasting morphologies that reflect different tectonic activities and evolutions, with the present-day reactivation of the Ligurian margin,
- "*sedimentary settings*": the proposal concerns two end members types of fans, one of which has never been documented by drillings, and both emplaced on siliciclastic margins,
- "*climatic settings*": the fans are both of Plio/Quaternary age and located at intermediate latitudes, where ice cover strongly fluctuated during Plio/Quaternary glacio-eustatic cycles, in contrast to the low latitudes, and equatorial climatic setting of the Amazon Fan.
- "and *oceanographic settings*": in contrast to open ocean conditions prevailing during deposition of the Amazon Fan, the Rhône and Var fans are both emplaced within a relatively small and confined basin, the Western Mediterranean Basin.

The Var Fan belongs to the small sand-rich active type of fans that, although common both in modern and ancient turbidite systems, has not yet been drilled. It represents a type of turbidite system different from the Mississippi and Amazon fans that were drilled respectively during DSDP Leg 96 (Bouma *et al.*, 1986) and ODP Leg 155 (Shipboard Scientific Party, 1994). Contrarily to these large inactive turbidite systems, the Var Fan shows a morphology that suggests important deposition from both sandy and muddy turbidity currents (Savoye *et al.*, 1993). Deposition has continued through the Holocene, with a turbidity current as recent as 1979 (Gennesseaux *et al.*, 1980). The drillings aim to better understand the relationships between fan architecture, character of the source area, and type of turbidity current through at least several glacial to interglacial cycles.

The Golfe du Lion and associated Rhône Fan, of the "detached" type of fan, offer the possibility to study the Plio-Quaternary sedimentary evolution of a large siliciclastic margin from the inner shelf to the deep basin. This type of integrated study was initiated during the ODP Leg 150 (Mountain, Miller *et al.*, 1994) on the New Jersey slope and rise. Drillings on the continental shelf is presently being realized (Leg 174A). However, drillings on the New Jersey slope and rise essentially collected informations on the Oligocene and Miocene series. Drillings on the Rhône Fan will investigate in details the Plio/Quaternary period of the Icehouse stratigraphic interval.

The possibility to compare, in the same basin, two margins and fans with contrasting sedimentary and architectural styles is of great interest and will provide informations about global factors that influenced sedimentary evolution since the Messinian in order to understand and quantify the role of local parameters responsible for specificities of the margins and associated turbidite systems.

GENERAL SCIENTIFIC OBJECTIVES

I - Sedimentological and architectural characters of two end members turbidite systems of the same basin and at intermediate latitudes

I.1 - A small sandy fan , the Var Fan

The sand-rich Var Fan is fed by a short but active river, that is connected to the Var Canyon. Trapping of sediment in shallow water is low, due to the very narrow continental shelf, the sector is a seismically active area. The fan is characterized by coarse sedimentary input (up to gravel and boulder size in the Var River and Canyon), small size (about 300 km from canyon head to distal lobe), high percentage of coarse-grained deposits, asymmetrical shape and presently active gravity processes.

It is an area of active sediment transport, where at least three major types of sediment transfer process are identified : hyperpycnal turbid plumes (Mulder *et al.*, 1996b), shallow failures generated by excess pore pressure during river flood periods (Mulder *et al.*, 1996a), and large earthquake-triggered slides.

The last two processes might generate some so-called "high-density turbidity currents" at different scales. Hydrological data, direct observations of the seafloor, geotechnical testing and numerical modelling confirm the very high frequency of these sediment transfer events. The Var submarine sedimentary system thus appears as an interesting area, where the relative importance and occurrence of the different types of mass-wasting processes can be accurately estimated using ground-truth data.

This type of turbidite systems needs to be documented with enough detail and accuracy to be compared to other now better-known mud-rich fans. This implies :

- to drill the various environments of the fan (including valley/channel and levee in successively more distal transects of the turbidite system, and distal depositional lobe observed off Corsica) in order to determine facies associations, processes of transport and deposition, lithological significance of seismic facies and downfan evolution of deposition,
- to establish the specificities, if any, of depositional processes (turbidity currents and mass-movement processes),
- to estimate the effect of sediment partitioning, flow stripping on depositional areas,
- to establish an absolute chronology for the main fan units and major phases of deposition in order to evidence the chronostratigraphic evolution of depocenters.

I.2 - A large mud-rich fan under the same climatic conditions, the Rhône Fan

The Rhône Fan belongs to the family of the "detached" large muddy turbidite systems such as the Mississippi or Amazon Fans drilled in 1983 and 1994 respectively.

Drilling the Rhône Fan is another crucial step to progress on the question of the influence of external forcing factors.

The main interest in drilling this fan lies in the comparison with the nearby Var Fan located in the same basin, at same latitude and that grew under same climatic conditions. Because of the similarity of some forcing factors (eustatism, climate), the main expected scientific inputs of combining drillings on both fans is the clear identification and quantification of effects of physiography and tectonic activity in basins.

This comparison is expected to furnish significant results and should be based on a minimum of drilling sites at locations equivalent to those of the Var Fan.

II - Fan activity and chronostratigraphic evolution of the margins

Sequence stratigraphy (Posamentier *et al.*, 1988; Posamentier and Vail, 1988) is considered as an useful approach to study sedimentary evolution of margins. Sequential concepts consider that sequences are created essentially in response to global factors such as sea-level changes. This implies that sequences should be more or less synchronous at a worldwide scale, unless local factors (tectonic) interplay to create non synchronous stratigraphic events.

Testing these basic concepts in an integrated manner constitutes a primary objective promoted in the SGPP White Paper. A series of tests began with Leg 150 (New Jersey continental slope and rise) where age estimates of shelf sequence boundaries were shown to correlate with glacio-eustatic lowerings. However basin sedimentation revealed a mainly uniform, homogeneous hemipelagic deposition since the Middle Miocene, so that problems related to integration of gravity deposition addressed by our proposal were not investigated. Pleistocene stratigraphic response to high frequency, large amplitude sea-level changes of a fan at low latitudes was later investigated during Leg 155 (Amazon Fan). Results of Leg 155 confirmed that glacio-eustastic changes control deposition in large muddy fans of the "detached" type. However, exact links between the shelf depositional units and slope/basin units is unknown because drillings were not realized on the upper fan and slope domains and seismic is not useful on the shelf due to high sediment gas content.

II.1 - Sedimentation on a narrow margin with active deep basin deposition during sea-level highstands : the Ligurian Margin and Var Fan

By now, stratigraphic response to eustatic fluctuations have only been tested for wide margins characterized by a significant discontinuity between land and deep basins and thought to be mainly controlled by sea-level changes. As recommanded by SL-WG, progress in sea-level researches also requires tests on other types of margins including margins with narrow shelf and steep slopes where local factors are known to interplay significantly with eustatism. The exact contribution of these factors remains unconstrained and have to be documented.

The Ligurian margin, in the Northeast Mediterranean (Fig. 1) provides the possibility to document the stratigraphic response on such a narrow margin where the presently active sand-rich Var Fan accumulated from Middle Pliocene (?) to present time. Off Nice, this margin is characterized by a mountainous backland, an extremely narrow shelf, locally absent and a very steep slope (up to 11°) that corresponds to deltaic deposits of Plio-Pleistocene age. Tectonic subsidence is inferred to have been quite similar to that recorded in the Golfe du Lion (acceleration during the Plio/Quaternary). However, the margin is presently recording a compressional reactivation of deep seated faults. Recent works on the Var Fan (Droz, 1991; Savoye *et al.*, 1993; Piper and Savoye, 1993; Duc, 1995) have hypothezised that its overall evolution is not primarily controlled by sea-level changes alone, but most likely by a combination of several factors, including variations of volume of input (related to climatic evolution and eustatically-induced base-level fluctuations), physiographic setting of deposition (inherited from previous sedimentary, tectonic or eustatic events) and synsedimentary tectonic evolution of the margin and sedimentary source. Even if the area is seismically active, there is no evidence for major tectonic control of the marine Plio-Quaternary sedimentation. However salt diapirism and differential subsidence at the base of the slope area have locally controlled sedimentation.

II.2 - Sedimentation on a wide margin with inactive deep basin deposition during sea-level highstands : the Golfe du Lion and Rhône Fan

The Golfe du Lion margin is particularly appropriate to study the stratigraphic response of sedimentary architecture to sea-level changes and to test sequential concepts because of the similarity of the depositional contexts in both the sequence stratigraphy conceptual model and this margin: passive progressive margin characterized by a flat backland dominated by an extended delta, a wide continental shelf – about 50 km off the Rhône Delta – which induces a great discontinuity between the Rhône River and Petit-Rhône Canyon, a marked shelf-break and a gently deeping continental slope (Fig. 1). Tectonic subsidence was moderate since the end of the rifting (Aquitanian times), but accelerated in the deeper part of the basin during Plio/Quaternary times (~170 m/Ma).

Because of the discontinuity between the source and the deep basin, sea-level changes, even of low amplitude, are expected to be well recorded by marked shifts of depocenters from shallower to deeper parts of the margin and reciprocally. In addition, the existence of the well-developed Plio/Quaternary Rhône Fan (Droz and Bellaiche, 1985) provides the opportunity to determine the true stratigraphic relationship between the shelf and basin sedimentary sequences and to document and better integrate gravity sedimentation within the models. The slope area constitutes a key sector where shelf sequences are interstratified with basin (fan) sequences and where stratigraphic relationships can be observed.

- In addition to expected results of a comparison with the nearby Var Fan (see I.2), an important input will be brought by in confronting results in the Rhône Fan with results obtained by drillings in fans of the same family especially the Amazon Fan that grew under different climatic conditions (equatorial climate).

- Besides its mainly "detached" characteristics and main activity during lowstands or lowerings of sea-level, the Rhône Fan was active at specific period of highstands or rise of its evolution : Pliocene rise of sea-level (Complex RFI) and Holocene highstand (neofan).

Within deep environments, alternative active turbidite deposition during lowstands/inactivity during highstands was confirmed by drilling the Amazon Fan (Leg 155 Preliminary Report, 1994), for margins characterized by wide shelves that induce a great discontinuity between the fluvial source and the deep basin. An important anomaly to this general trend is constituted by significant turbidite deposition during sea-level rises or highstands, a particularity that was not investigated during previous drillings in the Amazon and Mississippi Fans. Deposition during sea-level highstands is conceptually described by Mutti (1985) as type III systems (channel/levee complex), that are deposited if adjacent shelves are characterized by sufficiently high rates of deltaic progradation. Deposition in fans during sea-level rise is also mentionned by Kolla and Perlmutter (1993).

-Timing of slope instability processes and their relation to eustatic cycles remain unresolved. This problem was addressed from drillings on the Amazon Fan that, up to now, failed to relate preferential instability behaviour of sediments to sea-level stands. Drilling on the New Jersey margin (Mountain, Miller *et al.*, 1994) inferred that Pleistocene mass wasting events correlate with transition from interglacials to glacials, i.e., during glacio-eustatic sea-level falls. On another hand, on the base of stratigraphic and geographical position within the Rhône Fan, it is suggested that mass movements preferentially occurred during rises of sea-level (Droz, 1991): the slided material is concentrated at specific stratigraphic levels of the fan (the top of the three Quaternary chanel/levee complexes), attesting of some cyclicity of the triggering processes. Large mass-movements seem to be lacking in the Pliocene seismic sequence indicating that instability conditions were not established at that time and that these processes are more relevant to the Quaternary period (due to rapid changes of sea-level, important progradation of the margin that resulted in thick, rapidly deposited and unstable sediments on the slope, intensified halokinetic movements or a combination of several of these parameters ?). Torres *et al.* (1995) and Tesson and Allen (1995) also inferred that Late Quaternary mass movements at the shelf edge occurred at the end of lowstands/beginning of following sea level rises.

Contradictory interpretations raise doubts about the relation of mass-movements to eustatic cycles and suggest the possible significant contribution of local factors to their initiations. It must be noticed that large debris-flow units seem to be present in the Amazon Fan at similar (?) stratigraphic position as in the Rhône Fan, and synchronism of these instability events needs to be tested

III - Plio-quaternary climate fluctuations and development of alpine ice cover

Both fans being fed through alpine rivers, it is anticipated that study of terrigeneous sediments of the fans will allow to obtain a high resolution record of climate fluctuations during the Plio-Quaternary glacial-interglacial cycles at intermediate latitude and to document the subsequent development of Alpine ice cover. As shown from results of Leg 155 (Shipboard Scientific Party, 1994) high sedimentation rates on levees will assure high resolution record of climate changes.

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Cyclic sedimentation in the Eastern Mediterranean : the need for high-resolution geochemical investigations

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Introduction

Cyclic variations in color, carbonate content or clay mineralogy are displayed in sediments from land sections of Calabria, Sicily, and Crete of Miocene to Holocene age (e.g., Hilgen, 1987; De Visser *et al.*, 1989; Hilgen, 1991; Van Os *et al.*, 1994; Foucault and Mélières, 1995; Nijenhuis *et al.*, 1996). These sedimentary cycles, including intercalated sapropels, correspond to the precession-related ~22 kyr periodicity in Northern Hemisphere summer insolation (Lourens *et al.*, 1996) which suggests an astronomically forced climatic mechanism. Several authors have proposed that such regular variations in sediment composition are primarily caused by humid-arid climatic oscillations with higher precipitation rates and runoff during times of sapropel formation (Rossignol-Strick, 1983 and 1987; Wijmstra *et al.*, 1990; Rohling and Hilgen, 1991; Foucault and Mélières, 1995). Recently these hypotheses have been confirmed by high-resolution geochemical studies on Pliocene hemipelagic sections (Wehausen and Brumsack, 1998; Brumsack and Wehausen, 1999; Wehausen, 1999). Furthermore, such investigations allow to assess whether changing water currents, *e.g.*, a reversal from anti-estuarine to estuarine circulation, occurred during times of sapropel formation or not (Wehausen, 1999; Wehausen and Brumsack, in press). In this short paper a review of our recent advances will be presented.

Sediments and investigated proxies

Pliocene, between 2.3 and 3.1 Myr old, sediments recovered during ODP Leg 160 in the Ionian Sea (Site 964), on the Mediterranean Ridge south of Crete (Site 969), and at Eratosthenes Seamount (Sites 966 and 967) were analyzed at high-resolution (3-4 cm depth intervals) by inorganic geochemical methods. Precise bulk parameter and XRF-measurements (for methodology see Wehausen, 1999) provide a large set of different geochemical proxies which are related to biological productivity (TOC, carbonate, Ba), terrigenous detrital matter provenance (*e.g.* Si/Al, Ti/Al, Mg/Al, K/Al, Zr/Al ratios), or redox-state (*e.g.* Fe, S, Mn, Mo, V).

Results and discussion

In contrast to the carbonate content, which does not show a consistent behavior, cyclic variations in terrigenous-detrital matter composition (*e.g.* Si/Al, Ti/Al, Mg/Al, Zr/Al and partly K/Al ratios) were detected at all sites investigated (Wehausen, 1999; Wehausen and Brumsack, in press). Sapropels (TOC $\geq$ 2 %) or sediments showing signs of enhanced bioproductivity (Ba-enrichment) are characterized by a higher fraction of fluvially derived terrigenous-detrital matter. In case of Eratosthenes Seamount sediments this material of predominantly Nile river origin is characterized by low Al/K ratios (Fig. 1) indicating higher smectite and lower illite contents.

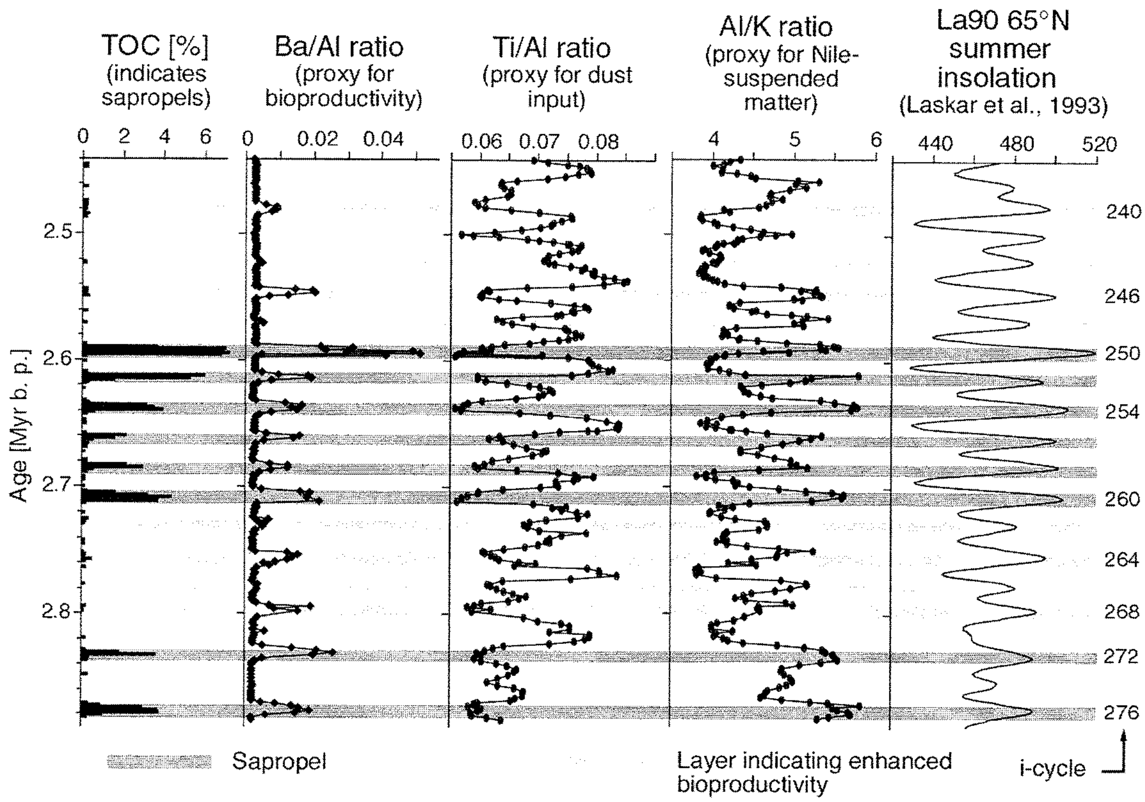

Figure 1. High-resolution geochemical profiles of Late Pliocene sediments from ODP Site 967 (lower northern slope of Eratosthenes Seamount, south of Cyprus) compared to the La90 65°N summer insolation target curve. Age-model after Wehausen (1999); i-cycle codification after Lourens *et al.* (1996).

At the more western Sites (964 and 969) the terrigenous material during "wet" periods must be introduced by rivers of the northern borderlands of the Eastern Mediterranean (NBEM). This material is enriched in Mg, Cr, and other elements typical for ultramafic rocks (Fig. 2; Wehausen, 1999; Wehausen and Brumsack, in press). The source of this material is probably located on mainland Greece.

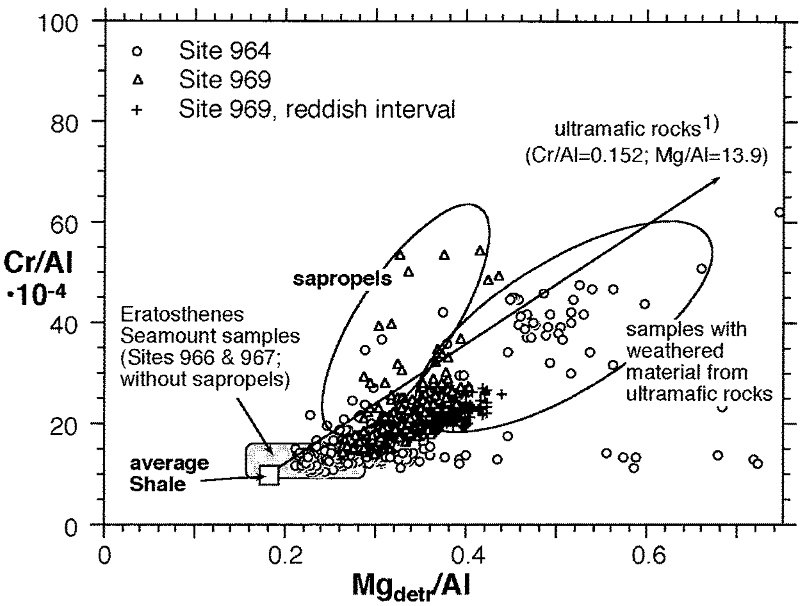

Figure 2. Relationship between Mg_{detr}/Al and Cr/Al ratios in sediments of Site 964 und 969. Mg_{detr} = carbonate-free magnesium; 1) Hartmann and Wedepohl (1993).

The "dry" sedimentary intervals are characterized by higher proportions of eolian dust, mainly of Saharan origin. This material has a rather uniform composition basinwide and is characterized, *e.g.*, by higher Ti/Al ratios (Fig. 1).

The geochemical record of Site 967 provides evidence that Eastern Mediterranean sedimentary cyclicity can best be explained by the La90 65°N summer insolation target curve (Laskar *et al.*, 1993) as proposed by Lourens *et al.* (1996). The Ti/Al ratio, however, shows a near linear response to northern hemisphere summer insolation (Lourens *et al.*, 1998) and offers the opportunity to create cyclochemostratigraphic age models.

Our terrigenous-detrital matter provenance study furthermore allows testing water circulation models, in particular the possibility of circulation reversals during humid intervals. Site 969, located south of Crete, serves as a reference location, as it may receive terrigenous material from three distinct source areas (Venkatarathnam and Ryan, 1971 : The Northwest Aegean (Mg- and Cr-rich material from the Greek mainland; see above), the Southeast Aegean (weathered material from Anatolia), and the Sahara. A significant decrease in Ti/Al ratio in some of the sapropels of this site was detected, which cannot be explained exclusively by a lower dust input. Additionally a shut-off of the current induced westward transport of Ti-rich material from a source in the East (Fig. 3; Wehausen, 1999; Wehausen and Brumsack, in press) must have been obstructed. During deposition of the sapropel-barren reddish intervals such a change in water current pattern did not occur and Ti/Al ratios remained relatively high.

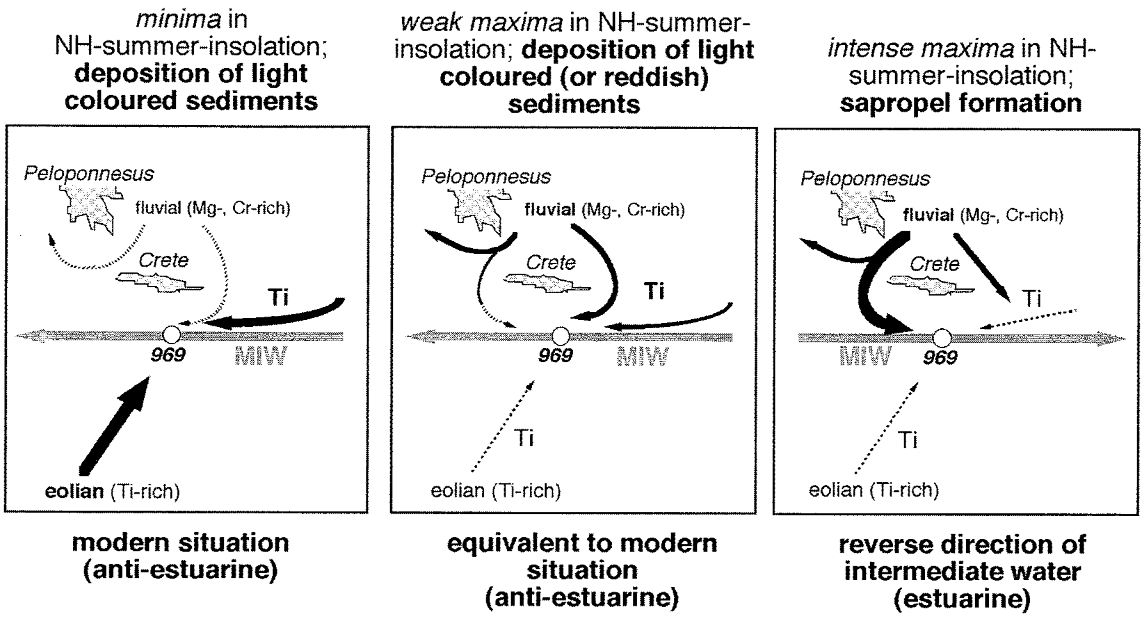

Figure 3. Source strenghth and transport direction of three discrete particulate matter assemblages South of Crete for three different paleoceanographic scenarios. Material from the Northwest Aegean is characterized by high Mg and Cr contents. Eolian derived material from the Sahara is enriched in Ti. Another source for Ti-rich material exists further to the East (Southeast Aegean/Anatolia); MIW = Mediterranean Intermediate Water.

Based on these findings the following paleoenvironmental scenario for the Pliocene situation seems likely:

• During northern hemisphere summer insolation minima and corresponding oligotrophic conditions, similar to those persisting in the modern Mediterranean, sedimentation is rather uniform and sediments have received high proportions of eolian material, mainly derived from the North-African continent.

• In times of insolation maxima climate is more humid and may have a more or less profound impact on the Eastern Mediterranean paleoenvironment. During weak insolation maxima sapropels are not formed and reddish sediments are deposited. In this situation water circulation seems to be similar to the modern Mediterranean (anti-estuarine mode). Moderate to intense insolation maxima lead to the deposition of organic carbon-rich sediments (sapropels), accompanied by at least a temporary inversion of surface and intermediate water currents (estuarine circulation mode).

CONCLUSIONS AND PERSPECTIVES

There is a strong link between astronomically forced climatic changes and Eastern Mediterranean paleoenvironment. Paleoenvironmental fluctuations are reflected in sediment composition. The high resolution geochemical study of longer sediment sections allows to detect such fluctuations also in "red intervals" devoid of enrichments in organic carbon (sapropels). If the sources of the clastic material are significantly different in chemical composition, transport paths of terrigenous detrital material may be reconstructed at distinct locations, *e.g.* the Mediterranean Ridge.

Drilling through the Messinian salt during a future campaign would close a large gap in our knowledge on Miocene deep-water sedimentation in the Eastern Mediterranean. Studies on land sections, *e.g.*, have revealed that the mechanism of sapropel formation was the same for the last 10 Myrs (Schenau *et al.*, 1999). High-resolution investigations on pelagic sediments of Miocene age would permit new insights into the sedimentary processes and paleoceanographic conditions during that time. As a marginal sea the eastern Mediterranean serves as an important model ocean for the Mesozoic and perhaps even Paleozoic black shale episodes.

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High resolution studies in sediments of Eastern Mediterranean key-areas on global paleoclimatic changes

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Sediments in the Eastern Mediterranean are known to be ideal recorders of Global paleoclimatic continental and marine signals. This is partly due to (1) the highly favourable semi-enclosed nature of the basin, and (2) the various surrounding landmasses.

1 - Semi-enclosed basin

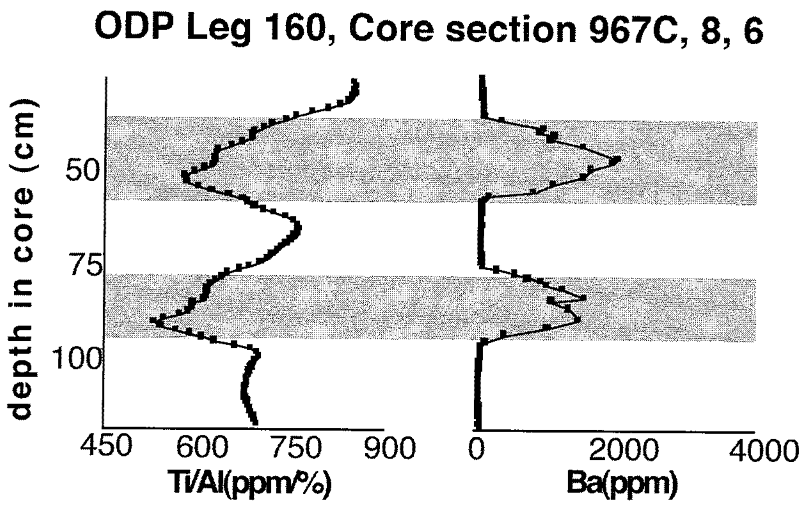
The rather restricted circulation in the Mediterranean basin results not only in a delicate oxygen balance, but also in a bottomwater formation that is very sensitive to global climatic variations.

This is probably one of the reasons that Mediterranean sediments resemble open ocean sediments from periods of possibly restricted circulation, in that they contain regular intervals that are extremely rich in organic matter. This astronomical cyclicity serves as a perfect time-marker for Mediterranean Miocene to recent sediments, which permits an unprecedented comparison of samples in identical time-slices but from different locations.

2 - Various surrounding landmasses

Around the Mediterranean there is a large variety of continental characteristics not only in geological signature but also in vegetation and climatic zones. This makes it easier to detect subtle changes in global paleoclimatic conditions in this area, using geochemical, petrological, and palynological proxies. As a consequence, climatic variations are accurately recorded not only by giving variations in typical "marine" signals, but also in typical "continental" signals. The "Monsoonal index" is strongly associated with the paleoclimatic conditions in the area around the Eastern Mediterranean, i.e. Sahara/ Africa, Middle East, Southern Europe. This association is clearly present and visualized in its sediments, mainly in a ~ 21 kyr precession-controled cycle : during "wet" climatic periods organic-rich sediment (Sapropel) is deposited containing strong river and marine productivity signals, whereas during "dry" climatic periods organic-lean sediment is deposited containing high dust input signals. The various ages and compositions of continental rock surrounding the Eastern Mediterranean facilitate establishing paleo-origin of dust material using a suite of major, minor, and radiotracer elements.

The Eastern Mediterranean, therefore, is an ideal area to study land-sea interactions of global paleoclimatic variations. In particular, as this area is influenced and preserves paleoclimatic signals from the mid to high latitude northern borderlands to the low latitude Monsoonal influenced southern borderlands. Because of the extreme sensitivity of these borderlands to subtle climatic



Example of astronomically controled cyclicity as expressed intwo geochemical proxies; Ba considered to represent productivity, and Ti torepresent dust transport (arid conditions)

changes, the Eastern Mediterranean is a potential goldmine for paleoclimatic research, provided that sites of high sedimentation rates can be obtained.

High resolution, i.e. with a time resolution of better than a few 100 years, paleoclimatic studies in the Eastern Mediterranean were hampered due to the relatively low sedimentation rates (2-4 cm/kyr) of sites studied thus far (*e.g.* Emeis *et al.*, 1998; ODP Leg 160). Recently, a few sites were found in "key areas" with sedimentation rates of 10-20 cm/kyr. These sites are all located in areas of potential major changes in paleo-bottomwater formation, i.e. Adriatic Sea, and Southern Aegean Sea, or with major changes in climatically controled freshwater influx (Nile plume). Preliminary study of the former sediments for the last 10 kyrs indicates an unprecedented time resolution, and the accurate detection of rather abrupt major changes in probably climatic (continental/marine ?) conditions.

The major advantages for such high sedimentation rate sites are :

1. limited or no oxidation and consequent (selective) removal of several climatic proxies (*e.g.* org.C, dino-cysts, organic geochemical biomarkers, pollen,...);
2. limited mixing due to bottom biological activity;
3. higher time resolution permits the detection of abrupt relatively short timescale climatic changes (potentially Heinrich-type events).

Leg 160 has resulted in a wealth of scientific paleoclimatic results in particular for the organic-rich intervals. The organic-lean intervals in between, are nearly barren in organic matter, contain insignificant amounts if any of dinocysts, pollen, and organic biomarkers. If present, the great majority of the initial "climatic" markers has been changed dramatically so that no conclusions can be based on the occurrence of such proxies in the organic-lean intervals nor in the oxidized (top part of) previously organic-rich intervals. This considerably limits the potential interpretation of these records.In the above mentioned high sedimentation rate sites will it not only be possible to study these proxies in the intervals between the organic-rich intervals, but also to detect timescale events that are much shorter than the 21-23 kyrs cyclicity. Heinrich-type events have been found amongst others in Atlantic and N. Indian Ocean sediments, and possibly in the Alboran Sea. It seems therefore likely that these rapid climatic events will also have been recorded in this environment that is sensitive to climatic changes. The excellent time control from Recent to Miocene or beyond for the high sedimentation rate sites in the Eastern Mediterranean would permit not only the detection of such events, but also the establishment of their exact timing beyond 14C ages down to at least the Miocene (if present), and their relation to the astronomical cyclicity.

DRILLING

To obtain the paleoclimatic record for the last 1-4 Myr, 3 multiple Holes (200-400 m) in a depth transect in the Adriatic Sea, 3 multiple Holes in a depth Transect in the Aegean Sea, and potentially a similar transect at the Nile.

Seismic background information is available for the Adriatic sea (Bologne), possibly to a limited extent also for the Aegean Sea, and recently nice data were obtained for the Nile plume.

DEEP BIOSPHERE

1. Microbes buried during organic-rich sedimentation are separated from adjacent distinct organic-rich intervals by sediment intervals that are barren in food. This would limit the upward migration of microbes during deeper burial in these sediments The organic-rich environments have been anoxic at and briefly after deposition, but suboxic ever since. The organic-lean intervals have been oxic for a period of usually 15 kyrs (between deposition of two consecutive distinct organic-rich layers), and suboxic ever since

2. Microbes in high-sedimentation rate sediments have been continuously in a high-reactivity organic matter environment, can thus “freely” migrate upward upon deeper burial. This environment has been continuously suboxic to anoxic from very soon after deposition. The diagenetic environment is likely to change from sulphate reducing to methane producing at relatively shallow depths

3. In certain sedimentary environments in the Eastern mediterranean sites, a rather large increase in salinity and thus sulphate content occurs *versus* depth. As a consequence, these sediments may be anoxic but not sulphate-depleted, thus not methane-generating.

4. In Mediterranean mud dome areas, high upward methane fluxes limit the sediment interval where sulphate reduction occurs, create not only an environment of extreme rates of methane oxidation, but also one of high methane content but otherwise relatively reactive and abundantly available organic matter at relatively shallow sediment depths.

Comparing different settings in an otherwise similar area is needed so as to understand the potential pathways of microbes under various environmental and diagenetic conditions. For this purpose a high sampling resolution microbiological- and geochemical (porewater and sediment) effort is needed. For this purpose a dedicated mini-Leg seems necessary. In addition, a rapid transfer to landbased Laboratory facilities may also be needed. For all of the Eastern Mediterranean sites mentioned an international airport is within 24 hours of shiptime.

Drilling unusual Mediterranean sedimentary sequences in search of the deep sub-seafloor biosphere

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In the early to mid-1990's, geomicrobiologists working with samples recovered from drill holes cored by the Ocean Drilling Program (ODP) discovered that bacteria are not only present at much greater depths (>750 meters) beneath the deep seafloor than was previously thought, but they actually thrive there in colossal numbers (Parkes *et al.*, 1994). This exciting discovery has led to a major new initiative within ODP to study the deep sub-seafloor biosphere. The extent of this major biosphere and the nature of the "extremophiles" living there are essentially unknown. Ocean drilling offers the potential to probe this unexplored world of the deep sub-seafloor, which represents a unique habitat that couples biosphere/geosphere cycles. Exploring down to the base of the deep sub-seafloor biosphere will have important societal implications for new biotechnology applications, for better understanding the generation of hydrocarbons and ore deposits, for defining as yet unknown components of the carbon cycle, and for evaluating the origins of life on Earth and elsewhere.

The Mediterranean Sea is an ideal location to undertake drilling campaigns to investigate the deep sub-seafloor biosphere. During the late Neogene, the Mediterranean sedimentary basins were repeatedly the location of peculiar environmental conditions, which led to the deposition of highly organic carbon-rich sediments, known as sapropels. In addition, during the Messinian Salinity Crisis in the Mediterranean, a thick sequence of evaporite sediments was deposited basin-wide with the desiccation of the deepest basins. Beneath the evaporite are older sediments, which also contain high amounts of organic matter. The thick evaporite sequence essentially serves as a cap-rock seal limiting the upward migration of altered organic matter (petroleum) or gases. This trapping effect produces an obvious safety/pollution hazard and has prevented drilling deep into and through the Messinian evaporites. If it were possible to drill through these traps using advanced drilling technology with blowout prevention equipment, an unusual isolated deep biosphere community could be penetrated and sampled.

On the other hand, the close proximity of microbially viable organic matter in the sapropel layers and the underlying evaporites in relatively young (not deeply buried) sediments is rather unique to the Mediterranean. Where fluids have penetrated the evaporite seal and migrated upward through the overlying Pliocene/Pleistocene sediments, pore water analyses indicate elevated salinity due to the dissolution of the more soluble minerals along their pathway. These fluids are particularly enriched in sulfate ions, which can be used as a terminal electron acceptor to promote anaerobic degradation of the organic matter in the sapropel layers. Thus, the ingredients for an active deep sub-seafloor biosphere are available and easily reached with the drill-string, making the Mediterranean sediments a fertile system in which to explore for the deep sub-seafloor biosphere.

Preliminary microbial studies were undertaken on the recent ODP Legs 160 and 161 with encouraging results. In particular, studies were conducted on the sedimentary sequence from Site 969, which is located in 2202 m deep water in the Eastern Mediterranean and contains approximately 80 sapropel beds (Cragg *et al.*, 1998). The collected data demonstrate that microbial activity occurs with depth throughout the entire 116-m-thick Pliocene/Pleistocene sequence, even in sediment as old as 5 myr. The microbial activity varies within the sequence, with the bacterial counts being higher in the sapropel layers than in the surrounding sediments. High sulfur concentrations present in the form of pyrite also reflect this bacterial activity. The total amount of sulfur increases with depth showing that bacterial sulfate reduction does not occur only at shallow depths but continues after deep burial. This continued activity is supported by the flux of sulfate from below, as shown by the pore-water analyses. The sulfate concentration throughout the sequence was always equal to or greater than seawater and increased with depth. This preliminary work indicates that the combination of viable organic matter in the sapropel layers and sustained high sulfate concentrations are essential ingredients for promoting continued bacterial sulfate reduction with burial.

Thus, an excellent potential to study the processes governing the deep sub-seafloor biosphere exists in Mediterranean sedimentary deposits. In particular, the regular injection of organic matter into the sediments at frequent intervals to form the sapropel layers provides conditions for controlled experiments in a natural laboratory. The sapropel layers are produced at specific intervals, approximately every 20 kyr., in response to astronomically controlled climate change. Knowledge of this timing allows for good age control, making it possible to study changes in the microbial community and their organic substrate with depth and determine how such a system evolves with time. Future drilling of the deep sub-seafloor biosphere in the Mediterranean will require a dedicated leg(s) to undertake such experiments and will be possible with the currently available drilling technology. To study the even deeper and potentially more active and more isolated biosphere will require the technical ability to drill in regions which have been previously avoided, such as drilling into the Messinian evaporite sequences and penetrating potential hydrocarbon oil and gas rich zones. Such a program in the Mediterranean must await the arrival of a drill-ship capable of drilling safely in these environments.

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Deep sea drilling programme in the Black Sea. Climate change and sedimentation in the Black Sea region in response to Pleistocene climatic cycles: a letter of intent

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INTRODUCTION

Black Sea sediments contain important records of continental paleoclimate in Central Europe (drained by the Danube River), the Russian Platform (drained by the Dnieper and Don Rivers), the Great Caucasus (drained by the Kuban and smaller rivers), and Northern Turkey (drained by numerous smaller rivers) (Fig 1) as well as important records of marine/lacustrine climate. Drilling in the Southern Black Sea during DSDP Leg 42B (Sites 379-381; May-June, 1975) (Fig.2) demonstrated that Pleistocene climate alternated between forest and steppe (based primarily on analysis of pollen and spores) and documented changes in Black Sea fauna and flora related to past lake climate and chemistry. However, while paleoclimate records could be reasonably well correlated between sites, an absolute stratigraphy has not been developed for these sections (Ross, Neprochnov *et al.*, 1978; Collective, 1980). Also, the terrestrial paleoclimatic records obtained were not specific to any particular drainage region because the drill sites were located in the central and southern parts of the basin.

While Leg 42B did not result in a definitive paleoclimate record, a high-resolution continental climatic documentation of long duration in the Black Sea region (including Central Europe and the Russian Platform) remains of great interest because this area was not directly affected by the large continental glaciers in Fennoscandia or the Alpine-Carpathian region, and at the same time was very dependent on the melt waters of these glaciers. Continental climate here is moderated by the North Atlantic circulation and the Gulf Stream. Therefore, the record from this region is likely to be different from the pollen, diatom, and other records being studied in Lake Baikal in Siberia which is much more removed from oceanic effects (Lake Baikal Paleoclimate

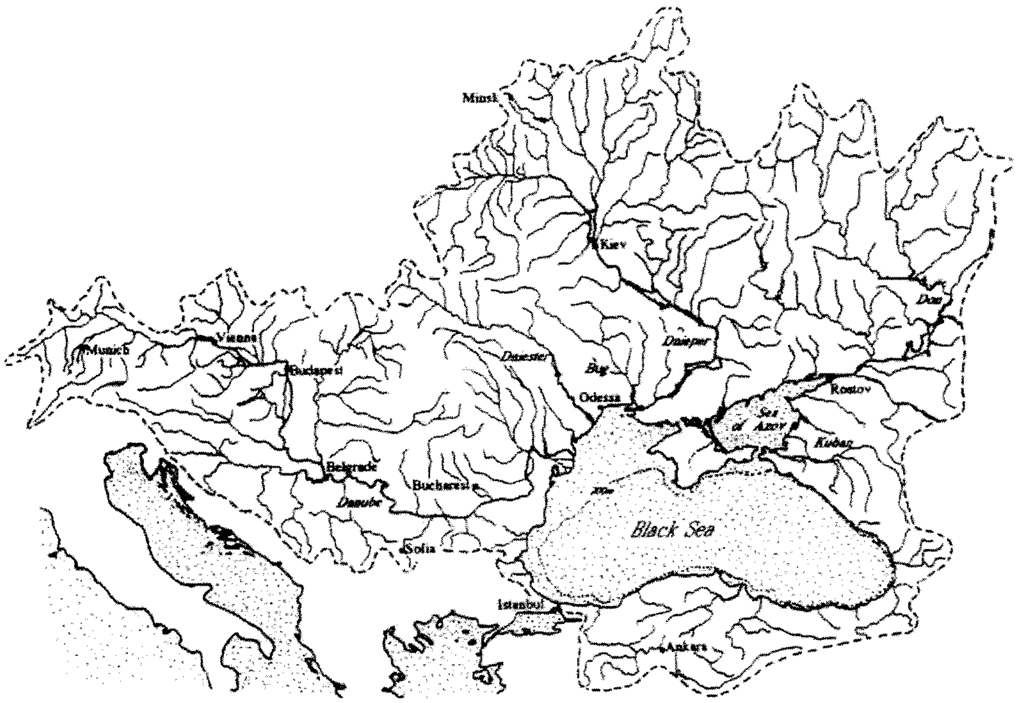

Fig. 1. The Black Sea drainage basin.

Project Members, 1992; Coleman *et al.*, 1995). A high-resolution continental climatic record from the Black Sea would thus complement studies underway in Lake Baikal and in the Mediterranean Sea as well as in other continental and marine settings including the nearby Caspian Sea.

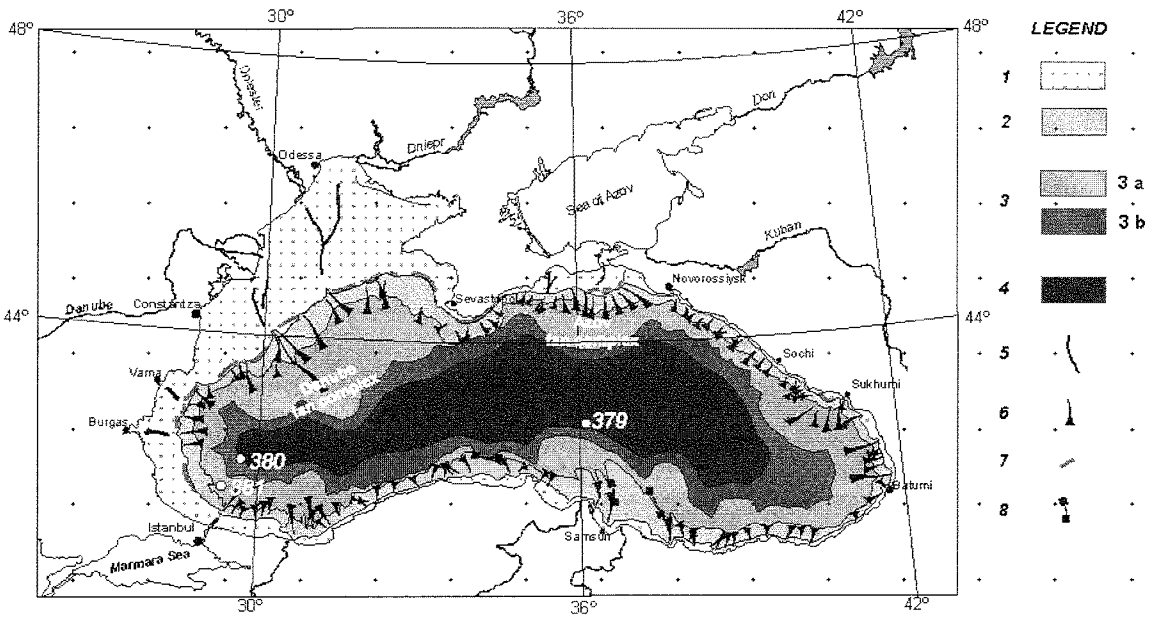

Fig. 2. Geomorphologic zonation of the Black Sea (after Panin & E. and G. Ion, 1997). The locations of drillings of DSDP Leg 42B are shown.
Legend; **1**, continental shelf; **2**, continental slope; **3**, basin apron: **3 a** - deep sea fan complexes; **3 b** - lower apron; **4**, deep sea (abyssal) plain; **5**, paleo-channels on the continental shelf filled up with Holocene and recent fine grained sediments; **6**, main submarine valleys - canyons; **7**, paleo-cliffs near the shelf break; **8**, fracture zones expressed in the bottom morphology.

The probability of obtaining a well-dated, high-resolution climatic record from the Black Sea has increased considerably since 1975 because of (1) improved core recovery and analysis capability on the drill ship, (2) improved understanding of sea-level fluctuations, sedimentary processes and geochemical characteristics of Black Sea sediments, (3) improved understanding of how to exploit large, muddy fans to determine high-resolution paleo-environmental records, (4) improved high-resolution paleomagnetic stratigraphy for the late Brunhes (developed in part in the Mediterranean Sea and Lake Baikal), and (5) improved political climate that should allow access to the Northern Black Sea, a region not visited during Leg 42B. All of these factors suggest that a return of scientific drilling to the Black Sea now will yield the high-resolution climate records promised for Leg 42B.

Sedimentary sequences in the Black Sea are strongly affected by sea level changes driven by global glaciation and deglaciation. The level of the Black Sea followed only to a certain extent the eustatic changes. It has long been recognised that the Black Sea was isolated from the Mediterranean Sea during glacial intervals when the levels of the Black Sea and the Mediterranean dropped far below the level of the Bosphorus sill (*e.g.*, during the last glacial, about 20-18 ka BP, the level of the Black Sea dropped to -130 to -150 m). Once separated from the Mediterranean basin, the level of the Black Sea fluctuated according to the regional climate and water supply independently of changes in the global oceans.

The postglacial warming and melting of ice caps which started 15 ka BP resulted in a general rise of sea level. For the variation of the Black Sea level during this period of time there are, at the present, different hypothesis, which are taking into account the regional independent behavior mentioned above. The mains of them are the following:

(1) It has been postulated that the supply of water towards the Black Sea from glaciers covering the Russian Platform and the Carpathian Mountains was extremely high, and around approximately 12 ka BP, the water level rose beyond the Bosphorus sill much more rapidly than in the Mediterranean basin. A large flux of fresh water flowed through the Bosphorus-Dardanelles towards the Aegean Sea. When the Mediterranean and the Black Sea reached the same level (close to the present day level) some 7.5 ka BP, a two-way water exchange was established and the process of transformation of the Black Sea into an anoxic brackish water body started. This hypothesis is supported by scientists from riparian countries (since seventies), Stanley and Blanpied (1980) and recently by Aksu *et al.*, (1999).

(2) On the other hand, Ryan *et al.* (1997) proposed a new hypothesis on changes in the level of the Black Sea in the upper Pleistocene-Holocene. They suggested that beginning at about 12 ka BP, retreat of the ice front on the Russian Platform redirected for a limited period of time melt water towards the North Sea. In this way, after an episode when fresh Pontic water flowed towards the Aegean Sea, the Black Sea, deprived of this melt water during the younger Dryas (~11 ka BP) up to 9 ka BP, and under the influence of an arid and windy climate, experienced a new sea level fall (down to -156 m). At the same time, the Mediterranean continued to rise, reaching by 7.5 ka BP the level of the Bosphorus sill, thereby generating a massive input of salt water into the Black Sea basin. Ryan *et al.* (1997) suggested that the water flux was several hundred times greater than the largest waterfall known and caused a rise of the level of the Black Sea by tens of cm per day (up to 30-60 cm), filling up the basin in a very short time (within a one to two year period).

Understanding the influence of this rapidly varying local sea level on the stratigraphic record of the Black Sea may provide important clues to the effect of local tectonics and climatic factors on stratigraphic sequences in a tectonically active area.

Analysis of sediments recovered during recent drilling on the Amazon Fan (ODP Leg 155) suggests that high-resolution continental climatic records can be developed from muddy fan deposits where the fan structure is well known (Fig. 3; Haberle, in press; Hoorn, in press; Piperno, in press; Flood, Piper, Klaus *et al.*, 1995; Flood and Piper, in press). During Leg 155, paleomagnetic methods (paleo-intensity, secular variation, and events as well as magnetic susceptibility) were combined with more traditional isotopic and paleontological methods and seismic profiling to develop a stratigraphy for sediments deposited over the past ca. 200 ka and to

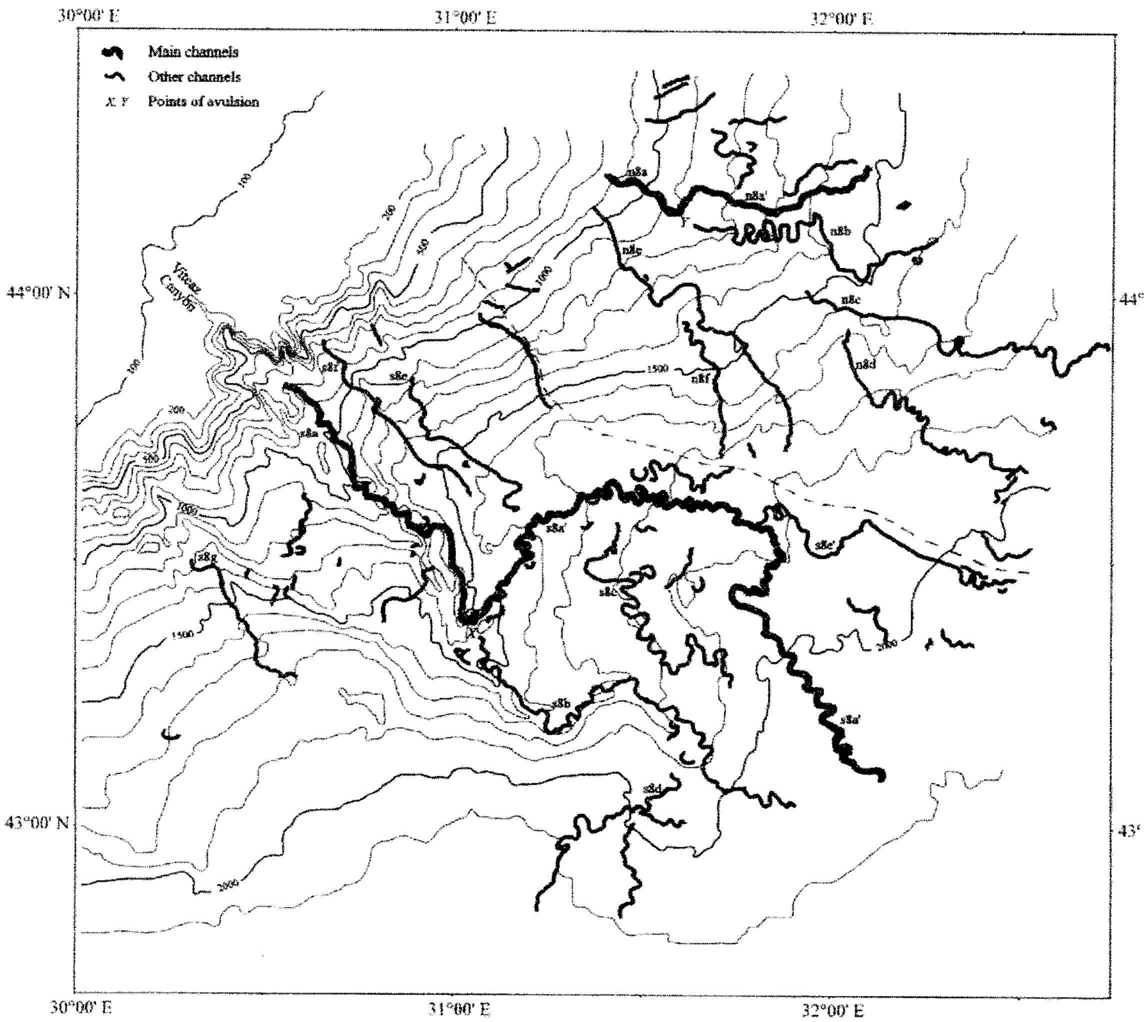

Fig. 3. Danube deep-sea fan complex - bathymetry and localisation of the main channels (after Wong *et al.*, 1997).

correlate between sites. Paleomagnetic techniques prove to be very valuable in understanding an absolute stratigraphy in Lake Baikal, and will also work in the Black Sea. It is noteworthy that routine paleomagnetic measurements were not made during Leg 42B. Routine collection and analysis of paleomagnetic data during future Black Sea drilling operations will significantly enhance the stratigraphic value of the sediment samples.

Of particular interest in the Black Sea are the recent detailed investigations off the Danube and Dniepr Rivers (Collective, 1985; Wong *et al.*, 1994, 1997; Lericolais *et al.*, 1998, Shimkus *et al.*, 1994; Shimkus *et al.*, in press, and unpublished data) where high-resolution "Chirp" and seismic profiles, long-range side-scan data and swath bathymetry have identified two distinct but interfingering deep-sea fans: one related to the Danube River and the other to the Dniepr River (Figs. 3, 4). Drilling in the Danube Fan will recover sediments (and pollen) that originated in Central Europe while drilling in the Dniepr Fan will recover sediments (and pollen) that originated on the Russian Platform (Shimkus *et al.*, 1977, 1979; Komarov, 1986; Wong *et al.*, 1997). The sediment records will also provide information on the time-varying sediment flux to the Black Sea and its dependence on sea level change and climate. To accomplish these goals, sites must be carefully chosen based on high-resolution seismic data so that all seismic units necessary to reconstruct this composite record can be sampled. During the joint French-Romanian survey of 1998 carried out on board the French R/V *Le Suroît*, evidence for an earlier lowering of the level of the Black Sea was found. This evidence consists of very deep incisions (up to -800 m bsf) of the Dniepr and the Danube into the continental shelf, probably during the Messinian

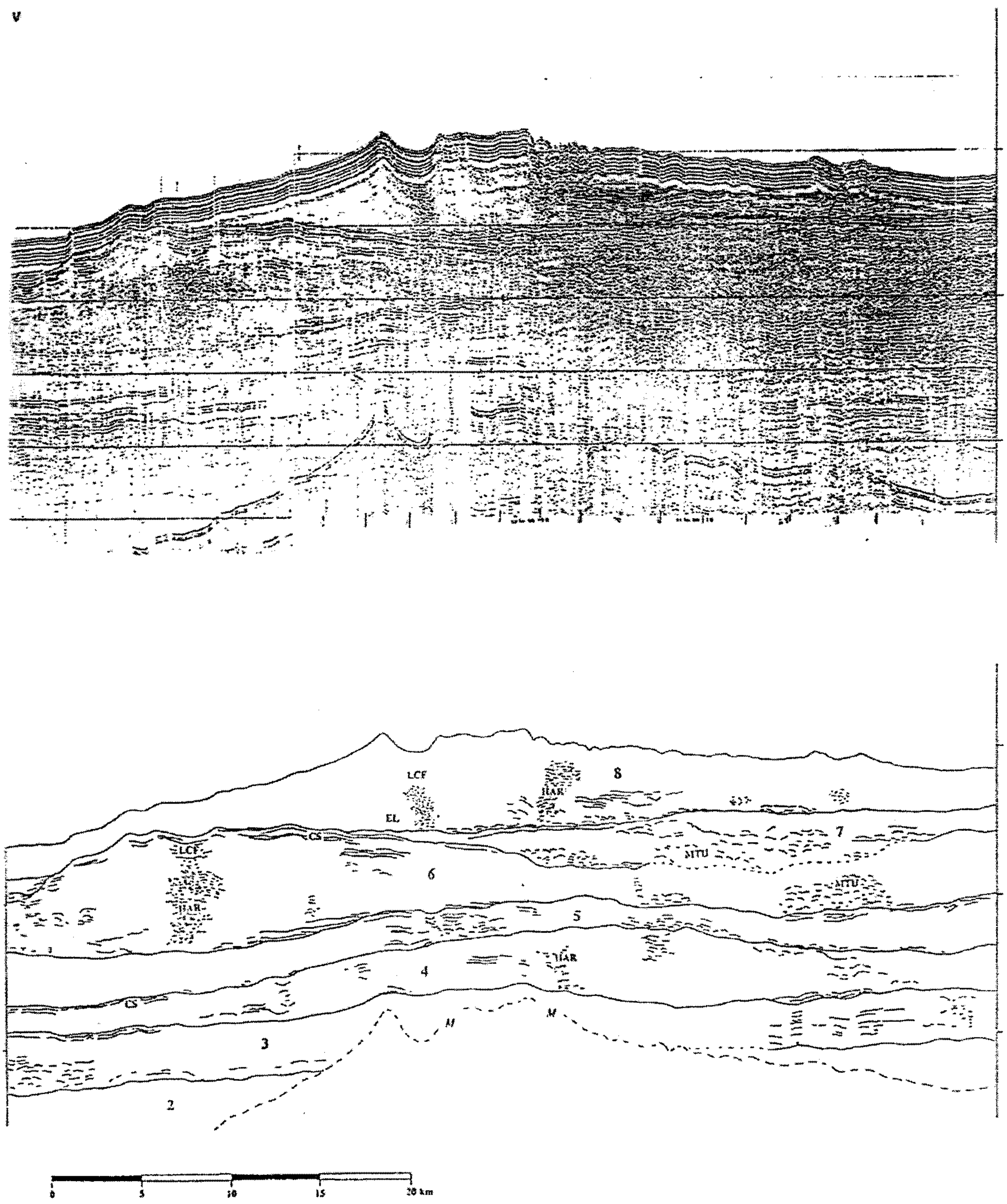

Fig. 4. Air gun profile (No.1293) across the deep-sea Danube Fan Complex (after Wong *et al.*, 1994) **HAR** = high amplitude reflectors, **LCF** - late channel fill, **L** = levee, **MTU** = mass transport unit, **CS** = condensed section, **1. . . 8** = sequence numbers, M - multiple.

crisis, which has hitherto not been clearly documented for the Black Sea. Two or three younger incisions nest inside these deep channels, the youngest (formed probably during the last glacial) being about 120 m deep. Sampling and dating the sediments inside and outside these incisions will clarify the sequence of events described.

The Black Sea, being the type anoxic basin, has been the site of a number of geochemical investigations focused primarily on the carbon cycle. The results of several major expeditions to the Black Sea (in addition to DSDP Leg 42B) have been compiled in Degens and Ross (1974), Izdaz and Murray (1991), Murray (1991), Strakhov (1971), Shimkus *et al.* (1975) and Emelyanov *et al.* (1982), including biomarker studies of sediments from both the present-day anoxic and the late-glacial lacustrine environments as well as of the sapropel unit that separates them. These studies provide an important basis for interpreting a longer core record of the Black Sea sediments, both in fan and non-fan settings.

While the Danube/Dniepr fans and the Amazon Fan show definite similarities to one another and to other mud-rich fans (including the existence of large, meandering, levees channels; Figs. 3, 4), they are formed under potentially somewhat different conditions as the Black Sea was a fresh-water lake during most time intervals when the fan complex was active. In fresh-water systems, hyperpycnal flows (flow of turbid river waters directly into a lake and along the lake bottom) are possible under many conditions while hyperpycnal flows occur only rarely in a marine setting (Mulder and Syvitski, 1995). Also, fine-grained sediments transported by river into fresh-water do not flocculate to the same degree as when they are transported by rivers into salty water. This change in sediment input conditions and state of flocculation could lead to differences in the size or frequency of turbidity currents and the resulting turbidite deposits. Understanding these potential differences is important for interpreting paleo-environmental conditions from sediment deposits, especially in tectonic settings where large lake bodies can develop.

Our potential drilling philosophy for the Black Sea is similar to that followed in the Western Equatorial Atlantic (Legs 154 and 155) where sites located on topographic features provide dominantly pelagic records at lower accumulation rates and sites located on fans provide dominantly terrestrial records at higher accumulation rates. Adequate data exist as a result of recent French/Romanian/German/Russian/Ukrainian surveys and other recent work for initial site selection, but additional site-specific data may be needed prior to drilling. A continuation of this common survey in the next two years will collect additional and more detailed "Chirp", seismic and multi-beam bathymetry data on the shelf and the Danube and Dniepr and fans. An initial estimate suggests that 6-8 holes ranging up to 400-600 m bsf from both fan and non-fan regions would be needed to collect the required sediments.

RELEVANCE TO THE LONG RANGE PLAN OF ODP

Black Sea drilling addresses aspects of all three scientific themes developed under dynamics of Earth's environment and under Initiative I (understanding natural climate variability and the causes of rapid climate change). The recovered sediments will provide an important high-resolution continental climatic record covering at least the same glacial and early interglacial time interval as in Lake Baikal and in ice cores (in a region inhabited by early man at the time) and perhaps down to the upper Pliocene and Messinian events. They would also address the causes and effects of local sea level change driven in part by global variations and in part by local tectonics and climate. We will be able to determine the sedimentological response of sea level change that occurs over a range of time scales from very fast (a few years) to much longer. Anoxic basins play an important role in the carbon cycle, and a record of changing carbon preservation and organic diagenesis can be determined here. Also, fluctuating oxygen levels should lead to variations in bacterial communities. This record may be particularly interesting because Leg 155 studies suggest that many bacteria are associated with plant material in turbidite layers.

OPERATIONAL CONSIDERATIONS

The first Letter of Intent was an outgrowth of an international workshop on "Fluvial-Marine Interactions" in Malnas Spa, Romania (October, 1996). The present second letter is the result of a much larger discussion organized by CIESM, the Marine Geology Committee, in the framework of a workshop on "Mediterranean Scientific Drilling Perspectives" (Granada, Spain, June, 1999). The participants plan to broaden the appeal for scientific input to a potential drilling plan within the Mediterranean-Black Sea basins, through linkages to different international organizations and communities and SCORE working groups, through workshops, and through direct discussions. For the Black Sea, the co-operative project involving riparian and other European countries will create a favorable political and scientific climate which will enable possible difficulties due to the lack of internationally recognised marine boundaries between countries around the Black Sea to be overcome more easily (although discussions between coastal countries are underway). We have also discussed with TAMU (Texas Art and Manufacture University) potential physical problems of getting the *Joides Resolution* into the Black Sea. In 1975, the *Glomar Challenger* cleared the one bridge that crossed the Bosphorus then with 2 m to spare. TAMU advises us that the *Joides Resolution* will also fit beneath the two bridges that now exist, although some precautions may be necessary such as transiting at night when the bridge sags less under reduced traffic.

CONCLUSIONS

Continental margins are important repositories of information about the Earth's history. Sediments deposited in this environment, although sometimes difficult to decipher, contain records of sediment flux into the ocean (related in part to sea level changes), ocean circulation, and land and ocean climate. Margin environments are of particular importance because sedimentation rates are usually high (thus allowing for high-resolution records), and they are located where marine and terrestrial records interfinger. Interpreting this record requires a detailed understanding of sediment processes and distribution patterns as well as terrestrial and marine climate analogues, including pollen, spores, stable isotopes and biomarkers.

Recent drilling on the Amazon Fan (ODP Leg 155) demonstrates that high-resolution terrestrial and marine records can be obtained from muddy deep-sea fans provided sites are carefully chosen (Flood, Piper, Klaus *et al.*, 1995; Flood and Piper, in press). This approach of obtaining INtegrated Terrestrial and Oceanic records through FAN coring (INTOFAN) can be undertaken on a systematic basis on large fans from many different margins to obtain climate records from several different continental interiors. The Amazon Fan provided a first high-resolution application of this approach.

We propose here a similar approach in the Mediterranean and the Black Sea, and note that the Black Sea continental climate record of the Danube and Dniepr fans will compliment a potential climate record from southwestern Europe proposed for the Rhône Fan as well as the record of continental climate in Central Africa, which could be documented within the Nile Fan.

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Is there a Mediterranean-North Atlantic climate feedback? Testing the hypothesis

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Abstract

The Mediterranean Sea circulation can be regarded as a mini-conveyor type, with water from the Atlantic Ocean flowing in and Mediterranean water flowing out at depth. The balance between inflow and outflow is controlled by the basin's heat and salt budgets. These are mainly set by the properties of the North Atlantic climate and water mass flowing in. However, there is also a possibility that the outflow water, by playing a role in the oceanography and climate of the North Atlantic, can give a feedback to these budgets. Yet, whether and how the Mediterranean system, oceanography and climate, is coupled to both the North Atlantic and the global system is unknown. Progress in this area, demands therefore new drilling in the Western Mediterranean. Specifically at two sites: beneath the path of Atlantic Water skirting the North Africa and the Gulf of Lyons. The results are crucial to develop models of climate change patterns affecting Europe and the Mediterranean.

Specific Objective: Provide answers to the key question: whether there is a feedback between the Mediterranean and North Atlantic systems. This question is addressed by land-sea correlation after proxy records from sea surface temperature, sea surface and deep-sea productivity, continental temperature and rainfall. From analysing the proxy records, the phase relationships (leads and lags) between conspicuous climate events traceable in both Mediterranean and Atlantic (e.g. Heinrich and Dansgaard-Oeschger cycles) can be obtained.

The Mediterranean is coupled to the Atlantic via the ocean (inflow-outflow regime) and the atmospheric circulation (influencing deep-water production and precipitation). Unraveling the precise nature of this coupling under different climate forcings requires new drilling in the Mediterranean. The sites needed are located at the North Africa Margin and the Gulf of Lyons (Fig. 1).

1 - Scientific relevance and innovative aspects of the drilling proposal

The Mediterranean Sea is a landlocked marginal basin of the Atlantic Ocean connected to the Atlantic by the Strait of Gibraltar. Although the basin itself lies within the domain of the subtropical high-pressure belt, along which aridity prevails, its climate and oceanography are strongly coupled to those in the Atlantic, especially the Western Basin. In fact, the Mediterranean thermohaline circulation works in such a fashion that demands fresher and cooler water from the

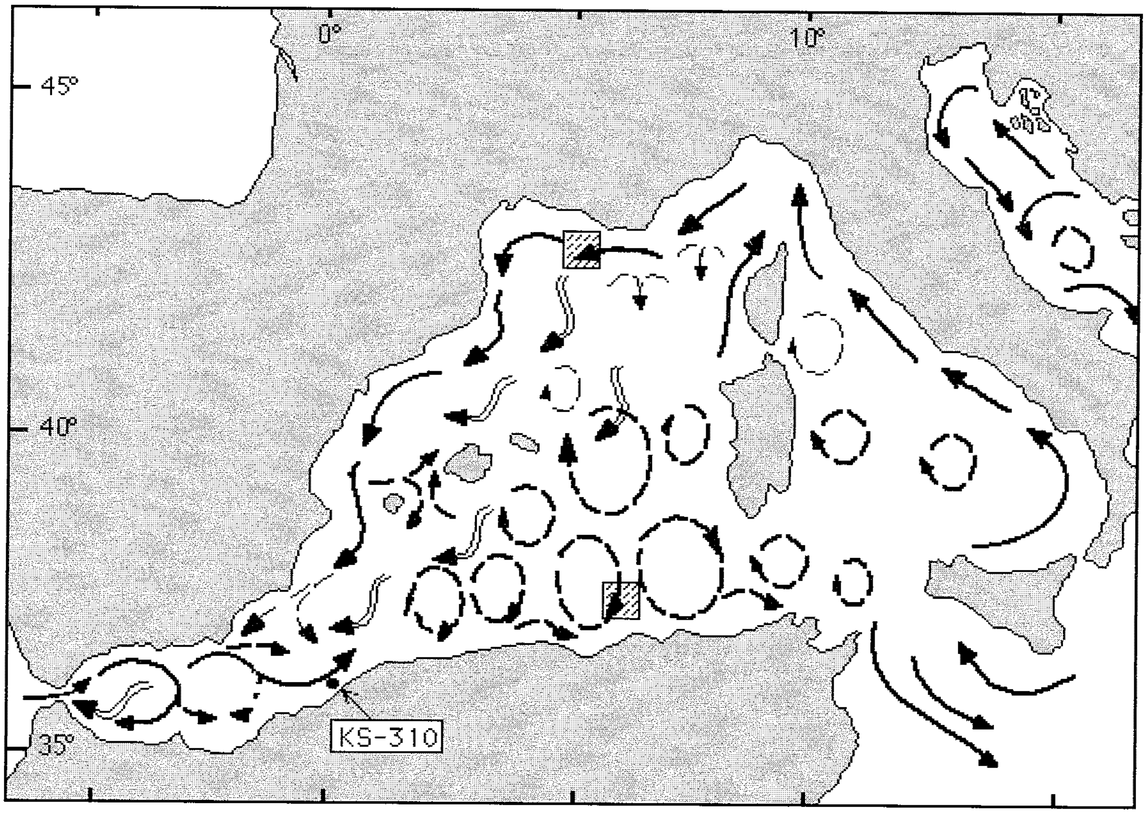

Fig. 1. Map of the Western Mediterranean region showing the surface (solid arrows) and deep circulation (hollow arrows) and the location of the proposed drilling sites. Star indicates site of core KS-310 in Fig. 3.

Atlantic Ocean while giving saline and warm water back at depth. A share of this Mediterranean Outflow Water (MOW) travels then to the northern North Atlantic. There, it contributes to the forming of North Atlantic Deep Water (NADW) and therewith to the North Atlantic thermohaline circulation. This circulation is regarded as a conveyor belt, drawing heat and salt from the North Atlantic to the North Pacific (Broecker 1995). On the other hand, forming NADW implies the release of large amounts of heat into the atmosphere. By driving cyclogenesis, this heat sets motion to the North Atlantic depression system and storm tracks (Fig. 2). Thus, the North Atlantic is regarded as one of the major components of the world climate system.

Properties of the Atlantic water inflow and the mean position of the Atlantic storm tracks are both key factors in setting the heat and salt budgets of the Mediterranean Sea. On the one hand, salinity and temperature of the Atlantic inflow are slowly modified by the regional climate along the path of inflow. While, polar wind outbreaks in the Gulf of Lyons, related to North Atlantic cyclones entering the Mediterranean, lead to extensive water-cooling and to the steering of the regional cyclonic gyre. Water from intermediate depths wells up and mixes with surface water, forming deep water that will later outflow over the sill of Gibraltar.

Therefore, MOW properties and volume have the potential to influence the North Atlantic thermohaline circulation and climate (Johnson 1997). However, the North Atlantic atmospheric system has the possibility to give a feedback by influencing the deep-water production in the Gulf of Lyons, and the Mediterranean climate. Investigating these feedbacks will provide insight not only on the coupling between the Mediterranean Sea and North Atlantic Ocean systems, but also how different components of the global climate may interact with each other.

1.1 Testing the hypothesis: investigating coeval abrupt climate changes

Testing the "feedback hypothesis" can only be done by investigating at a high resolution the leads and lags in rapid climatic and oceanographic changes that can be traced in both the North Atlantic and the Mediterranean. Such scenarios are found during the last glacial period, when the Northern Hemisphere ice sheet collapsed several times. ,Consequently, large amounts of icebergs

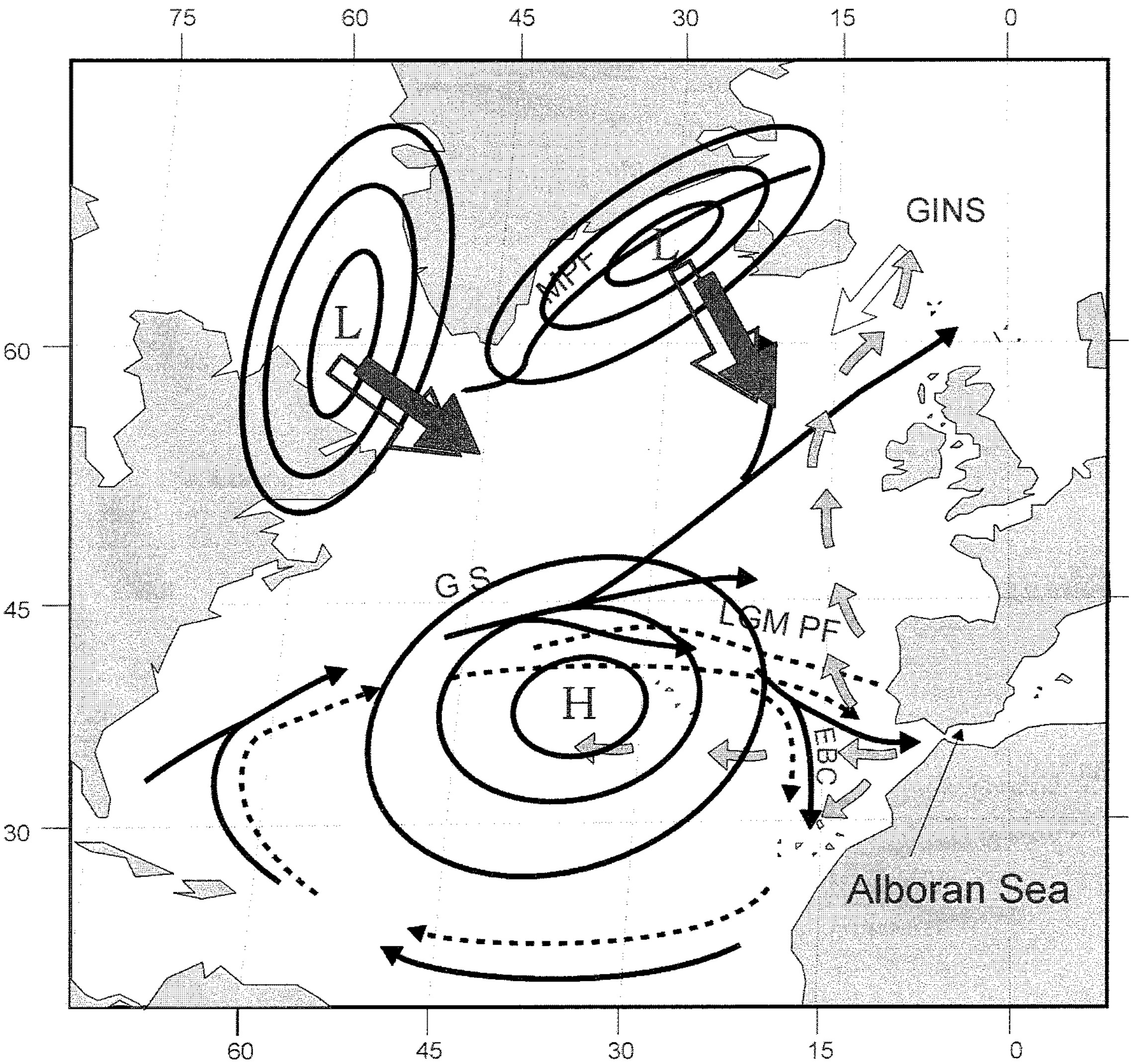

Fig. 2. Map illustrating the relationships between the North Atlantic circulation, the ciclogenesis, and the formation of deep water.

were released into the Northern North Atlantic in episodes known as Heinrich events (Heinrich 1988; Broecker *et al.* 1992). A suite of six events, numbered H1 to H6, has been recognized: 12,010-15,820 (H1), 20,023 (H2), 28,686 (H3), 33,110-36,060 (H4), 52,000 (H5), and 67,077 yr. BP (H6) (Grousset *et al.*, 1993; Lebreiro *et al.*, 1996). Melting of these icebergs reduced surface salinity and temperatures of the northern North Atlantic, and thus influenced the formation of deep water and northward heat export by the ocean. Paleoclimatic proxy records from Greenland, Arabian Sea, North America, Antarctica, are now showing clear evidence that Heinrich events had a global impact on the climate (Bond *et al.*, 1993; Broecker, 1994; Clark and Bartlein, 1995). Yet, the largest impact is expected on the climate of regions downwind the North Atlantic, NW Europe, Mediterranean borderlands, and NW Africa.

Evidence is now emerging that indeed the Mediterranean terrestrial and marine ecosystems were severely affected. For instance, peaks of sub-arctic dinoflagellate and foraminifera species are found in the Alboran Sea and Gulf of Lyons at times of Heinrich events (Targarona 1997, Rohling *et al.*, 1998, Cacho *et al.* submitted). In a colder North Atlantic, the region of deep-water formation shifts southwards and with it the region of cyclogenesis, at present between Iceland and Greenland. With the shift, more depressions are expected to enter the Mediterranean. In such scenario, a higher frequency of polar air outbreaks would increase formation of deep-water in the Gulf of Lyons. Climate change is however more difficult to document. Mainly, because long high-resolution pollen records are virtually lacking. However, pollen records over NW Europe reveal severe aridity during a time interval that might be correlated with H1 (Van Campo, 1984). This idea is further supported by a palynological study of core KS-310 (Fig. 3). The diagram shows that low sea surface temperatures at the time of H1 are related to aridity in the continent. Furthermore, this conclusion is consistent with observations that low SST over the North Atlantic are concurrent with the summer aridity in the tropics and winter aridity in temperate latitudes such as the Mediterranean (Street-Perrot and Perrot, 1990).

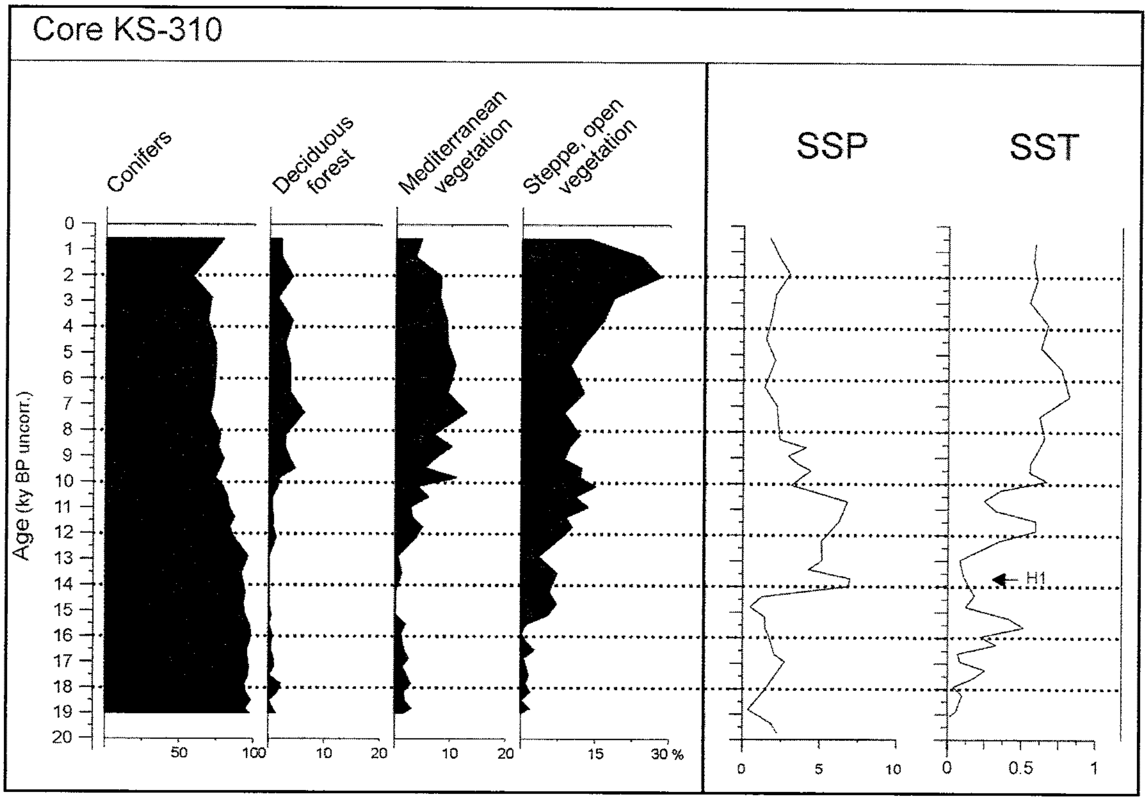

Figure 3. Land-Sea correlation of events over the last glacial-Interglacial trasition in core KS-310 from combining dinoflagellate cyst (sea surface temperature and productivity) and pollen records. Note the increase in steppe during H1, together with low percentages of Mediterranean vegetation requiring warm winters and lack of deciduous forest which demands summer rainfall.

Finally, the significance of investigating Heinrich events is that they provide boundary conditions for a singular scenario. A climate change induced in the Mediterranean by an extreme lowering of sea surface temperature and salinity over the northern North Atlantic. In addition, because of their influence over such vast areas, the study of Heinrich time-intervals can provide insight on how different components of the global climate interact with each other. A knowledge, which is crucial to build a predictive capability into climate models.

2 - Methodology

To investigate leads and lags in the climate and oceanographic change induced by Heinrich events we aim at a first-order land-sea correlation. This correlation will be achieved in a multidisciplinary framework. Within this framework, several proxy records will be integrated. The parameters and the proxies used and aimed at describing the marine and terrestrial environments are the following: sea surface temperature ($\delta^{18}O$, U^{K}_{37}, MAT (foraminifera and dinoflagellate cysts), salinity ($\delta^{18}O$, chroman ratio CR), oxygenation (benthic foraminifera oxygen index, $\delta^{13}C$ epibenthic forams, sedimentary oxi-hydroxides (Fe, Mn), bottom flow rate (clay minerals: Kaolinite/Chlorite), nutrient utilisation ($\delta^{15}N$), biological production (TOC, alkenone and dinosterol concentrations, barite, accumulation rates of infaunal benthic foraminifera, % of $CaCO_3$, opal accumulation rates), terrestrial climate (pollen), runoff (lignin, pollen from aquatic freshwater plants).

3 - Drilling needs

Testing the research hypotheses requires a minimum of two drilling sites in the Western Mediterranean Basin. To monitor changes in the properties of the Atlantic Water inflow, a core should be drilled in the North African margin. While, in order to monitor changes in deep water production a second drilling site should be the Gulf of Lyons. These positions were not covered during the last ODP Leg in the Mediterranean, although they are crucial to have a complete picture of the Mediterranean Sea paleoceanography.

The proxy records obtained in the cores, can be correlated with those from ODP sites in the Alboran Sea and North Atlantic. Such correlation will enable to portray a complete picture of the coupling between the Mediterranean and Atlantic Ocean.

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The Atlantic-Mediterranean gateway

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Abstract

Since the Messinian "salinity crisis" was postulated more than two decades ago a great number of researchers have speculated on the events which led to the isolation of the Mediterranean Sea from the world's oceans and the possible effect on global hydrography and climate (Benson *et al.*, 1991; Bryden *et al.*, 1991). In spite of the fact that the origin of the Messinian evaporite deposits in the Mediterranean had provoked discussion and controversy until recently, the model of a deep-basin desiccation has gained more acceptance due to widespread evidence of the deep basins, subaerial erosion, brackish water deposits deeply buried at present and the lack of evidence for a 2 to 3 km widespread subsidence (Hsü *et al.*, 1977; Got *et al.*, 1985; Campillo *et al.*, 1992; Maldonado *et al.*, 1992). As a result a major effort has been made during the last few years to identify the location of the main gateways between the Atlantic/Mediterranean and the dynamics of these connections (Maldonado, 1992; Maldonado and Nelson, 1999a; Nelson and Maldonado, 1999). In this respect the study of the Gulf of Cadiz and the Alboran Sea is significant precisely because all possible connections have been located in that region (Maldonado *et al.*, 1992, 1999).

At present the Mediterranean/Atlantic water exchange is regulated by the Strait of Gibraltar, which imposes a low heat exchange by marine advection with the open ocean (Nelson *et al.*, 1993, 1999; Johson, 1997). The complex bottom relief of this strait, containing a western shallow sill and deep basins in the eastern and central sectors, imposes an internal hydraulic control at various points modifying the pycnocline depth and the over-mixing of Mediterranean/Atlantic waters (Figs. 1, 2). The excess of evaporation in the Mediterranean, the geometry of the thresholds and the characteristics of the Atlantic waters are the main driving mechanisms governing the water exchange, which is probably one of the most significant factors in the control of the Mediterranean Sea's present evolution. In addition, it has been proposed that the deep Mediterranean outflow influences circulation in the Atlantic, including the formation of the North Atlantic Deep Water and, in consequence, world climate as a whole (Rodero *et al.*, 1999).

The climatic and oceanographic factors have not remained constant through time and hence, contrary to the present anti-estuarine regime in the Mediterranean, hypotheses of estuarine type circulation and current reversals at several time periods from the Miocene to the present day have been suggested and debated (Thunell and Willians, 1989). The closing of the marine Betic and Rif corridors between Iberia and Africa at the end of the Miocene, which initiates the temporal desiccation of the Mediterranean represents only one of these events, although its consequences are certainly very spectacular (Hsü *et al.*, 1977; Beson *et al.*, 1991).

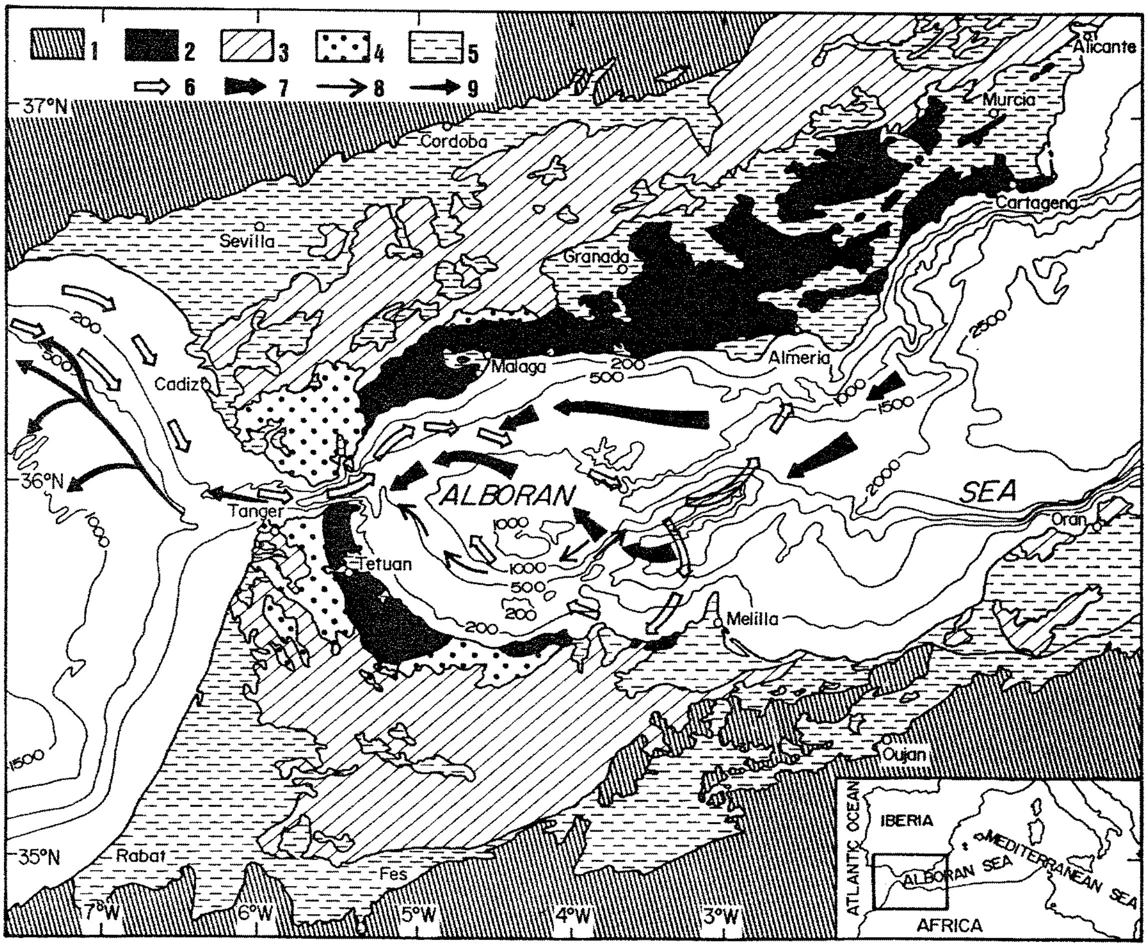

Fig. 1. Location chart of the Alboran Sea / Gulf of Cadiz region. The Iberian and African foreland **(1)** and the Alboran domain **(2)**, represent the emerged areas during most of the Miocene time. The South Iberian and Magribian domain **(3)** and the Tertiary flysch units **(4)** are also indicated. Late Neogene marine basins in the Betic and Rif cordilleras, where the pre-Messinian connections between the Mediterranean and Atlactic Ocean could be located are depicted by a dashed pattern **(5)**. Open arrows indicate the present surficial inflow of Atlantic water into the Alboran Sea. Solid black large arrows show the pathways of intermedian Mediterranean outflow water in the Alboran Sea. Short black arrows indicate the paths of deep Mediterranean outflow waters. Dendritic black arrows in the Gulf of Cadiz, depict the distribution of Mediterranean outflow water

The recent human cultural changes in the Mediterranean area may significantly increase the Mediterranean outflow volume to influence the sedimentary regime of the Cadiz margin. Most important, increased outflow may modify the global climate. Recent studies of climatic conditions and inferred oceanic circulation changes suggest that decreases in Milankovitch insolation can weaken African monsoons and decrease Nile River discharge (Johnson, 1997). Reduced freshwater discharge increases Mediterranean salinity and consequently, Mediterranean outflow volume. Increased outflow in turn may have the potential to modify North Atlantic water circulation and to trigger growth of the Canadian ice-sheet. If this hypothesis is correct, then man has the potential to cause new ice ages because damming of all major rivers during the past 50 years has reduced input of river water to the Mediterranean Sea to as little as 3% of normal Holocene amounts (Nelson, 1990).

Significantly reduced inflow, coupled with secondary effects of global warming that increase evaporation rates, further increase the generation of Mediterranean outflow water. The significantly reduced freshwater input to the Mediterranean already is a reality (Got *et al.*, 1985; Stanley, 1988; Palanques *et al.*, 1990; Nelson, 1990; Maldonado and Nelson, 1999b) and evaporation also is increasing as the sea surface temperatures rise because of the CO2 increase in the

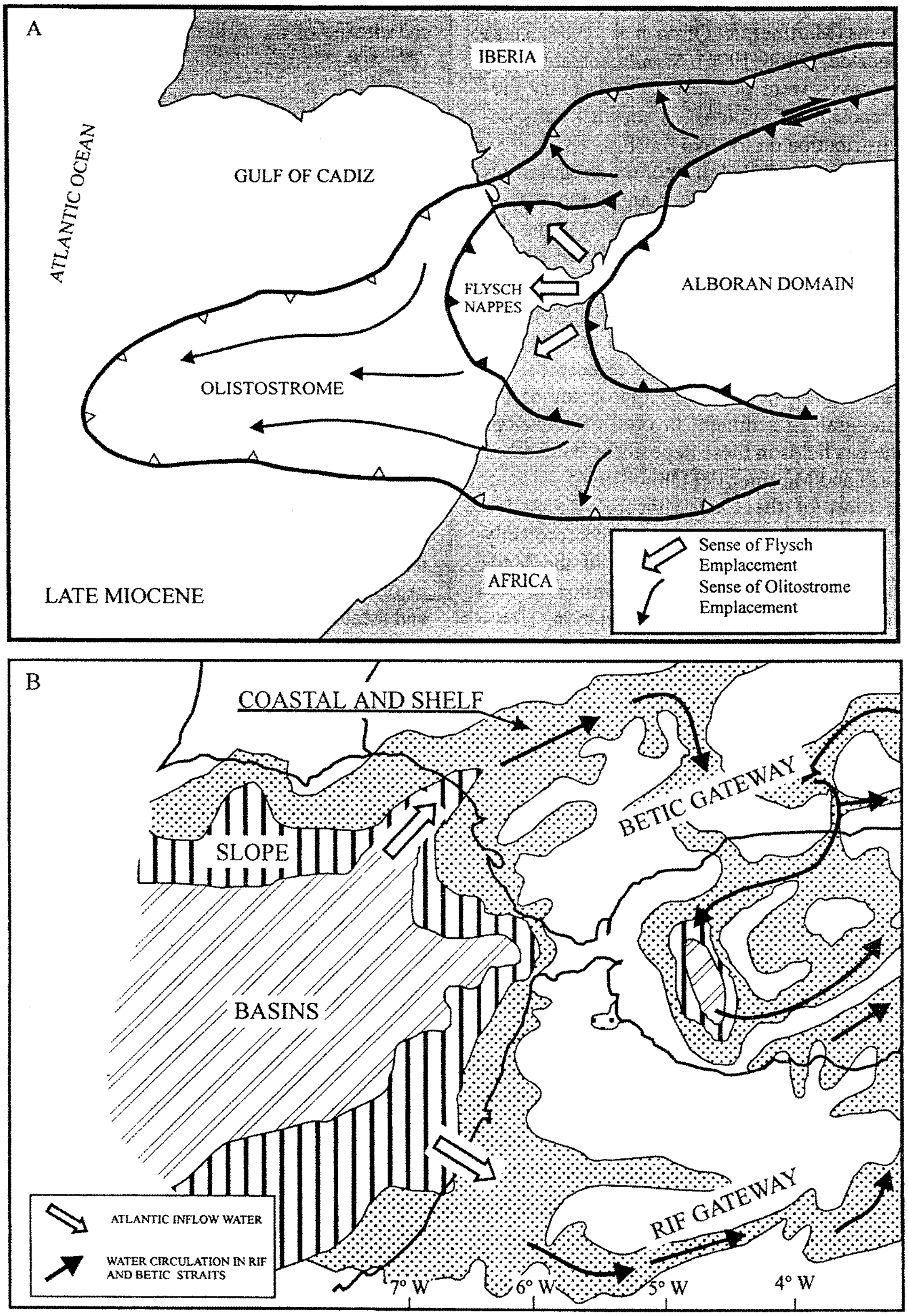

Fig. 2A. Simplified tectonic sketch of the Gulf of Cadiz and surrounding areas during the late Miocene. Open triangle, olistostrome front; Bold triangle; Alboran Domain and Gibraltar Arc flysch nappes thrust fronts. Modified from Sanz de Galdeano (1990) and Maldonado *et al.* (this issue).

Fig. 2B. Simplified palaeogeographic sketch of the Gulf of Cadiz and surrounding domains during the late Miocene showing the distribution of depositional environments and the current patterns. The southern Iberian gateways were located along the Betic, whereas the northern African gateways were located along the Rif.

atmosphere resulting from the activities of humans. Although these facts are known, this hypothesis that increased Mediterranean outflow may trigger development of North American ice sheets (Johnson, 1997) is only one of many hypothesis concerning the complex problem of global climate change. At a minimum, the detailed link of past Mediterranean outflow history to climate change needs to be investigated to evaluate the potential effect of the continuing significant increase of Mediterranean outflow during the past few decades.

New reflection profiles of the Gulf of Cadiz and Alboran Sea collected during the last few years clearly show several stratigraphic sections where deep drilling will be necessary in order to answer these fundamental questions that range in age from paleoclimatic changes of the betic gateway to present day potential anthropogenic effects. The paleoceanographic evolution of these gateways and, in consequence, of the world oceans could be precisely addressed by this drilling.

ODP drilling studies are mandatory to confirm the link between the Mediterranean outflow and glacial epochs. Within the Gulf of Cadiz contourite-drift deposits, it is necessary to examine detailed lithologic and microfaunal assemblages related to climatic variation and Mediterranean outflow fluctuations (Faugeres *et al.*,1985; Nelson *et al.*, 1993, 1999; Sierro *et al.*, 1999). New studies of foraminiferal assemblages show that there are micro-palentological techniques to correlate deposition of individual contourite sand beds with maximum glacial melt episodes during the Holocene transgression of sea level (Sierro *et al.*,1999). These techniques can be applied to ODP drill cores taken in sediment drift sequences of Betic and Gibraltar Gateway paleoceanographic systems. Lithologies of contourite drifts, turbidite facies and a variety of seismic systems tracts from the Cadiz margin, based on ODP drill holes, will need to be compared with the near-by and more typically developed facies architecture of the Alboran Sea in order to understand water exchanges between the Atlantic Ocean and the Mediterranean Sea and the closing or opening of the main gateways.

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Detailed studies of a tsunamigenic structure offshore SW Iberia : the chance offered by the tectonic source of the 1755 Lisbon Earthquake, a preliminary ODP proposal

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Abstract

Episodically tsunamis affect the coastlines of several countries, causing hundreds casualties and compelling civil authorities and scientific community to devise effective strategies for mitigating human losses and damages. In SW Iberia, offshore Cabo de S. Vincente, a single, 50 km long, active thrust structure with total dip-slip displacements up to1100 m and decollement surface recognizable down to 10 sec TWT (about 12-15km depth) has been discovered. This tectonic structure is located on a present day active seismic area and is inferred to be the most probable location of the large "1755 Lisbon Earthquake" epicenter. This structure is presently under intense geophysical and geological investigation sponsored by the EC through the project BIGSETS (Big Sources of Earthquake and Tsunami in SW Iberia). The precise localization of a tsunamigenic source in a narrow area could offers straightforward opportunity in the study of tsunami generating mechanisms, propagation and warning. The OPD sites here proposed will be a crucial step to reveal its tectonic history through time and to monitor its present and future activity. We suggest one borehole across the fault plane above and below the discontinuity to measure both the physical properties of the rocks and the *in situ* stress field. This borehole will serve as seismic observatory either to monitor the seismic activity either to extend the seismological data collection at sea, also improving the resolution of tomographic imaging of the Earth's interior. A second borehole is planned to collect the necessary stratigraphic information for the understanding of the deformational history of the structure that could allow a statistical evaluation of the seismic risk potential.

Introduction

One of the most important issues regarding tsunami mitigation and warning is the likelihood of generation of destructive water waves after land recording of a strong earthquake occurring at sea. About 90% of the world's large, shallow earthquakes occur in the circumpacific belt, with an even higher percentage for intermediate and deep earthquakes. Only a few percent of these major earthquake events actually generate tsunami waves (Ward, 1980). Tsunami warning should prevent the effectively few catastrophic events among those earthquakes that potentially may generate a tsunami. Unfortunately tsunami warning is presently still unreliable: only 25% of warning alarms emitted in the Hawaiian area is effectively followed by a tsunami event (Milburn, 1996). This unreliability, producing fatalities, economics losses and a progressive dangerous erosion of credibility in the involved population (Milburn, 1996), is also due to the scarce field knowledge of tsunami phenomena. Presently warning is mostly based on earthquake's energy threshold criteria, being the warning threshold measured by a seismic network located mainly on land, and from an early stage monitoring of sea water disturbance. The study of tsunamigenic source geometrically well constrained and showing well defined structures, like shape, extension, decollement surface position, depth and length, etc. can give a real improvement in the understanding of tsunami generation problem and can be used as a field test laboratory to infer the most critical parameters of a tsunami generator.

As a matter of fact sub-oceanic structure, while probably have little influence on tsunami propagation, could have great influence on tsunami generation. To give a rough idea Ward (1980) suggest that *"the variation in tsunami excitation, solely due to the Earth structure maybe around 20% even in similar Earth models"*.

In Western Europe catastrophic tsunami are relatively rare and they are associated with the seismicity caused by the plate convergence between Europe and Africa.

One of the most catastrophic historical earthquake and tsunami that struck Western Europe was the 11. 1. 1755 Lisbon Earthquake. This earthquake is famous in literature because it was one of the largest episodes ever occurred in Western Europe. It caused about 10,000 casualties, about 1,000 of which attributed exclusively to the tsunami (Baptista *et al.*, 1998a). Recently, the tectonic structure which probably caused the "1755 Lisbon Earthquake" has been imaged (Fig.1) by one deep penetrating multi-channel seismic (MCS) profile collected offshore Cape San Vincente (Zitellini *et al.*, 1999). The location of the structure, in this proposal named "Marquês de Pombal", is consistent with the source area for the 1755 earthquake on the basis of backward tsunami modeling (Baptista *et al.*,1998 a, b). Moreover the structure is well confined and allows to attack the tsunami generation problem with a novel strategy, i.e. trying to measure the sea water perturbation during the earthquake, down to very low magnitudes seismic events.

After this identification the EC Environment and Climate Program 1994-1998, Technologies to Forecast, Prevent and Reduce Natural Risks, funded a two year (1998-1999) project (contract n° ENV4-CT97-0547) called BIGSETS (Big Sources of Earthquake and Tsunami in SW Iberia) to further investigate the structure. The planned strategy of the study was developed in three main aspects: 3D imaging of the fault pattern and of the deep decollement surface that bound the structure. The study and the monitoring of the present day seismicity. The monitoring of the seafloor movements and of the eventually associated sea water perturbation.

These goals were the main objectives of the investigation undertaken on behalf of the EC project BIGSETS to be accomplished through :

1) two week multibeam survey encompassing the whole structure to obtain the sea bottom morphology and the a real extension of the structure and to select the safest sites for a successive OBS deployment;

2) 30 days of high resolution MCS survey to illuminate the fault pattern and to collect sediment's cores to infer the age of the deformation;

3) one week deep penetrating MCS profiling using the single bubble technique coupled with active OBS monitoring and wide angle land based refraction recording to achieve a 3D imaging of the structure and the detailed interval velocity of the strata;

4) three months of continuous passive OBS monitoring and land station recording of the natural seismicity;

5) tide gauges monitoring of seawater perturbation.

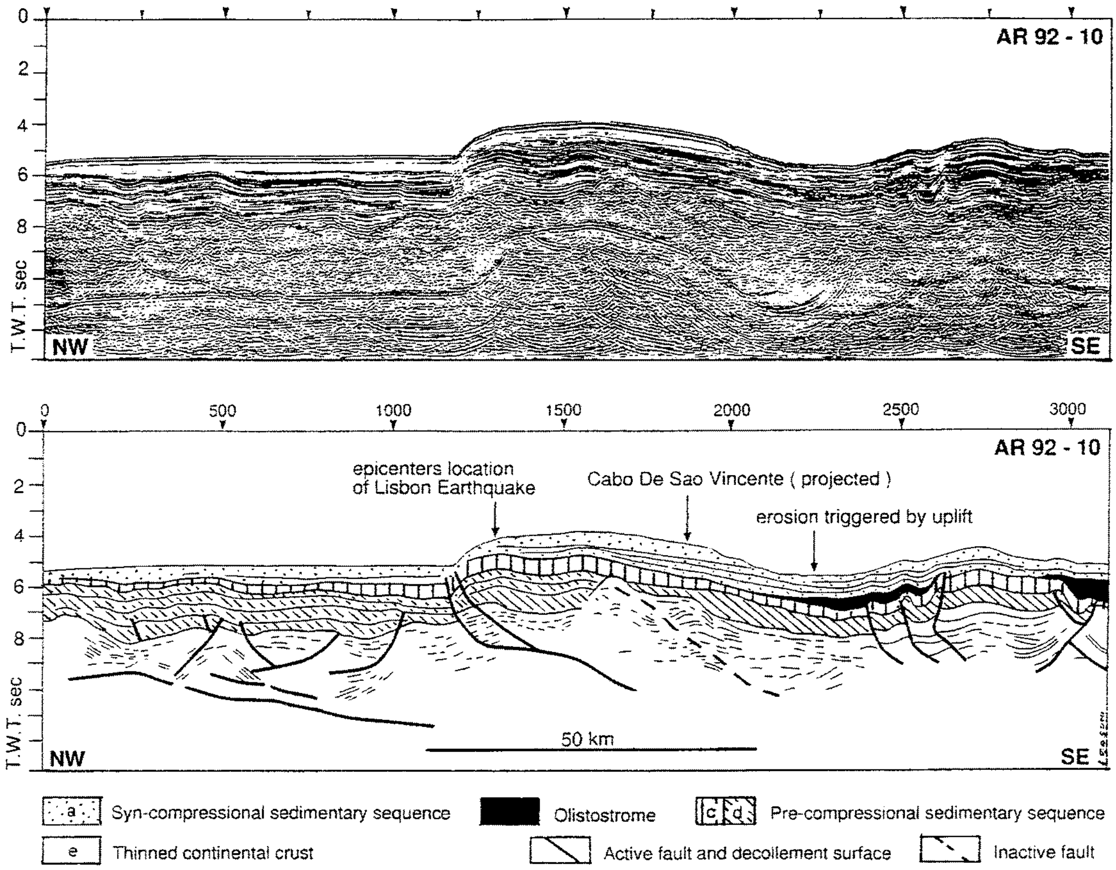

Fig.1. Seismic line Line AR92-10 after post-stack time migration (for location see fig.2). The thrust structure is (SP 1200-2000) associated with clear evidences of an ongoing tectonic deformation (SP 2400-3000) with intense folding, breaking of stratigraphic units and uplift of the seafloor. The deformed area encompasses the whole Line (about 200 km in length) and the thrust structure alone can be followed for more than 50 km. It is worthwhile to stress that in no other of the lines that were shot, such as those reported in Sartori *et al.*, 1994, and Torelli *et al.*, 1997, structures with a similar significant and active displacement of the seabottom have been observed, even in the areas with the highest concentration of instrumentally recorded seafloor seismicity.

From Oct. 31 to Dec. 9 1998 the high resolution MCS and sampling survey (Fig. 2) was performed with the collection of 2,700 Km of seismic lines and 6 gravity cores. We have just finished the preliminary MCS processing of the whole data set down to the Kirchhoff time migration obtaining well-detailed seismic images of the tectonic structure (Fig. 3).

Geology of the area

The complexity of plate tectonics in this area is shown by the present day diffuse pattern of seismicity. Moreover the historical seismicity shows that tsunamigenic earthquakes of large magnitude, such as the "1755 Lisbon Earthquake" (M>8.5), occurred in the recent past.

The "Marquês de Pombal" structure is at least 3000 Km^2 wide, it strikes N15E and shows vertical separation of more than 1 Km. This structure was imaged by nine MCS lines (Fig. 2) among which Line AR 92-10 (Fig. 1) is the one showing the deeper structural information.

The scarce vertical resolution (about 30 m) of the AR92-10line does not allow to recognize fresh ruptures and deformations of the most recent sediment layers in front of the thrust faults (SP 1200), as it would be the case if the fault were active in historical times. The new MCS survey complemented with subbottom profiling enhanced the vertical resolution up to 3-5 meters and few centimeters. One of the cores, acquired in the place where the fault plane outcrops at sea bottom, shows clear evidence of high-angle compressive shear, even if at this stage we cannot

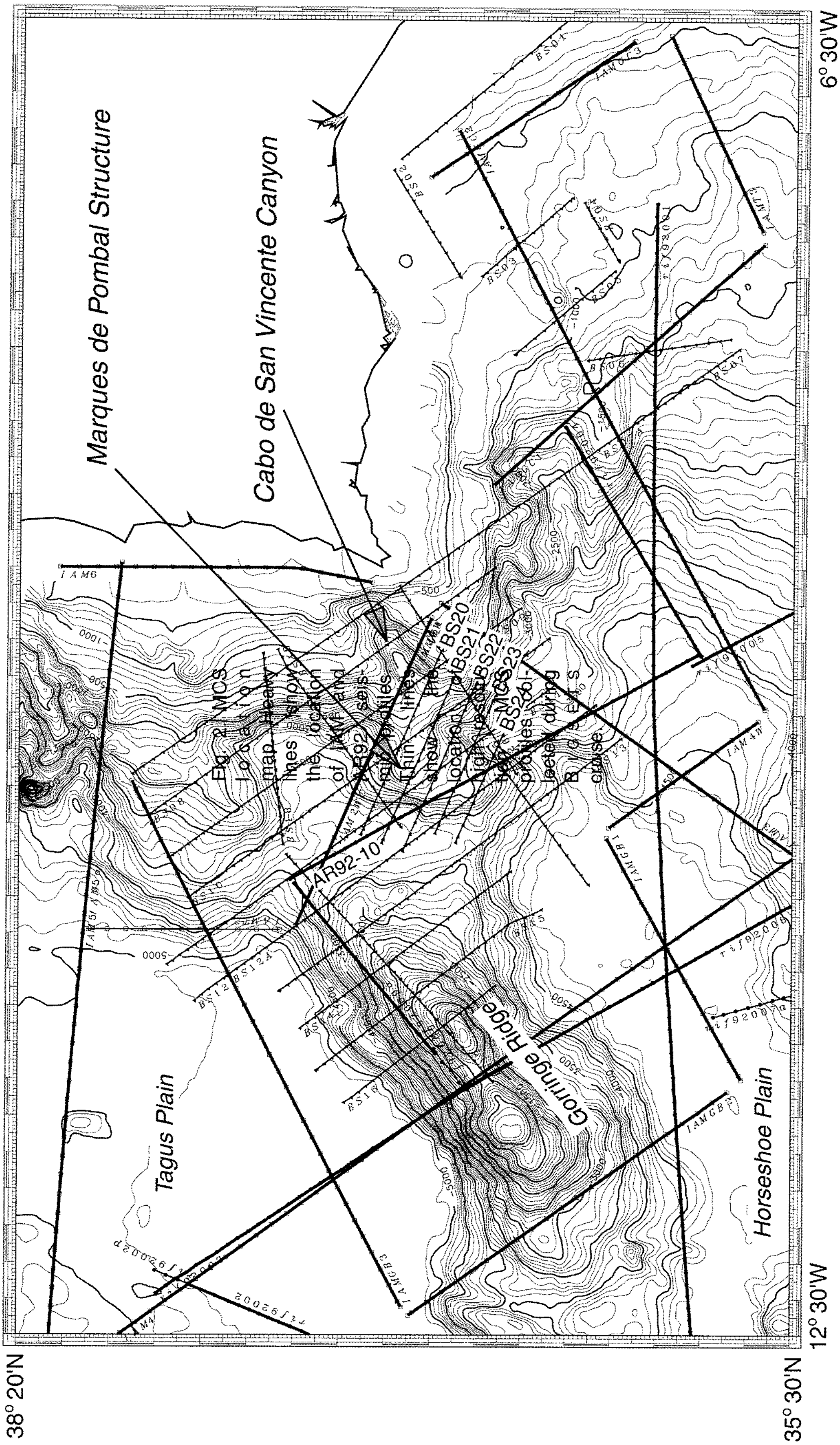

Fig. 2. MCS location map. Heavy lines show the location of IAM and AR92 seismic profiles. Thin lines show the location of high resolution MCS profiles collected during BIGSETS cruise.

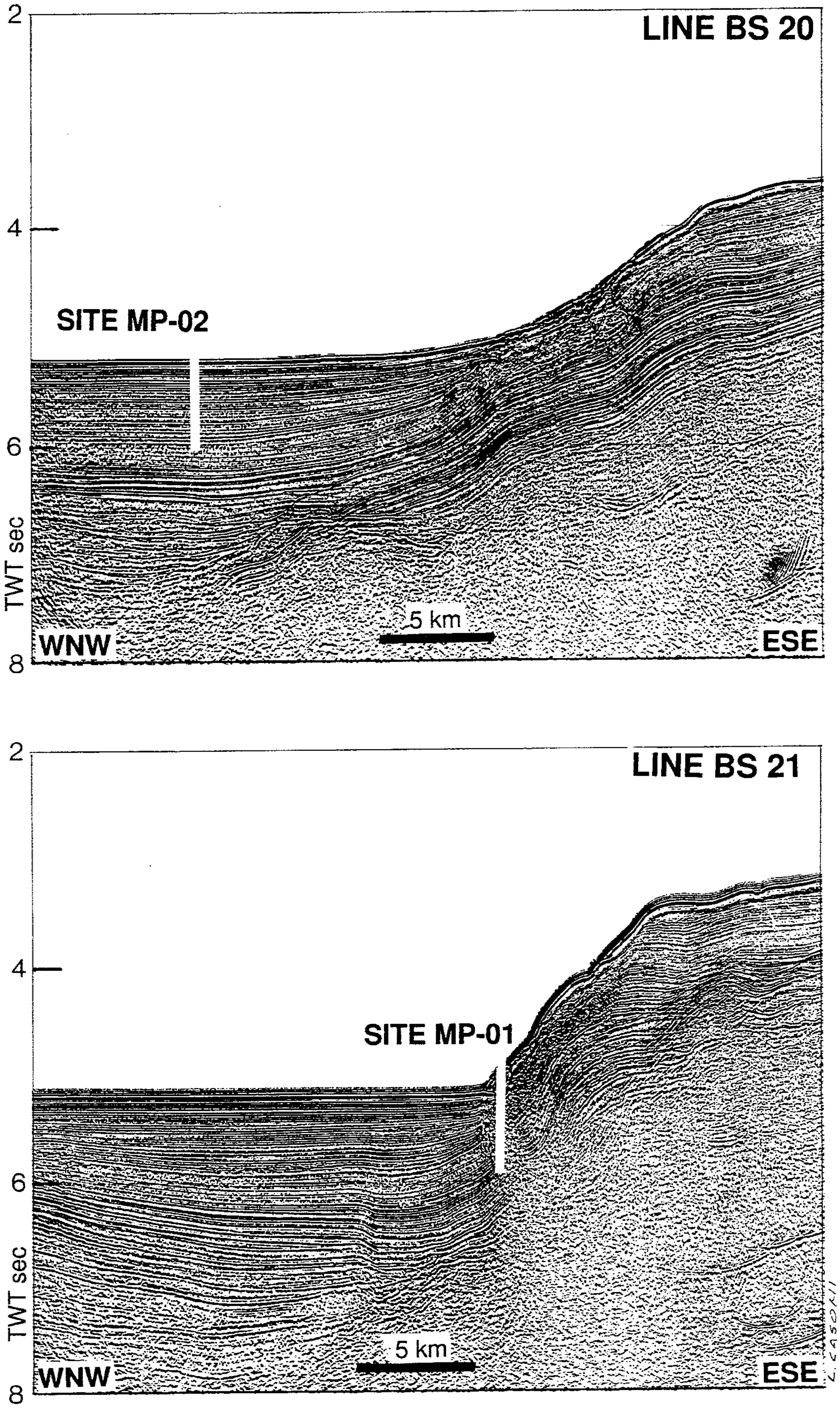

Fig. 3. Seismic line BS20 and BS21 (for location see Fig. 2) and location of proposed drill sites MP-01 and MP-02

exclude that the shear were caused by sedimentary process associated to gravitative episodes. From a preliminary interpretation of the new MCS data set we can conclude:

a) The "Marquês de Pombal Thrust" is an active tectonic structure and it is the most probable source of the "1755 Lisbon Earthquake".

b) the Recent thrusting on the NNE-SSW faults appears to sole out in the upper crust along low-angle extensional faults, probably assimilable to the "S reflectors" found northward, along the Galicia margin (Reston *et al.*, 1996). The "S reflectors" are related to the extension leading to the separation between Iberia and the Grand Banks. The compressional reactivation appears oblique with respect to the previous extension.

c) We have not detected important folding/faulting along the Cabo de San Vincente Canyon, not withstanding the present day intense seismic activity in this area. Here the decollement surface is deeply seated giving an other important constrain to the computation of the possible rupture area associated with the "1775 Lisbon Earthquake".

In particular by the five MCS lines BS20 - BS24 we can observe the deformation pattern associated with "Marquês de Pombal" structure which evolves, going northward, from a fold-thrust to a thrust and finally to a fold with maximum vertical displacement at the thrust's location.

Drilling targets

A large geophysical data set has been already collected in the area. More data will be available during the next year, once the planned surveys will be completed.

The next step toward a deeper comprehension of the seismic and tsunamigenic potential of the "Marquês de Pombal" structure will be the *in situ* measurement of stress field and of the physical and mechanical properties of the rocks surrounding the fault (Fig. 3, line BS21) combined with a long term monitoring of the seismicity of the tectonic structure. This could be achieved by a drilling hole, which will allow either to measure these quantities either to deploy a 3 component seismometer for a long term monitoring. The emplacement of the seismometer in the borehole will significantly reduces the noise level allowing the detection of very low magnitude seismic events. The measurements of the crustal properties around the fault are required for amore accurate tsunami modeling. Moreover a borehole data will furnish the stratigraphic information to infer the deformation history of the structure and allowing a tentative evaluation of its related seismic and tsunamigenic potential.

The northernmost seismic line BS20 (Fig. 3) shows a large gentle fold without brittle breakage of the sedimentary sequence. Basinward, the growth of the fold is continuously recorded by the progressive on laps of the turbiditic sequence the fills the low during the up-lift of the "Marquês de Pombal" structure. The neighboring Tagus Abyssal Plain and Horseshoe Abyssal Plain (Lebreiro *et al.*, 1997) show that, in the last 21,000 years, the emplacement of turbidites occurs at rate of 27 turbidites/10,000 yr, during glacial period, and 10 turbidites/10,000 yr during interglacial, with average sediment rate deposition of 5 cm/ky. After their sedimentation they are successively involved in the deformation episodes thus, acting as an indicator of the deviation from horizontality, with a mean "horizontality" sampling rate of about to 1 turbidite/500y. Ribeiro (1994) estimated a returning period ranging from 300 up to 1500 years for events having a magnitude of about 8.5, comparable to that of the 1755 Lisbon Earthquake. Thus our indicator of "past-horizontality" could furnish the data for a palinspastics structural restoration of the "Marquês de Pombal" structure. Applying this technique we will obtain a rough evaluation of both the number of relevant up lift events, of their age and amplitude and of the past mean motion of the structure. Concluding we propose:

One drill hole across the fault plane to recover the *in situ* stress field, the physical and mechanical properties of the rocks bounding the fault plane. In this borehole we intend to deploy a 3 component seismometer for long term monitoring (Site MP-01, Fig. 3).

One drill hole basinward of the fold to recover the stratigrafic information (Site MP-02, Fig. 3).

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Challenges for future drilling in the Western Mediterranean: potential targets in the Alboran and South Balearic basins

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INTRODUCTION

In the Westernmost Mediterranean, the late Cretaceous-to-Paleogene continental collision between the Eurasian and African plates has resulted in regions of complex lithosphere deformation from post-collisional tectonics. These regions correspond to the westernmost orogenic segment of the Alpine belt – the Betic, Rif, and Tell Cordilleras – and are the sites where the Alboran and South Balearic basins were formed. Kinematic models for this segment of the plate boundary show variable directions of relative plate motions since the late Cretaceous. Between the mid-Oligocene and late Miocene, Africa and Eurasia experienced only about 200 km of roughly North-South convergence, followed by about 50 km of Northwest-Southeast convergence from the latest Tortonian (9-8 Ma) to the Present (*e.g.*, Dewey *et al.*, 1989; Srivastava *et al.*, 1990).

Current awareness of Western Mediterranean geology indicates that Miocene basins, often described as Mediterranean "back-arc basins", originated by late-orogenic extension on the sites of former orogens constructed due to the Cretaceous-to-Paleogene collision. Significant debate and controversial hypotheses on the genesis of these basins focus on the processes that caused the Alboran and South Balearic basins, behind the Gibraltar Arc, and its genetic link with the tectonic evolution of the Betic-Rif-Tell Cordilleras and the formation of the Arc. Thus, this area is considered an appropriate scenario to conduct thematic investigations on lithosphere deformation mechanisms that originate extensional basins overcoming boundary conditions in regions of continental-plate collision and convergence.

Despite significant results provided by ODP Leg 161 (Comas, Zhan, Klaus *et al*, 1996) on Neogene extensional processes in the Westernmost Mediterranean, the origin of the Alboran Basin, and particularly its possible relationship with the adjacent oceanic South Balearic Basin has not yet been completely addressed. The processes that produced the rapid evolution of a collisional zone into a locus of extreme crustal stretching and adjacent contraction, the exhumation of deep crustal rocks, and the westward Gibraltar Arc migration need to be adequately explained. Furthermore, the magma and oceanic-crust generation in this geodynamic context should be investigated in order to constrain the competing hypothesis for the origin of the late-orogenic extension that caused these basins. Therefore, thematic tectonically-oriented drilling targets have only been partially accomplished in the Westernmost Mediterranean, and fundamental scientific questions of the dynamics of Earth's interior in this region deserve more extensive exploration by ocean drilling.

SCIENTIFIC BACKGROUND

The Alboran Sea and the South Balearic Basin are located in the inner part of the Betic (Southern Spain), and Rif and Tell (Morocco) chains, which connect through the Gibraltar Strait. The region as a whole is bounded to the North and South by the Iberian and African continental forelands, to the West by the Atlantic Ocean, and by the Sardino-Balearic Basin to the East (Fig. 1, inset map).

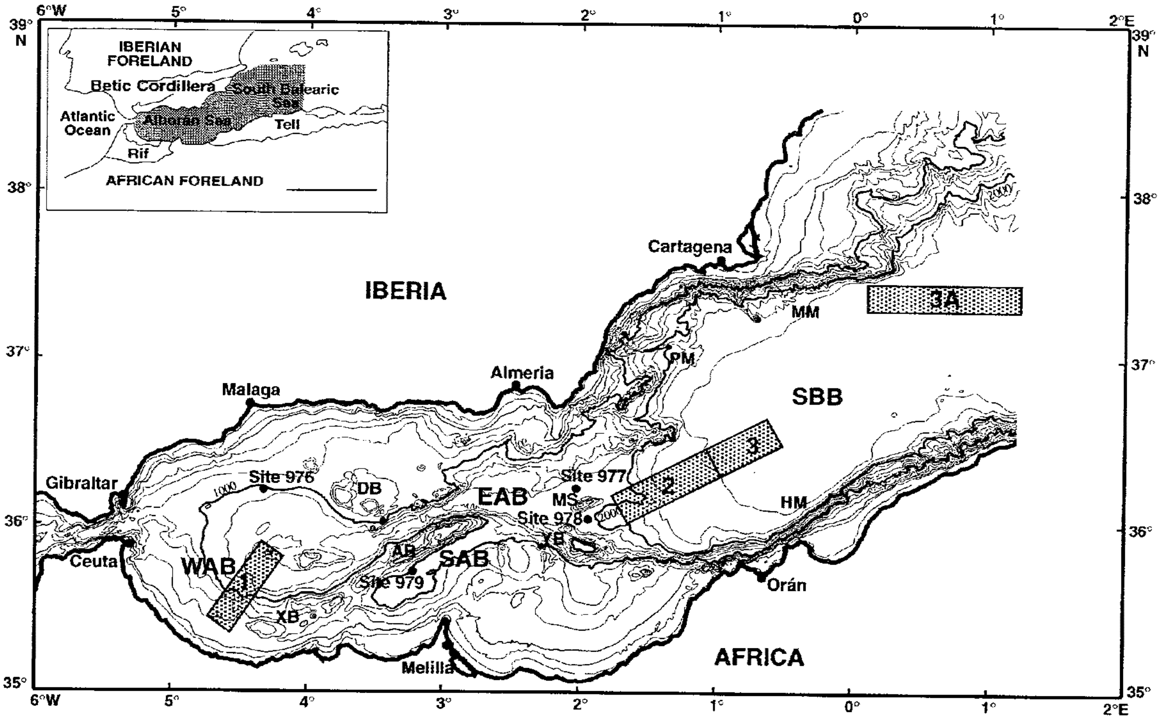

Fig. 1. Bathymetry of the Westernmost Mediterranean (Alboran and South Balearic seas) showing location of ODP Leg 161 and sectors of potential drilling targets (dotted areas 1 to 3). Bathymetry contours in meters, contour interval 200 m. Inset map: location of the Alboran Sea between the Betic and Rif Cordilleras. **AR:** Alboran Ridge. **DB**: Djibouti bank. **EAB**: East Alboran Basin. **HM**: Habibas Margin. **MM**: Mazarron Margin. **MS**: Al Mansour Seamount. **PM**: Palomares Margin. **SAB**: South Alboran Basin. **YB**: Yussuf Basin. **WAB**: West Alboran Basin. **XB**: Xahuen Bank.

The Alboran Sea is about 400 km by 200 km and exhibits a complex seafloor morphology with a maximum depth of 2 km. The Alboran Ridge (180 km in length), the most prominent northeast-southwest linear relief across the Sea, emerges locally to form the small, volcanic Alboran Island. Three main sub-basins, the West, East and South Alboran basins, are distinguished. Toward the East, the adjacent South Balearic Basin reaches a maximum depth of 2600 m at its rather flat basin-plain area, and extends for more than 500 km till 5° E meridian (Fig. 1).

A number of recent geophysical data provide compelling evidence for crustal structure from the surrounding chains to the marine basins (Fig. 2). The crust thins from 36-30 km in the Internal Betics and Rif, to about 16-14 km beneath the central Alboran Sea, and to less than 12 km at the Easternmost Alboran Basin. A steady W to E decrease in lithosphere thickness occurs from 140 km in the Gibraltar Strait, to 60-90 km in the West Alboran Basin and less than 45 km toward the East, just at the transition to the South Balearic Basin (Torné *et al*, in press). There is no witness for the existence of Cenozoic oceanic lithosphere at the Betic-Rif-Alboran region. Deep seismic reflection data, however, suggest the presence of oceanic crust East of 1° W meridian in the South Balearic basin, where the crustal thickness is probably about 6 km (Comas *et al.*, 1997; Gallart *et al.*, 1997). Magnetic and gravimetry data also suggest an oceanic-type crust under the South Balearic basin-plain area (Galdeano *et al.*, 1974), which is predicted Oligocene-Aquitanian in age (*e.g.*, Maufrett *et al.*, 1992).

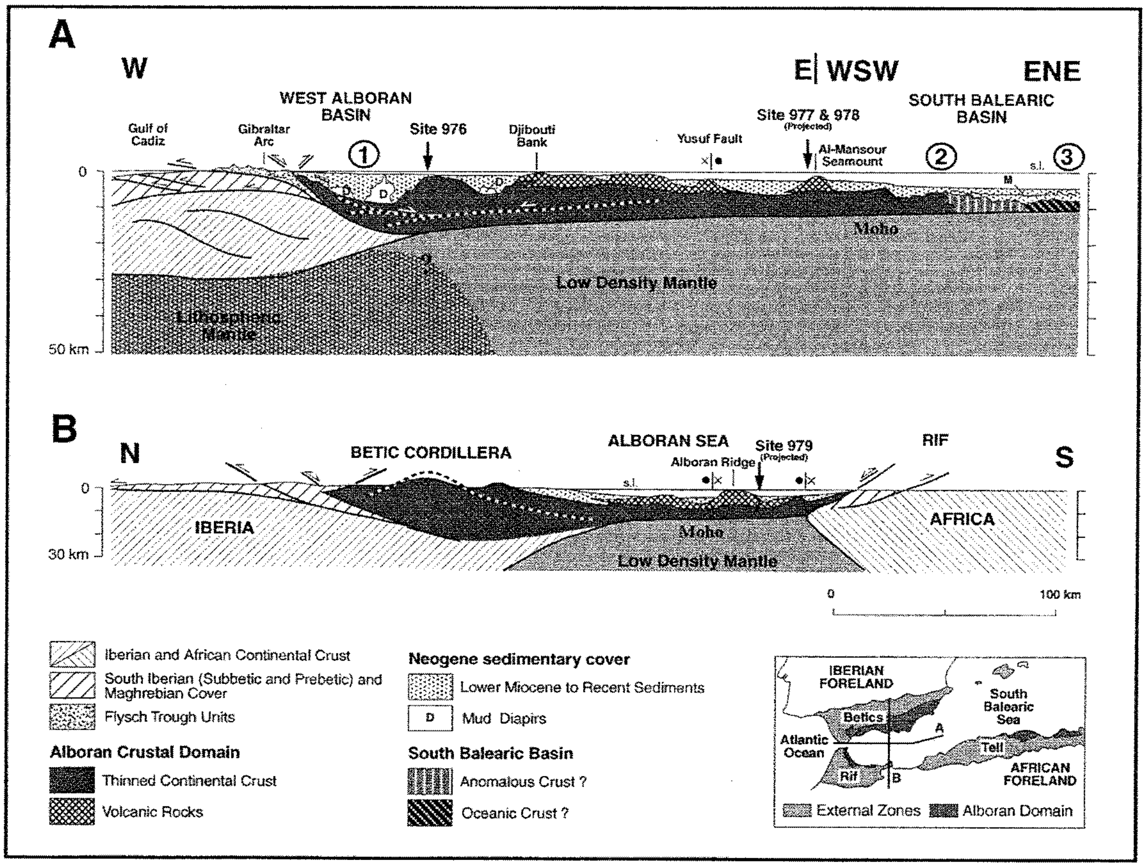

Fig. 2. **A**: Schematic true-scale section from the Gibraltar Arc to the South Balearic Basin showing the E-W crustal structure of the Westernmost Mediterranean. **B**: Schematic true-scale section to illustrate the N-S crustal structure of the Alboran Basin. Hatched white lines in the Alboran Crustal Domain are extensional detachment faults. Encircled numbers correspond to potential drilling sectors as mentioned in the text. The modeled crustal thickness is based on seismically-derived estimates of the Moho depth, and 3D modeling considering gravity, surface heat-flow, and elevation data (modified from Comas *et al.*, 1999).

ODP drilling (Leg 161, Comas, Zahn, Klaus *et al.*, 1996) confirms the presence of continental crust and the N-S continuity of the stretched Alboran Crustal Domain (the internal complexes of the Betic- Rif orogen) beneath the West Alboran Basin. The metamorphic basement sampled at Site 976 belongs to units of the Alpujarride Complex cropping out in the Western Betic Cordillera. East of 4° W meridian most of the residual highs at the Central and Eastern Alboran Sea (*e.g.*, the Al Mansour Seamount) and in the Western South Balearic Basin appears to be formed of volcanic edifices, as revealed by dredging and diving data; notwithstanding, the nature of the basement at these eastern regions is unknown (Fig. 2).

Up to 7 km-thick lower Miocene to Pleistocene sedimentary sequences occur in the West Alboran Basin; however, in the South and East Alboran basins and Western South Balearic Basin the sedimentary cover may be less than 4 km thick (Comas *et al.*, 1992; Watts *et al.*, 1993). Messinian evaporite developed only in the South Balearic Basin (salt domes beneath the abyssal plain), thins towards the North and South margins and disappears in the Alboran Basin to the West (Figs. 2 and 3). The age of the pre-Messinian sedimentary cover in the East Alboran and South Balearic basins (Fig. 2 A) is unknown since these sequences have not yet been sampled by drilling (Comas, Zhan, Klaus *et al.*, 1996).

The structure of the Alboran and South Balearic basins (Fig. 3) resulted from superimposed extensional and contractional tectonics. In the Alboran Basin, extension and progressive exhumation of the metamorphic Alboran Crustal Domain took place at the latest Oligocene and continues to the late Miocene (from about 27 Ma to about 9 Ma). Generalized middle Miocene calc-alkaline magmatism (from 15 Ma to 9 Ma), as well as notable mud diapirism in the West

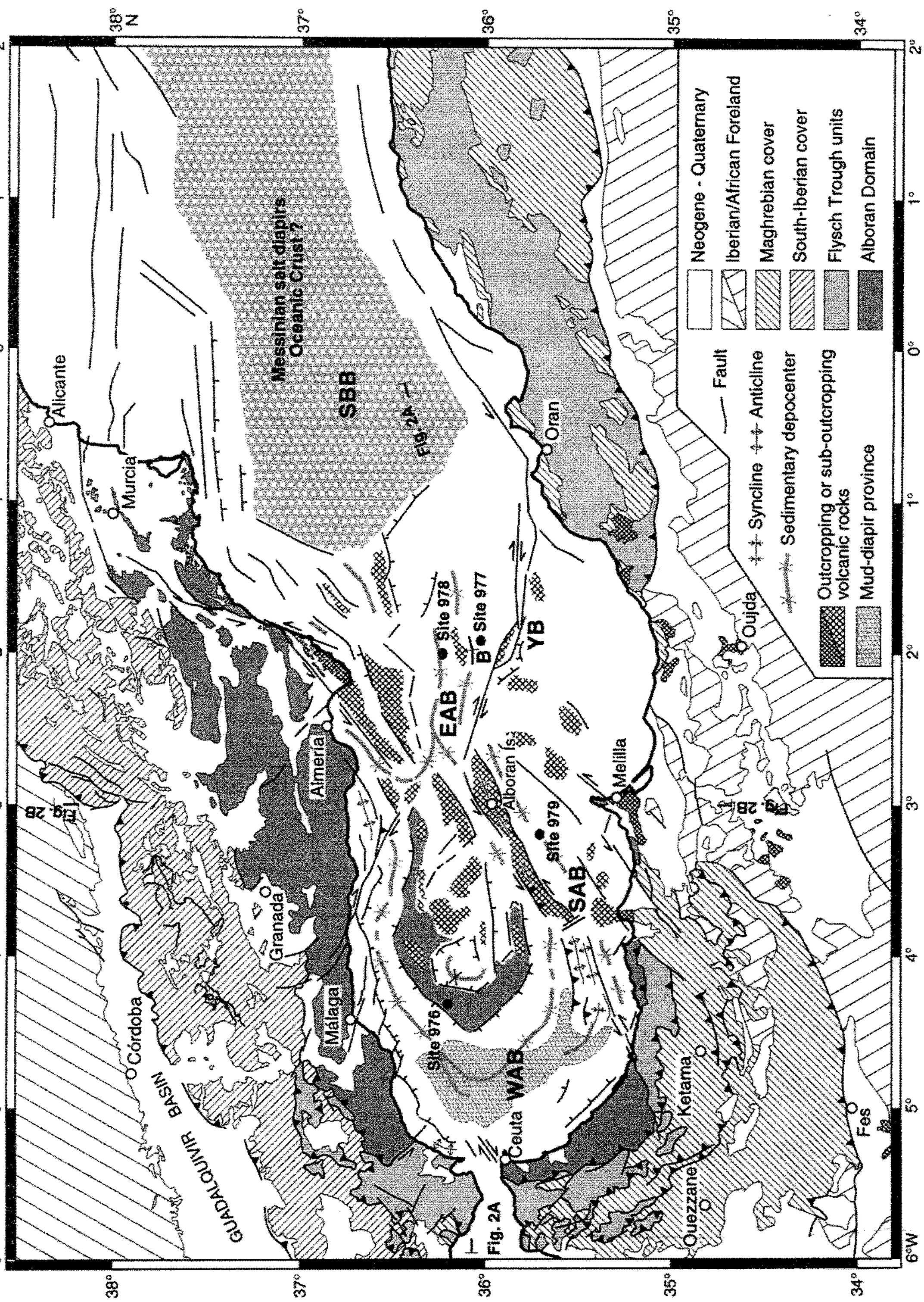

Fig. 3. Tectonic map of the Westernmost Mediterranean (Alboran and South Balearic basins) and surrounding areas showing early Miocene to Holocene structures and main sedimentary depocenters. Note that the limits of the Messinian salt diapirs in the South Balearic Basin seem to fit with the inferred anomalous continental or oceanic crust as shown in Fig. 2. The position of cross-sections in Fig. 2 is marked; **B** marks the change of direction of cross-section in Fig. 2A. **EAB**: East Alboran Basin. **SAB**: South Alboran Basin. **YB**: Yussuf Basin/Yussuf Fault. **WAB**: West Alboran Basin. (modified from Comas *et al.*, 1999).

Alboran Basin, have resulted from the extensional processes (Fig. 2). Latest Miocene and Pliocene-to-Recent contractional tectonics caused a major reorganization of the basins, which resulted in peripheral uplifting and emersion, and subsequent N-S shortening of the marine realm. This contractive tectonics was also accompanied of widespread volcanism (shoshonitic and lamproitic lavas and alkaline basalts), and post-Messinian contraction lent to resume mud-diapirism in the West Alboran Basin till reaching the sea floor at present (Comas *et al.*, 1999, and references therein).

Major-fault systems determine the morphology of the South Balearic margins (Mazarron, Palomares and Habibas margins from the homonymous fault-systems), and form the limit between the Alboran and South Balearic basins (Figs 1 and 3). Flanking the Northern South Balearic margins, volcanic rocks of unknown nature form numerous submarine highs (with high-amplitude magnetic anomalies) bordering or within the predicted oceanic crust. Present-day seismicity in the Habibas Margin (Habibas fault system) shows a transpressive dextral kinematics for faults that limit the oceanic crust in the African margin. These major structures are consistent with the late Neogene-to-Present plate kinematics, and are thought to involve present-day crustal boundaries.

The Alboran and South Balearic basins are considered as originated by extension at the site of a former collisional orogen now represented by the extended fragments of the Internal Zones of the Betic, Rif and Tell mountain chains. As far as the extensional origin of the Alboran Basin is concerned, the hypotheses currently most widely debated have emphasized the “rollback” of a coeval subduction zone beneath the Alboran region (*e.g.*, Royden, 1993; Lonergan and White, 1997), the convective removal of a cool and dense lithosphere root (*e.g.*, Platt and Vissers, 1989), or a delamination (peeling off) of the lithospheric mantle from beneath the crust (*e.g.*, Docherthy and Banda, 1995; Comas, Zahn, Klaus *et al.*, 1996; Seber *et al.*, 1996) as alternative processes responsible for the extension. Cogent evidence from basement rocks at ODP Site 976 High (Fig. 3) favors models that invoke removal of the continental lithosphere mantle beneath the Alboran Crustal Domain as the driving force for extension generating the Alboran Basin (Comas *et al.*, 1999; Platt *et al.*, 1999). The strong E-W asymmetry of the mode of lithosphere extension is consistent with the extensional westward transport of the Alboran Crustal Domain, in the context of a West directed removal - asymmetric detachment- of the subcrustal lithospheric mantle during the Miocene (Torné *et al*, in press). Furthermore, a genetic relationship between the initial stretching of the Alboran Crustal Domain and the opening of the South Balearic Basin can be suggested from new geophysical data.

POTENTIAL DRILLING TARGETS

Recent developments of broad impact in the geology of the Westernmost Mediterranean, and advances based on ODP cores in the Alboran Basin (Comas *et al.*, 1999), prove that further and deeper drilling is the only means of addressing fundamental Earth processes that caused post-collisional lithosphere deformation at this segment of convergent-plate boundary. Deep-penetration JOIDES Resolution-type drilling and riser drilling into tectonic exposures of the exhumed metamorphic terranes, intracontinental and intraoceanic volcanic rocks, and adjacent igneous basement – the oceanic crust – will be necessary to learn about major tectonic events along the post-collisional history.

Three sectors, involving W-E transects of drill sites from the West Alboran Basin to the South Balearic Basin, are envisaged as potential targets for possible drilling proposals in the Westernmost Mediterranean (Figs. 1 and 2A). A complete plan for drilling in the three sectors can be suggested as follows:

• Sector 1 : two deep-drill sites to yield a complete coring of the early Miocene (?) to Recent sedimentary cover in the West Alboran Basin, and for further penetrating in “tectonic windows” of the exhumed “orogenic” basement;

• Sector 2 : a transect of drill sites, with deep penetration, to sample shallow occurrences of volcanic rocks within the extremely thinned continental crust, or anomalous crust, in the transition between the East Alboran and the South Balearic basins;

• Sector 3 (3 and 3A) : a transect of deep to relatively shallow drill sites to sample the oceanic crust and the intraoceanic volcanic ridges (?) in the South-Balearic Basin.

A deep-drill site for sampling the sedimentary cover at Sector 1 (Figs. 1 and 2A) is critical in order to constrain the timing of lithosphere stretching and complete – tectonic and thermal – subsidence history of the continental margin – the Alboran Basin. Furthermore, there should be interesting questions within these sediments in the field of fluid flow and venting (fluid compositions, flux rates, microbial geology) carry from depth to the seafloor; among others, the nature and origin of larger-scale mud diapirs and mud volcanoes occurred in extensional *versus* compressional setting. Drilling and sampling deeper metamorphic rocks in the basement (to complete Site 976 results) will provide fundamental data on exhumed rates from deep crustal levels, in controlling tectonic-uplift, on fluid chemistry, and on the thermal and strain histories of the "orogenic" terrane through the extension.

Drilling results from potential sites in Sectors 2 and 3 (Figs. 1 and 2A) will probably open innovative perspectives for investigations on the continental lithosphere behave in post-collisional convergent settings, and major tectonic events that initiate and end extremely high magma production rates and oceanic basement growth. Post-collisional processes that have caused lithosphere stretching, continental break-up and opening of ocean basins overcoming the "continental suture" remain among the least understood problems in Earth science. Sampling by means of a series of holes extending from the volcanic rocks to the igneous basement (intrusive and extrusive) is critical to conduct geochronological, petrological and geochemical (isotopic signatures and trace elements) studies that document ages, magmatic signatures and distribution of the magmatic products. The removal of the continental lithosphere mantle beneath the former orogen, and its interaction with the astenosphere upwelling (as thought from a tectonic model proposed for the region), should have resulted in a complex magmatic history (*e.g.*, thermal and material exchanges, mass fluxes and depletion of fluids, crustal metasomatism and melting) that can be tackled by drilling strategies. Thus, it will make possible to validate geophysical and geochemical models for tectonic conditions leading to extreme lithosphere stretching in convergent geodynamic settings.

On the other hand, it is important to stress that direct long-term observations at drill sites near active major crustal-fault systems (*e.g.*, near Mazarron and Palomares faults in the Iberian margin, and Habibas fault in the Argelian margin; Fig. 3) will allow measurements of contemporary convergence rates and will constrain strain and crustal deformation in response to active present-day convergence. Besides, monitoring drill-sites in these seismogenic zones can help to evaluate seismic hazard in the Westernmost Mediterranean by studying the earthquake cycle, and its nucleation and distribution-depth within the convergent plate boundary.

Drilling at this part of the Mediterranean should also improve land-sea integration and can increase the interest from interdisciplinary shore-based scientists in ocean drilling challenges. Positive co-operations between on-going research projects in progress is providing a prominent geological and geophysical field and analytical data-set to fulfill strategic purposes, and site survey requirements, to support future drilling proposal in the Westernmost Mediterranean basins toward the Scientific Ocean Drilling Phase IV, currently dubbed the "Integrated Ocean Drilling Program" (IODP).

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Subsurface structuring of the Eastern Mediterranean Tunisian basins

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ABSTRACT

The Eastern margin of Tunisia is bounded by the Mediterranean Sea and comprises the gulf of Hammamet to the North and the gulf of Gabès to the South. It continues to the East by the Pelagian Sea. Western onshore part of the margin is represented by the Cap Bon Peninsula to the North and the Sahel platform to the South. In the onshore regions Mesozoïc and Cenozoïc sedimentary series are poorly cropping out. The main geologic investigations are based on petroleum well and reflection seismic data. Geologic and geophysic studies carried out on this margin by Universities and petroleum societies since the 1980's by seismic stratigraphy, isopach and isochron structural mapping of Mesozoïc and Cenozoïc horizons reveal new results concerning the tectonic and the basin structuring and the sequence stratigraphic infilling. These results show a tectonic structure framework characterized by deep-seated flower structure strike-slip fault corridors trending East-West and North-South. These faults distribute the Mesozoïc and Cenozoïc sedimentary cover according a space-time basin organization of platforms, grabens, rim synclines, folds and synclines. Along the major strike-slip fault corridors alcaline intrusive and extrusive magmatic rocks encountered in the petroleum wells accompanied the transtensive and transpressive fault reactivations since the Triassic until the Miocene. Triassic salt diapirism appears in the western part of the Sahel area whereas clay intrusives and diapirs characterize the thick Neogene deposits in the eastern and northern offshore zones. A tentative of basin modelling in three dimensions permits to visualize the relationship between faults and basin structures. As these structures had been highlighted by seismic data and some surface controls, deep drilling projects in such zones can help to recognize and discover these structures for scientific and economic interests.

INTRODUCTION

Tunisia constitutes the eastern prolongation of the Maghrebian Atlas fold belt. The structural units of the Tunisian country are composed by the North, Central and Meridional Atlas fold belts globally directed northeastern-southwestern. The Atlas fold belt is limited to the South by the Saharan platform. Whereas to the East, the Atlas domain continues by the Sahelian oriental platform and the Pelagian sea. (Fig. 1). The Eastern margin comprises the Cap Bon Peninsula and the gulf of Hammamet to the North and the Sahel area and the Pelagian Sea to the center and the gulf of Gabès to the South. The marine bathymetry is varying from the Tunisian eastern gulfs of

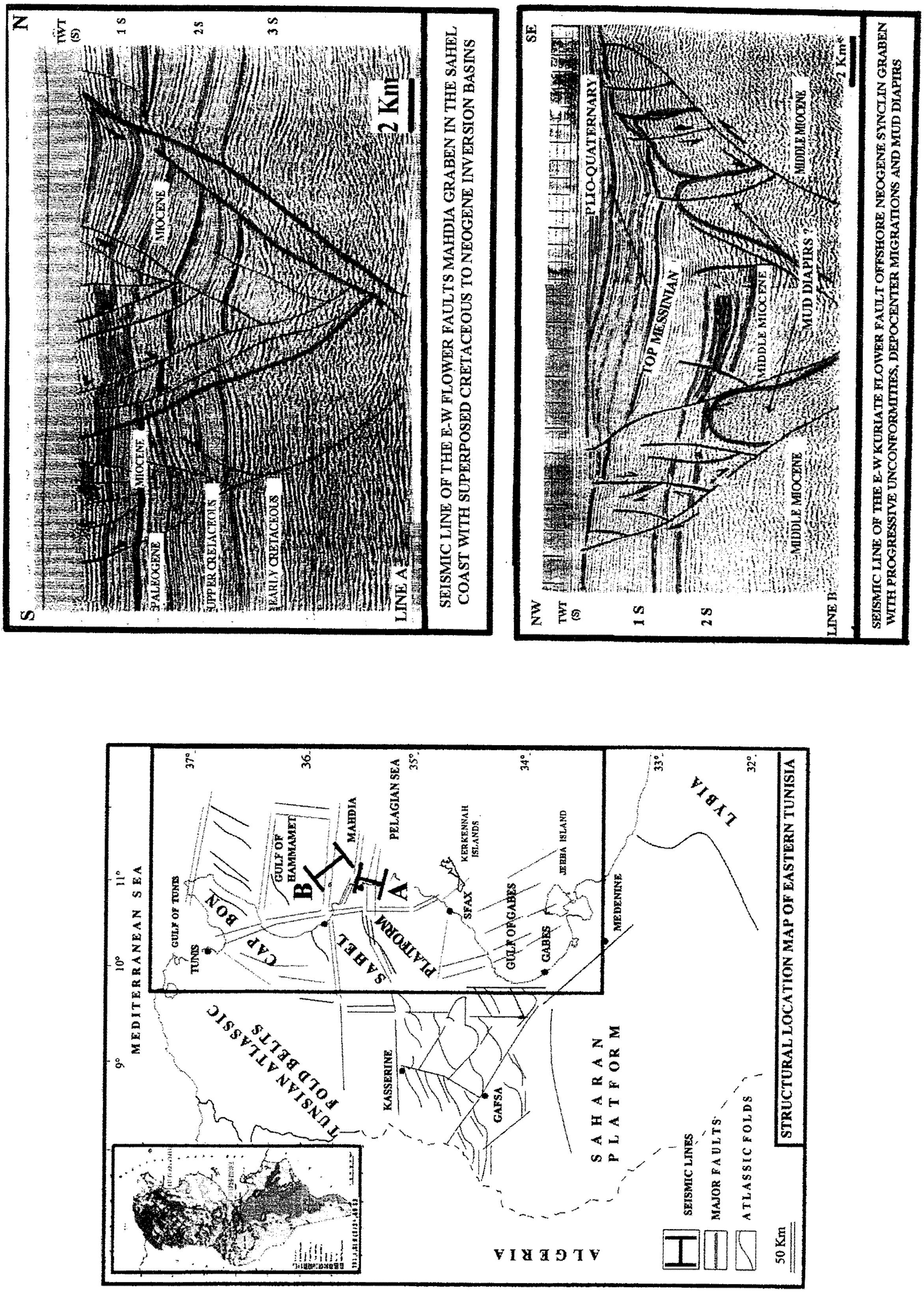

Fig. 1. Subsurface Basin structuring of Eastern Tunisia

Hammamet and Gabès to the Sicilian-Tunisian trough from fifty to two hundred meters. The East-West Kerkennah islands high platform limits the two Tunisian gulfs with a low rate of bathymetry ranging from ten to fifty meters. The target of this presentation is to propose a synthesis of the geological and the geophysical characteristics from the onshore to the offshore Mediterranean eastern margin basins of Tunisia in terms of stratigraphic units and structures according the results of field geology, gravimetry, geothermy, seismic and diagraphic petroleum well data.

LITHOSTRATIGRAPHIC UNITS

The poor geologic outcrops in the eastern platform of Tunisia conduct to use the petroleum well data to investigate the lithostratigraphic Formations. The several wells cored in the onshore and offshore blocs in this area had permitted to recognize the Mesozoïc and Cenozoïc lithostratigraphic Formations known in the outcrops of the interior Atlassic fold belts.

Lithostratigraphic Mesozoïc Formations are composed by thousands of meters of deposits distributed from Triassic to Albian. At the base, Triassic series are composed by deltaic sandstones, clays, dolomites, salt and evaporites with Middle to Upper Triassic basaltic beds (Laaridhi-Ouazaa N., 1994). Jurassic sequences consist on shallow to deep marine platform deposits of marls, limestones and dolomites comprising in some offshore wells Middle to Upper Jurassic basalts. Lower Cretaceous deposits are characterized to the South by deltaic shallow marine platform deposits of sandstones, clays, dolomites and evaporites and varying laterally to the North by deep-sea fan carbonates and sandstone turbidites (Saadi *et al.*, 1994; Souquet *et al.*, 1997). Albian to Aptian series represents reefal limestone platform and black shale deposits with interbeded alcaline magmatic rocks (Laaridhi-Ouazzaa, 1994).

Upper Cretaceous series are composed by several hundreds of meters of an alternation of platform to deep-marine marls and carbonates with black shales and reefs extending from the Cenomanian to the Maastrichtian. Cenomanian and Senonian deposits show in the onshore and offshore wells volcanic alcaline explosive rocks. Tertiary deposits are represented by Paleocene marls, Eocene platform carbonates, deep-marine marls and black shales. Oligocene deltaic and fluvial sandstones succeed to Eocene deposits. Paleocene to Eocene series are intercalated by volcanic alcaline magmatic explosive rocks. Miocene deposits extending from Aquitanian to Messinian comprise deep marine to thick deltaic series marked by an alternation of marls, platform carbonates and clay packages with sandstone turbidites. Burdigalian to Langhian series are interbeded in some offshore wells by basaltic rocks. To the offshore basins Pliocene deposits are characterized by an alternation of thick deep marine marls and sandstone turbidites that outcrops in the Cap Bon region. Quaternary Pleistocene and Holocene littoral sandstones and Continental red beds and caliches overly the ancient series.

Several recent sequence and seismic stratigraphic works have been carried out to classified a chart of sequence deposits of the Mesozoïc Triassic (Peybernès *et al.*, 1993; Soussi *et al.*, 1996; Bédir, 1995), Jurassic (Soussi *et al.*, 1991; Bédir, 1995), Early Cretaceous (Saadi *et al.*, 1994; Souquet *et al.*, 1997; Ben Youssef, 1999), Upper Cretaceous (Bédir, 1995; Ben Youssef, 1999) and Cenozoïc (Bédir, 1995; Bédir *et al.*, 1996; Bédir *et al.*, 1998) outcrop and subsurface sedimentary series of the central to eastern Atlassic margin of Tunisia.

BASIN STRUCTURING AND TECTONIC STYLE

Geologic surface and subsurface data by Bouguer and residual gravimetry (Midassi, 1982; Haller, 1983), and reflection and refraction seismic investigations (Buness *et al.*, 1992; Bédir, 1995) have highlighted the structural framework of the eastern onshore and offshore regions. This domain is characterized by deep structural discontinuities oriented North-South, East-West and Northwestern-Southeastern corresponding to a deep-seated flower fault corridors (Bédir, 1988; Ben Ferjani *et al.*, 1990; Bédir, 1995) (Fig. 1). The Mohorovitchi discontinuity depth evolutes from Southwestern Tunisia to the North and the Northeastern Sahelian and Pelagian sea from forty to twenty kilometers at the longitude of the Pantellaria and Linosa volcanic islands (Buness *et al.*, 1992). The Moho rising to the northeastern margin can explain the important magmatic activity in these zones from the Triassic to the Quaternary times and the high geothermal rates encountered in the petroleum wells (Ben Dhia, 1987). The tectonic movements of fault corridors guide the basin and platform blocks since the Mesozoïc times according a strike-slip transtensive and transpressive kinematics (Bédir *et al.*, 1992; Bédir, 1995; Bédir *et al.*, 1996). The earlier Mesozoïc displacement of these faults has created a mozaic of inside and outside fault corridors, rhomboedral blocks, subsiding grabens and more high platforms (Fig. 1). The faulted limit borders of these blocks had been progressively folded at Upper Cretaceous and Paleogene Alpine orogeny and Miocene and Quaternary Atlassic compressions (Bédir, 1995). They represent the actual Atlassic folds of the Cap Bon, the Sahel and the eastern offshore zones. The deepening and the precocious activity of the Master faults are also marked by the magmatic rocks encountered in the petroleum wells since the Triassic (Laaridhi-Ouazaa, 1994; Laaridhi and Bédir, 1997). Triassic halokinetic movements and salt intrusives characterize the onshore Atlassic fold structures along the strike-slip fault corridors (Haller, 1983; Bédir, 1988 and Bédir, 1995). The halokinesis movements began earlier since the Jurassic in the Tunisian Atlassic domain (Bédir, 1995; Boukadi et Bédir, 1996). They have been reactivated by the transtensive and transpressive fault plays during the Thetyan, Mesogean and Oligo-Miocene rifting and the Alpine and Atlassic compressions. In the other hand, claykinesis and intrusives occurred in the thick offshore deltaic and turbiditic Miocene and Pliocene deposits along the strike-slip fault corridors (Bédir *et al.*, 1996; Bédir *et al.*, 1998).

CONCLUSIONS AND PROSPECTIVES

The eastern margin of Tunisia known along times as a simple passive margin is in fact an active transform margin affected by Transfer Master flower faults that had been blocked and averted along the Mesozoïc and Cenozoïc stages (Bédir *et al.*, 1992; Bédir, 1995; Laaridhi-Ouazaa et Bédir, 1997). The Mediterranean offshore margin of Tunisia is known by its several oil fields extending from the Jurassic to the Miocene series along a classic structure of highs of platform and folds. This is due probably to the well maturation of Mesozoïc and Cenozoïc black shales by the existence of a high geothermal gradient (Ben Dhia, 1987) and magmatic activity in these zones. Recent subsurface geodynamics studies of sedimentary basins in this area reveals a new unexplored subsurface structures of strike-slip flower fault grabens, rim synclines and block borders with sequence deposits infilling and distribution marked by turbidites, pinch outs and sedimentary unconformities. The time-space magmatic migration along fault corridors is coeval with basin migration, black shale maturation mechanisms and Neogene mud diapirism and intrusives with hydrothermal and/or hydrocarbon fluids. The Triassic facies changes to the East where the halokinetic structures disappear and the nature of the basement are many scientific problematics that are discussed now in Tunisia and can offer a new proposal of deep drilling programme in integration with similar problematics of other limitrophe Mediterranean countries.

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The Black Sea : structure, evolution and sedimentology

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INTRODUCTION

The Black Sea is one of the world's largest marginal sea having anoxic conditions below 80-120 m, with an area of about 432 000 km^2 and a volume of 534 000 km^3 (Fig. 1). The Black Sea is connected to the Mediterranean Sea via the Sea of Marmara and the shallow Bosphorus and Dardanelles straits. The Black Sea is a large marginal sea located within a complex folded chain of the Alpine system, represented by the Balkanides-Pontides belt to the South, and by the Caucasus and Crimea Mountains to the North and Northwest. Two basins coalesced late in their post-rift phases in the Pliocene, forming the present single depocentre. The mountain-building

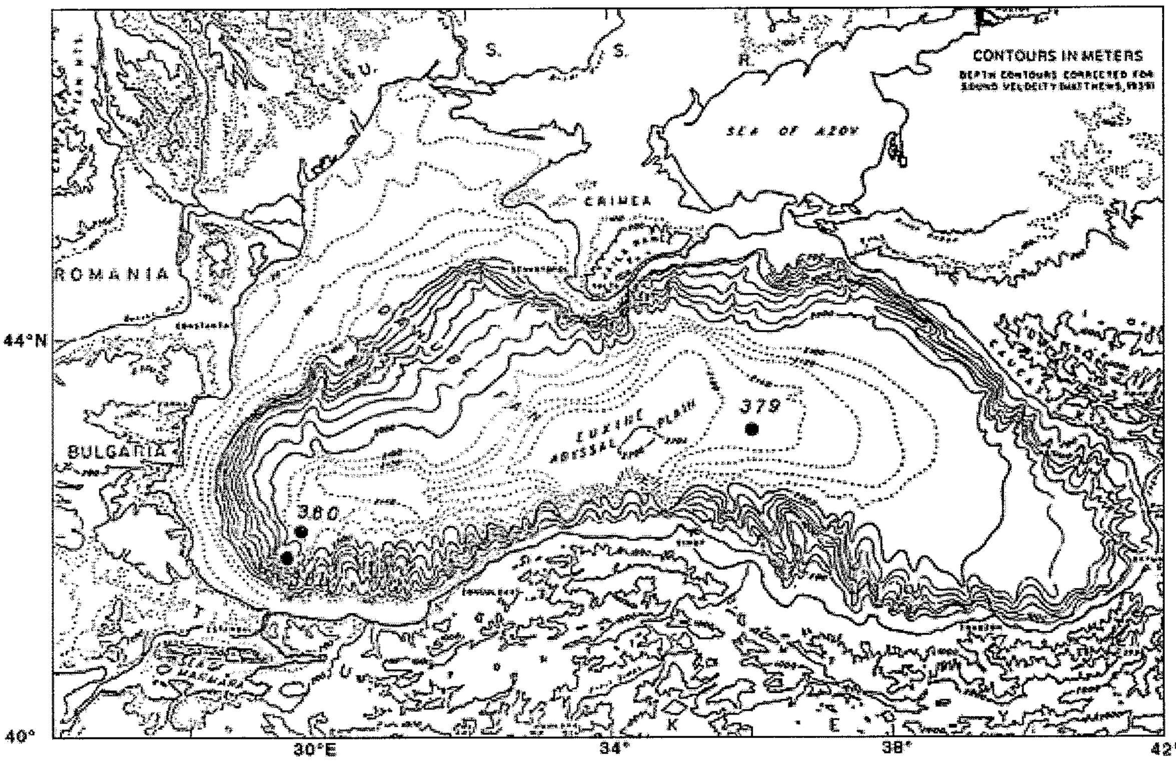


Fig. 1. Bathymetric map of the Black Sea (379, 380 and 381 are DSPD sites).

processes and their subsequent erosion around the basin have contributed to high sediment input. Seismic studies indicate a 15 km thick blanket of sediments with unusually low seismic velocities (3.0-4.5 km/s) that reach potentially back to the Early Cretaceous (130-110 Ma). It was found from the interpretation of seismic reflection data that is quite evident that the lower part of the southern margin of Black Sea basin generally preserves the extensive tectonics associated with the rift processes that generated the Black Sea. Frequently the compressive deformation was superimposed on pre-existing distensive faults, which commenced their activity in the Upper Cretaceous or at the end of the Mesozoic and continued into the Paleocene. The uplift and subsidence described is an extensive phenomenon traceable to regional tectonics of the Tethys belt (Sengor and Yilmaz, 1981). The mechanism of the immense subsidence of the Black Sea basin has given way to the deposition of the thick sedimentary sequence. The strong subsidence of the Black Sea basin is mainly due to isostatic adjustment of the crust in response to the thick sedimentary cover. On the modern continental slope the upper horizons of the Quaternary deposits occur in conformity with the sea floor. Where the steep slope is formed by rocks of the acoustic basement, numerous scarps-connected with rupture dislocations-occur. They have fresh walls indicating very young movements. These data clearly indicate that subsidence has been active recently and that the basin is still actively subsiding (Ross *et al.*, 1978; Belousov *et al.*, 1988; Finetti *et al.*, 1988).

Tectonic framework of the Black Sea

The Black Sea comprises two extensional basins formed in a back-arc setting above the northward subducting Tethys Ocean, close to the southern margin of Eurasia (Fig.2). According to the most modern views and consistent with the geological/geophysical evidences, the deep Black Sea basins do not show a "granitic" layer, but a lower crust with about 6.8 km/s seismic velocity, indicating oceanic type (Fig. 3). Observing and analyzing the extensional tectonics of the Black Sea and the of the Mid-Black Sea ridge, it is possible to show that this region was affected by two main rifting phases (Middle Jurassic and the upper part of the Lower Cretaceous). During the last geodynamic process, the opening of deep Black Sea took place as a consequence of the formation of two back-arc basins behind the West and East-Pontides. The Western Black Sea basin evolved to the stage of complete crustal opening with a basaltic basement getting progressively younger from North to South. At the same time, the Eastern Black Sea basin evolved to the stage of a very thin continental crust affected by numerous listric faults and block-tilting.

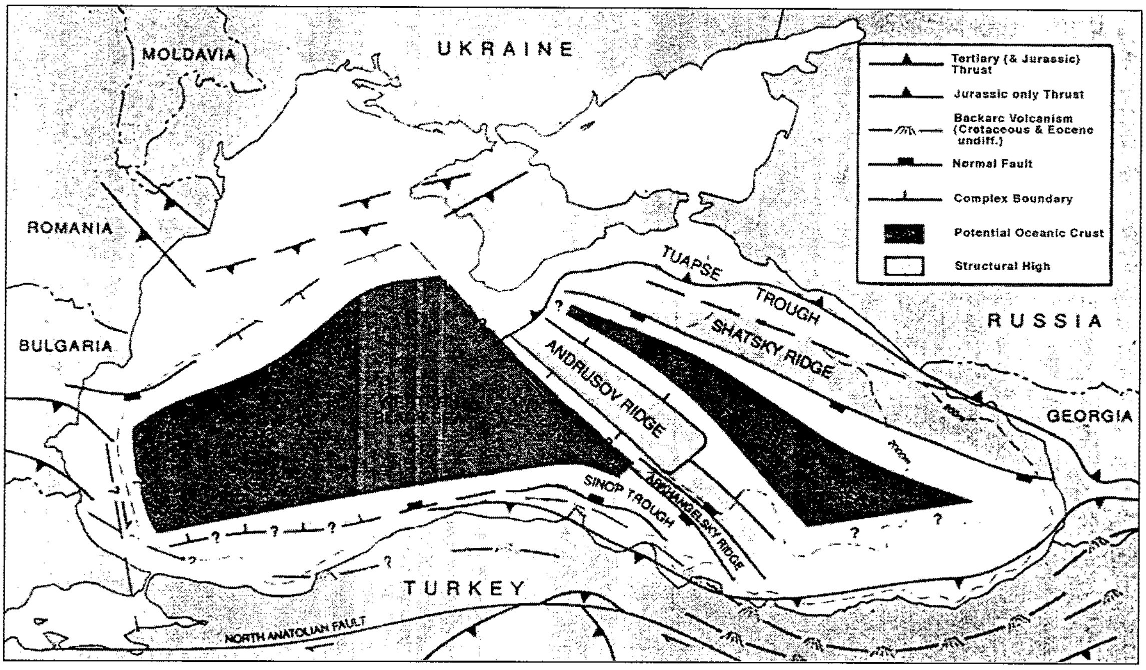


Fig. 2. General tectonic framework of the Black Sea and the geological provinces (West and East Black Sea basins; Mid-Black Sea ridge).

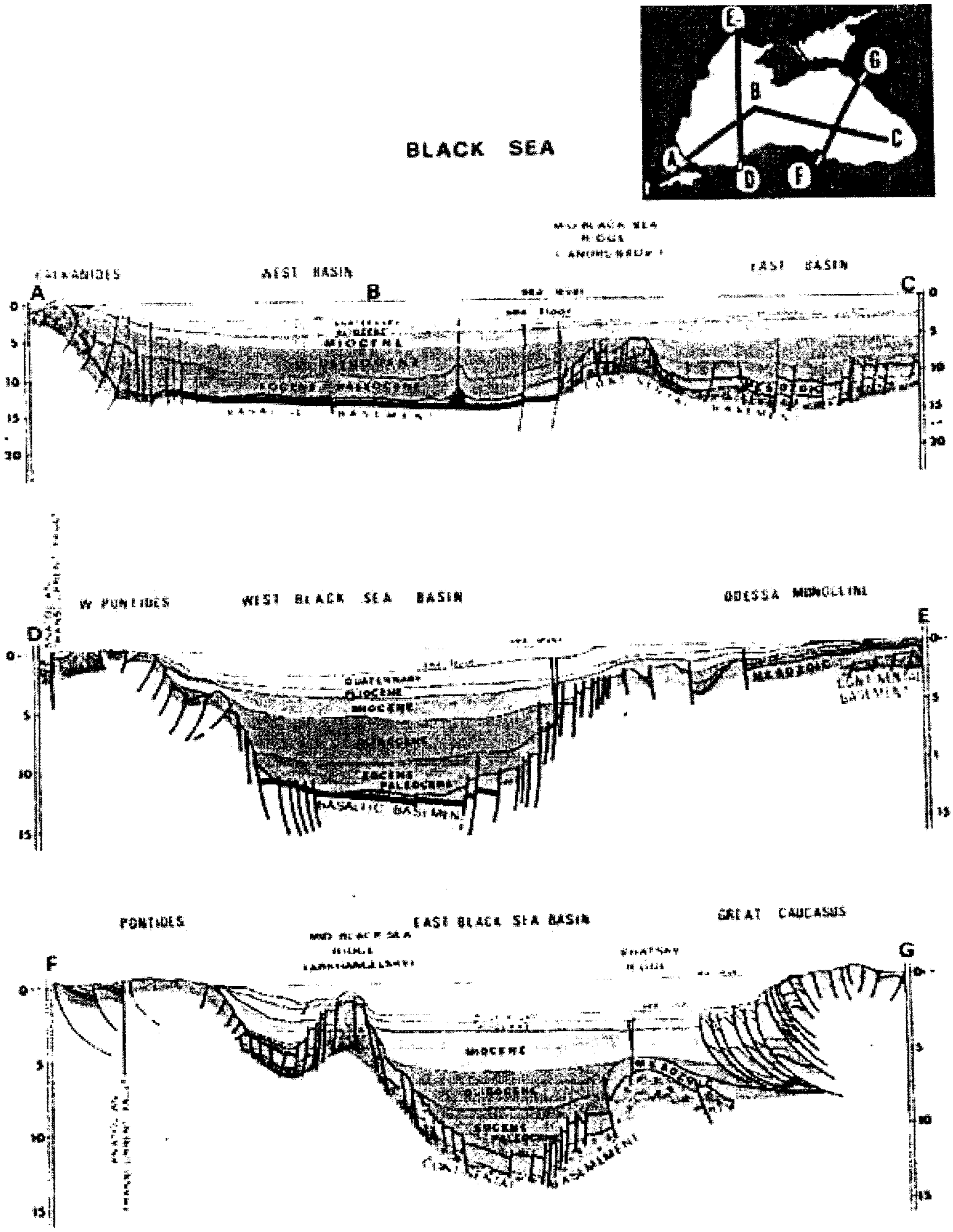


Fig. 3. Geological cross-sections of the Black Sea deducted from the seismic data (from Finetti *et al.*, 1988).

Although the Black Sea is today a single depocentre, deep reflection seismic studies have shown that it comprises two major extensional basins, probably of different ages, separated by a complex NW-SE trending high block (the Mid-Black Sea High) and flanked by other extensional high blocks such as the Shatsky Ridge. The Western Black Sea opened by the separation of the Western and Central Pontide continental strip from the Moesian Platform and Odessa shelf, moving between two major transform faults. The transform on the southwest margin is conjectural, as it has since been overridden by compressive structures. The Eastern Black Sea opened between

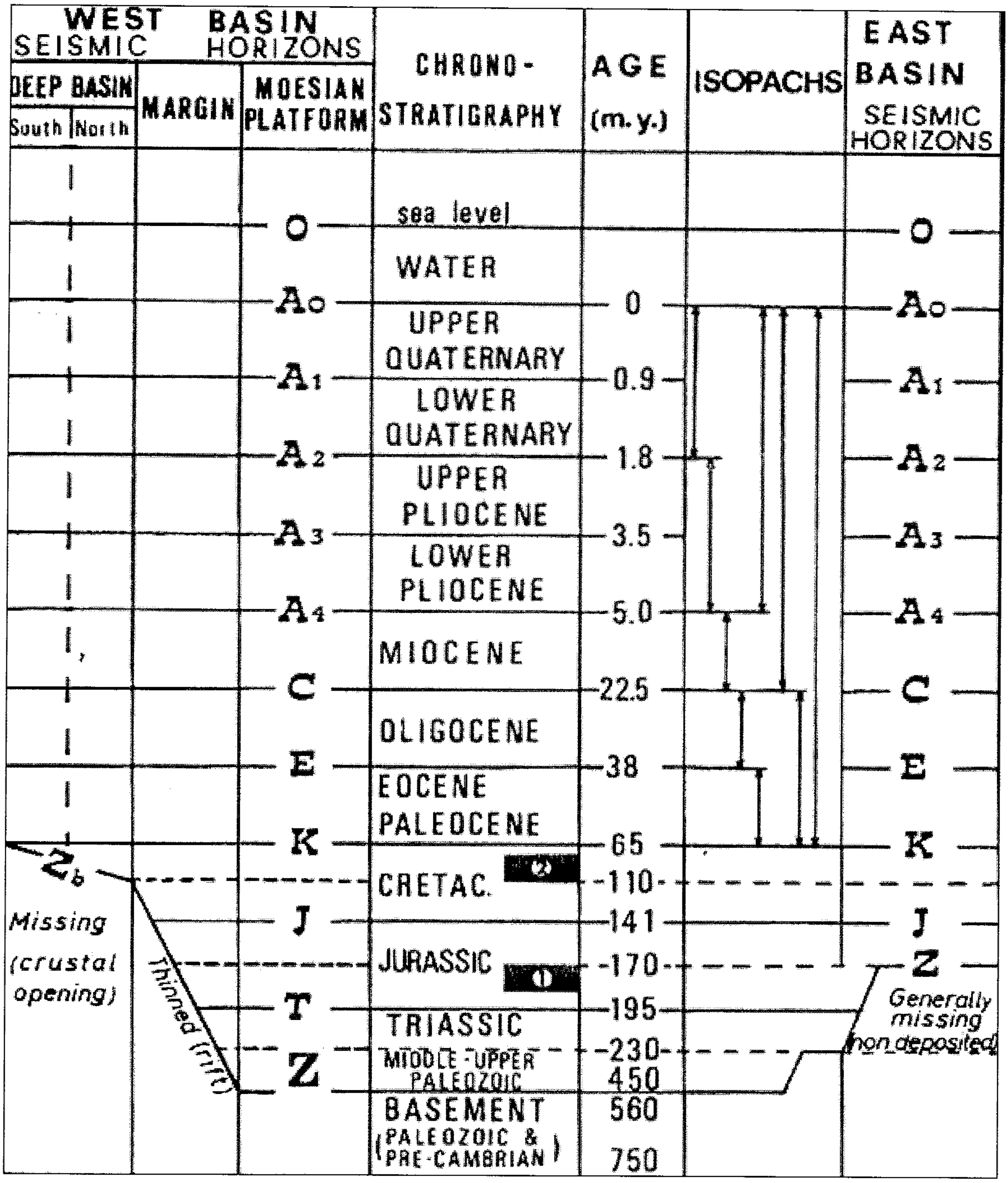


Fig. 4. Chronostratigraphy of the Black Sea (Finetti *et al.*, 1988).

the Shatsky Ridge and the Mid-Black Sea High by rotation about a pole West of Crimea. Its southeast margin has been obscured by the Eastern Pontide thrust belt.

The deep Eastern and Western Black Sea basins are marked with two elongated Bouguer gravity anomalies reaching up to 140-180 mGal (using correction density of 2.67 g/cm^3). The local variations in the free-air anomalies generally divided into two categories : (i) where the anomaly variations accord with the variations in topography and subbottom topography, (ii) where they do not accord (Ross *et al.*, 1978). The Western Black Sea basin is thought to be floored by oceanic crust, and the Eastern Black Sea is highly thinned, possibly oceanic. The frontal folds of the Tertiary compressive deformation lie in most areas close to the present coastline. The Black Sea region has a long and complex history determined by its position above a subduction zone at which the Tethyan Ocean was being consumed northwards, probably from Late Triassic time to its final closure in the mid-Tertiary. The back-arc was subjected to alternating extension and compression, the present Black Sea being the result of the latest phase of extension (Mid-Cretaceous to Eocene), modified by the ensuing and final phase of compression. This history has resulted in a wide variety of structural and sedimentary environments and facies, and also in widespread and repeated volcanism.

Western Black Sea and Eastern Black Sea basins are separated by a prominent regional ridge of NW-SE trend (Mid-Black Sea ridge) made up of two positive features named Andrussov and Arkhangelsky ridges. This structure is very important for the understanding of the Black Sea opening because it preserves the old rift-tectonics produced when the sea was produced. The extensive deformation is here almost completely non-contaminated by successive compressive movements. It is also important because it is possible to observe the complete seismic stratigraphy from the Quaternary down to the acoustic basement attributable to the geologic basement (Figs. 5 and 6). The Mid-Black Sea is also important because it allows a comparison with the different conditions with regard to their lower sedimentary layers, types of basement and stages of crustal opening. The southeastern part of Mid-Black Sea ridge (Arkhangelsky) locally shows a moderate compressive deformation connected with the orogenic movements of the Pontides. Drilling on the Arkhangelsky ridge (offshore part of Samsun) at water depths around 300-400 m can give information down to the Cretaceous.

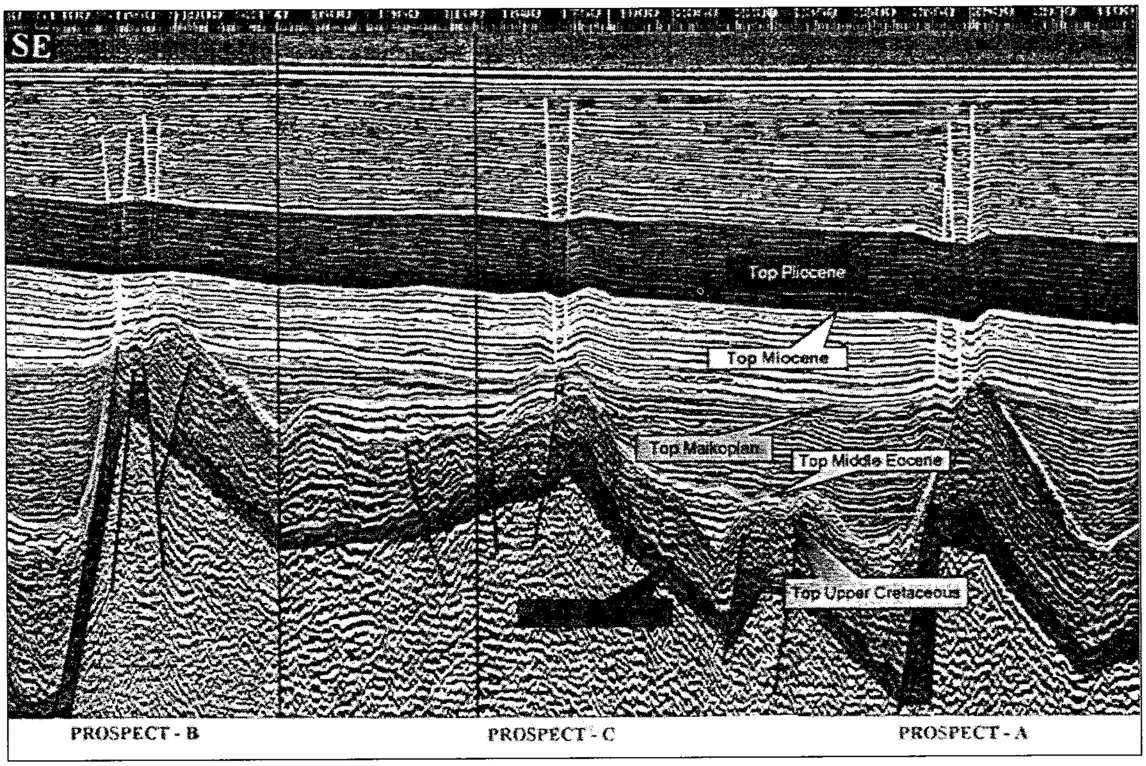


Fig. 5. Seismic section (SE to NW direction) over the Andrussov ridge (TPAO/BP data).

SEDIMENTARY SEQUENCE

The huge subsidence of the two deep Black Sea basin is mainly due to isostatic adjustment to the thick sedimentary deposition (Degens *et al.*, 1983). In the Eastern basin an important contribution to the subsidence was also the thrusting, especially of the East-Pontides, where the collision of the Arabic plate has deeply deformed the area with a strong restriction of the original wider Paleocene basin.

Basin fill consists of very thick mostly due to Eocene sediments with more than 3 s reflection time in two deep basins, and more than 5 s in the foredeep of the Balkanides (Finetti *et al.*, 1988). A thick Oligocene follows with more than 2 s in the two basins. Miocene is more than 1.6 s in the W-basin and more than 2 s in the eastern. This is explained by the more intense activity of

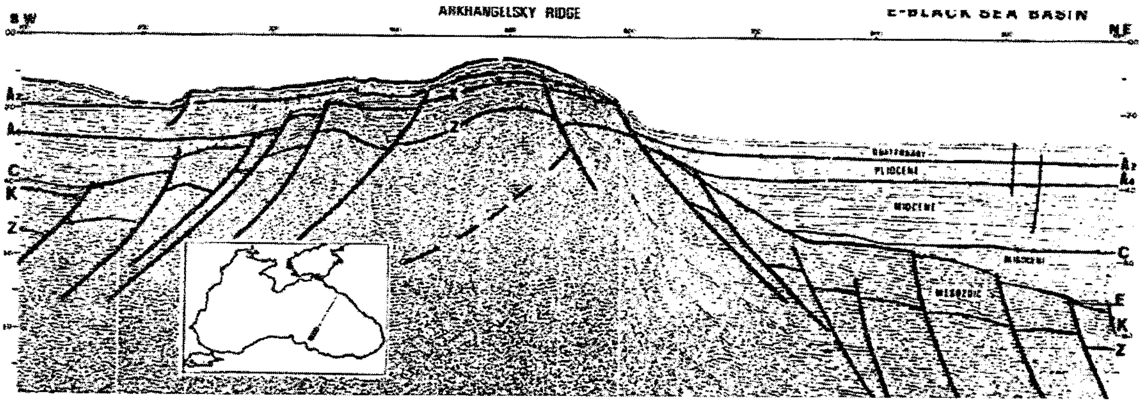


Fig. 6. Seismic section (SW to NE direction) crossing the Arkhangelsky ridge (from Finetti *et al.*, 1988).

Miocene times in the surrounding areas of the Eastern basin (Caucasus, East-Pontides). Pliocene and Quaternary are characterized by the thick Danube fan deposition in the Western Black Sea basin.

Chronostratigraphic position of seismic horizons (Fig. 4) was given by Finetti *et al.* (1988). An acoustic basement (horizon “Z”) is much more affected by distensive faults than (horizon “K”). Between “K” and “Z” exists a Mesozoic having a thickness variable from 0.4 to more than 1.4 s (about 800 to 2800 m). There are evidences that many faults commenced in middle-lower part of the reflecting Mesozoic interval and ceased their activity much before the end of Cretaceous. Regarded in its totality, the Mid-Black Sea ridge shows two fans affected by listric faults, which connect the feature to two basins having different crustal characteristics. In the Western Black Sea basin interval “KZ” (Mesozoic) becomes progressively thinner to missing. In the deep Western Black Sea basin horizon “K” corresponds, or it is very close to the acoustic basement and is attributable to the top basaltic basement. In the Eastern Black Sea basin, the basement (“Z”) is everywhere covered by a Mesozoic (interval “KZ”) of varying thickness, but with seismostratigraphic characteristics similar to these of the flank of the Mid-Black Sea ridge. The Southeastern part of Mid-Black Sea ridge locally shows a moderate compressive deformation connected with the orogenic movements of the Pontides.

Sediment back stripping and corrections for isostatic compensation (Degens *et al.*, 1983) show that the Black Sea proper originated as a marginal basin in the Upper Cretaceous (Letouzey *et al.*, 1977; Sengor and Yilmaz, 1988). The basin has been under going more-or-less continuous sedimentation and tectonic subsidence. The interval sedimentation rate varied between 0.1-0.6 m/ka for the period 5.3-0.7 Ma, but increased sharply to 1.2-1.3 m/ka starting in the Cromerian, when lacustrine megavarve deposition and episodic slumping set in. During the past 20 ka, the sedimentation rate has been controlled primarily by climatic changes (Paluska and Degens, 1979) and the impact of man. During the peak Weischel Ice age, rates were characteristically low because of the wide areal coverage of ice sheets and permafrost in a reduced drainage area. From 15 to 7 ka before present, there was a rapid increase in sedimentation rate as a result of deglaciation and massive release of detrital material. From there on to about 2 ka before present, it is averaged around 10 cm/K, only to rise again as a consequence of the activities of man, especially via deforestation and land use. Although there is excessive supply of terrigenous sediment (exceed 100 million tones Per annum) in Black Sea, pelagic sedimentation plays the major role in the deep basin. Those sediments are rich in calcite and organic carbon, the latter showing a high degree of presentation due to anoxia in waters below 100-150 m (İzdar and Ergun, 1991).

Economical potential of the Black Sea and recent studies

Recent studies in marine geology indicate potential geo-resources in the Black Sea. Burial history modelling and source kitchen mapping indicate that the oil-prone source rock of most probably Late Eocene age, is currently generating both oil and gas in the post-rift basin. The Black Sea is bordered by two of the world’s oldest petroleum provinces : to the Northeast, the Indolo-Kuban basin, to the northern foreland basin to the Greater Caucasus, and to the Northwest, the

Eastern Greater Carpathians and their foreland, the Moesian Platform. There are also small compressional structures off the northern Turkish coast related to the Pontide deformation; these may include Eocene turbidite reservoirs. These extensional fault blocks of the Andrusov Ridge (Mid-Black Sea High) are seen as having the best potential for large hydrocarbon volumes, but in 2200 m of water (Fig. 5). Explorations are underway and some drilling sites have been determined and shall be drilled during the very near future.

If the expanding hydrocarbon exploration and production industries of the region are to operate safely then the threat from methane seeps must be properly assessed. In the deep basin mud volcano eruptions are certainly formed by breakdown of methane hydrate on huge scale. Turbidites are common features of the Black Sea. The source of energy required to trigger turbidite flows is unknown, but three possible agents are methane production and earthquakes, both of which can lead to sediment instability and slope failure and oversteepening of delta fronts.

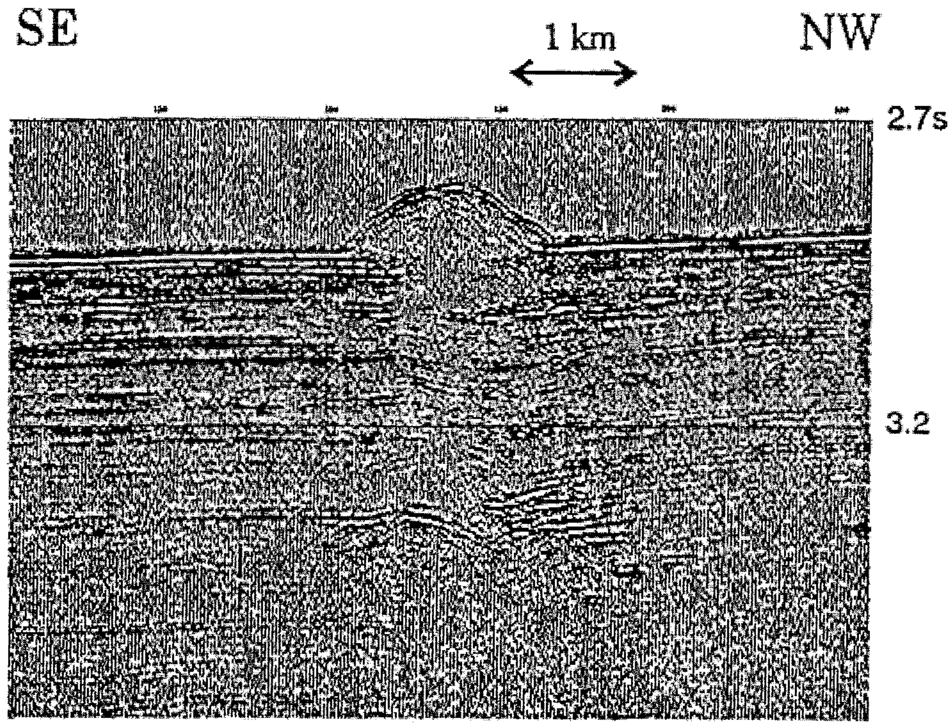
Some marine geophysical surveys have been carried out in the Black Sea using state-of-art technology to produce sonar and high-resolution maps. Since 1991 the Black Sea has been investigated by the group formed around the UNESCO/TREDMAR Training-Through-Research program. Works were carried on the subjects of :

- geochemistry of organic matter in sediments and rocks of the Black Sea;
- the Black Sea mud volcanism: origin, geochemistry and composition of mud breccia;
- nature of acoustic anomalies on seismic and sonar records;
- gases and gas hydrates in the Black Sea;
- stability and geohazard problems on the continental slope areas.

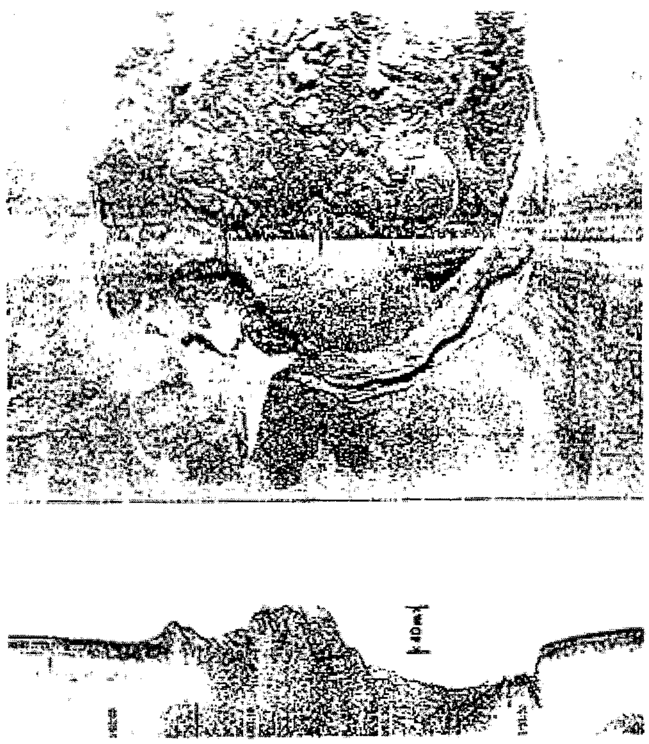
The depositional record in the Black Sea sediments is complicated but contains clues for understanding the climatic and geological history of the surrounding region. The key issues about the Black Sea sediments revolve around establishing the accumulation chronology and the "pluffy layer" transition from particles settling through the water column to those permanently buried in the sediments. The preservation of organic carbon in the sediments is poorly understood.

The Black Sea is one of the richest waters having immensive hydrate accumulations. Methane seeps are a common feature around the Black Sea basin, and mud volcanoes have been identified (Fig. 7). It has been suggested that shelf and slope sediments of high deposition rate are methane sources, whereas the deep basin is methane sink. Methane is geologically (and economically) important for three reasons. First, it is postulated that methane production and migration in sediments may be one cause of massive slope failures, second, methane seeps may indicate the presence at depth of hydrocarbon reservoirs, and third, methane hydrate may be an important source of energy in its own right.

Deep-sea mud volcanism is known from many different parts and tectonic settings from all over the world. These features are important, because they can provide unique information about the deeper geological structures and lithologies and, through the study of the composition and age of the associated gas and traces of hydrocarbons, on the source rocks and geochemical conditions at depth. The known Black Sea mud volcanoes are randomly distributed at depths below 2 km in an area of about 65-km^2 South of the Crimean Peninsula. They generally have a mushroom or cone-like shape with diameters varying from 1 to about 3 km and rise 20-150 m above the surrounding, relatively flat seafloor. The central part of the Black Sea, where the mud volcanoes are situated, structurally belongs to the West Black Sea subbasin. It is underlain by suboceanic crust and contains a sedimentary basin-fill on top of the basement of up to 15 km thick. The sedimentary layers are almost horizontal in the greater part of the subbasin; but in the mud volcano area they locally influenced by low amplitude folds, flexures and normal faults. The mud volcano feeder channels, which may originate in the thick Maikopian Formation, are expressed on seismic sections in the form of columnar disturbance with chaotic and indistinct seismic reflection patterns, in contrast to the well -stratified basin-fill sediments. Sediments bend down towards the feeder channel with increasing bright spots occur at different depths, but their greatest number is between 400 and 600 ms (TWTT) below the seafloor.



(a)



(b)

Fig. 7. **(a)** Seismic reflection profile over the Malishev mud volcanoe. **(b)** Side scan sonar and subottom profiler records over the Tredmar mud volcanoe.

Reasons for scientific drilling in the Black Sea

Although ODP (then DSDP) work was carried out in the Black Sea during early 1970's and 3 holes (379, 380 and 381) were drilled (Ross *et al.*, 1978). But all these were for the purpose of understanding of the recent sedimentation in the basin and they gave the information to the horizon of the top of the Pliocene only. However it may be time to understand the structure and evolution of the basin through the drilling over the Mid-Black Sea Ridge because it could be reached down to the levels of the Paleocene/Cretaceous especially over the Arkhangelsky ridge are of reasonably shallower waters. Also it would be interesting to drill some of the mud volcanoes for the understanding their formations and gas hydrate problem.

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A multidisciplinary *in situ* investigation on the physics of crustal deformation: the Gulf of Corinth Deep Geodynamic Laboratory

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Fluids and faults

The goal of this project is to develop an *in situ* laboratory for obtaining data on the physics of earthquakes and, more generally, on fault mechanics. Particular emphasis will be placed on documenting the role of fluids on fault behaviour and the role of faults on fluid flow in an active rift.

The fact that fluids play an active role in earthquake rupture processes has long been recognised, either from geological observations on exhumed fault material (Sibson, 1992, 1994) or from physical considerations, in particular the lack of anomalous heat flux along the San Andreas fault (Lachenbruch and Zoback, 1992). But very few data are available concerning hydrological response to seismic excitation. They all involve surface, or subsurface observations (Roeloffs, 1988). No data has ever been recorded in active faults during earthquakes. Further, the hydrologic properties of faults remains poorly documented, even if some data starts coming out from recent investigations on core samples collected within the fault associated with the Kobe earthquake (Naka *et al.*, 1998)

Surface hydrological observations (Muirwood and King, 1993) together with recent SAR deformation images obtained after the Landers earthquake (Pelzer et al, 1998) suggest that fluid flow associated with earthquakes may affect very large domains for long periods of time. But Pelzer *et al.*'s considerations come from satellite observations of deformation. No direct hydrologic data are available. In order to document the proposition that earthquakes involve large-scale pore pressure variations, the idea is to set up in a seismically active zone a set of measuring points at various depths for monitoring pore pressure variations.

Although fault healing is well known to occur because of scaling, depending on pressure and temperature conditions as well as on the mixing of fluids with various origins (Boulègue, 1997), its consequences on the rate of change in permeability as well as on the strength of the fault are not well documented. This comes mainly from the lack of data on the *in situ* conditions with respect to temperature, pressure, flow rate, morphology of the interconnected pore space and its relation to the chemical composition of circulating fluids. So, one of the main objectives of this project is to provide data on *in situ* flow conditions, below, within and above a recently activated fault. Furthermore, plans are to provide means for recording continuously the pore pressure before, during and after an earthquake within a fault zone and around it.

Results from the Parkfield experiment in California (Nadeau and Johnson, 1998) have shown that downhole seismic recording provides the possibility of detecting much smaller events than standard surface recording techniques. The large data sets on microseismic activity gathered at Parkfield during the last 10 years has shown the existence of asperities which slip apparently at recurrent times possibly linked with fluid diffusion. The question arises as to whether this is specific to the San Andreas Fault system or whether it is a characteristic of most fault behaviour.

In order to answer these questions, it has been proposed to develop a deep *in situ* laboratory so as to gather data on earthquake sources and on fault mechanics. The most suitable place in Europe for such a laboratory is in the Gulf of Corinth because of its active tectonics (Fig. 1).

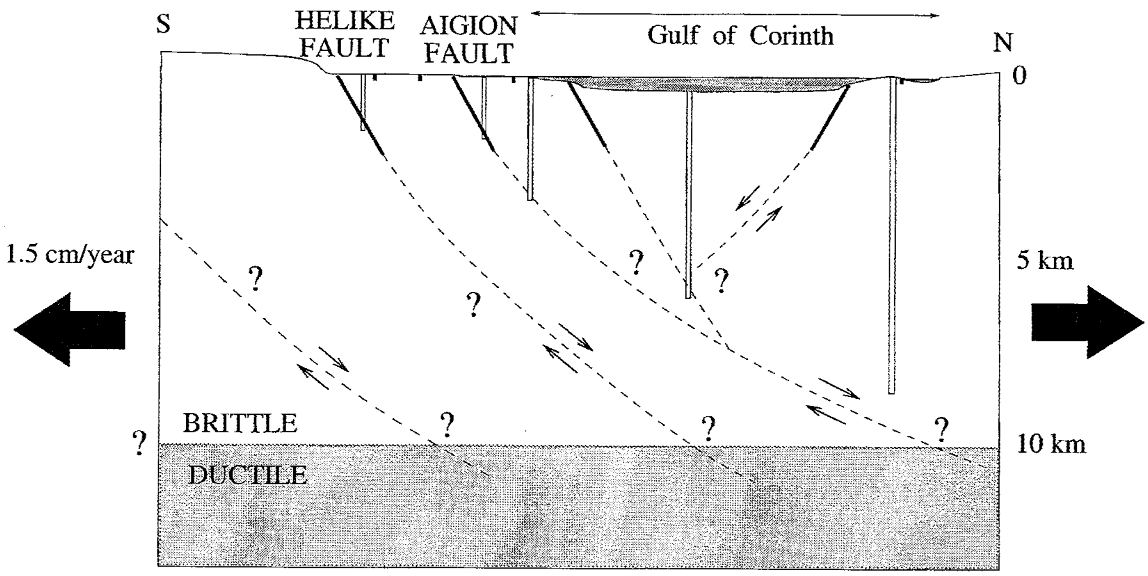

Fig. 1. Development of the Deep *in situ* Geodynamic Laboratory in the Gulf of Corinth : Plans are to install in increasingly deep boreholes various sensors for documenting the relationship between fluids and fault mechanics.

THE GULF OF CORINTH DEEP GEODYNAMIC LABORATORY

The Gulf of Corinth is presently the fastest opening continental rift in the world with an opening rate somewhere between 10 and 15 mm/y and the tilting and uplifting of its southern shore at a rate which reaches locally 1 mm/y (Armijo *et al.*, 1996). This fast opening is associated with a shallowly northerly dipping seismic zone located at depths ranging from 6 to 9 km. Five events of magnitude larger than 6 have been observed in this region within the last 30 years Comparison between GPS observations (Kahle *et al.*, 1996) and cumulated seismic activity shows some discrepancy which may be attributed to non seismic deformation in the upper 4 to 5 km of the crust (Briole, 1999). Yet the significance and the mechanics of this non-seismic deformation remains to be documented.

Ten years of multidisciplinary observation and collaborative research in the Gulf of Corinth, supported in particular by EC programs, have allowed the selection of a target area (Bernard *et al.*, 1998). It is located on the normal fault system close to the city of Aigion, which is one of the most seismically active areas of the Euro-Mediterranean region (see figure 2). The city of Aigion itself was struck by a magnitude 6.2 earthquake in 1995.

An ICDP (International Continental Drilling Program) supported international workshop, held in Athens in October 1997 (Cornet *et al.*, 1998), helped mature this idea. Now the project of

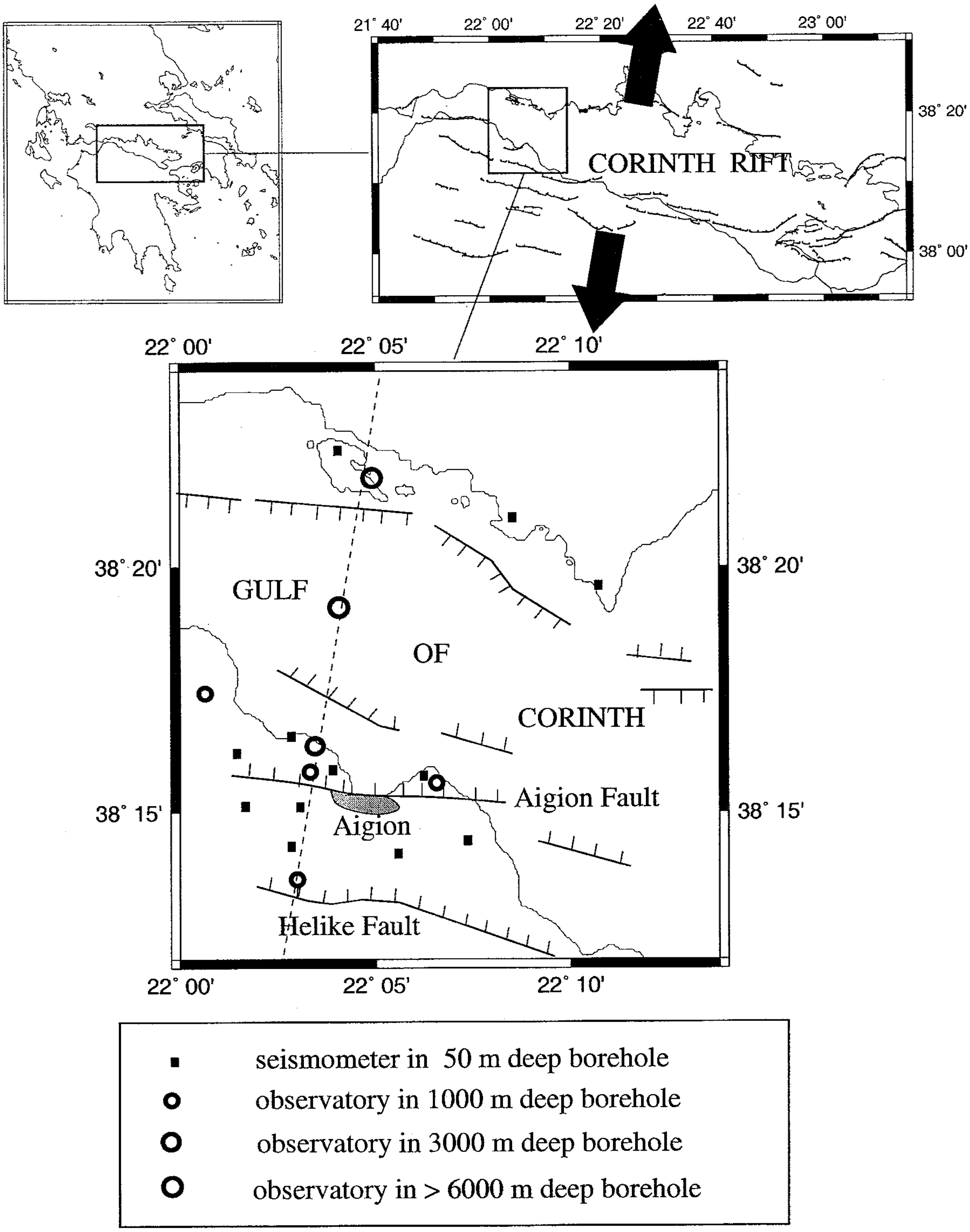

Fig. 2. Location and instrumentation of the Gulf of Corinth Deep Geodynamic Laboratory.

developing a Deep Geodynamic Laboratory in the very active rift of Corinth has been endorsed by ICDP and some funding has been obtained for setting up a local permanent sub-surface seismic network in the Aigion-Eratini area. A long term, multiphase project has been defined. Each phase, of 4 to 5 years duration, involves increasingly deep boreholes (1 000 m, 2500 to 3 000 m onshore, 6 000 m offshore, 8 to 10 km onshore), and, correlatively, increasingly deep *in situ* continuous observations.

Present activity : Instrumenting, on shore, from ground surface down to 1000 m

Onshore, near Aigion, two active faults can be investigated, the Aigion fault and the Helike fault. The Aigion fault is relatively short (less than 10 km) but it has been reactivated in 1995 by a magnitude 6.2 earthquake. Very little evidence of surface deformation was mapped after the event. Hence it is anticipated that the rupture front died out progressively as it got toward the surface. One of the goals of the project is to try to document possible variations in fault hydraulic characteristics as one gets closer to ground surface. The much longer Helike fault (more than 50 km) has not been activated since 1861 when it gave rise to an earthquake of magnitude somewhere between 6.5 and 7. Hence it is anticipated that the healing process is quite developed in that fault.

This area has been chosen for installing downhole seismic sensors so as to determine whether the apparent lack of seismic signals in the upper 4 km is linked to attenuation effects or whether indeed no signal is generated within this depth range. In addition, some continuous GPS stations are being deployed so as to monitor precisely the deformation process of this sector.

It is planned to document the hydraulic properties of both the Aigion and the Helike faults so as to investigate the consequences of healing. This will be done by drilling through the faults first at a depth of 1000 m. The boreholes will provide means to retrieve hydraulic, mechanical, geochemical and geological data, thanks to logging, coring and *in situ* measurements (stress measurements, vertical and oblique seismic profiles, temperature profiles). Evidence for repeated breakage and sealing of cracks and veins in the cores will be looked for, and interpreted in terms of successive earthquake ruptures. These results will be confronted to observations retrieved from fault trenching at ground surface

Because one of the main goals of this *in situ* laboratory is to document the faults hydraulic characteristics and their variation both in time and space, the sites will include two additional boreholes intersecting the strongly dipping faults around a depth of about 400 m. This will make possible running hydraulic interference tests coupled with chemical tracers so as to characterise the permeability of the fault systems and to monitor its possible variation in time.

A preliminary site reconnaissance will be conducted with seismic and electromagnetic profiles in order to identify precisely the geometry of the faults. These data, correlated with logging, borehole seismic profiles, core data, and the results from monitoring the microseismic activity will help obtain an accurate 3D understanding of the velocity field of the site together with a precise description of the fault geometry and its variation with depth. This is one of the key questions raised by the understanding of the rifting activity around the Gulf of Corinth : Is the observed low dipping seismic zone the result of listric faulting or does it result from a dense pattern of steep dipping normal faults and their antithetic conjugates ? If listric faulting occurs, it has been proposed to link fault dip variation with depth with changes in material properties. Accordingly accurate determination of the fault zone mechanical properties will be conducted in the laboratory thanks to the cores retrieved from the wells.

Project : Instrumenting the Seismogenic zone by offshore drilling

The program to be run in the 1000 m deep onshore boreholes will constitute a very useful learning process and will help improve our understanding of the downhole fault geometry. But it will not provide data from the seismogenic zone and thus will fail answering the precise questions on the physics of earthquake faulting. It is only once the seismogenic zone has been instrumented that answers to the exact role of fluid on the dynamics of rupture processes will be documented. Also, it is only through *in situ* measurements that the stress state and the temperature field will be evaluated. Further, the determination of the mechanical properties of the material required for modelling the rift opening process can only be obtained from cores collected at the right depths. Analysis of the borehole failure processes that are likely to occur at those depths will help further constrain the constitutive equations of the geologic materials encountered at those depths.

It is anticipated that an intermediate depth (2500 to 3000 m) borehole may be necessary to further refine our understanding of the fault geometry. But it is only when a 5 to 6 km deep well is drilled offshore that it will be possible to gather the required data for advancing our understanding of earthquake mechanics. Hence our proposition to ODP to perform the required deep well and to help deploy offshore seismometers and possibly downhole instruments in shallow wells (in the order of 500 to 1000 m) in order to obtain better constraints on fluid flux and location of seismic activity in this fast opening rift.

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The Hellenic Subduction Zone, a world site to study the mechanics of roll back

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SIGNIFICANCE OF THE HELLENIC SUBDUCTION ZONE AND THE ISLAND OF CRETE

The Eastern Mediterranean hosts one of the most prominent retreating convergent margins worldwide. Moreover, rollback at the Hellenic subduction zone is recorded over the past ca. 35 million years, with an intermittent stage of microcontinent collision between about 30 and 20 Ma, and incipient collision with the passive African margin today. The island of Crete represents a horst structure developed within the last 5 million years in the central forearc and provides excellent onshore access to the internal structure of the forearc at various levels. Thus, the Hellenic subduction zone is considered an ideal region to study the mechanics of roll back and related tectonics in space and time.

ACTIVE TECTONICS DOMINATED BY ROLL BACK

For the area of Crete (ca. 25° E / 35° N), the geology based NUVEL-1A model of relative plate motion predicts a convergence between Africa and stable Eurasia with a rate of 0.9 cm/year and a direction of 353°. On the other hand, space geodesy reveals that Crete and the southern part of the Aegean is moving to the SSW with respect to stable Eurasia. The velocity of this motion is ca. 3 to 4 cm/year (Jackson, 1994; Le Pichon *et al.*, 1995) and represents the rate of roll back, resulting in a net convergence rate of 4 to 5 cm/year at the plate boundary. The Benioff Zone seismicity reaches down to ca. 200 km, being located at a depth of ca. 140 km beneath the magmatic arc, with active volcanism on the islands of Aegina, Milos, Santorini and Nisyros. The slab has been traced to 600 km by tomography (Wortel *et al.*, 1990). The thickness of the crust beneath the Sea of Crete, i.e. between Crete and the magmatic arc to the North is locally reduced to less than 16 km (Makris and Röwer, 1986; Makris pers. comm.) correlated with a high heat flow. Active crustal stretching has not been detected by space geodesy, however. Deep topographic furrows to the South of Crete represent forearc basins commonly attributed to strike slip motion (*e.g.* Le Pichon *et al.*, 1995). The "backstop" to the active accretionary complex beneath the Mediterranean Ridge (Mascle and Chaumillon, 1997) is located further to the South. Thin continental crust of the upper plate extends for more than 100 km to the South and Southwest of Crete (Makris, pers. comm.; Truffert *et al.*, 1993). This means that a thin lid of continental crust is sliding on top of the downgoing plate and that its southern edge acts as the backstop to active accretion.

PRE-NEOGENE HISTORY OF CRETE, THE RECORD OF COLLISION AND EXHUMATION

Crete represents a window that provides insight into the internal structure and tectonic history of the forearc. The major part of the pre-Neogene basement exposed on Crete (comprising the "lower nappes") is derived from the sedimentary cover of the microcontinent (*e.g.* Bonneau, 1984; Papanikolaou, 1984), that – as a part of the African plate – entered the precursor of the Hellenic subduction zone in the Oligocene/Miocene. In the course of collision, the sedimentary cover of the microcontinent (apart from a unit that was offscraped in a shallower level) has been buried to ca. 30 to 35 km depth, as recorded by the ca. 25 to 20 Ma high pressure-low temperature metamorphism (*e.g.* Seidel *et al.*, 1982; Jolivet *et al.*, 1996). These rocks were exhumed within a very short time span after HP-LT metamorphism, forming the footwall of a major extensional detachment (Fassoulas *et al.*, 1994), and were back in the upper crust by about 19 Ma (Thomson *et al.*, 1998a). Both, the rates of burial and exhumation with the given time constraints cannot be accounted for by Africa-Europe plate convergence, but require roll back, as demonstrated in the model proposed by Thomson *et al.* (1998a; 1999) and shown schematically in Fig. 1. Oblique exhumation of the microcontinent into the space created by continuing roll back, driven by buoyancy forces after detachment from the downgoing lithosphere, has been termed "buoyant escape".

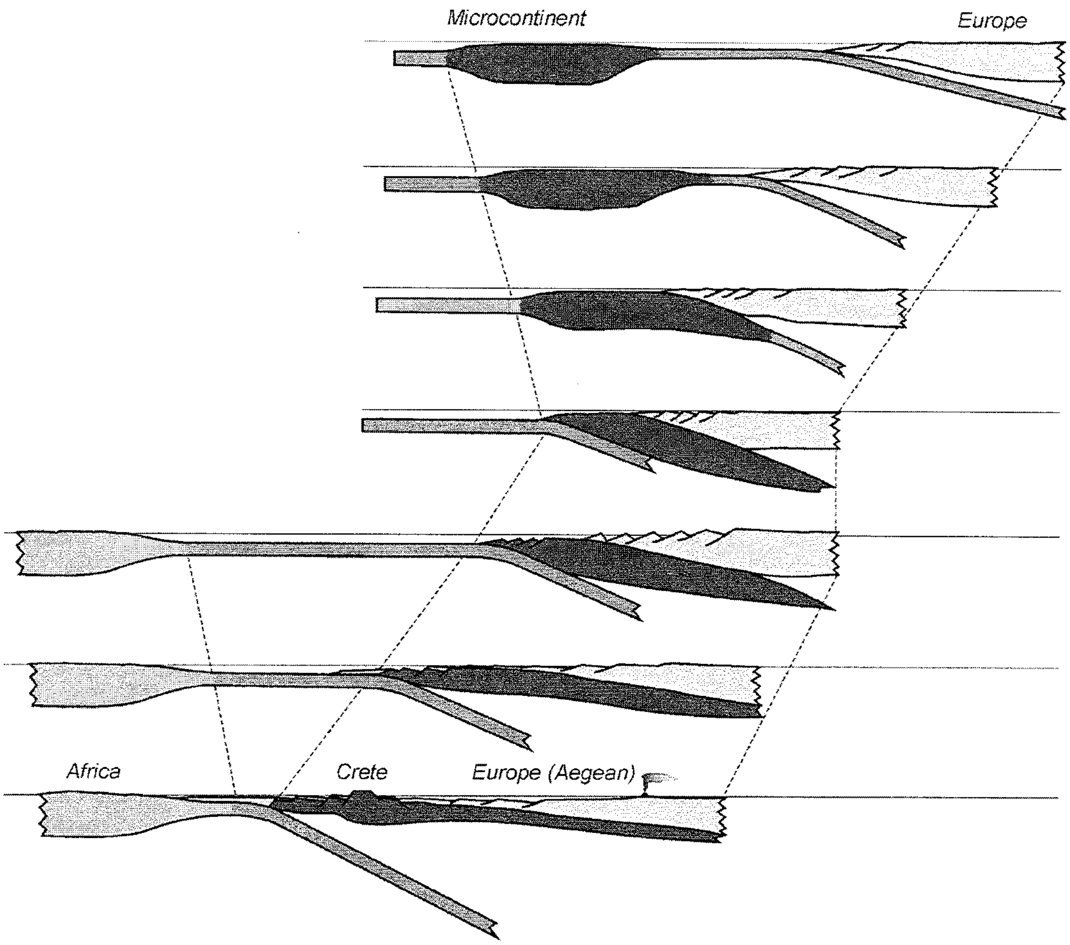

Fig. 1. Inferred tectonic evolution of the Hellenic subduction system since about 35 Ma in NNE-SSW cross section (not to scale). Note the continuous relative motion between Africa and Eurasia and the significant contribution of roll back to the net convergence at the active margin. According to the model proposed by Thomson *et al.* (1998a, 1999), exhumation by buoyant escape compensated extension within the upper plate for a short time, followed by renewed extension mainly localized in the sea of Crete. Also note that Crete became a morphological high only since about 4 Ma, for yet poorly understood reasons.

Whereas the deformed and metamorphosed sedimentary cover of the microcontinent is exposed on Crete, the original basement of these series is generally not exposed and largely unknown. The nearly continuous stratigraphic record from the late Paleozoic to the mid-Tertiary, when the onset of flysch sedimentation signals the approaching active margin, unequivocally suggests that sedimentation took place on continental crust of normal thickness. Since the original width of the microcontinent has been estimated as up to 300 km (Bonneau, 1984), tectonic models need to predict the present whereabouts of a considerable volume of continental material. According to the buoyant escape model, the microcontinent is expected to constitute the bulk of the crust in the present forearc, from Crete towards the South, strongly thinned by radial and tangential extension. Thus, the inner backstop to the presently active accretionary wedge (Mediterranean Ridge) may be formed by the more or less disintegrated original southern passive margin of the microcontinent.

The buoyant escape model of extensional exhumation gets strong support from the fact that thin veneer of remnants of the active continental margin of the upper plate to the Oligocene/Miocene collision zone has been preserved on the very top of the Cretan nappe pile (Fig. 1). These remnants (even found on the southernmost island of Europe, Gavdos) constitute a mixture of crustal slices with pre-Tertiary metamorphism, including ophiolites of Jurassic age, and are referred to as "Uppermost Tectonic Unit", according to their structural position on Crete. In sharp contrast to the HP-LT metamorphic sedimentary cover of the microcontinent, the remnants of the active margin have resided in the upper few kilometers of the crust throughout the collisional process, as shown by low-temperature thermochronometric results (Thomson *et al.*, 1998b). Thus, their preservation precludes a significant contribution of erosion to the exhumation of the HP-LT-metamorphic microcontinent, as accounted for by the buoyant escape model (Fig. 1). More important, the Uppermost Unit appears to represent a perfect analogue to the present day situation, with a thin lid of continental crust spreading on top of the downgoing plate. The mechanics of these processes, i.e. the coupling between the plates, the transfer of forces and the resulting stress field that drives extension of the upper plate are poorly understood and remain to be analyzed in detail.

Neogene history of the Hellenic forearc, stretching due to roll back

At the time of collision in the early Miocene, the active margin was situated several hundreds of kilometers to the North of present Crete (Angelier *et al.*, 1982). During the first post-collisional stage, roll back may have been fully accommodated by buoyant escape of the microcontinent (Fig. 1; Thomson *et al.*, 1999). Subsequently, stretching and crustal thinning became inhomogeneously distributed over the forearc, with a period of localization in the Sea of Crete. The margin became strongly convex towards the South, presumably controlled by along strike variations in the negative buoyancy of the subducted African plate. The frontal part of the forearc is now undergoing contraction due to incipient collision with the African passive margin. On Crete, the local kinematic pattern is recorded by faulting history (*e.g.* Armijo *et al.*, 1992) and stratigraphy of the exhumed Neogene basins (*e.g.* ten Veen *et al.*, 1998). A more complete understanding requires information on the transfer of tectonic activity in space and time over the entire forearc. This is particularly true for the region between Crete and the backstop to the Mediterranean Ridge and for the Sea of Crete as the site of prominent crustal stretching, both areas only accessible by marine geophysics and offshore drilling. Finally, it is not understood which forces cause the strong localized uplift of Crete during the past few millions of years.

Fundamental questions to be solved

Fundamental questions related to both, the specific Hellenic setting (as a world site for retreating subduction zones) and the mechanics of roll back and subduction in general, can be formulated as follows:

(1) How is the mechanical coupling between the plates?

(2) Which forces drive the extending forearc continental lid to slide onto the incoming plate?

(3) At which level has the thin veneer of upper plates continental crust originally been decoupled? What are the subsequent kinematic pathways and their structural record?

(4) What are the geometrical pathways of the extensional exhumation of the subducted micro-continent? Is the proposed asymmetric buoyant escape process feasible? Can this model serve as a general concept for continental growth at retreating subduction zones?

(5) How is forearc extension partitioned in space and time? Over which time span and by which process did the Sea of Crete form? When and within which kinematic framework did the deep forearc basins, the so-called trenches form? What can be learnt from the lateral transfer of active deformation on the coupling between the plates?

(6) What determines the position of the boundary between contractional and extensional deformation – the "backstop"?

(7) What makes Crete actually rise up? When and why did this uplift commence and what is the mechanical significance?

The fact that most of these questions can be addressed both from points of view, the present day physical state of the subduction zone as well as the record of the recent geological past, makes this situation particularly attractive and stimulating for interdisciplinary research.

The role of scientific drilling

An international research program is currently on the way, that encompasses proposals of scientific drilling, both onshore Crete and offshore, in order to provide the required complete information on the upper crustal deformation history and the present physical state along a transect normal to the plate boundary (Fig. 2). For the given physiographic situation, offshore drilling in combination with marine geophysics provides the only access to direct information on the history and provenience of the basement, the stratigraphic/tectonic record of the Neogene cover and the nature of the physiographic features developed at the seafloor. Thus, marine geophysics and drilling are both essential to resolve the forearc evolution in space and time, in combination with

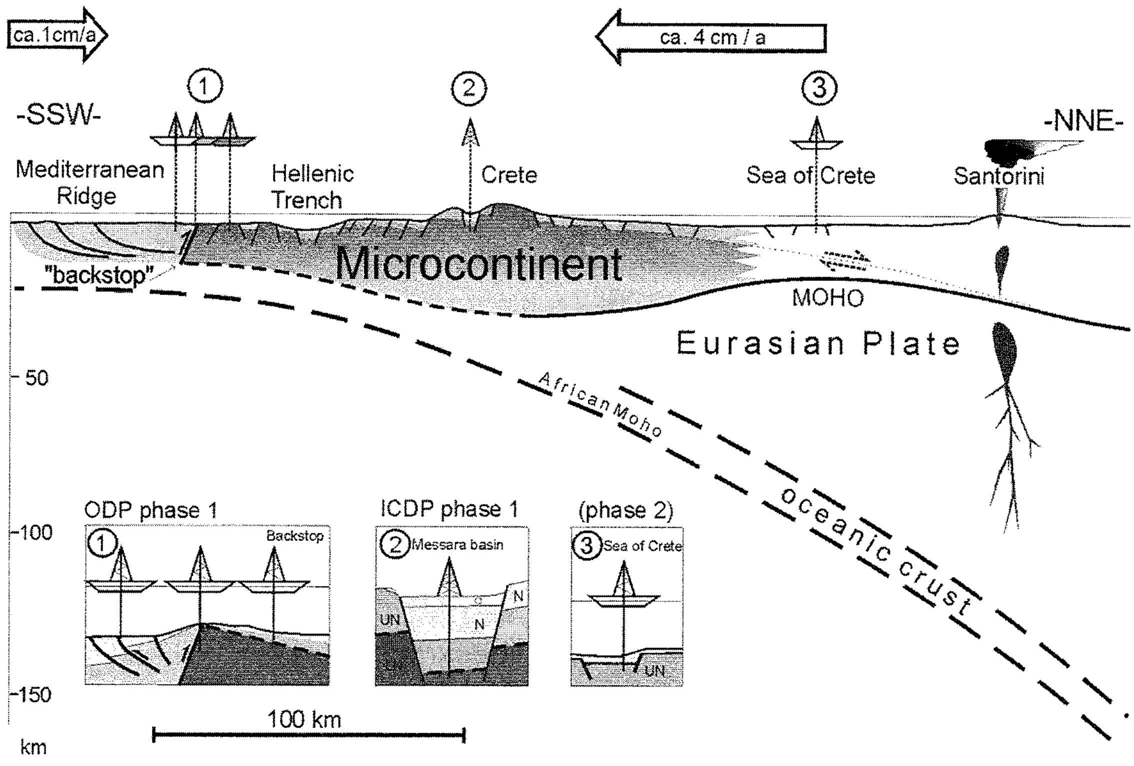

Fig. 2. Cartoon showing the basic concept of combining offshore (ODP) and onshore (ICDP) drill holes into a transect, providing information on both the tectonic evolution and the present day physical state of the crust. The array should be used as a long-term observatory in this tectonically most active region of Europe and the Mediterranean Sea.

the excellent onshore access on Crete. More important, onshore and offshore drilling are the only means to obtain information on fundamental properties like heat flow and state of stress as a function of depth, both related to interplate coupling.

It is suggested to develop an integrated drilling concept within the scope of the Ocean Drilling Program (ODP) and the International Continental Drilling Program (ICDP), based on the following presumptions:

(1) the program should be designed on a modular basis with long-term planning and coordination between onshore and offshore activities;

(2) multi-purpose holes are to be preferred, with a series of targets to be reached at increasing depths (with increasing risk and costs) and benefit to a broad community;

(3) selection of drill sites should be based on optimization between the requirements of the individual targets and on the fit into the desired final array. In general, this may require compromises;

(4) all drill holes should be used for the installation of a long-term observatory to record active processes ("Earth Window").

For instance, a current ODP proposal suggesting offshore drilling into the backstop of the Mediterranean Ridge (Fig. 2; site number 1) is primarily designed to study the actual hydrological conditions at the rear of the accretionary wedge and get access to the deep biosphere. However, it may simultaneously provide the possibility to test the tectonic hypothesis outlined above. Recovery of samples of the pre-Neogene basement beneath the backstop would allow to identify the nature of the rear of the microcontinent (if the model is right) and its thermal and tectonic history. In terms of onshore activities, a 3 to 4 km drill hole in the Messara Graben in Southern Crete is under discussion (Fig. 2; site number 2). This hole is expected to provide (1) a continuous record of post-collisional sedimentation related to tectonics, (2) information on the nature and internal structure of the Uppermost Unit, undisturbed by the otherwise ubiquitous landslides, (3) information on the structural record at the base of the Uppermost Unit as a fossil analogue to the base of the present thin forearc lid emphasized above, and – at maximum depth – (4) the structural and thermochronometric record at the top of the high pressure-low temperature metamorphic cover of the microcontinent beneath the extensional detachment. The latter information is essential to test the buoyant escape hypothesis along a prolonged North-South baseline on Crete. Finally, a four kilometer hole yields invaluable information on heat flow, fluid phases, state of stress and other fundamental crustal properties related to the present day geodynamic situation, undisturbed by surface effects. Future drilling targets would be the area with thinned crust and high heat flow beneath the Sea of Crete (Fig. 2; site number 3) and the continental crust of the inferred microcontinent beneath Crete.

In combination these drill holes constitute a geophysical laboratory that allows studying fundamental crustal properties and effects of subduction, including – with proper instrumentation – their variations in time ("Earth Window"). To establish and maintain such a laboratory in the tectonically most active region of Europe could be an outstanding European task, last not least in view of the evaluation of seismic hazards, that clearly require an improved understanding of the mechanical state of the system.

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Land-based drilling project in the forearc of the retreating Hellenic subduction zone, Crete, Greece

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Introduction - Geodynamic position of Crete

The tectonic units of the Hellenides can be grouped in nine domains, each one representing a distinct tectonostratigraphic terrane (Papanikolaou, 1992, 1996, 1998). Four terranes (Pindos-Cyclades, Vardar-Axios, Circum Rhodope and Volvi-East Rhodope) are of oceanic origin, representing distinct basins of the Tethys Ocean. The rest five terranes (External Hellenides Platform, Internal Hellenides Platform, Paikon Block, Rhodope Massif and Vertiskos Massif) represent pre-alpine continental crustal fragments drifted away from the passive Northern African margin during Late Paleozoic - Middle Triassic and covered mainly by shallow-water carbonate sedimentation during their Mesozoic to early Tertiary paleogeographic evolution within the Tethys Ocean.

The overall alpine development of the Aegean lithosphere is the result of the continuous convergence process comprising: (i) subduction of the Tethyan oceanic domains, (ii) micro-collision events between the Eurasian active margin and the incoming continental terranes (micro-continents) and (iii) rollback of the Hellenic subduction zone.

The presently active, retreating Hellenic subduction zone in the Eastern Mediterranean, is a prominent example of convergent plate boundary over the last 35 Ma, including an intermittent stage of collision with a micro-continent (External Hellenides Platform) between about 35 - 20 Ma b.p. The structure developed by the collision of the micro-continent with the Eurasian plate during Oligocene - Miocene is preserved and partly exposed on Crete Island.

Beneath Crete, the Moho is located at about 30 km depth and is expected to represent the Moho of the subducting African plate (Makris and Egloff 1998). Above the African plate, the upper portion of these 30 km – partly exposed on Crete – consists of the overriding Aegean (European) crust. It is composed of:

a) the basement of the micro-continent (not exposed) which collided with Eurasia 20-35 Ma b.p.;

b) the, in part HP/LT metamorphic, sedimentary cover of the micro-continent and

c) remnants of the upper (Eurasian) plate to the Oligocene/Miocene collision zone on top.

The latest, called Uppermost Tectonic Unit of Crete, is a fossil analogue of the thinned Aegean (European) crust which extends to the South of Crete and forms the backstop to the presently active subduction.

The subducted micro-continent became rapidly exhumed by extension concentrated in a low angle detachment fault and, according to the proposed "oblique buoyant escape" model, was driven by buoyancy into the space created by continued rollback of the subduction zone. After the exhumation of the HP metamorphic rocks (micro-continent and part of its sedimentary cover) in Miocene, the entire stack of tectonic nappes exposed on Crete represents the Aegean (European) upper plate to the presently active subduction. This upper plate has been extremely thinned by radial and tangential extension, related to the rollback of the subduction zone, while the precise history of thinning is poorly understood.

Geological structure of Crete

The alpine structure of Crete represents an accretionary complex composed of nappes with Oligocene - Miocene HP metamorphism (Seidel *et al.*, 1982; Theye and Seidel, 1991), in the tectonically deeper levels, and nappes lacking a Tertiary metamorphism in the tectonically higher levels (Fig. 1).

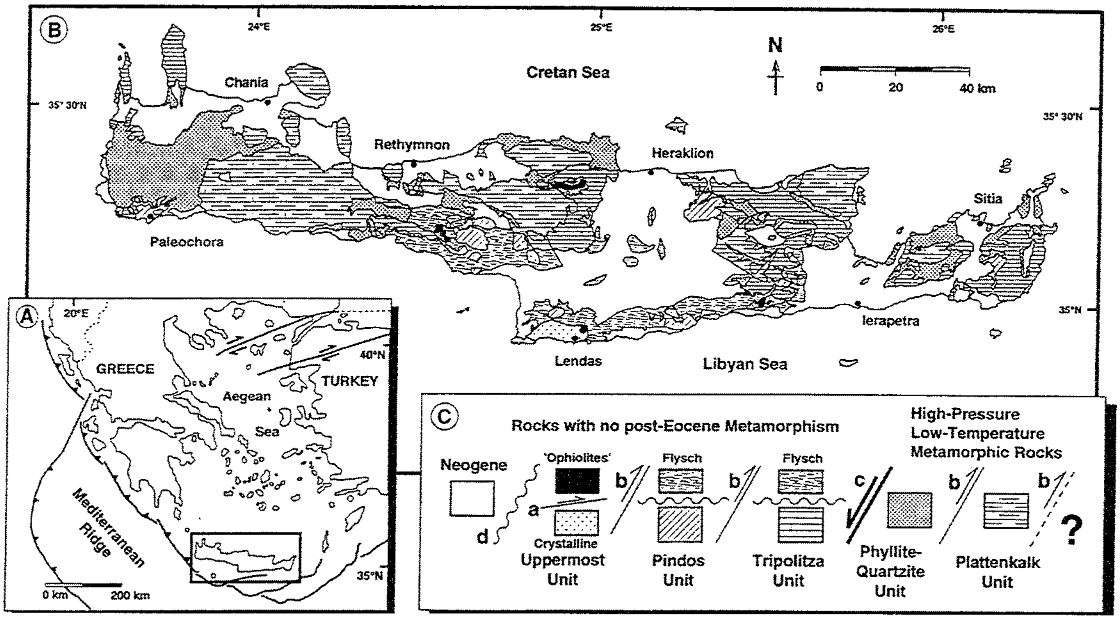

Fig. 1. Simplified tectonic map of Crete and scheme showing the stacking of the tectonic units (from Thomson *et al.*

The HP-metamorphic nappes (the "autochthonous" Plattenkalk unit and the Phyllite-Quartzite unit) and the lowermost unmetamorphic nappe (Tripolitza unit) represent the sedimentary cover of the micro-continent, namely the External Hellenides Platform, that entered the precursor of the present-day Hellenic subduction zone between about 30-20 Ma b.p.

The upper nappes without Tertiary metamorphism represent in part remnants of the oceanic realm separating the External Hellenides Platform micro-continent from the European margin prior to the collision (Pindos unit), and in part the front of the upper plate to the mid-Tertiary subduction zone (Uppermost tectonic unit). The remnants of this front of the upper plate are various, tectonically juxtaposed, crustal slices (metamorphic units of Mesozoic age with Jurassic to Cretaceous age of metamorphism, ophiolites, very low-grade metamorphic clastic sediments etc.).

Recent thermochronometric, microstructural and thermobarometric studies of the HP/LT metamorphic units (Theye and Seidel, 1991; Stoeckhert *et al.* 1999; Jolivet *et al.* 1996; Kuester and Stoeckhert, 1997; Thomson *et al.* 1996, 1997, 1998) have shown that the sedimentary cover of the micro-continent was subducted with plate velocity, detached at 30 to 35 km depth, and returned into the upper crust within a few million years. A major extensional detachment separates the unmetamorphic higher and the HP-metamorphic lower units (Fassoulas *et al.* 1994; Kilias *et al.* 1994, Jolivet *et al.* 1994; Truffert *et al.* 1993)

Since about 13 Ma b.p. Neogene sediments have been deposited on top of the exhumed accretionary complex (Meulenkamp *et al.* 1988). Extension and block faulting has continued (Angelier *et al.* 1982) and is active today, also reflected by seismicity and significant vertical displacements (Peters *et al.* 1985; Pirazzoli *et al.* 1982).

The present day geodynamic configuration of the island of Crete displays a rather atypical forearc high - horst structure, uplifted within the last 5 Ma, in the central part of the Hellenic forearc, on top of the shallow portion of the presently active subduction zone. It is bounded by E-W as well as N-S trending normal fault systems with cumulative displacement of 5-10 km and provides excellent onshore access to the internal structure of the forearc at various structural levels. The highest elevations on Crete are about 2,4 km with the lowermost tectonic units exposed on top of the mountains. The causes of the sudden and intense uplift of Crete during the last 5 Ma are not understood. This process may be related to the onset of collision with the Libyan margin before 3-6 Ma.

DRILLING STRATEGY

The concept proposed for the scientific drilling program is displayed on a schematic cross section in Fig. 2 (Papanikolaou and Stoeckhert, 1999). In view of the narrow island of Crete, the combination of land-based and offshore drilling offers the opportunity to study the crustal record, properties and present day physical conditions along an extended N-S baseline perpendicular to the southern segment of the Hellenic Arc.

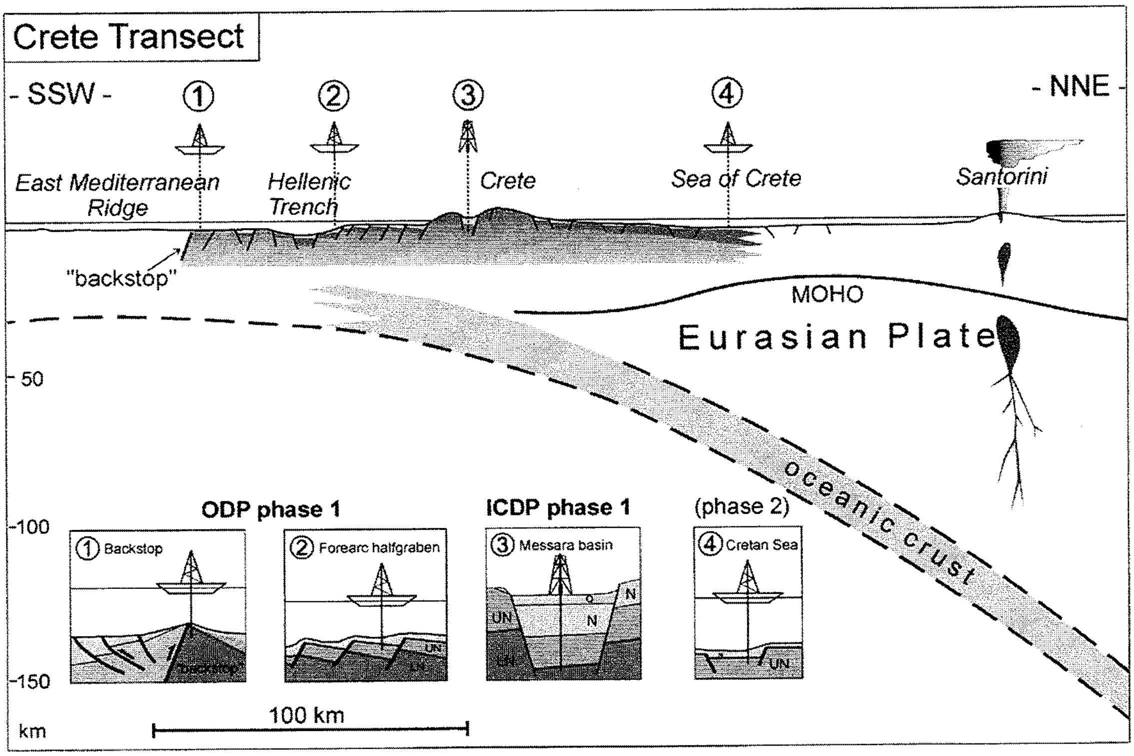

Fig. 2. Schematic cross section showing the principal features of the proposed concept for the scientific onshore and offshore drilling at the retreating Hellenic Subduction Zone.

Such prolonged baselines normal to strike are essential for, *e.g.*, the test of the models proposed for the exhumation processes of the subducted micro-continent (oblique buoyant escape model or symmetric stretching), the transfer of tectonic activity recorded in the Neogene stratigraphy and structures in space and time, or the present day gradients in stress field or heat flow, both related to the mechanical coupling between the subducting African plate and the overriding Aegean plate.

Thus the principal scientific goals of onshore and offshore drilling, which are listed below, are either identical or complementary :

Actual physical state of the crust: stress field, not influenced by topography, heat flow, not influenced by surface effects, hydraulic properties and fluid flow;

Tectonic evolution in the past 15 Ma, recorded by thick Neogene-Quaternary sedimentary sequences deposited in graben and half graben structures developed in the brittle upper crust due to tangential and radial stretching of the forearc;

Information on the collisional episode of 30 - 20 Ma and on the nature of the crust of the micro-continent, to testify/falsify the proposed exhumation concepts.

Furthermore the correlated approach within the scope of ICDP and ODP is in mutual agreement with the concept proposing a merger of both into an Earth Drilling Program from 2003.

Regarding the offshore drill sites, a full proposal has been already prepared and submitted to ODP by A. Kopf, A.H.F. Robertson, E.S. Screaton and J. Mascle. A brief description of the main concept of the ODP proposal is included in this volume too. The drill sites proposed to ODP are located to the south of Crete, from the Eastern Mediterranean Ridge accretionary prism across its backstop to the north , and correspond approximately to those labelled 1 and 2 in the scheme of Fig. 2. The drill site labelled 4 in the same scheme is located in the Sea of Crete and represents a possible future prolongation of the transect.

Two phases are foreseen in the proposed land-based drilling project on Crete :

Land-based drilling phase 1: Messara basin

An intermediate depth (3-4 km) land based drill hole is proposed in the Messara Graben, which corresponds to the site labelled 3 in the scheme of Fig. 2.

The Messara basin represents an E-W directed graben formed during Middle to Late Miocene (Late Serravallian - Tortonian) as a result of the extension, which has affected the Southern Aegean landmass at that time.

The basin is filled up by Middle to Upper Miocene clays, limestones and sandstones, Messinian gypsum, Pliocene marls, clays and sandstones and Quaternary terrestrial deposits as conglomerates and sand as well as gravitational deposits (fault breccia and talus). The Quaternary deposits indicate an increased neotectonic activity, which is consistent with the rapid uplift of the entire island since Upper Pliocene - Pleistocene.

However recent studies and preliminary observations from the Neogene - Quaternary basins of Crete (Kleinspehn, 1998), as well as from equivalent basins south of Crete (Finetti *et al.* 1990) indicate that they have experienced shortening suggesting that the strain is more complex than simple extension and may be partitioned in response to the obliquity of the convergence between Africa and Aegean.

The proposed drill hole will be based on the Quaternary deposits of the basin while the precise location remains to be defined based on results of ongoing geophysical experiments and pre-site surveys.

The drill hole is expected to reach the HP/LT lower units (Phyllites-Quartzites unit or Plattenkalk unit) at a depth of 3-4 km (Fig. 3), after having bored through the Quaternary-Neogene deposits of the Messara basin, the Uppermost tectonic unit, the Pindos and the Tripolis unit and the detachment zone, and to provide insight into :

(a) the late Tertiary to Quaternary sedimentary record of N-S extension and uplift of Crete;

(b) the internal structure, evolution and thickness of the Uppermost Tectonic Unit of Crete, and

(c) the nature of the detachment fault between the upper - non metamorphic - and the lower - HP metamorphic - units, and

(d) the thermal history of the HP/LT metamorphic rocks beneath the detachment.

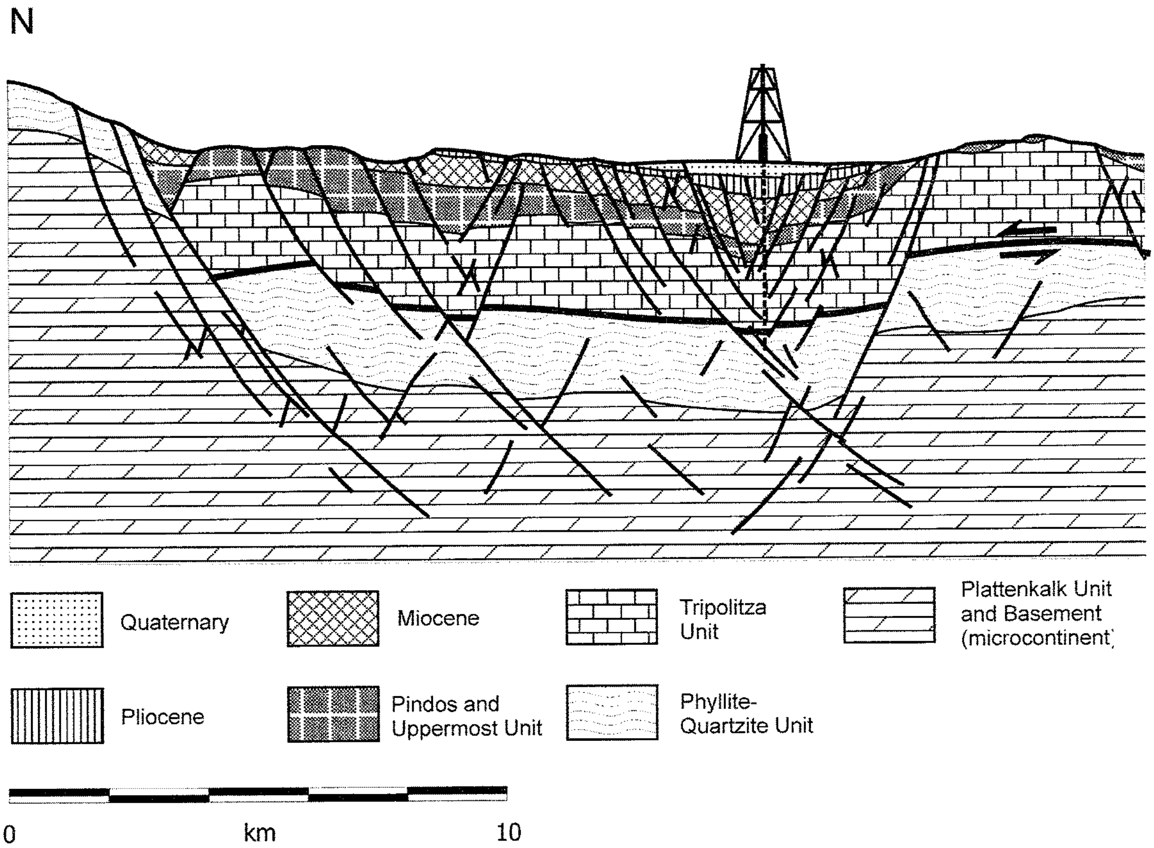

Fig. 3. Cross section (no vertical exaggeration) through the Messara basin, modified after Le Pichon and Angelier (1979), with approximate position of the extensional detachment between the HP/LT metamorphic units and the unmetamorphic upper nappes.

Land-based drilling phase 2 : basement of the micro-continent

During a later phase a second moderate to intermediate depth land based drill hole is proposed, to recover the basement of the lowermost tectonic unit (Plattenkalk unit) exposed on Crete. This basement is expected to be the continental crust of the micro-continent (External Hellenides Platform), which entered the subduction zone about 30 - 20 M.a. b.p.

Such a drill hole will allow to obtain information on the nature of the crust and the provenance of the micro-continent as well as on the depth of burial and the internal deformation of the basement during collision.

The second drill site will be located in a suitable position on the Plattenkalk unit, which will allow to reach the basement of the micro-continent in relative shallow depth below the surface, after having penetrated through the lower horizons of the Platenkalk unit. Since the Plattenkalk unit is widely exposed on Crete, the precise location of this drill hole will be defined on the base of the results of the appropriate pre-site surveys, which are in progress.

Finally, the proposed drill holes will serve for a seismological observatory as well as they will provide the base for geophysical experiments to obtain information on the actual physical state of the crust and fundamental properties related to the mechanical coupling of the plates like stress field at a given depth (not influenced by topography), heat flow (not influenced by surface effects), hydraulic properties and fluid flow.

CURRENT RESEARCH ACTIVITIES

Current research activities directly related to the land-based drilling program include :

- evaluation of existing data (geology, geophysics, neotectonics, seismicity, data from existing shallow drill holes) (Athens);

• combined onshore/offshore seismic program designed to obtain an improved image of crustal thickness along and across the proposed transect from the Eastern Mediterranean Ridge to the South through the "back-stop" and Crete Island to the Cretan Sea (Aegean) to the North (Hamburg);

• passive seismics using local arrays designed to obtain a high resolution image of seismicity and of seismic velocities as a function of depth (in particular crustal low velocity zones and slab position) (Bochum, Chania);

• measurement of gravity field - interpretation of gravity anomalies (Hamburg, Bochum);

• stratigraphy and structural record of Neogene deposits exposed on Crete (Patras, Berlin, Iraklion);

• neotectonic analysis in Crete (Athens);

• geomorphology related to Quaternary and active tectonics (Bayreuth);

• Plio-Quaternary clastic aprons (Minneapolis);

• low-temperature thermochronometry (Bochum);

• tectonic history of the HP/LT sedimentary cover of the micro-continent and the extensional detachment (Iraklion, Yale, Frankfurt, Karlsruhe, Cologne, Bochum);

• basement and autochthonous cover of the micro-continent (Athens, Berlin, Stuttgart, Cologne);

• pre-Neogene tectonic history of the upper nappes (Iraklion, Bochum).

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Tectonics Of Subduction and Collisional Arcs (TOSCA)

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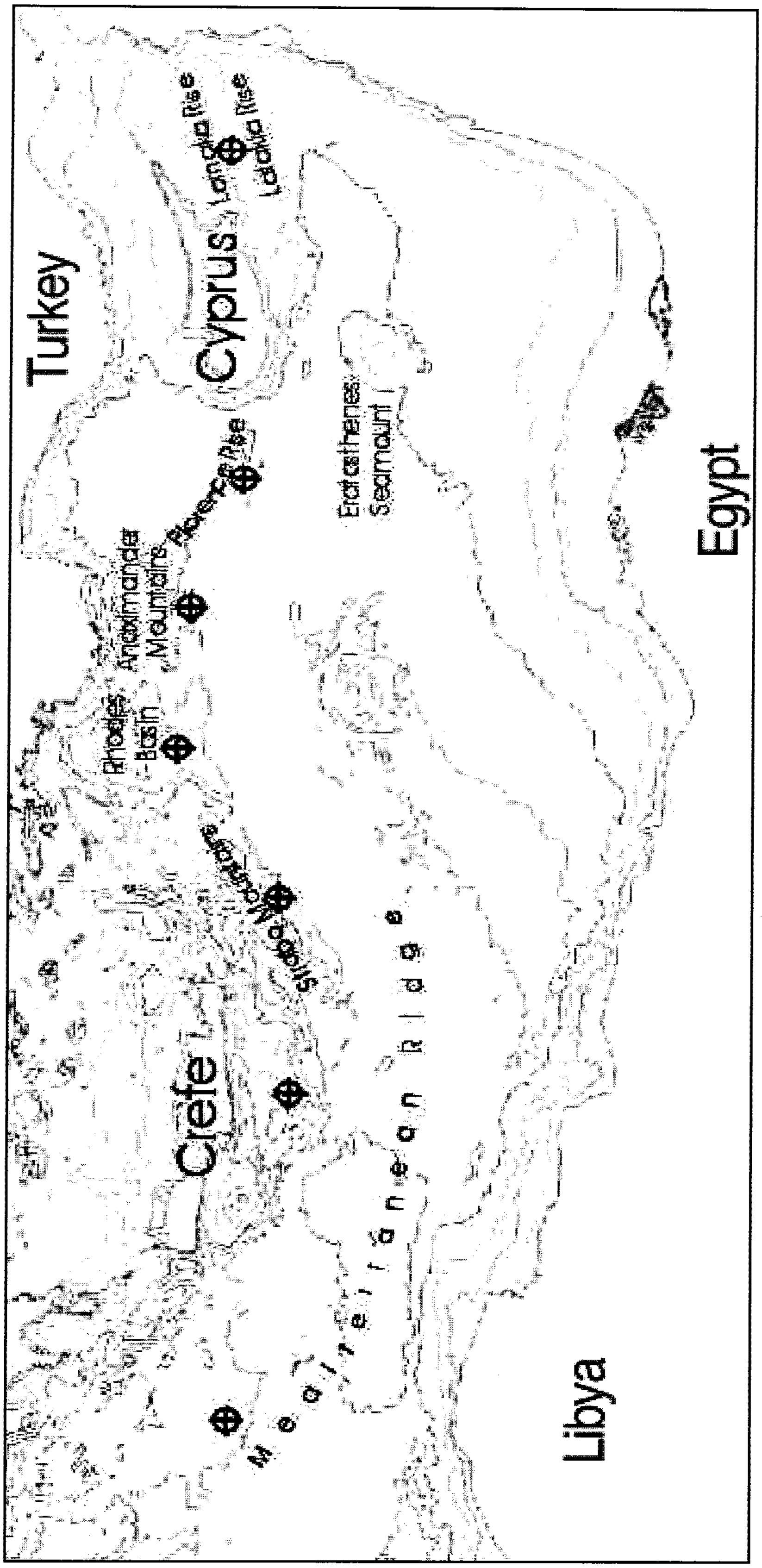
Several problems surrounding subduction and plate collision can be addressed very conveniently in the eastern Mediterranean Sea where different stages in the process are observed. The arc systems centered on Crete and Cyprus are in incipient or advanced stages, respectively, of collision. During subduction, fragments of the European plate were rifted southward and submerged beneath the Mediterranean Sea. With plate convergence and collision, these fragments are involved in collision zone deformation, acting as "backstops" for the accretionary prism near Crete, or forming part of a broad zone of deformation east and west of Cyprus. As collision progresses, continental fragments from Africa may be mixed in with the fragments rifted south from Europe. The actual subduction zone becomes impossible to define exactly because the broad deformation is taken up on several fault systems which do not necessarily lie solely on one side of the accreting fragments or on another.

South of Cyprus, the Eratosthenes Seamount, a supposed fragment of the African plate which is in collision with Cyprus and is slowly breaking up itself (e.g. Robertson, 1998), has slowed or effectively stopped subduction there. The relict subduction zone lies between Cyprus and Eratosthenes where the seismically active underthrusting occurs. But to the west, the principal plate motion is transpressive dextral transform (Woodside *et al.,* 1999), while to the east, several discrete sinistral transpressive transform fault systems define slivers of the east Cyprus Arc (Ben-Avraham *et al.,* 1995) connecting the stalled subduction zone with the East Anatolian Fault zone.

Convergence south of Crete continues with lubrication from Messinian salt within the accretionary prism and the development of mud volcanoes and fluid seeps on the accretionary prism accompanying thrusting over the backstop (*e.g.* Cita *et al.*, 1996). Like the Cyprus Arc, the Hellenic Arc exhibits substantial shearing in the forearc area: sinistral to the east of Crete and dextral to the west (*e.g.* Le Pichon *et al.*, 1995). In the case of the Hellenic Arc, however, deep trenches form to the south in the forearc region north of the accretionary prism. This has not occurred to the south of Cyprus probably because of slower convergence.

The geology of Syria, Cyprus, southern Turkey and the southern islands of Greece is distinctive and reasonably well-known or mapped for the most part. Thus it has been hypothesized and partly demonstrated that large blocks along both arcs have been rifted from the plates to the north. Samples of the Anaximander Mountains show distinct correlations with the Bey/Susuz Daglari, Lycian Nappes, and the Antalya Nappes Complex) (Woodside *et al.*, 1997, 1998). Samples of the Strabo Mountains and seamounts south of Crete appear to be Hellenide like Crete and the neighbouring islands (*e.g.* Mascle *et al.*, 1986a, 1986b). Moreover it is inferred that there is geological continuity between Cyprus and Syria/Turkey to the east (Limonov *et al.*, 1992; Ben-Avraham *et al.*, 1995). The edge of the European plate can thus be followed into the subduction complex but is still identifiable and drillable.



Eastern Mediterranean Sea showing series of drilling sites along the forearc region of both the Hellenic and Cretan arcs.

Fig. 1. General bathymetric of the eastern Mediterranean based on the International Bathymetric Chart of the Mediterranean (IBCM; IOC-UNESCO, 1987), showing the approximate locations of the sites proposed and some of the features referred to in the text.

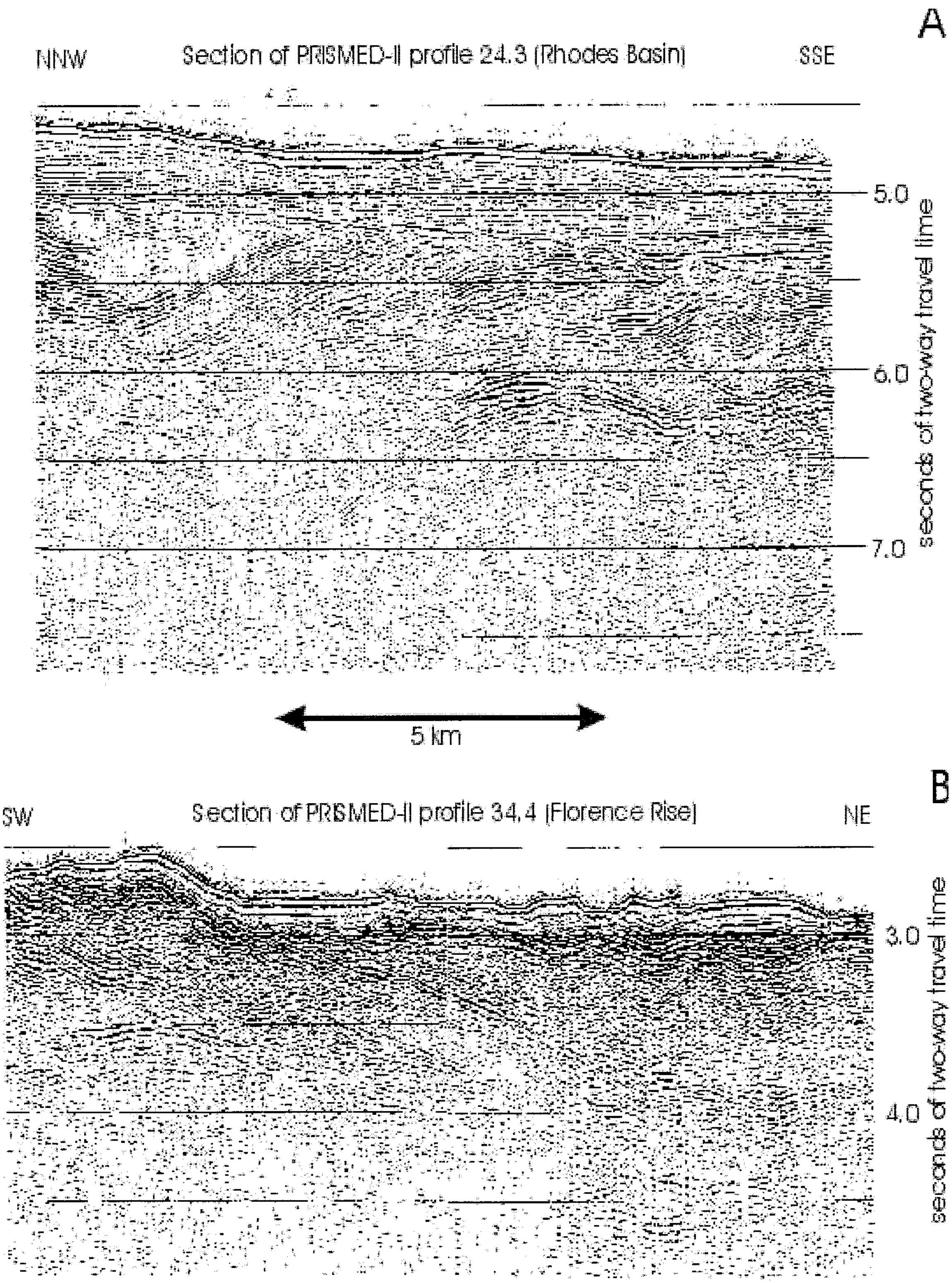


Fig. 2. Seismic reflection profiles from PRISMED-II (courtesy J. Mascle) across (**A**) part of the Rhodes Basin (Woodside *et al.*, 1999) and (**B**) a section of the Florence Rise (Mascle, pers. com. 1999). Note that there are no Messinian evaporites. Deeper deformed Alpine basement units are separated from the Pliocene to Recent sequence by erosional unconformities. The Pliocene to Resent sediments in these examples are less than 0.5 s thick (two-way travel time) or roughly less than 425 m assuming a seismic velocity of 1700 m/s for the sediments.

The Anaximander Mountains, Rhodes Basin, and Florence Rise are post-Miocene tectonic products of plate convergence with limited covering sediment and without Messinian evaporites (Woodside *et al.,* 1999, 1998, 1997). All three appear have submerged to their present depths in post-Miocene time. They are reasonable targets for drilling and will provide constraints on the nature and timing of the southward rifting events, subsidence, stalling of Cyprus Arc subduction, and subsequent compressional deformation. If this rifting/fragmentation of the European plate is a product of some form of "roll-back" then the process can be examined here through drilling and associated fieldwork both at sea and on the adjacent land areas. Successions of rocks drilled at sea can thus be compared with those on land from the point of view of common but later divergent histories.

The nature of the backstop arcward of the mud volcanoes is the subject of continuing discussion and could be easily addressed with holes south of Crete (and with related holes further along the arc to investigate the extent of the southward-rifted Hellenide/Tauride rocks which probably form the backstop). This is of general interest also since it is easier here to determine the evolution of this transition zone between the accretionary prism and the arc behind, on account of the distinct geology of the rifted blocks and their specific diagenetic history. It is here that the TOSCA proposal overlaps and supports the drilling transect from the Cretan Sea, across Crete, and on to the backstop (Kopf *et al.*, this volume; Papanikolaou *et al.*, this volume; Stöckhert, this volume).

In summary, TOSCA is a proposal to drill a series of holes in the forearc region between Syria and the Peloponnesus. The following sites are proposed: (1) Larnaca/Latakia Ridges, (2) Florence Rise , (3) Anaximander Mountains, (4) Rhodes Basin, (5) Strabo/Ariane Mountains, and (6) backstop and Hellenic Trench. The goal is to drill to the basement alpine rocks and to establish the timing and development of its rifting and subsidence.

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The Western foreland of the Mediterranean Ridge accretionary complex

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The Mediterranean Ridge (MR) is an accretionary complex, the relief and the internal structure of which vary along its axis. In front of the northwestern and western parts of the MR, free forelands (Ionian and Sirte Abyssal Plains, Ionian Gap; Fig. 1) show tectonic bottom and subbottom peculiarities which are not caused by the accretionary processes but pre-existed and controlled the sedimentation regime, particularly during the Messinian evaporation period: SW-NE oriented small, elongated horsts separate broader depressions (Fig. 2; Hieke *et al.*, 1998).The most conspicuous horsts are the Medina-Victor Hensen Structure (Hieke and Dehghani, 1999; [2] in Fig. 1; Fig. 2 B) and a feature comprising the Conrad Spur and the central elevation of the Bannock Basin ([4] in Fig. 1). They are dissected by left-lateral faults which have a considerable vertical component as well.

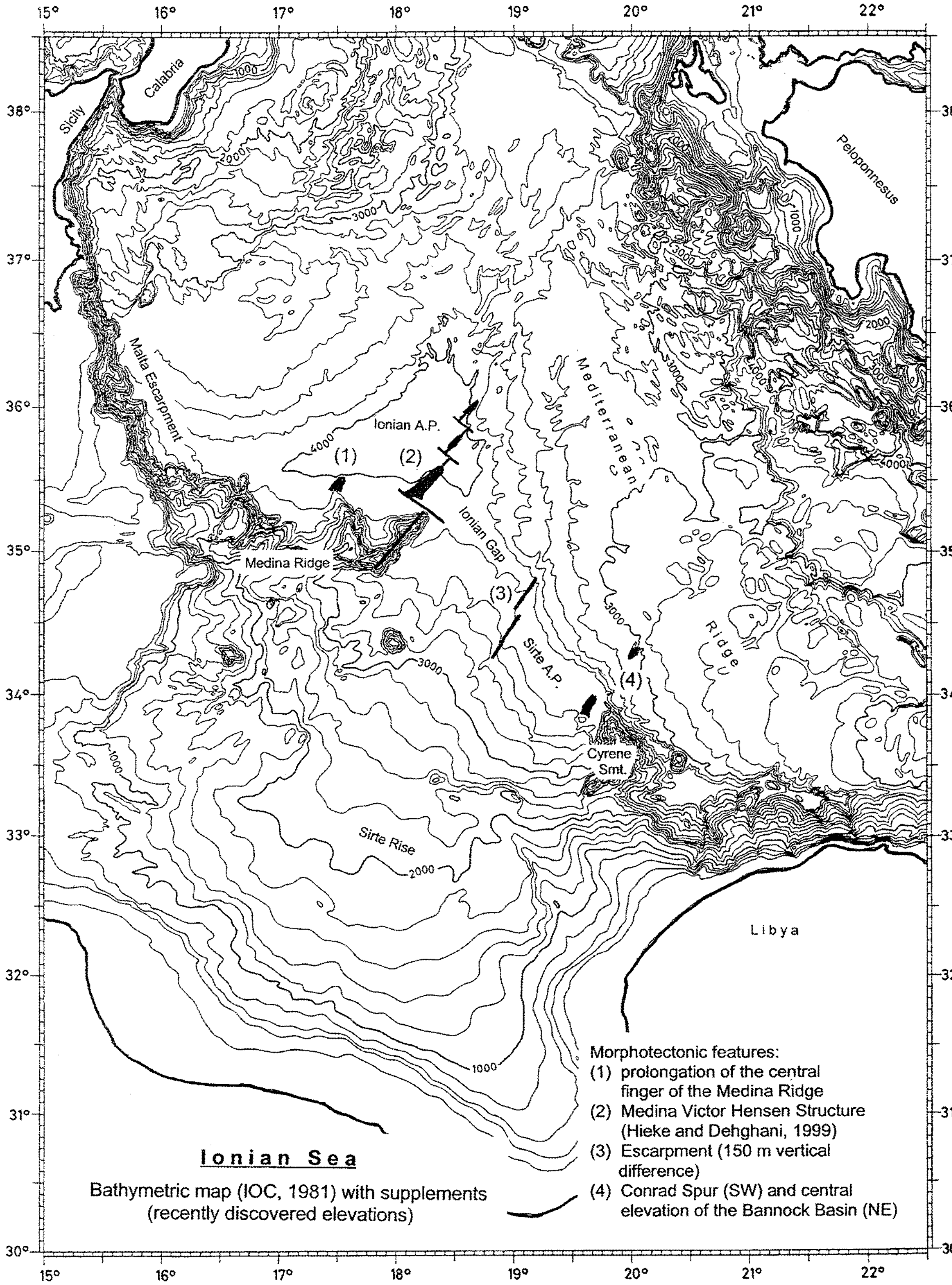
The Medina-Victor Hensen Structure and the central elevation of the Bannock Basin offer resistance against the accretion which is documented in the MR relief near the deformation front. At least the Victor Hensen Seahill (VHS) is still tectonically active (Avedik and Hieke, 1981; Hieke and Wanninger,1985).

The alternation of areas with a thick evaporite layer and without evaporites in the present foreland suggests similar relations within the accretionary complex: the evaporites do not occur as a coherent layer. Incoming structural elements of the former foreland, incorporated at earlier periods and being now far from the deformations front, can be still observed (central elevation in the Bannock Basin; von Huene *et al.*, 1997).

The deeper parts of the MR foreland show close structural relations to the Medina Ridge and Malta Escarpment areas which are considered to be underlaid by (thinned?) continental crust. At least the Ionian A.P., however, is considered controversely to be underlaid by old oceanic crust or by thinned continental one (Hieke and Dehghani, 1999).

In order to understand what happened (and is still going on) at the plate boundary between Africa and Eurasia (small-scaled structural variations of the down-going plate, thinning of continental crust), it would be helpful to know the pre-Messinian paleogeographical and tectonic evolution which can be studied in the foreland areas of the MR. Such knowledge would be also important for the reconstruction of marine gateways.

Potential drill sites (to avoid penetration of the Messinian evaporites) can be located on the Victor Hensen Seahill (proposed several times in the past) or other parts of the Medina-Victor Hensen Structure, on the Conrad Spur in the Sirte A.P. and at some other places according to the unpublished data avail-able from recent cruises.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38° 37° 36° 35° 34° 33° 32° 31° 30°
Calabria
Sicily
Peloponnesus
Malta Escarpment
Ionian A.P.
(1) (2)
Medina Ridge
Ionian Gap
(3)
Mediterranean
Ridge
Sirte A.P.
(4)
Cyrene Smt.
Sirte Rise
Libya
1000
2000
3000
4000
Ionian Sea
Bathymetric map (IOC, 1981) with supplements (recently discovered elevations)
Morphotectonic features:
(1) prolongation of the central finger of the Medina Ridge
(2) Medina Victor Hensen Structure (Hieke and Dehghani, 1999)
(3) Escarpment (150 m vertical difference)
(4) Conrad Spur (SW) and central elevation of the Bannock Basin (NE)

Fig. 1.

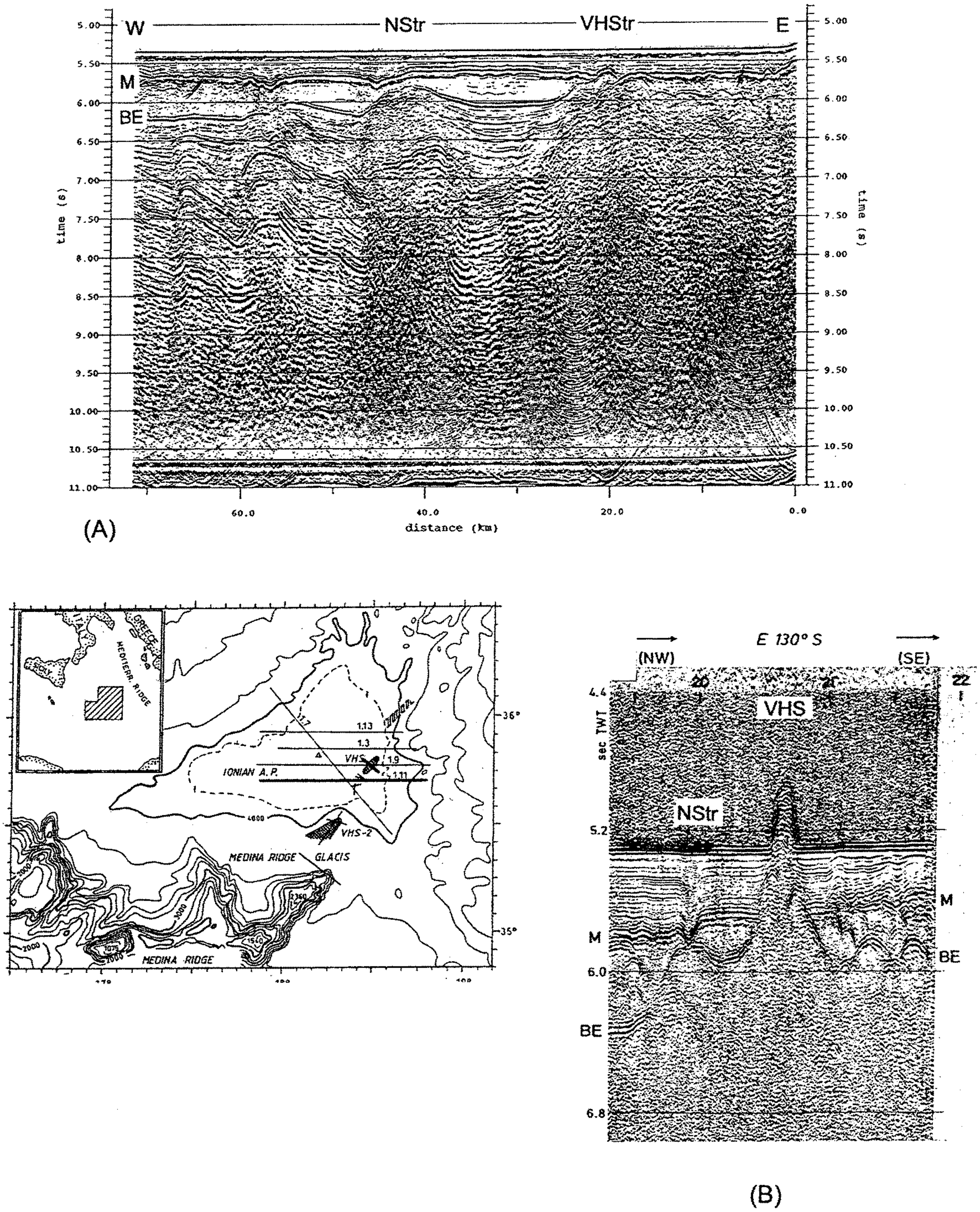

Fig. 2. Subbottom structures beneath the Ionan Abyssal Plain.

(A) MCS line 1.11 (Hieke *et al.*, 1998)
(B) SCS line crossing the Victor Hensen Seahill (Avedik and Hieke, 1981).
Positions on the enclosed maps (bold lines)
BE = Base of evaporites. **M** = reflector M (top of evaporites), **NStr** = Nathalie Structure,
VHS = Victor Hensen Seahill, **VSH-2** = Victor Hensen Seahill 2, **VHStr** = Victor Hensen Structure.

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Accretion and incipient continental collision: phase-2 deep drilling into the Mediterranean Ridge accretionary complex, Eastern Mediterranean

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Abstract

We propose a second phase of deep drilling into the Mediterranean Ridge accretionary complex to understand the deformation processes of accretionary complexes and the role of fluids in sediment accretion, by drilling the Pre-Messinian accretionary wedge (Site A: three holes) and the backstop area (Site B: two holes), in the Eastern Mediterranean convergent margin system.

The Mediterranean Ridge complex

Convergent margins are the sites of both continental growth (through accretion and magmatism) and continental dismantling (trough sediment subduction and tectonic erosion). All of these processes are primarily controlled by the regional stress distribution and are strongly influenced by the complex interaction between tectonic deformation and the transport of sediment and fluid (Langseth and Moore, 1990). The Eastern Mediterranean is a unique example of such a system, as it offers the opportunity to study fundamental accretion and collision processes, associated with terminal subduction-incipient continental collision, progressively occurring at the African-Aegean convergent margins.

Plate tectonics reconstructions of the Mediterranean area (*e.g.* Olivet et al., 1982) show that for the last 80 Ma Africa has been moving North relative to Eurasia, resulting in gradual subduction of the Mesozoic lithosphere and closure of the Tethyan ocean. Convergence and eventual collision has led to the formation of the Alpine-Himalayan Belt, of which the Mediterranean Ridge is presently one of the most active parts.

The Mediterranean Ridge accretionary complex represents a large and actively deforming sediment pile resting against a continental margin ("backstop") of variable width, located arcward of the wedge (*e.g.* Le Pichon *et al.*, 1982; Kastens *et al.*, 1992; Truffert *et al.*, 1993; Lallemant *et al.*, 1994; Camerlenghi *et al.*, 1995; Chaumillon *et al.*, 1996, Reston *et al.*, 1996; Chaumillon and Mascle, 1997, Polonia *et al.*, 1999). A sequence of low permeability evaporites of Messinian age is present, with variable thickness, in the whole area, lying within the sediment blanket at a depth of a few hundred meters beneath the seafloor.

The accretionary wedge is mainly composed of sediments accreted from the African plate, which is subducting towards Northeast beneath the Aegean, at a current convergence rate of about 3 centimetres per year (Le Pichon *et al.*, 1995; Noomen *et al.*, 1996).

The accretionary complex shows some distinctive features, such as: 1) lack of bathymetric expression for the subducting trench, 2) very low dip angle for the incoming plate and 3) unusual width and flatness of the accretionary complex itself. Whereas 1) and 2) are likely related to the collisional context in the area, 3) is related to the presence of the evaporites, in the way they influence the dewatering of the Pre-Messinian sediments (Reston *et al.*, 1996).

As the Pre-Messinian sequences compact (by sediment accretion and underthrusting), the expelled pore fluids are trapped beneath the impermeable cap, causing fluid overpressure at the base of the evaporites. In places where the evaporites are thin, fluids might vent at the seafloor along faults and structures (Moore *et al.*, 1987). Because of the effect of fluid overpressure on the strength of materials, fluids are significant to the tectonic and dynamic evolution of the system.

There is general agreement on the nature of the Mediterranean ridge structure, but there are still differing models and interpretations on the evolution of the accretionary wedge – such as thickness of the evaporites, structure of the wedge and depth to the decollement – and on the structure and nature of the backstop (*e.g.* Ryan *et al.* 1982; Le Pichon *et al.*, 1982; Truffert *et al.*, 1993; Lallemant *et al.*, 1994; Reston *et al.*, 1996; Chaumillon and Mascle, 1997).

The MEDRIFF-IMERSE corridor (Fig.1) and the corresponding cross-section (Fig. 2) are a representative example of the western Mediterranean Ridge accretionary complex, where a near-orthogonal terminal subduction-initial collision is taking place.

A first shallow drilling phase across the collisional margin of this system was successfully carried out during ODP Leg 160 (Robertson, Emeis, Richter and Camerlenghi eds., 1998). One focus of the drilling concerned collisional processes related to the tectonic history of the Eratosthenes Seamount, a crustal fragment in the process of collision with the overriding Cyprus plate to the north. A further tectonic-related objective was the drilling across two mud volcanoes located on the northern margin of the Mediterranean Ridge accretionary complex, in an area where the Mediterranean Ridge is thrusted over a backstop of continental crust to the North. A third objective was to study subduction and accretion in an area where subduction is still taking place, by drilling on the inner deformation front of the accretionary wedge.

GENERAL OBJECTIVES

The scientific objectives to be addressed by this second phase of deep drilling are strongly figured in ODP themes outlined in several documents, such as: "Ocean Drilling Program Long Range Plan into the 21st century (ODP Report, 1996)", "Ocean Drilling Program Long Range Plan 1989-2002 (ODP Report, 1990)", "The Role of Fluids in Sediment Accretion, Deformation, Diagenesis and Methamorphism at Subduction Zones (NATO/NSF Report, 1988)" and the Report of the Second Conference on Scientific Ocean Drilling (COSOD II Report, 1987). The future perspectives concerning these themes were also discussed in the ODP-COMPLEX Meeting in Vancouver (May 1999).

On the Mediterranean Ridge, the focus is particularly on the following themes:

- subduction factory;
- styles of deformation and properties of the rocks through the accretionary prism;
- source, distribution and expulsion of fluids through the complex;
- influence of fluids on the mechanical properties of rocks and permeability changes with lithology, stress and strain;
- geochemical and heat fluxes associated with dewatering and accretion;
- deep biosphere;
- tectonic processes and seismogenic zones.

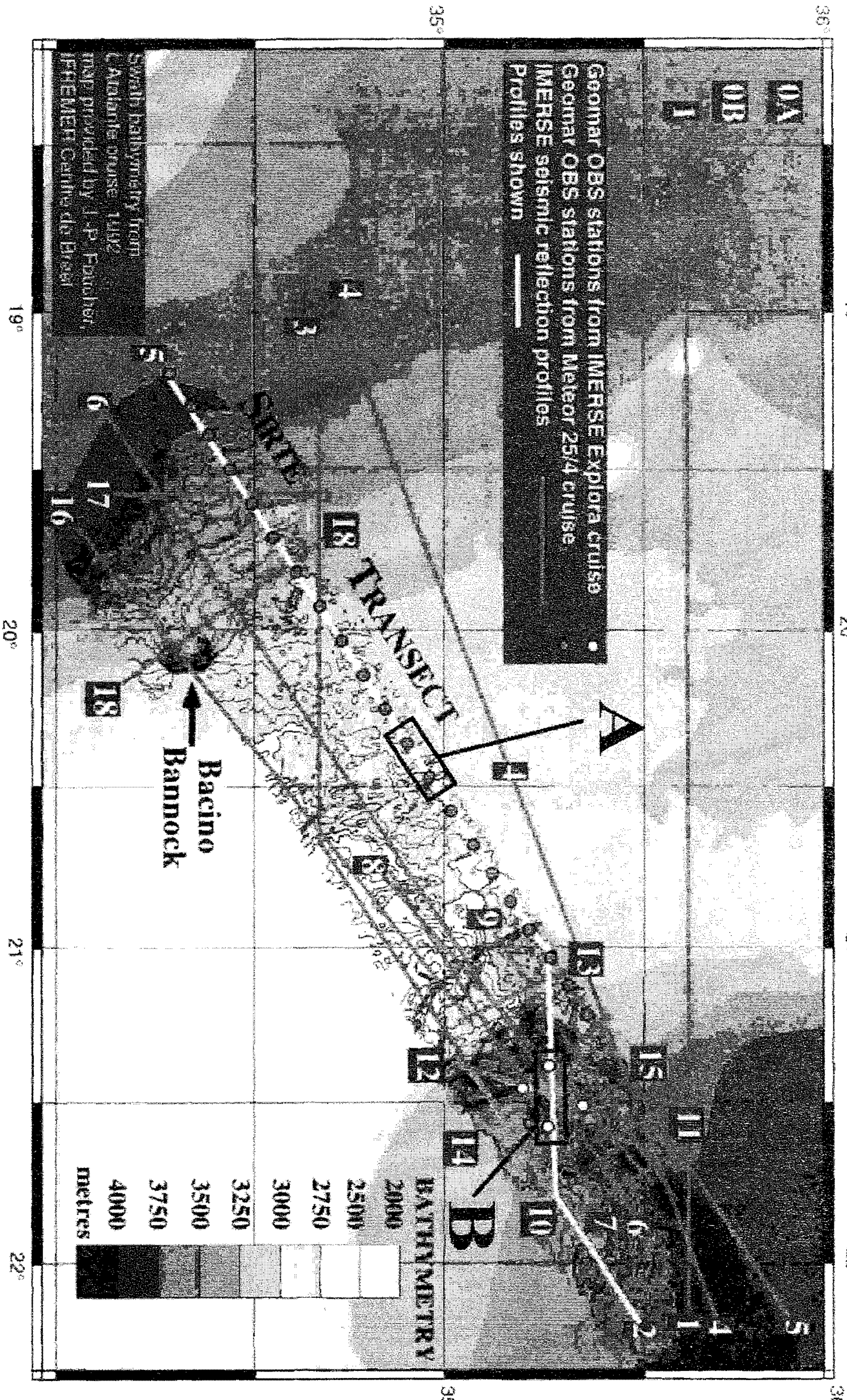

Fig. 1. Bathymetric map of the MAST II MEDRIFF and IMERSE Corridor, showing IMERSE seismic profiles and deployed ocean bottom hydrophone stations (after Reston *et al.*, 1996). The location of the proposed drilling sites is indicated.

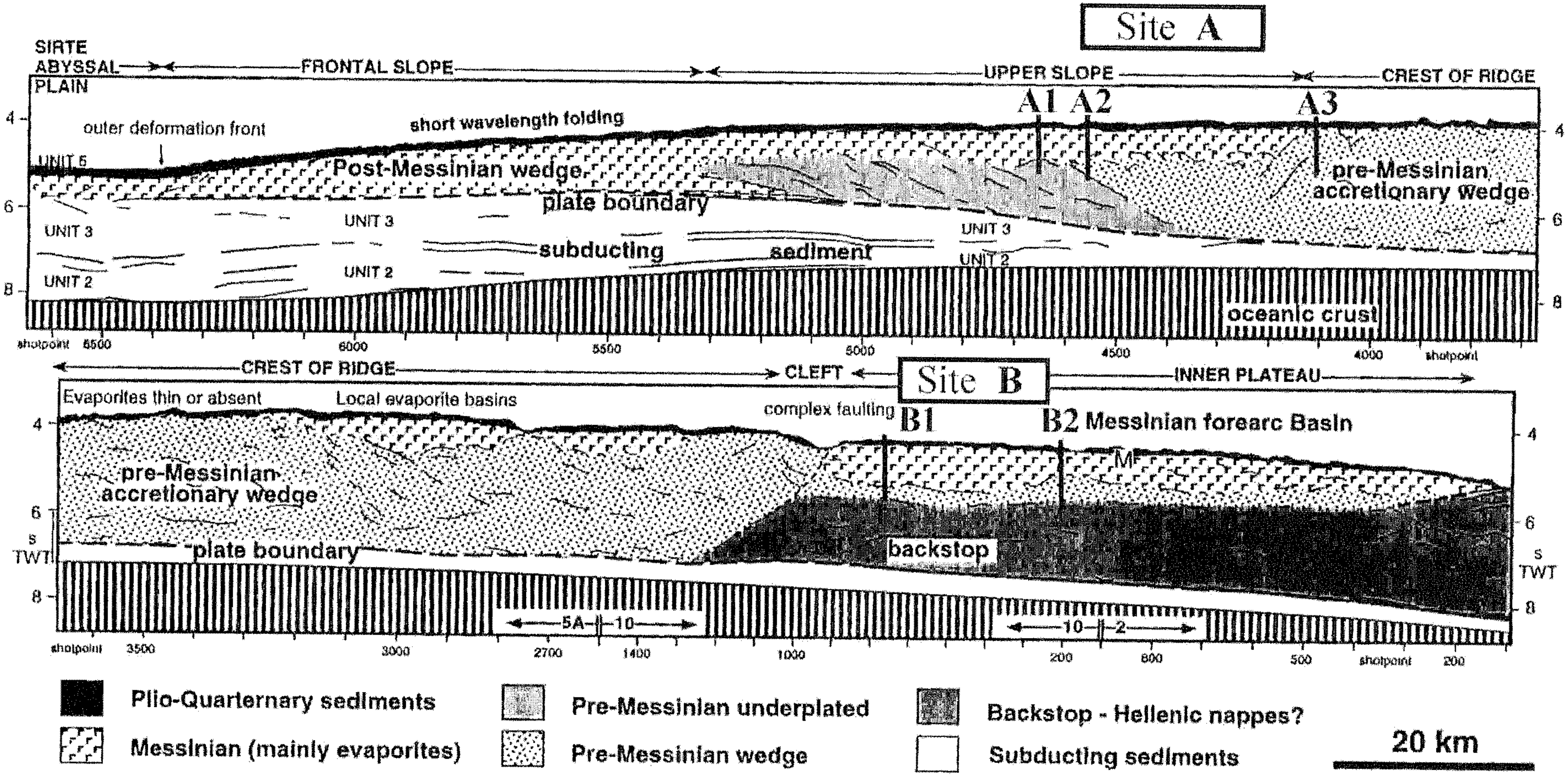

Fig. 2. Cross-section through the Mediterranean Ridge based on the results of the IMERSE Project, in particular on Profiles 5A, 10 and 2 (see location in Figure 1), supplemented by velocity information from wide-angle data (after Reston *et al.*, 1996). Key features are the presence of the Pre-Messinian accretionary wedge under the crest of the Ridge, a region of under-plated Pre-Messinian sediments and a thick accumulation of evaporites on the inner plateau-backstop area. The decollement cuts down from the base of the evaporites probably to Aptian shales within the backstop. The location of the drilling sites on the frontal portion of the Pre-Messinian accretionary wedge (A) and on the backstop (B) is also indicated.

Mediterranean objectives

Besides the above basic objectives, related to a convergent margin system, there are some peculiar tectonic objectives in the Mediterranean Ridge accretionary complex, that are still matter of discussion and that could be addressed by deep drilling. We propose to investigate deeper into the accretionary complex to test some of the hypotheses advanced on the base of the recently acquired observations, datasets and ODP Leg 160 results. The hypotheses to test concern the structure of the complex and the processes involved in its formation and evolution, i.e.:

- thickness and stratigraphy of the Messinian evaporites;
- fluid overpressure at the base of the evaporites, fluid source, migration and expulsion;
- compaction and dewatering of the Pre-Messinian sediments;
- architecture and evolution of the accretionary complex before and after the Messinian;
- nature of the master decollement;
- heat and geochemical transport by fluids from beneath the Messinian evaporites;
- Messinian forearc basin on the backstop area;
- nature and significance of the backstop.

The above targets could be reached through deep drilling (of the order of 2 km b.s.f.) on the Mediterranean Ridge complex, including drilling through the Messinian evaporites, the pre-Messinian sediments and the top of the backstop basement. The drilling is preliminary proposed in two selected sites (Figures 1, 2): the frontal upper slope of the Ridge (Site A) and the inner plateau-backstop area (Site B).

Available data

Several seafloor observations and geophysical datasets have been recently collected in the Eastern Mediterranean. Pasiphae cruise 1988 (De Voogd *et al.*, 1992; Truffert *et al.*, 1993), PRISMED cruise (Chaumillon and Mascle J., 1995; Chaumillon *et al.*, 1996; Chaumillon and Mascle J., 1997; Mascle and Chaumillon, 1998), MAST II (1993-1996) partner projects MEDRIFF (Integrated investigation of fluid flow through the Mediterranean Ridge) and IMERSE (Innovative Mediterranean Ridge seismic experiment) (Von Huene *et al.*, 1997; IMERSE Working group, 1997), ODP Leg 160 (Robertson, Emeis, Richter and Camerlenghi eds., 1998) and seafloor observations have provided excellent information.

This includes swath-bathymetry and seafloor observations, high-resolution seismic imaging, very good normal-incidence and wide-angle seismic data, shallow ODP drilling, coring and heat flow measurements.

A targeted comprehensive study for the understanding of the Mediterranean Ridge complex was particularly accomplished by partner projects MEDRIFF and IMERSE (1993-1996) (Westbrook *et al.*, 1995; IMERSE Working Group, 1997). They investigated a 300 km long corridor, crossing the entire western Mediterranean Ridge from the Sirte abyssal plain to the Hellenic trench system, with a multidisciplinary approach that combined seafloor observations with a high-resolution mapping of acoustic velocities and structures.

Moreover MEDRIFF discovered evidence for extensive brine circulation through the sediment of the western Mediterranean Ridge, including the discovery of three brine lakes (Westbrook *et al.*, 1995).

The main results show as the evaporite deposits beneath the Mediterranean Ridge complex have a variable thickness, from about zero on the Mediterranean Ridge crest to about 2 km in the Inner Plateau area (NE of the Mediterranean Ridge crest). These results revealed much about the internal structure of the complex, integrating with greater detail the results from previous seismic reflection investigations. On the MCS seismic lines there is evidence of the Pre-Messinian accretionary wedge and possibly of subcreted Tertiary clastics underneath the frontal part of the Pre-Messinian accretionary wedge (Fruehn *et al.*, 1996; Reston *et al.*, 1996). (Figures 2 and 3).

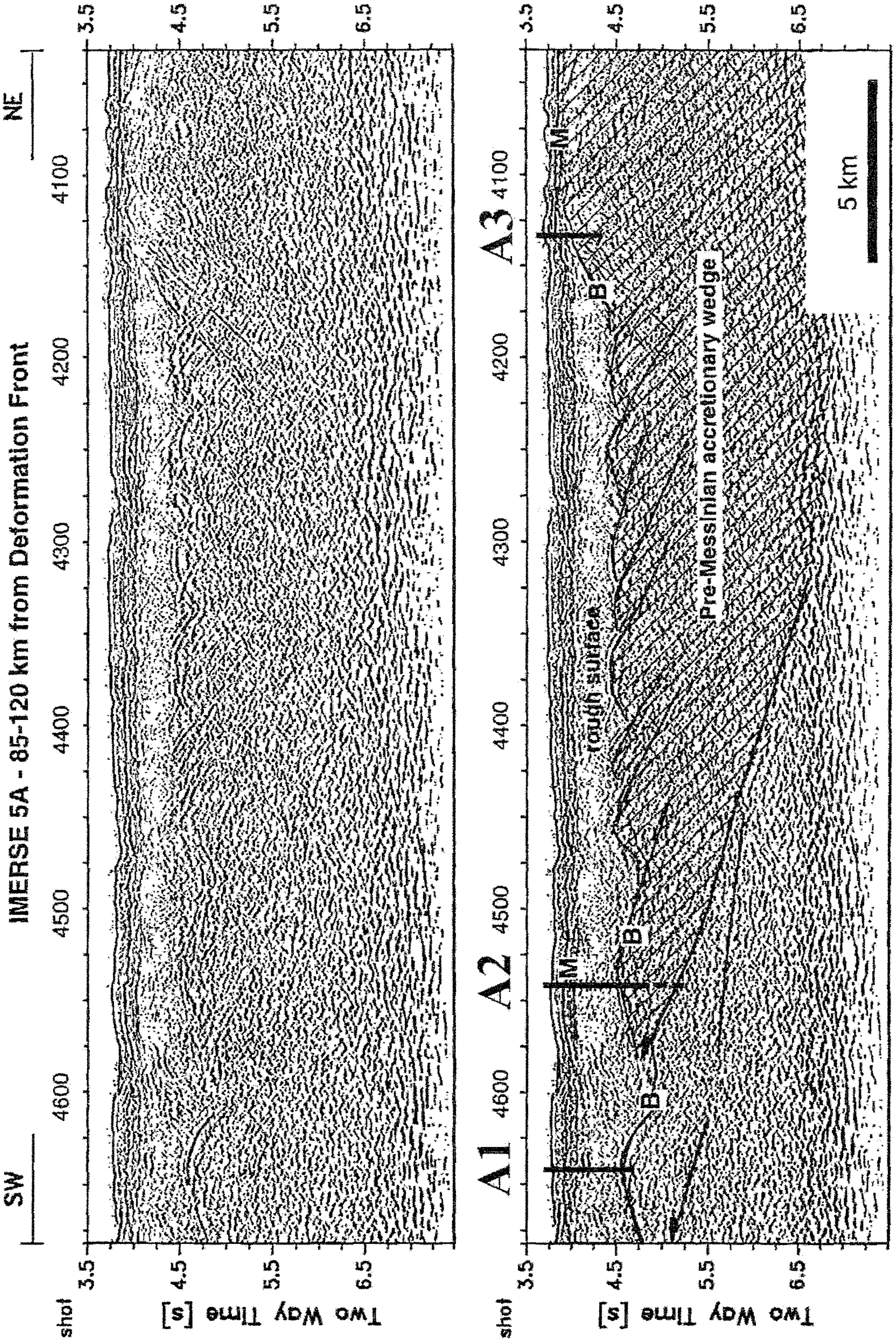

Fig. 3. Frontal portion of the Pre-Messinian accretionary wedge from IMERSE 5A multichannel seismic line. M marks base of Plio-Quaternary; B base of Messinian. The interpreted location of the Pre-Messinian accretionary wedge is marked by diagonal shading. A region of possibly underplated Pre-Messinian sediments is located to the SW of the wedge (see also Figure 2) (after Reston *et al.*, 1996). The location of the drilling holes on the frontal portion of the Pre-Messinian accretionary wedge is indicated.

In the Inner Plateau area, the top of Messinian almost approaches the seafloor in correspondence with the structures that form the brine lakes (Westbrook *et al.*, 1995). Beneath the evaporite deposits, a thin pre-Messinian sequence is present on top of the backstop basement. The wide-angle seismic data (Jones *et al.*, 1996) show as the back-stop has a high velocity, increasing from 5.1 km/s at its top to 6.6 km/s at its base, and has a wedge shape that pinches out towards the cleft basins (Figure 4). Reston *et al.* (1996) interpret this wedge as well-lithified carbonates of the Hellenic nappes. The reflection data confirms the top of the basement at about the expected travel times (Jones *et al.*, 1996). The gravity modelling across the Mediterranean Ridge complex (Nicolich *et al.*, 1996), performed on the base of available seismic results and marine and satellite gravity data, provides a well constrained image of the deep structures (Figure 5). On the Inner Plateau area, the top of the backstop is at a depth of the order of 2 km b.s.f.

On the base of thermochronology of the high-pressure low-temperature metamorphic rocks of Crete, Thomson *et al.* (1998; 1999) suggest that Crete and likely the backstop of the Mediterranean Ridge are part of a microcontinent which entered the Hellenic subduction zone in Oligocene-Miocene, was buried at about 30 km depth and was rapidly exhumed in Miocene times. This hypothesis would support an African origin for Crete and the backstop.

The available dataset (including a full multibeam bathymetric coverage along the MEDRIFF-IMERSE corridor and a wide-angle reflection and refraction survey) constitutes a remarkable site-survey that allows to locate a few crucial drilling sites on the Mediterranean Ridge complex and in the Inner Plateau area. Drilling is expected to go through the Messinian evaporite deposits, the pre-Messinian sediments and hopefully (in the Inner Plateau area) to the top of the backstop basement.

DRILLING STRATEGY

Deep drilling in the frontal upper slope of the Ridge (Site A) and in the backstop area (Site B) should allow to study the Pre-Messinian accretionary wedge and the backstop, respectively, in the Eastern Mediterranean convergent margin system; a very preliminary drilling strategy for each of the two areas is here briefly outlined.

A) Accretionary complex area: one transect of 3 holes A1, A2 and A3 (Figures 2 and 3)

A1 is expected to penetrate the Messinian evaporites (about 1.5 km thick) and reach the Pre-Messinian sediments underplated beneath the Pre-Messinian accretionary complex. A2 is about 6 km north-east of A1, and is expected to meat the Pre-Messinian accretionary complex itself, beneath the evaporites and hopefully the tectonic contact between the underplated and accreted sediments. A3 is near the crest of the Ridge (21 km Northeast of A2) and should drill a thin evaporitic sequence and the upper part of the Pre-Messinian accretionary complex. The three holes should be able to address the following:

- stratigraphy of the Messinian evaporites;
- Pre-Messinian underplated sediments and Pre-Messinian accretionary complex;
- changes in the properties of rocks through the accretionary prism;
- high fluid overpressure at the base of evaporites and prism dewatering;
- hydrothermal and chemical fluxes through the Pre-Messinian sediments;
- stress regime and role of the fluids in the Pre-Messinian sediments;
- evolution model of the Mediterranean Ridge accretion.

B) Backstop area and Messinian fore-arc basin

Two holes (B1 and B2) located about 18 km apart and coincident with the position of OBH-2 and OBH-3 (Figures 2 and 4), are proposed. They are expected to penetrate the Messinian evaporites (about 1.5 km thick, or more) of the Messinian fore-arc basin and an undefined thin sequence (500 m ?) of Pre-Messinian sediments, to reach the backstop basement (Vp > 5.2 km/s) at a depth in excess of 2 km. The holes will allow to address the following scientific questions:

- Messinian evaporites and Messinian fore-arc basin of the inner plateau area;
- Pre-Messinian sediments;

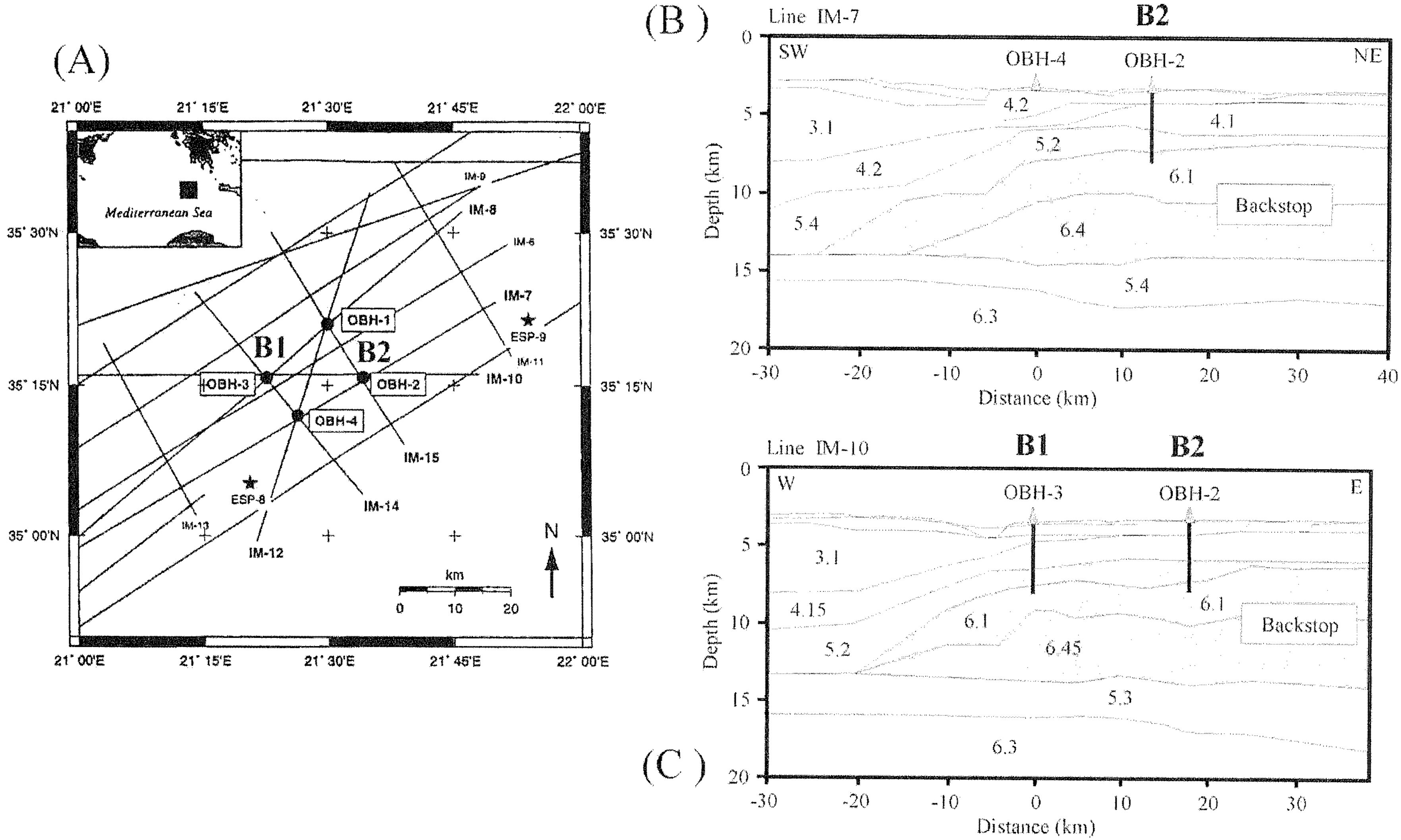

Fig. 4. **A**) Location map of IMERSE reflection lines, OBH deployments and ESP-8 and ESP-9 mid-point positions. Profiles IM-7, IM-8, IM-10, IM-12, IM-14 and IM-15 form six wide-angle, multi-azimuth, velocity-depth profiles. **B**) Final velocity-depth models for IMERSE line IM-7 and IM-10 (**C**) (after Jones *et al.*, 1996). The location of the indicative drilling holes through the evaporites and down to the backstop is shown.

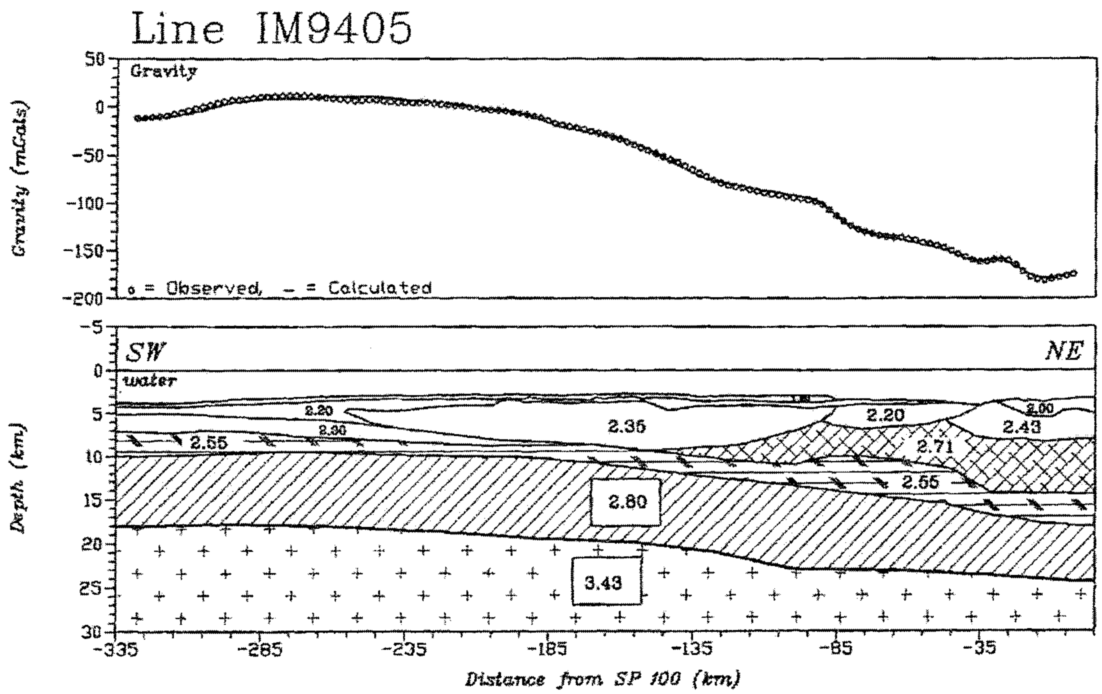

Fig. 5. Free air gravity model predicted along the profiles IM-5 and IM-5A, on the base of the cross-section obtained from seismic results (Fig. 2), is compared to gravity data collected along IMERSE ship tracks. Notice the excellent match between calculated and observed gravity. Location of the drilling site to reach the backstop is indicated (After Nicolich *et al.*, 1996).

- source, distribution and expulsion of fluids through the backstop;
- fluid overpressure at the base of evaporites;
- hydrothermal and chemical fluxes through the Pre-Messinian sediments;
- stress regime, mechanical properties and the role of fluids;
- presence, nature and significance of the backstop.

The deep offshore drilling on the Mediterranean Ridge complex could become of even more crucial interest if it could be integrated with the deep continental drilling proposed by ICDP on Crete (see Stöckhert *et al.*, this volume).

Since the offshore drilling targets are at the moment out of the reach of present drilling capabilities, we should probably wait for more adequate drilling ships. They might become available in the Mediterranean area, in the next 10 years or so.

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Drilling an incipient collision : the Central Mediterranean Ridge (Eastern Mediterranean Sea)

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The MR is a wide accretionnary wedge having evolved during early stages of collision between Europe and Africa, in Eastern Mediterranean (Finetti, 1976). Numerous results already showed it to be in probable contact with the North African margin (Chaumillon and Mascle, 1997) with thick sections of off-scrapped and deformed sediments piling up against a rigid back-stop formed by the Southern Aegean-Anatolian continental micro-plate (Lallemant *et al.*, 1994).

From previous swath bathymetric data across the Western MR (Foucher *et al.*, 1993), near bottom sonar surveys (Limonov *et al.*, 1999), refraction (Immerse Working Group, 1997) and multichannel seismic data (Chaumillon and Mascle, 1997), the MR has been shown to display a large variety of tectonic structures as a consequence of contrasting regional settings. Among the factors that control its development are:

(1) Regional kinematics - This includes the relative motions of the two major, African and European plates, and of the interfering Anatolian-Aegean microplate. A three plates kinematic model predicts a frontal compression along the Southwestern edge of the MR and oblique convergence along its Southeastern domain (Le Pichon *et al.*, 1995).

(2) Nature of the subducting lithosphere - It is likely that the deep Ionian sea, at the Southwestern corner of the MR (Truffert *et al.*, 1993) and possibly the Levantine basin, Southeastward, are remnants of an old, Mesozoic, oceanic African lithosphere subducting beneath Europe. The Central MR, however, between Crete Island and the Libyan continental margin, is though to record the effects of current collision between the two passive African and active Aegean continental margins.

(3) Nature and thickness of incoming sediments - Large portions of the outer MR, within the Ionian and Levantine basins, result from thrusting, stacking and progressive folding of thick evaporitic sediments including halite (Chaumillon *et al.*, 1996) The evaporite had been deposited in deep basins during repetitive dessication events that occurred in Mediterranean sea, in latest Miocene (Messinian, 5 Ma ago ; *e.g.* Ryan, Hsu *et al.*, 1973). Such ductile layers may have provided particularly efficient decollement levels that have greatly increased MR Southward development, since Pliocene time. Eastward, towards the Nile deep-sea fan, the increasing thickness of recent sedimentary cover has also been shown to contribute to deformational variations seen along the Eastern outer MR (Chaumillon and Mascle, 1995).

In March 1993 and in February 1998, we have conducted two underway geophysical survey of large portions of the Eastern Mediterranean on board the R.V. *Nadir* and *l'Atalante* (IFREMER) respectively. These surveys were designed to investigate :

- for the first one, the deep geological structures of several areas of the Mediterranean Ridge along regional lines, using a multichannel seismic equipment, and

- for the second one, to analyze, at a full bathymetric coverage, areas that we inferred represent different structural settings and major sedimentary processes that compete to imprint and shape the sea floor of the Eastern Mediterranean and on which some of the mulichannel seismic reflection data were available (Chaumillon *et al.*, 1996).

This paper focuses on the results obtained on an approximately 250 km by 200 km (almost 50.000 km^2), area of the sea floor, which covers most of the Central MR (Fig. 1) that we believe to record the onset of collision between two major continental plates, Africa to the South and Europe to the North.

During Prismed I survey, multichannel data were collected using an array of 6 GI Air gun and recorded through a 96 channels streamer and a Sercel acquisition system. Standard processing was made aboard using a SPW processing package and, later on in Strasbourg Seismic Processing Center, using a CGG Geovector processing package. Few lines have been re-processed at Geomar for pre-stack migration attempts. Details of data processing are given in Chaumillon *et al.* (1996) and in Chaumillon and Mascle (1997).

During PRISMED II survey the seafloor bathymetry and backscatter images were mapped using a Simrad EM12D multibeam system with 162 beams, providing 150° angular coverage over a swath of seafloor with an average of 15 km wide beneath the ship. Such acoustic data resolved sea floor details of horizontal and vertical scales up to 20m. The seismic system was comprised of two GI airguns and a six channels streamer, both towed at 7 m depth. Processing was made using a Globe Claritas software.

SWATH BATHYMETRY

In plan shaded views (Fig. 1), the surveyed area clearly shows major morphological provinces well characterized by distinct bathymetric features and trends.

From South to North, we successively recognize:

- The Northwest-Southeast trending African continental slope; locally the slope appears cut by deep canyons, particularly just East of 24°E, where a Northwest-Southeast direction in trend with the Eastern submerged border of the Cyrenaica promontory offsets the slope towards North by more than 50 km.

- Disconnected from the Libyan slope by narrow, Northwest-Southeast oriented deeps, the MR front of deformation characterizes either as an almost linear and steep escarpment or (West of 24°E) as a series of small crescent-like scarps.

- The sea floor of the central MR can be divided into several domains. We first observe an outer region characterized by important bathymetric trend variabilities. Small scale relief in this region, East of 24°E, is on the order of 100 m and comprises numerous elongated (to several km) Northeast-Southwest tending features. This area widens from a few km, at 24°E, to about 80 km in the Southeastern corner of the survey area,where the sea floor forms irregular, curved trends along which more pronounced ones that appear to follow closely the various directions of the nearby Southern African continental slope. Further North, the MR exhibits some remarkable morphological characteristics. To the East, it characterizes by a very gentle surface where only small and subdued sea floor features occur. Towards West, however, particularly West of 24°E, the sea floor shows a much more complex morphology in a significantly shallower area (1700 m water depth on average). We observe elongated and curved features aligned in a North-South trend and a series of 1 to 2 km diameter cones that delineate a Northwest-Southeast oriented belt ending near 33°10N, 24°20E. Most of the bathymetric features here appear to partly reflect trend variations detected along the Southern MR front and along the African slope more than 60 km away.

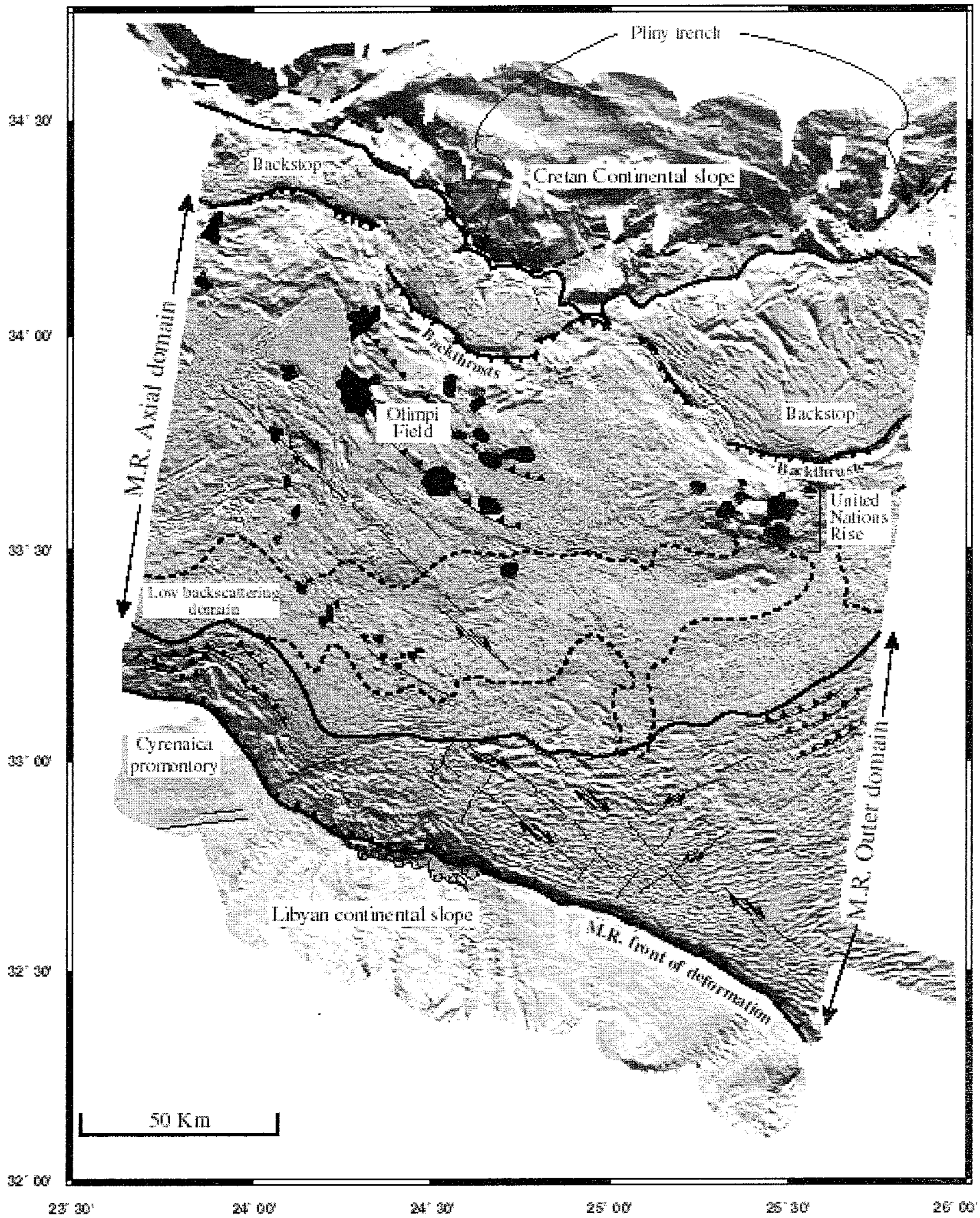

Fig. 1. Shaded bathymetry of the central Mediterranean Ridge (MR) with interpreted structural features and morphologic domains identified. Dark patches indicate the locations of mud volcanoes and related mud flows.

- North of this outer region the MR contains numerous circular features (several km in diameters and a few hundred m in elevations). These are concentrated into two main areas which correlate with the mud volcano Olimpi field (Camerlenghi *et al.*, 1992) and United nations field (Limonov *et al.*, 1999). From the Prismed II survey these features appear to be far more abundant than previously anticipated. Zones of small scale sea floor features seen in this area do not display any well defined trend. As an exception some "en echelon" features form a North-South boundary, approximately along 24°E 10', between the shallower Western MR area (averaging less than 1700 m depth) and the deeper Eastern domain which has an average depth of 2300 m. Further North the MR topography is characterized by large-scale crescent-like relief, expressed in a series of elongated basins and bordering highs. These relief are believed to delineate a general back-trusting of the MR against its probable continental backstop.

- Just North of the backthrust, the bathymetry is deeper and characterized by a gentle surface slightly inclined towards North. The area is, however, broken either by local important relief (Western area) or by an irregular pattern of isolated depressions. The Northern margins of this probable backstop is bounded by slightly curved and gentle slope segments facing a series of disconnected deep troughs that constitute the Pliny (Hellenic) trench system.

- In most of the survey area, the Pliny trench defines the base of the steep Crete island continental slope, with a series of deep, almost disconnected, "en echelon" troughs arranged along a general Northeast-Southwest trend. West of 24°30E, however, the Pliny trench progressively vanishs to be replaced by shallower and very narrow depressions oriented roughly Northwest-Southeast, between the base of the continental slope and the deep backstop area.

- The Cretan continental margin is formed by a series of high standing and massive blocks bounded by very steep cliffs, and slope basins. The main morphological trends are similar to those of the Pliny trench and Western Hellenic trench, but North-South directions are also common especially along massive promontories which disconnect the Pliny trench into depressions.

ACOUSTIC IMAGERY

Backscatter images recorded concurrently with multibeam bathymetry reveal or enhance bottom and subbottom features not well established from bathymetry. After onboard processing and further reprocessing using the recently developed Caraibes software (IFREMER), the backscatter data can be correlated with the bathymetry to assist in the subdivision and interpretation of various contrasting terrains.

The African and most of the Cretan continental slopes, as well as the deep areas, just North of the MR, are weak backscatter zones. Exception to this are areas of steep slopes, for example where canyons cut across the African slope or the rugged relief of the Cretan margin. The slope of the Cyrenaica promontory displays evidence of recent Northeast-Southwest trending faulting that can be detected over more than 20 km till the main slope offset (at approximately 24°E10').

The MR shows rather contrasted backscatter images. Its outer domain displays a series of elongated zones of alternatively high and weak backscatter that is clearly correlatable with sea floor features already detected on bathymetry. Close inspection of acoustic images, however, reveals details which are 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. We interpret these as acoustic images of a dense network of faults that cannot be detected on bathymetry due to their very low relief. We hypothesize that their strong acoustic backscatter may result from fluids release and the related development of scattered carbonates crusts along the fault paths. North of this domain the MR axial domain exhibits two large and distinct backscatter terrains. A Southern province is nearly homogeneous acoustically, with the exception of scattered patches and higher backscatter trends that can be correlated with bathymetric features. The Northern one contains several important irregular to subcircular features (up to 15 km in some cases) with very high backscatter. Comparison with bathymetric data indicate that this high backscatter images correspond to mud volcanoes and their mud flows.

The more widespread occurrence of mud volcanoes on the MR than was previously anticipated is inferred from occurrence of both the high backscatter acoustic signature and corresponding characteristic relief associated with known mud volcanoes. Prismed II results demonstrate that mud volcanoes are not randomly distributed.The majority of them occur, as suggested prior to the survey, in close relationship with thrusting. The data show that the two main fields (Olimpi and United nations) are located just where the inferred backstop extends further to the South. This suggests a regional increase of mud and fluids being forced upward to the sea floor as a consequence from 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 24°E, might be related to mechanisms other than backthrusting such as transcurrent faulting. These features do not characterize on bathymetry as cones but rather as irregular and subdued hills. In the acoustic imagery these features show up as irregular patches of high backscatter which can be up to 15 km long. On closer examination, one may observe different backscatter degrees, from high to weaker. Following 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.

Seismic reflection data

Processing and detailed interpretations of the Prismed I MCS profiles are already published (Chaumillon *et al.*, 1996; Chaumillon and Mascle, 1997; Mascle and Chaumillon, 1998). The 4000 km of seismic data collected during the Prismed II survey are still in analysis. Here we focus only on results which are relevant to better characterize, in term of deformational styles, the different sea floor domains recognized on swath bathymetry and acoustic imagery.

The African continental slope appears as a thick wedge of sub horizontal seismic units, either slightly tilted towards South, West of 24°E, or gently inclined towards the North elsewhere. In many areas, and particularly in the Southeastern corner, these units may be distinguished to distance up to 30 km beneath the overriding deformed wedge of MR sediments.

The MR front of deformation, facing the Cyrenaica promontory, is characterized as a narrow belt of stacked thrusts and accompanying small piggy back basins with frontal sedimentary slumps well displayed on MCS data (Chaumillon and Mascle, 1997). Eastward, the MR outer zone appears as a progressively widening folded belt. The folds, which clearly affect Messinian deposits, have a Northeast Southwest trend. They are often affected along strike by reverse faults and are intensively cut by a conjugate set of normal faults. Folds amplitude and wavelength progressively increase Eastward, as a direct consequence of progressive thickening of the recent, Pliocene and Quaternary, sedimentary cover as well illustrated on detailled studies of multichannel seismic data (Chaumillon and Mascle, 1995).

The axial MR region is itself seen as an almost reflection free terrain, with the exception of narrow tectonic corridors (thrust and wrench zones). This intriguing observation, together with the absence of any significant relief (with the exception of a belt of small cones potentially made of extruded mud), and an average very weak backscatter, remain difficult to understand. As explanations, we suggest, either that deformation is chiefly concentrated into narrow tectonic corridors, or more speculatively that the sedimentary pile being strongly compressed there is releasing a large amount of fluids which, in turn, might homogenize subbottom acoustic reflection.

Further North the internal tectonics of the MR can better be imaged. Thrust planes are observed which clearly correlate with bathymetric features such as backthrust reliefs.

The deep subdued areas, just North of the backthrust, inferred to belong to the backstop, contain a relatively thick recent cover above reflector similar to that of the Messinian (M reflector of Ryan *et al.,* 1973). We believe this backstop, which may be made of a relatively thin superposition of former alpine nappes (Lallemant *et al.*, 1994), is progressively deforming and tilting Northward here. As a consequence, its post-Miocene cover might be gliding Northward using the underlying Messinian evaporites as a decollement level. This may explain some specific morphological features like apparent flow structures and extensional fissures.

Seismic data are not of great help to better define the structure of Pliny trench and associated troughs. They show no evidences 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 thin continental backstop to the South and a thicker and more rigid pile of alpine units that constitute the Crete continental margin to the North.

The Central MR, an example of incipient collision

Integration of seismic data with detailed bathymetry and acoustic imagery allows to better asses the different deformational styles that characterize this area of the Mediterranean Ridge.

Besides obvious differences in width and in bathymetry, the two surveys of the Central MR reveal strong contrasts in structures, West and East of 24°E10'.

Facing a Southward tilted African margin segment, West of this meridian, the MR is characterized by a complex pattern of surface and subbottom deformations and tectonic features. This includes (1) a series of stacked frontal thusts, (2) the presence of inner thrusts that seem to reflect the Libyan margin morphology more than 60 km away, (3) North-South and Northwest-Southeast tectonic lineaments, (4) a belt of small mud cones which may be mud volcanoes, (5) widespread mud flows and (6) major crescent-like backthrusts to the North. North of this MR area, a deep subdued backstop appears quite narrow and only disconnected from the Cretan continental slope by fairly narrow and shallow depressions.

In contrast, the Eastern MR, East of 24°E, displays a more organized structural pattern, even though complex in detail. There the outer MR domain, which faces a gently inclined African continental slope, shows as a progressively Eastward widening folded belt, cross cut by a set of apparently conjugate transcurrent faults. This domain is disconnected from an almost flat axial area, also cross cut by linear tectonic corridors (wrench zones ?) by a series of thrusts. Finally, North of this enigmatic axial domain, extends a wide region chiefly characterized by the two, Olimpi and United nations, mud volcanic fields, and bounded to the North by backthrust-related reliefs.

As an hypothesis to be tested, we propose that the specific deformational pattern and structural trends of the Western Central MR are best explained by the onset of collision between the Mesozoic Cyrenaica-Africa passive continental margin, to the South, acting as a continental indenter, and the thinned edge of the Cretan margin made of staked alpine nappes. Such collisional setting would lead to increasing deformation and progressive uplift of the entire accretionary wedge; large scale crustal faulting may be expected to occur there. The geological structures, seen on the Eastern Central MR, would be the result of a chiefly oblique convergence, between Africa and the Anatolian-Aegean microplate, active on a thick pile of pre-Messinian, evaporite-bearing Messinian and Pliocene to Quaternary sediments.

We believe that this survey area of the Mediterranean Ridge may represent an unique opportunity for studying initial stages of collision between the passive margin of a major plate (Africa) acting as a continental indenter against the active margin of another one (Europe). More data, especially wide angle and deep penetrating MCS seismic, are, however, needed to better assess the nature and architecture of the underlying lithosphere, and to support Deep Scientific Drilling operations in this area.

Drilling data are crucial to better understand the mechanisms and styles of sedimentary deformation, the consequences on geochemical fluid budget and release, to evaluate *in situ* stresses and finally, to establish, or reject, a model of incipient collision.

We propose to promote a series of drill sites across this area of the MR, from its backthrust to its present day front of deformation. Such a transect could easily be part of a more extensive drilling strategy, including onshore and offshore drilling proposals, from the Cretan Sea extensional domain to the MR backstop.

ACKNOWLEDGMENTS

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Backstop hydrogeology and deformation mechanisms related to incipient continental collision and exhumation processes off Crete, Eastern Mediterranean

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We propose to drill a transect of three sites south of the island of Crete (Eastern Mediterranean) from the northern part of an accretionary prism (MedRidge) across its backstop to the North. Drilling a backstop (or buttress) setting is now essential to elucidate fundamental fluid flow processes and deformation mechanisms within an accretionary prism, following geophysical surveys and analog modeling. Variability in fluid flux across the wedge to its buttress is likely to influence fluid budgets of the accretionary complex. Specifically, dewatering along hinterland backthrusts could diminish fluid available for migration along the accretionary décollement. The area South of Crete is selected mainly because the backstop setting is well imaged, accessible to drilling, and comprises lithologies of different rheology, age and origin. The existence of the backstop is seen as a consequence of a relatively short-lived cycle of subduction slab breakoff, uprise and thrusting, accompanied by normal faulting within the forearc-high (Crete) and accretion further South (MedRidge).

Generally, nearly half of the sediment presently on the Earth's seafloor converges towards active continental margins as a result of plate kinematics. These sediments enter scenarios where an oceanic plate is subducting below an overriding plate of continental crust. The dynamic plate boundary is characterised geomorphologically by a deep sea trench (often several km of water depth), seismically by a landward-dipping zone of earthquake activity (recently known as seismogenic zone), tectonically by regional scale faulting and terrane emplacement, and magmatically by belts of eruptive activity (volcanic or island arcs). In the collision zone between the African and Eurasian Plates between Libya and Greece, an almost absent trench is the southern limit of the wide MedRidge accretionary wedge, which in turn is bounded to the north by the depressed, overridden Inner Ridge backstop as well as a forearc high, represented by the thrust stack of Crete. The Cretan Sea, the volcanic arc (*e.g.* the island of Santorini), and a back-arc basin, the Aegean Sea, follow towards the hinterland (i.e. North). In a subduction zone, an accretionary wedge forms only if material transfer from the lower to the upper plate occurs. In order to allow this, a mechanical abutment (the so-called backstop) to the subducting plate is inevitable. This backstop is a mechanical rather than geological feature, and it is defined by its rheology (relative to the prism) more than anything else. Often, it lacks a clear boundary to its prism, especially if convergence is going on for several million years. Therefore, the backstop setting is not only part of what is now referred to as the subduction factory, but has been shown to play a crucial role in tectonic dewatering, control of deformation, and the overall geometry during these fundamental mountain building processes.

However, a backstop has not yet been targeted in the Ocean Drilling Program at all. There is a variety of reasons for its neglect, and the main one may be its inaccessibility for study by deep sea drilling. In various settings, the buttress is either onshore (Nankai, Makran, Cascadia, partly Barbados/Antilles), covered by thick basin fill, buried by overturned thrust sheets (Alaska, parts of Barbados), or comprises rigid crystalline crustal rock (*e.g.* Peru, Chile, Costa Rica) unsuitable for deformation study due to the contrasts in rheological behaviour. On the other hand, it has been demonstrated on numerous occasions that, as result of the already decreased pore space in the hinterland, the backstop is in area where excessive pore pressures and out-of-sequence faulting occur. Pore fluids are either generated from mineral dehydration due to burial, tectonic shortening and diagenesis, or migrate from deeper levels through the faulted backstop. This can either be the décollement (and, consequently, a connection to the updip limit of the seismogenic zone), or from underthrust and underplated sequences or even alterated oceanic crust beneath. Faulting (and conductive fluid flow along the fault planes) and mud volcanism are possible mechanism to expulse the excess pore water and gas, so that they provide windows into much deeper seated processes.

For the above reasons, we have selected the Mediterranean Ridge because it is a type example of an accretionary prism in a setting of incipient continental collision, and it exhibits a wide backstop area that is accessible to drilling. As pointed out by others, the majority of the deep sea trenches are difficult to access (i.e. 5-7 km depth), and the geometry of the wedge also does not allow penetration anywhere near the décollement or seismogenic zone, apart from the toe area. The toe, however, has been studied on numerous occasions, and what has been learned is that it is only part of a much wider system, which is impossible to separate from its hinterland. The average dip of the forearc slope of accretionary prisms varies from several (2-3°) to up to 10-12° (the latter values along erosive margins with high basal friction), and the angles of dip of the downgoing slab (b) indicate that information regarding the deeper part of the backstop as well as the plate boundary geochemistry and pore pressures are unlikely to be reached by drilling in most scenarios (*i.e.* the typical subduction trenches are 5-7 km deep, like Nankai, or deeper). By comparison, in the Eastern Mediterranean a shallow taper (a+b) is seen (i.e. regarding the world-wide range, the MedRidge is at the upper, shallow-dipping end for both angles). Consequently, owing to an excellent regional framework of marine geophysical data and previous drill data (ODP Leg 160), and given the wealth of land-based information from Crete, investigation of the backstop structural and hydrogeology in the Mediterranean has been identified to be a high-priority target for deep sea drilling.

As has been successfully demonstrated, the study of processes which are highly variable perpendicular to strike is most efficiently done along transects of holes. We therefore propose a series of three sites South of Crete, covering the area from the northern part of the accretionary prism (with abundant backthrust faulting and mud volcanism) across its backstop (Inner Ridge) into the forearc-high of the Cretan margin to the North. Variability in fluid flux across the wedge to its buttress is likely to influence fluid budgets of the accretionary complex, but also affects the deformation mechanisms. The area south of Crete is selected mainly because the backstop setting is well imaged, accessible to drilling, and comprises lithologies of different rheology, age and origin. Despite the fact that the tectonic situation in the Eastern Mediterranean is rather complicated, a number of characteristic orogenic processes, namely imbrication (toe and central part), out-of-sequence faults (backstop), and exhumation and crustal thinning (forearc-high of Crete) can be studied. In order to add information to what has been gained from the ODP legs drilling toes of accretionary prisms, the three drillsites are targeting the backthrusted, landward part of the prism, the backstop, and the thrust stack of Crete, respectively (see Figure).

The history of the backstop itself can be envisaged very simply as two phases, which subsequently lead to two domains within the buttress, the Cretan margin forearc-high and the Inner Ridge.

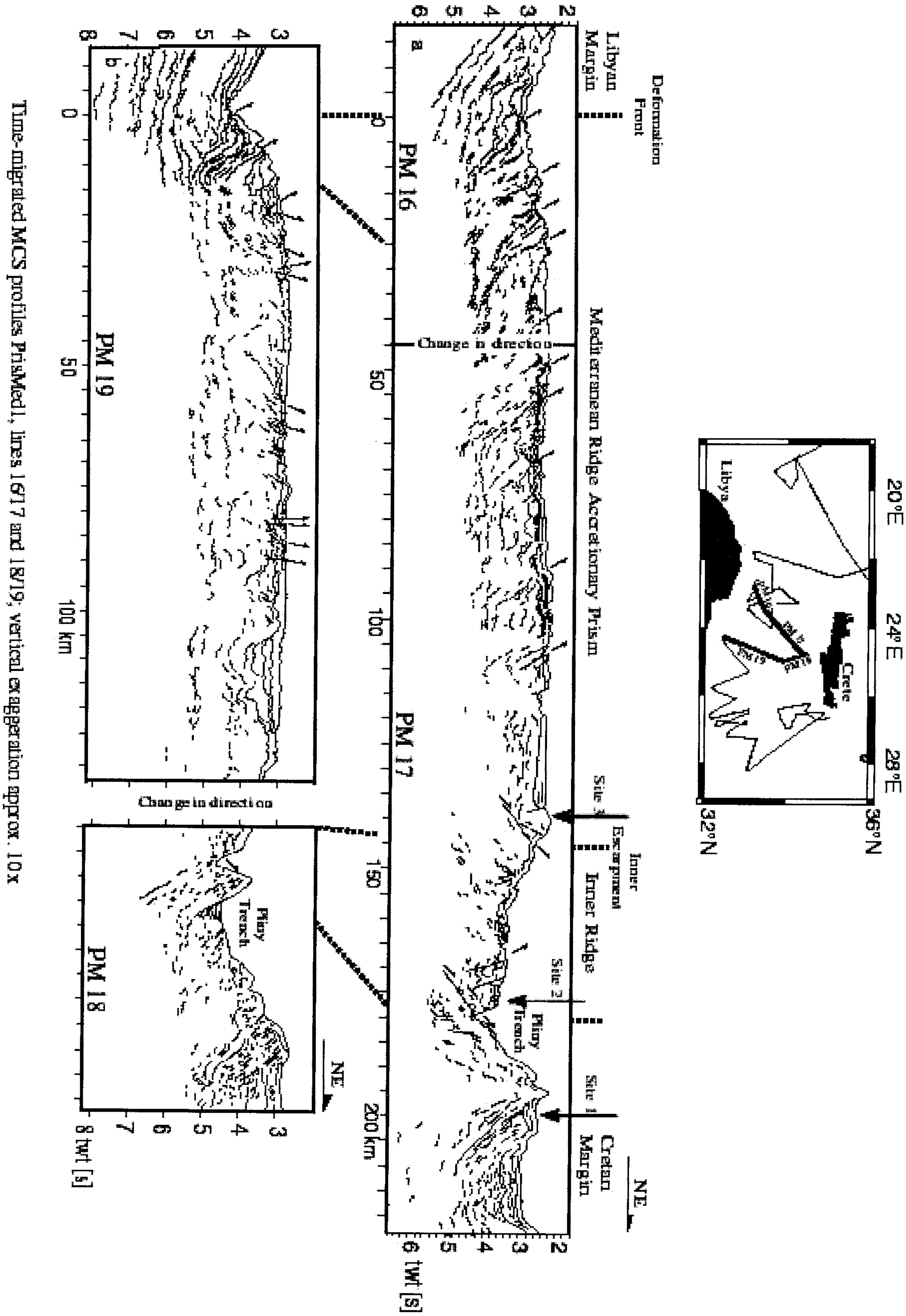

Figure. Interpretative line drawing of MCS line PM1 18/19, including the proposed locations of drilling (some projected). Vertical exaggeration is c10; modified after Chaumillon and Mascle, 1997, Marine Geology 138: 237-259.

Fluid flow through the floor of the Eastern Mediterranean: combined observations and experiments at the sea-bottom and in boreholes

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INTRODUCTION

Recent field observations made in the Mediterranean have revealed a variety of active phenomena of fluid flow through the seafloor. The Mediterranean Ridge accretionary complex in the Eastern Mediterranean basin is one area of particularly intense fluid flow. Fluid expulsion through the seafloor occurs there in association with mud volcanism and along deep active faults. The high activity of fluid flow phenomena on the Mediterranean Ridge is probably directly related to its peculiar tectonic setting. The beginning collision between the African and Eurasian plates generates large compressive stresses in the Eastern Mediterranean Basin, at the origin of an enhanced deformation by faulting of the Mediterranean Ridge accretionary complex. Consequently, the Mediterranean Ridge seafloor offers many opportunities to observe and monitor fluid flow processes associated with an exceptionally active subsurface deformation. The dynamics of gas hydrate systems, the role played by fluid flow in the triggering of large sediment slumps, or yet the interplay between microbial life and active fluid seepage, that are all fluid flow related processes of great scientific interest, can be addressed in the Eastern Mediterranean. Drilling the seafloor is an important component of most comprehensive field studies aimed at an experimental investigation of those processes.

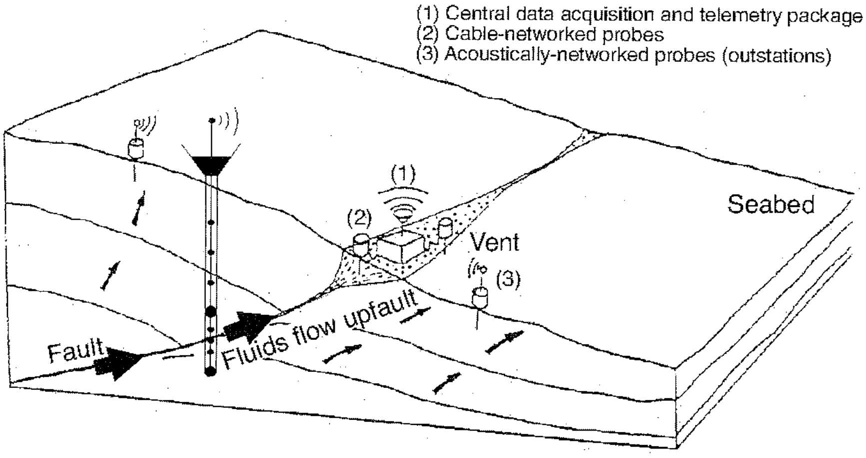
MUD VOLCANOES

Mud volcanoes are numerous in the Mediterranean. They stand out as patches of high reflectivity on acoustic images of the seafloor. The high reflectivity has been interpreted as a consequence of the presence of clasts in the erupted mud (Volgin and Woodside, 1996; Almendinguer and Guillon, 1997). Based on the identification of high reflectivity patches, over 200 mud volcanoes have been mapped on the Mediterranean Ridge (Foucher *et al.*, 1998). The high reflectivity patches define a belt, approximately 30 km wide, of mud volcanoes at the prism-backstop boundary. This belt includes the Pan di Zucchero, Prometheus 1 and 2, Olimpi and United Nations Rise mud dome fields. Mud volcanoes in this area have grown in an area of maximum contraction of the prism against the rigid backstop.

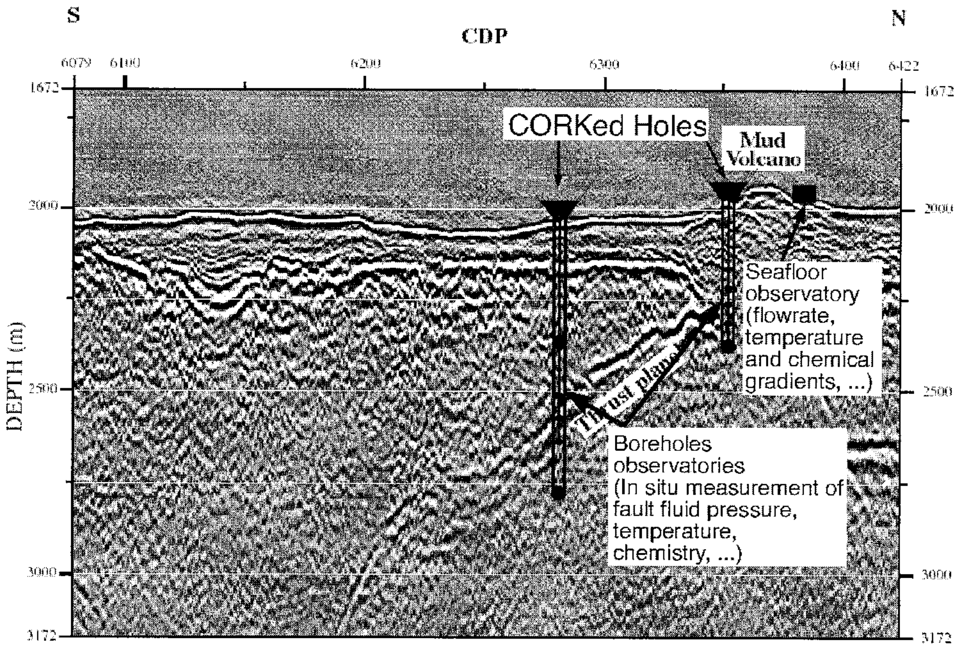
Two mud volcanoes of the Olimpi mud dome field, Napoli and Milano were drilled during ODP Leg 160. Drilling data indicate that hydrocarbon gas is venting from the crest of Napoli and gas was also detected on the crest of Milano (Robertson *et al.*, 1996). Submersible observations

Networked observations in a borehole and at the seafloor

1- Conceptual view



2- Exemple of application to a mediterranean mud volcano



PRISMED 2 - Line 6

made during the French-Dutch MEDINAUT expedition further indicate that brine seepage is active on the top of Napoli, with formation of several shallow brine ponds (Foucher, De Lange *et al.*, 1999). MEDINAUT observations also show that hydrocarbon plumes, with methane contents up to 10 000 times the background value, are present in the water column above the two volcanoes, thus confirming active degassing through their seafloor surfaces. Active fluid expulsion is not limited to the Olimpi field mud volcanoes. Intense degassing, with the presence in the water column of a large methane plume has also been observed at the surface of the Amsterdam mud volcano, in the Anaximander mountains region, South of Turkey. Active fluid expulsion, with high methane fluxes, could be a major feature of most Mediterranean mud volcanoes.

Mediterranean mud volcanoes contain gas hydrates. This has been demonstrated by preliminary core sampling (Woodside *et al.*, 1998). Based on the temperature and pressure conditions at the seafloor, methane gas hydrates are predicted to be thermodynamically stable in the Mediterranean sediments below 1 km water depth. The large methane fluxes through the seafloor inferred from the observed methane plumes in the water column favor massive methane gas hydrate formation in the mud volcanoes. Transient flows of warm fluid or episodic or gradual increases of the sea-bottom temperature could produce major events of gas hydrate dissociation and the release of large volumes of free methane into the water column. The amount of gas hydrate present and the stability/instability of the gas hydrate environments need to be determined.

Both areas of mud volcanism visited during the MEDINAUT expedition, the Olimpi mud field and the Anaximander mountains, show extensive microbiological activity, with observations of a variety of microbial mats, filaments or aggregates, at the seafloor. How microbiological processes interplay with geological and chemical phenomena in those areas is still poorly determined (Corselli and Basso, 1996).

FLUID EXPULSION ALONG FAULTS

There are several brine basins in the Eastern Mediterranean. Several years after the discovery of the Tyro and Bannock basins, the MEDRIFF consortium discovered three new large brine lakes, the Urania, L'Atalante and Discovery basins. Among those, the Urania brine lake has received considerable attention (MEDRIFF consortium, 1995). Warm brines have accumulated with a thickness of over 200 meters in the western pit of the Urania brine lake.

Recent submersible observations made during the MEDINAUT expedition allow discovery of the Nadir brine lakes located on an active fault linking volcanoes in the Olimpi mud dome area. (Woodside, Mascle *et al.*, 1999). In addition, the still unexplored Médée brine lakes located at the prism-backstop transition to the South-West of Crete, could be the largest ever found accumulations of brines in the Mediterranean Sea (Lallemant *et al.*, 1998). Several brine ponds are also associated with brine seepage through mud volcanoes, as shown by the presence of brine ponds on Napoli (Foucher, De Lange *et al.*, 1999) and Maidstone (Woodside *et al.*, 1996).

A current hypothesis for the formation of the Mediterranean brine lakes is that brine-forming fluids have migrated from deep overpressured horizons of the Mediterranean Ridge accretionary complex, to the seafloor. Flow of those fluids through the Messinian evaporites appears to be required to form the brines. Deep faults cutting through the Mediterranean Ridge accretionary complex would be privileged pathways for fluid migration because of their high permeability. Brines would accumulate in topographic lows of the seafloor.

Fluid expulsion along active backthrusts could account for the formation of the Médée brine lakes (Lallemant *et al.*, 1998). The high gas content measured in the Nadir brines is best explained by active fluid flow and degassing taking place along the fault (Woodside, Mascle *et al.*, 1999). Furthermore, based on CTD data gathered at a few months time interval in the Urania brine lake, which indicated a considerable time increase of the temperature of the brines, fluid flow is likely to vary with time (Corselli *et al.*, 1996).

DRILLING OBJECTIVES

1. The Eastern Mediterranean basin is an outstanding area of active fluid flow through the seafloor, especially suited for comprehensive field studies of fluid flow processes through the seafloor at selected sites of mud volcanism or deep faulting. Combined observations of temperature, fluid pressure, pore chemistry, permeability, among other important parameters, made both near the seafloor and in boreholes, would allow to characterize the origin, pathways and modes of functioning of fluid seepage through the seafloor and, so, better answer to the question of the nature of cold seep phenomena observed at an ever increasing number of discovered seepage sites on continental margins. Time variations of those processes and how transient events at the sediment surface relate to events at depths. could be determined from long-term observations, both at the seafloor and in boreholes.

2. The relation of fluid flow to the formation or dissociation of gas hydrates in the seafloor sediments is a particularly important question, both (a) to understand how gas hydrate forms in a strong gas (methane) flux and can lead to large accumulations of solid gas hydrate, potentially of economical relevance, and (b) to better assess the impact of gas hydrate dissociation on the seafloor and water column environment, and the risks induced, in particular because of the release of large volumes of water and free gas (methane) associated with gas hydrate dissociation. We need to develop borehole experiments to address the dynamics of gas hydrate systems in the subsurface sediments. We need CORKs-type borehole monitoring installations allowing for long-term observations.

3. There is a broad consensus that microbial processes play a considerable role in the diagenesis of sediments. The formation of carbonate and sulfide concretions could be controlled by microbial activity. In addition, mud volcanoes and brine accumulations could provide windows on the deep biosphere by bringing up to the seafloor originally deep-seated bacteria. We need to combine microbiological, chemical and geological observations at seafloor sites of active seepage, and in boreholes at intersections of fluid-carrying faults, in order to characterize how microbial processes interplay with chemical fluxes, pore water chemistry, and other sediment properties, in the diagenesis process.

As previously argued, the Mediterranean floor displays a number of sites, either at mud volcanoes or along fluid-expelling faults, where the above objectives can be addressed by drilling, with the perspective of good scientific return.

Monitoring experiments, both in boreholes and at the seafloor, would benefit from the proximity of land-based technical support teams.

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Easternmost Mediterranean: towards a regional tectonic model

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Introduction

The Eastern Mediterranean region offers an exceptional opportunity to integrate evidence from on land and under the sea with the aim of understanding the tectonic-sedimentary evolution during Mesozoic and Tertiary time. Here, some "milestone" contributions are mentioned, followed by an outline of a recently published plate tectonic synthesis (Robertson, 1998).

Marine studies

Plate boundaries in the Eastern Mediterranean were initially delineated by McKenzie (1972), based on earthquake evidence, although the location of the Africa-Eurasia plate boundary in the Easternmost Mediterranean (around Cyprus) remained unclear. Some of the first extensive bathymetric and reflection seismic data were provided by Woodside (1977). The results of DSDP Leg 42A (Hsu, Montadert *et al.*, 1978) were invaluable in demonstrating the presence of Messinian facies on the Florence Rise West of Cyprus. Important information on magnetic anomalies in the Easternmost Mediterranean, including the Eratosthenes Seamount, was provided by Ben-Avraham *et al.* (1976). Seismic refraction studies by Makris *et al.* (1983) demonstrated that the crust thins beneath the Levant Basin, suggesting this area as the site of a Mesozoic oceanic basin. A hint of the incipient collisional setting of the Easternmost Mediterranean, including Cyprus, as currently understood was provided by Ben-Avraham and Nur (1982). Following additional studies of all the available seismic reflection and other geophysical data essentially the present plate tectonic interpretation was published by Kempler and Ben-Avraham (1987) showing the Africa-Eurasia plate boundary running from the Levant through a location between Cyprus and the Eratosthenes Seamount. Studies of the bathymetry of the Eratosthenes Seamount by the scientific party of the *Akademik Nikolaj Strakhov* revealed important evidence of faulting (Krashenninikov *et al.*, 1994). The TREDMAR survey confirmed the existence of northward underthrusting (subduction) beneath a sediment-filled trench-like basin South of Cyprus (Limonov *et al.*, 1994; Robertson *et al.*, 1995). Subsequently, deep sea drilling during Leg 160 confirmed that the Eratosthenes Seamount shows stratigraphic affinities with the Levant margin, but differs strongly from the geological history of Cyprus (Emeis *et al.* 1996; Mart *et al.*, 1997; Robertson *et al.*, 1998) and also supported the existence of incipient collision between Cyprus and the Eratosthenes Seamount. Recently, preliminary results of the PRISMED-2 survey indicate the presence of nearly N-S faulting between the Eratosthenes Seamount and the Nile Cone, which may be an extension of Gulf of Suez rift system (Mart *et al.*, this volume) and also provided evidence for the nature of the plate boundary between Cyprus and the Anaximander Seamounts to the NW (Woodside *et al.*, this volume).

LAND STUDIES

Results from Cyprus were crucial. Gass and Masson-Smith (1963) interpreted the Troodos Massif as oceanic material that was emplaced by thrusting against the North African continent. Later, Gass (1968) interpreted the Troodos as a fragment of Mesozoic ocean floor formed by sea-floor spreading. Moores and Vine (1971) confirmed the similarity with oceanic lithosphere and demonstrated that 90 degrees of anticlockwise rotation took place since formation of the Troodos in the Late Cretaceous. Pearce (1975) interpreted the Troodos as having formed above a subduction zone rather than at a mid-ocean ridge. Following on from regional studies in Cyprus by Lapierre (1972), Robertson and Woodcock (1979) interpreted the Mamonia Complex of SW Cyprus as a Mesozoic passive continental margin adjacent to a southerly Tethyan oceanic basin. Building on extensive regional mapping in SW Turkey and, then, available studies of the Levant and North Africa, Robertson and Woodcock (1980) presented an initial synthesis of the Easternmost Mediterranean as a small southerly Neotethyan oceanic basin that opened in the Triassic and closed in the Tertiary, and this was incorporated into a regional plate tectonic model by Robertson and Dixon (1984). Dewey and Sengor (1979) gave an early plate tectonic model for the Neogene-Recent history of the Aegean and surrounding areas, while Sengor and Yilmaz (1981) presented a wider scale plate tectonic synthesis of Turkey including the adjacent Easternmost Mediterranean region. Building on an analysis of the Mesozoic structure of Israel in relation to the origin of the Eastern Mediterranean by Freund *et al.* (1975), Garfunkel and Derin (1984) documented the existence of a Triassic-Early Jurassic rifted margin in the Levant adjacent to a small Neotethyan oceanic basin. This was supported by recognition of part of the northern margin of this basin in the Kyrenia Range of Northern Cyprus by Robertson and Woodcock (1986). Additional evidence of Neotethyan ophiolites and Mesozoic margin sequences around the Easternmost Mediterranean was provided by Delaune-Mayere *et al.* (1976). Sedimentary studies on Cyprus initially summarized by Robertson (1977), charted the uplift and unroofing of the Troodos ophiolite and the role of Neogene extensional tectonics that was later attributed to supra-subduction zone extension. It later became possible to integrate evidence from SE Turkey, following regional studies that identified the role of northward subduction of Neotethys in Late Cretaceous-Early Tertiary time (Hall, 1976; Aktas and Robertson, 1984; Yilmaz, 1993).

The above works culminated in synthesis of both the southern (Garfunkel, 1998) and northern (Robertson, 1998) margins of the Neotethyan oceanic basin in the Eastern Mediterranean. The model given in the latter publication is summarized below (where a much fuller bibliography is to be found).

MESOZOIC-EARLY TERTIARY (FIGS. 1, 2A)

Although rifting may have begun in the Late Permian, there is copious evidence from the Levant, Cyprus and Southern Turkey of rifting and continental break-up to form a small Neotethyan oceanic basin in Late Triassic-Early Jurassic time. A Red-Sea type basin, rather than a back-arc basin setting is preferred, as the associated deep-sea sediments are terrigenous and the rift-related volcanics lack any identifiable "subduction component". The southerly Neotethyan oceanic basin was surrounded by subsiding passive margins during Early-Mid Jurassic time. There is limited evidence of a further marginal rift event in Late Jurassic-Early Cretaceous time, when further sea-floor spreading could have taken place. Regional plate convergence ensued and the Troodos ophiolite formed by spreading above a subduction zone around 80 Ma. The eastward extension of this ophiolite into the Baer-Bassit and Hatay ophiolites was emplaced in the latest Cretaceous, when the subduction trench collided with the Arabian passive continental margin. However, the Troodos ophiolite remained within a remnant of the Neotethyan oceanic basin and continued to undergo deep-sea sedimentation into Early Tertiary time. During the Mid-Late Eocene deformation took place related to closure of more northerly Neotethyan oceanic basins (in central Turkey). During the Oligocene-Early Miocene northward subduction was completed

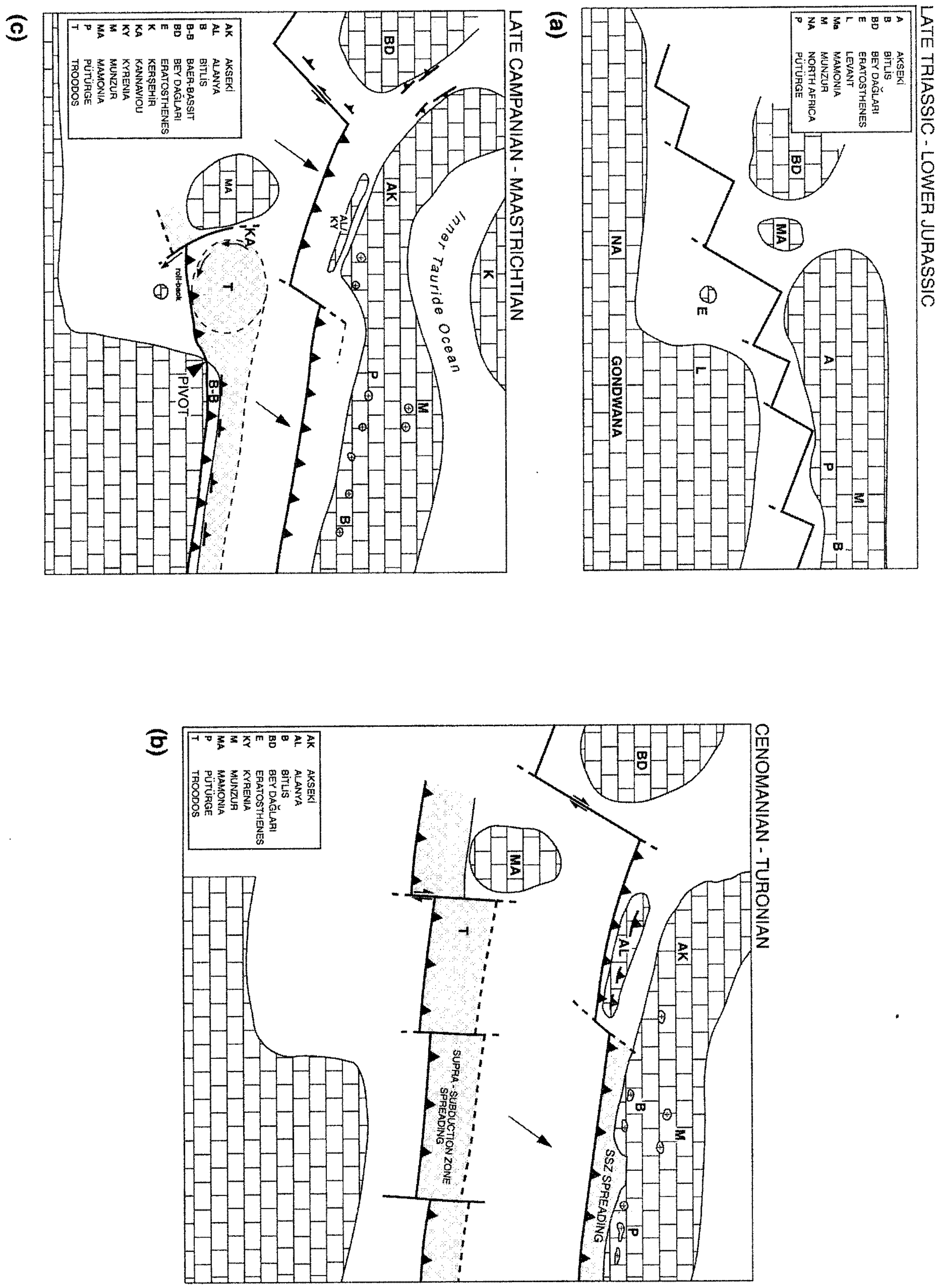

Fig. 1. Palaeogeographic sketch maps of the proposed tectonic evolution of the Easternmost Mediterranean region. **a,** Late Triassic-Lower Jurassic; **b,** Cenomanian-Turonian; **c,** Late Campanian-Maastrichtian (after Robertson, 1998).

along the northern margin of the southerly Neotethys ocean (*e.g.* in SE Turkey). Subduction then jumped southwards to near its present position in the Early Miocene, continuing until today, although disrupted by the effects of collision of the Eratosthenes Seamount with the Cyprus trench. The Oligocene to Recent history that is especially relevant to plans for future academic drilling in the Easternmost Mediterranean basin is summarized below.

OLIGOCENE

Early Oligocene was a time of relative tectonic quiescence throughout the Easternmost Mediterranean area, although faulting took place as Africa-Eurasia convergence continued. Erosion of various recently emplaced units ensued. Pelagic carbonates continued to accumulate on the Troodos ophiolite (Upper Lefkara Formation) in a relatively stable tectonic setting. During the Early Oligocene, compressional stresses probably magnified as Africa and Eurasia continued to converge. Then, in the Late Oligocene, a marked change took place, manifested in the Kyrenia-Misis-Andirin lineament to the NE. The Kyrenia Range of N Cyprus that hitherto had been receiving coarse alluvial sediment from the palaeo-Seyan river in Southern Turkey subsided and passed rapidly upwards into turbiditic sediments (Kithrea Flysch). The onshore Adana Basin subsided, ushering in marine sedimentation influenced by block faulting. Sedimentary mélange of Upper Oligocene-Lower Miocene age (Isali unit) formed relatively further South, in the Misis-Andirin Complex, within an extensional fore-arc setting. The clasts were mainly derived from earlier-emplaced units to the north (*e.g.*, Mesozoic limestone, ophiolites etc.). Limited acidic, calc-alkaline, arc-related volcanism (represented by tuffs) took place at this time, but a rifted back-arc basin did not develop at this late stage. Instead, the ophiolitic blocks in the melange were derived from previously emplaced (? Late Cretaceous) units. The "olistostrome" is interpreted as a trench-accretionary complex related to northward subduction of Neotethyan oceanic crust to the South.

MIOCENE (FIG. 2B, C)

Early Miocene time saw activity along the present subduction zone South of Cyprus, as part of the wider regional Africa-Eurasian plate boundary including the Aegean active margin (Aegean arc). A possible explanation for southward migration of the subduction zone is that remaining old (early Mesozoic) Neotethyan crust was consumed, juxtaposing younger, more buoyant supra-subduction zone-type Upper Cretaceous oceanic crust with the active margin to the North. This crust was difficult to consume, and the subduction zone then relocated itself within early Mesozoic oceanic crust further South. This subduction could effectively have reactivated a Late Cretaceous subduction zone above which the Troodos was previously created by supra-subduction zone spreading. During the Late Cretaceous, northward subduction had already carried the rifted Eratosthenes block (a continental fragment) towards the Troodos, then located on the opposing plate.

From the Early Miocene onward, Cyprus was located on the overriding plate of a northward-dipping subduction zone. The leading edge was dissected into sub-basins. Some of these reached sea level and were colonized by reefs, whereas others still underwent pelagic carbonate accumulation. In northern Cyprus, an extensional graben formed in the Northern Mesaoria Plain area, bounded by the Ovgos Fault to the South and the Kithrea Fault to the North. In the Adana and Manavgat Basins, subsidence in the Middle Miocene (Langhian) is attributed to extensional faulting. Extensional faulting also gave rise to large pre-Messinian marine basins, including the onshore Polis graben (Western Cyprus), the Antalya Basin, the Cilicia-Adana Basin and the Latakia Basin. The overall cause of this extension was possibly southward retreat ("roll-back") of an early Mesozoic-aged oceanic slab. The Messinian salinity crisis was superimposed on this highly variable tectonic setting. Highs such as the Eratosthenes Seamount, or the Akamas Peninsula of Western Cyprus were emergent and karstified. Gypsum was precipitated within previously shallow basins, as in Southern and Western Cyprus, whereas halite was precipitated in deep basins, as locally in the Mesaoria basin and extensively in the deep Levantine Basin and elsewhere.

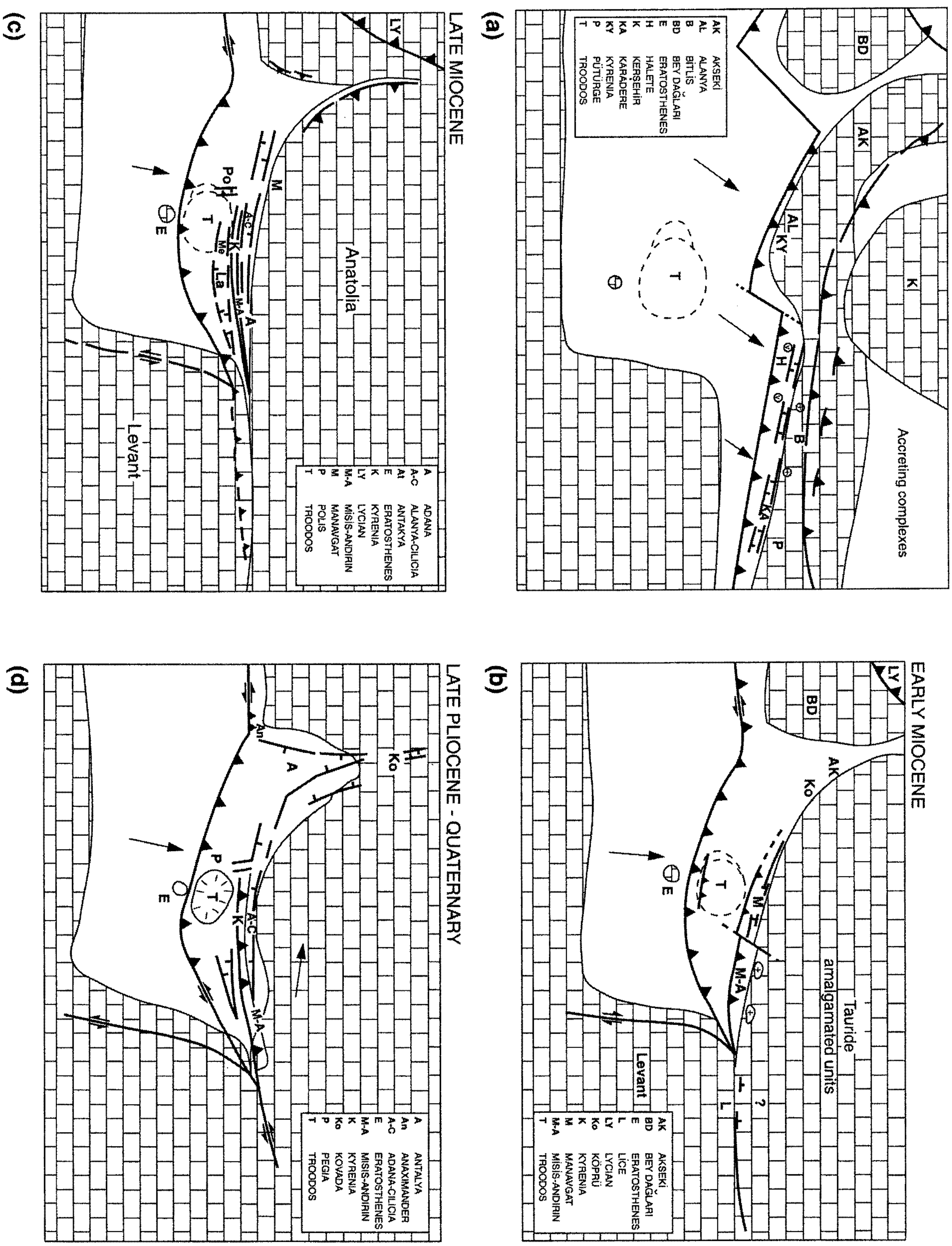

Fig. 2. Palaeogeographic sketch maps of the proposed tectonic evolution of the Easternmost Mediterranean region (contd.) **a**, Middle to Late Eocene; **b**, early Miocene; **c**, Late Miocene; **d**, Late Pliocene-Quaternary (after Robertson, I998).The Hellenic subduction zone – a world site to study the mechanics of roll back.

During the Miocene a division clearly existed between a pre-collisional setting in the Easternmost Mediterranean (West of the longitude of the Levant margin) and a collisional setting in Southeastern Turkey. In the East the Miocene Lice Basin originated as a foreland basin related to the final stages of southward thrusting of the over-riding allochthonous Eastern Taurus units. A foreland basin origin is less clear further West; an inferred transtensional basin origin still needs to be tested. However, it seems clear that on regional plate kinematic grounds that plate convergence was continuing during the Miocene, and thus a convergent margin-type setting is probable.

PLIOCENE (FIG. 2D)

Northward Africa-Eurasia convergence finally brought the Eratosthenes Seamount into collision with the Cyprus trench. As it approached the trench this block was flexurally loaded by the overriding plate, resulting in faulting associated with mass wasting of scarps and subsidence to bathyal depths during Early Pliocene time. Rapid collapse of the Eratosthenes Seamount took place after the Late Pliocene. During this time, rapid uplift of both Southern Cyprus and the Kyrenia Range began. The Kyrenia Range was uplifted to reach its maximum altitude North of the Eratosthenes Seamount collision zone. However, the Adana-Cilicia Basin to the North remained largely unaffected. Also, in Southwest Cyprus the onshore Pegia graben developed in Late Pliocene-early Pleistocene possibly influenced by westward tectonic escape from the Cyprus-Eratosthenes collision zone. Associated with this subduction and underthrusting of the Eratosthenes Seamount, ultramafic rocks within the overriding slab were serpentinized and rose upward diapirically, updoming the Troodos ophiolite and exposing serpentinite on Mt. Olympos. By contrast, within the Aksu and Adana basins of coastal Southern Turkey, extensional basins were infilled with shallowing-upward successions, with marine accumulation persisting longest in the Aksu basin (Antalya area). Regional uplift took place in Late Pliocene-early Pleistocene time, associated with further extensional faulting (Aksu basin) and transtension (Adana basin). In Southeastern Turkey, left-lateral strike-slip along the East Anatolian Fault/Early Pliocene began in the latest Miocene (after suturing of the Arabian and Anatolian plates) with a total displacement of <25 km and was accompanied by more pronounced left-lateral motion along the North Anatolian transform fault. The East Anatolian Fault Zone links eastward with the triple junction in the Karamaranmaras area. Deformation in the Misis Mountains is mainly extensional in the Pliocene-Pleistocene and there is little field evidence that the Late Pliocene-Pleistocene uplift of the Kyrenia Range was caused by transpression. Significant strike-slip along the Kyrenia stage is unlikely, as the Southern Antalya Basin to the West does not appear to be affected. Instead, the uplift of the Kyrenia Range probably relates to the effects of regional collision, specifically involving the Eratosthenes Seamount to the South. The Troodos ophiolite and the Kyrenia Range were both uplifted with respect to surrounding areas, which remained "basinal". Westward escape of Anatolia during Pliocene-Pleistocene time was accompanied by a reorientation of subduction from northward to more northeastward, consistent with the instantaneous GPS data for Southern Turkey (Reilinger *et al.* 1997).

PLEISTOCENE-HOLOCENE

Existing plate boundaries were active during this time. Northeastward subduction was active beneath Southwest Cyprus and the Southern Antalya Bay area. Crustal extension continued onshore in the Antalya Basin. The Florence Rise is probably located above the plate boundary. The Florence Rise is contiguous with the Anaximander Mountains, an offshore extension of units exposed in Southern Turkey, including the Antalya Complex (Woodside *et al.*, this volume). The southern margin of the Anaximander Mountains is seen as a left-lateral strike-slip zone that links with the Strabo trench to the West. Further West, the Eratosthenes Seamount is possibly now being thrust northeastward obliquely beneath Cyprus (perhaps causing rotation of the Seamount). Uplift of the Troodos ophiolite and the Kyrenia Range has diminished after mid-Pleistocene time. The eastward extension of the Cyprus trench is a zone of left-lateral strike-slip, passing into a zone of distributed strike-slip, transtension, and transpression within the "Cyprus-Latakia link zone" to the northeast left-lateral strike-slip continues along the East Anatolian Fault Zone, and also affects onshore areas of the Northern Levant margin further South (Latakia area). At present, the outstanding question in the nature and history of the plate boundary segment linking Cyprus with the Anaximander Seamounts through the Florence Rise area.

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Slow transpressional processes of conclusive subduction, early collision and incipient obduction: drilling the Cypriot Arc

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Abstract

A series of ODP drilling in the region of the Cypriot Arc in the Eastern Mediterranean is proposed. Its purpose is to investigate geochemical fluxes of sediment subduction, to study the effect of the subduction of Tethyan crust on younger sedimentary series, and to reconstruct the structural processes of plate collision, from subduction to obduction. Three transects and deepening of an existing borehole are suggested, which comprise 8 shallow boreholes, one deep borehole and deepening of ODP hole 967.

Introduction

The Easternmost Mediterranean, namely the Mediterranean East of the Rhodes Basin is characterized by the marked geological difference between its northern and southern flanks. The northern flank is collisional in its characteristics, and the southern is diversional, and the boundary between these two domains runs along the Cypriot Arc (Kempler and Ben-Avraham, 1987). The Cypriot Arc is a complex marine structure, that extends from the southern part of Rhodes Basin southeastwards to the bathymetric depression between Cyprus and Eratosthenes Seamount, then it swings northeastwards towards Latakiye in Western Syria (Fig. 1). The Arc is the central segment in the geosuture that marks the closure of the Neotethys, which stretches from Calabria along the Mediterranean Ridge through Cyprus and further eastwards to Oman.

The Cypriot Arc marks the boundary between the northern edge of the African plate and the southern edge of the Anatolian plate (McKenzie, 1970, Kempler and Garfunkel, 1994; Mart *et al.,* 1997; Robertson, 1998). The geological regime along the Arc and its flanks is distinguished by complex offsets of thrusting and sinistral strike-slip faulting, and large geological features north and south of the Arc characterize the overthrust and the underthrust blocks, respectively. The Troodos ophiolites in Cyprus, as well as Florence Rise and Hecataeus Plateau at sea, predominate the northern flank of the Arc, while Eratosthenes Seamount and the Levant basin are the dominant structures in the South. Thrusting of the Levantine oceanic crust under the Anatolian plate along the eastern segment of Cypriot Arc marks the final stage of the northward subduction of the Levantine Neotethys (Robertson, 1998). Concurrently, the thrusting of Eratosthenes Seamount under Cyprus and the Troodos Ophiolites shed new light on the transitional tectonic regime along the Arc that changes from subduction to collision and obduction. The

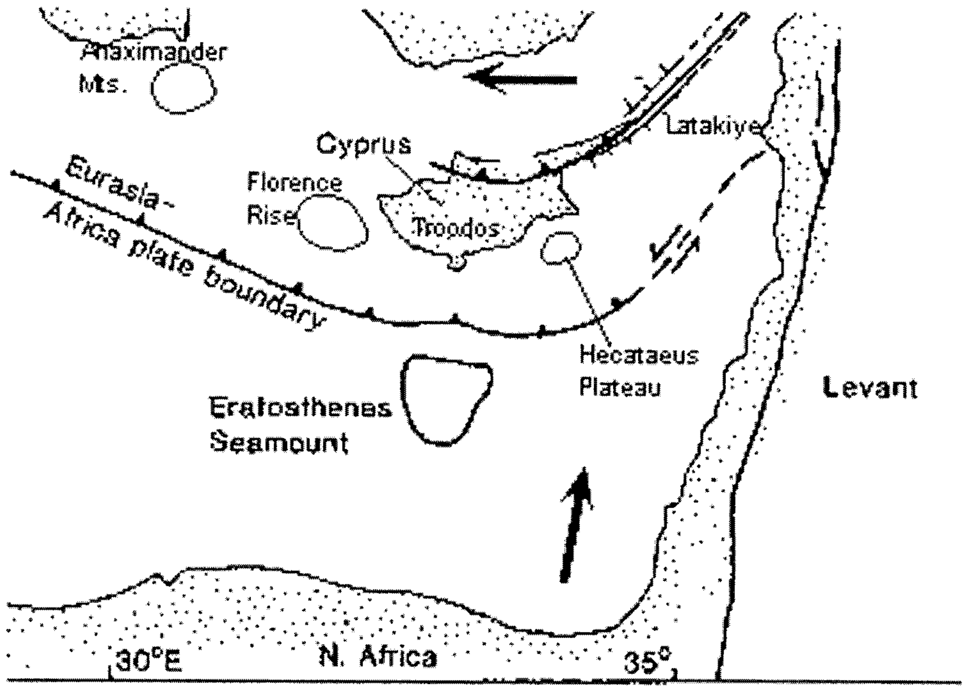

Fig. 1. Major geological features in the Eastern Mediterranean. Heavy arrows indicate direction of tectonic plate motion (after Robertson, 1998).

collisional regime, and the relative northward motion of Africa, is rendered more complex due to the westward motion of Anatolia, Known as "the Anatolian Escape" (Sengör *et al.*, 1985). This complex tectonic motion form collisional, transpressional and transtensional structures along the arc. Therefore the investigation of the Cypriot Arc offers a rare insight into a transitional site, where the tectonic regime of a segment of old oceanic crust, collide with the anomalous continental lithosphere of Southern Anatolia. The linkage of the old oceanic crust to the Eratosthenes segment of thinned Mesozoic continental crust, and its collision with the thick Cypriot crust, opens the research further to the complexities of transitional subduction-collision-obduction tectonic regime.

The Purpose of the drilling proposal

The purpose of this drilling proposal is to investigate the structural patterns and the geochemical fluxes along the Cypriot Arc – a slow, evaporite-rich, oblique subducting environment. The subduction of the Tethyan oceanic crust of the Levant Basin under the southern flank of the Anatolian Plate apparently lead to the structural uplift of Florence Rise, Cyprus and the Latakiye and Misis-Kyrenia ranges. The northward subduction became affected by the westward motion of Anatolia during the Neogene to form the oblique, displacement that occurs at present along the Cypriot Arc, which, due to the arcuate configuration, is transpressional in some places and transtensional in others Kempler and Garfunkel, 1994). The geological history of the Levant Basin and its oceanic crust (Mart, 1987; Makris and Wang, 1994) started probably in the Triassic, and a 12 km thick sedimentary sequence accumulated there. Messinian evaporites were deposited at the upper part of this sequence, and underneath, as indicated by drilling the structural window of Eratosthenes Seamount the early Cretaceous is found at depth of less than 600 m (Emeis, Robertson *et al.*, 1996).

The initiation of the subduction of the oceanic crust of the Levant Basin under the Cypriot Arc is not known, neither is the configuration of the Levant Basin prior to the subduction. However, the commencement of the westward motion of Anatolia is dated to the Neogene, and it probably turned the subduction into displacement – transpressional West of Cyprus and transtensional to the East (Kempler and Garfunkel, 1994). Diapirs that abound along the faults of the Latakiye and

Misis-Kyrenia ranges, as well as numerous earthquakes along the Cypriot Arc, suggest that the oblique subduction is presently active.

The convergent tectonic boundary of the Cypriot Arc is an outstanding location to investigate processes involved with the complex subduction-transform plate motion. It is known from previous geophysical surveys and drilling campaigns in the region (see Robertson (1998) for details) that pre-Messinian series are at shallow depths in Florence Rise, Eratosthenes Seamount, and most likely also Hecataeus Plateau. Furthermore, previous ODP drilling of Eratosthenes Seamount showed that the structural relationship between the seamount and Cyprus are those of initial obduction. The deep marine late Cretaceous Troodos ophiolites are in process of being thrust over the middle Cretaceous continental shelf deposits of Eratosthenes Seamount.

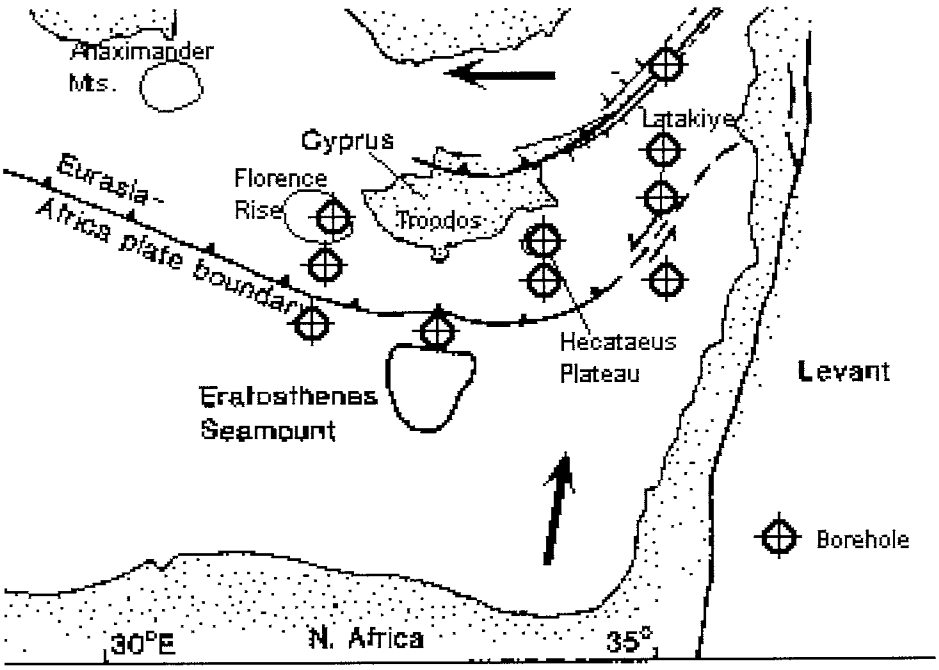

Fig. 2 . Locations of proposed ODP boreholes along the Cypriot Arc

RECOMMENDATIONS

The investigation of the region of the Cypriot Arc and its flanks would clarify some of the more complex processes involved with the conclusive stages of subduction, and their transition to thrusting and incipient obduction. Furthermore, although the Messinian evaporites are purposefully not a drilling target in this proposal due to safety considerations, their proximity is likely to affect the interstitial fluxes and the diagenetic processes along the Cypriot Arc. Therefore, in consideration of the prolonged and variable sedimentation on the Tethyan crust in the Levant Basin, and the complex plate motion along the subduction zone, the primary objectives of the proposed drilling campaign are:

• to investigate sediment subduction along Cypriot Arc subduction - transform system, and specifically to measure fluxes derived from diagenetic effects of Cretaceous and early Tertiary sedimentary sequences;

• to characterize the chemical fluxes released during the alteration of the Tethyan oceanic crust, and study their effect on younger sediments in both hanging- and footwall;

• to reconstruct the structural history of a mature subduction zone, from subduction, through collisional transpressive deformation to obduction.

In order to study the processes involved in the transition from subduction to obduction in the Cypriot Arc, the following four drilling targets are proposed:

1. Deepening borehole ODP 967 from 600 to 1,000 m, and leaving a re-entry cone there for further deepening in the future. The borehole bottomed at 600 mbsf in Aptian beds, and its deepening would open a window to the early Cretaceous and late Jurassic marine Neotethys. If the borehole could reach the volcanic series, that probably underlie the seamount, as indicated by its magnetic anomaly (Ben-Avraham *et al.*, 1976), could be reached, the borehole would yield valuable information regarding the processes of the evolution and destruction of marginal basins in the southern Neotethys. One deep borehole is proposed.

2. Drilling a transect across Florence rise, West of Cyprus. Florence Rise was drilled in leg 42-A, where pre-Messinian strata were pat shallow depth (Hsü, Montadert *et al.*, 1978). The gravity and the magnetic data obtained in the *Atalante* cruise (Mascle *et al.*, in prep.) seem to suggest major crustal transition across the southern boundary of the Rise. The gravity and magnetic transition does not correspond precisely with the present western extension of the Eratosthenes-Cyprus boundary - the Giermann Fault. Drilling here could reach the northward-dipping thrust fault and the underthrust block, and measure its age, and study the decollement, its lithology and geochemistry. Three shallow and one deep boreholes are proposed

3. Drilling a transect across the Latakiye submerged range. Following the cruises of R/V *Strakhov* and *Galendzhik* East of Cyprus (Krasheninnikov *et al.*, 1994; Limonov *et al.*, 1994), it seems that the transtensional fault system there could be drilled to the early Tertiary or the late Cretaceous without drilling through the Messinian evaporites. In this way the characteristics of the faulting patterns along the subduction zone – an oblique thrust faulting with a strike-slip component – could be sampled and studied. Samples obtained in this transect would illuminate the geochemistry of the fluxes in an evaporite-rich subduction. Furthermore, this transect could illuminate the structural history of the westward Anatolian escape, and its relation to the tectonic regime of the Levant Basin and its margin. Four shallow boreholes are proposed.

4. Drilling Hecataeus Plateau would show the lithological characteristics of an ophiolitic block, which is being thrust over a section of extended continental crust, and determine the geochemical characteristics of incipient obduction. Two shallow boreholes are proposed.

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