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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.

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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".

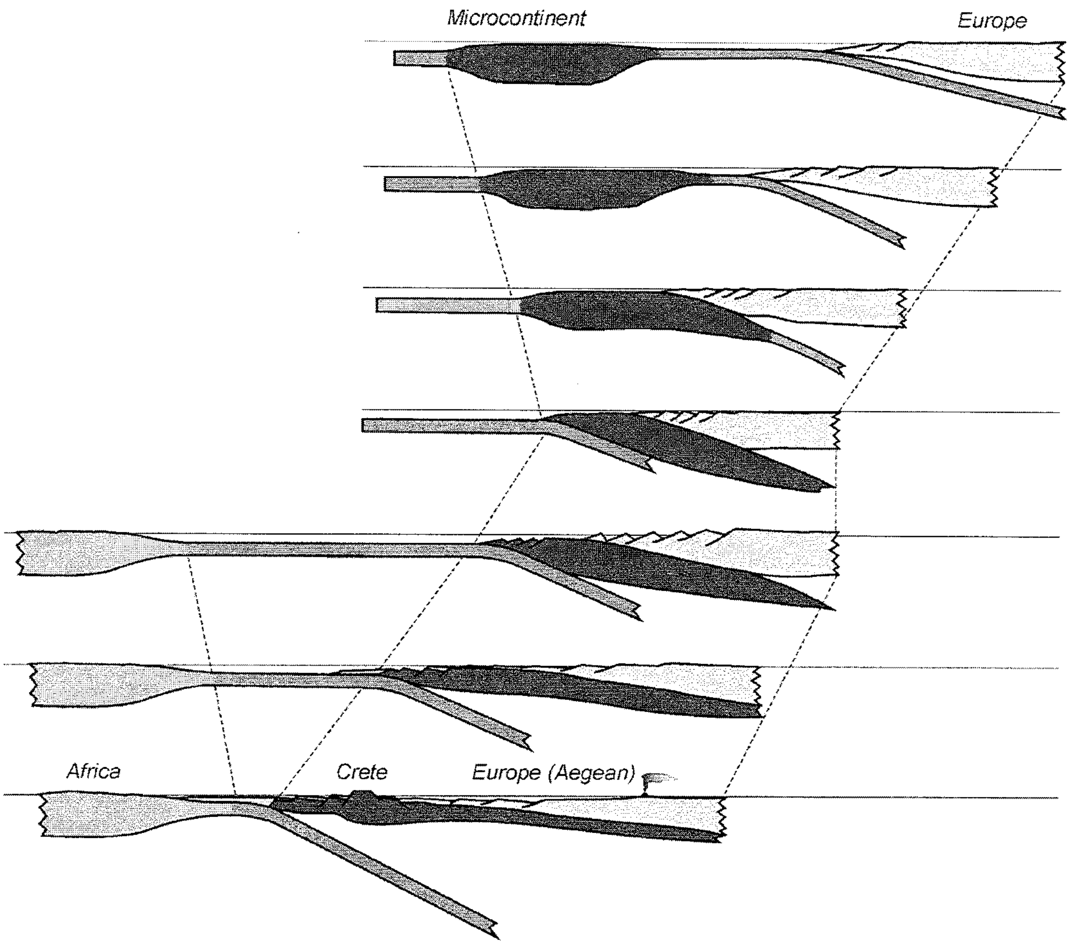

Fig. 1. Inferred tectonic evolution of the Hellenic subduction system since about 35 Ma in NNE-SSW cross section (not to scale). Note the continuous relative motion between Africa and Eurasia and the significant contribution of roll back to the net convergence at the active margin. According to the model 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.

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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?

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(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

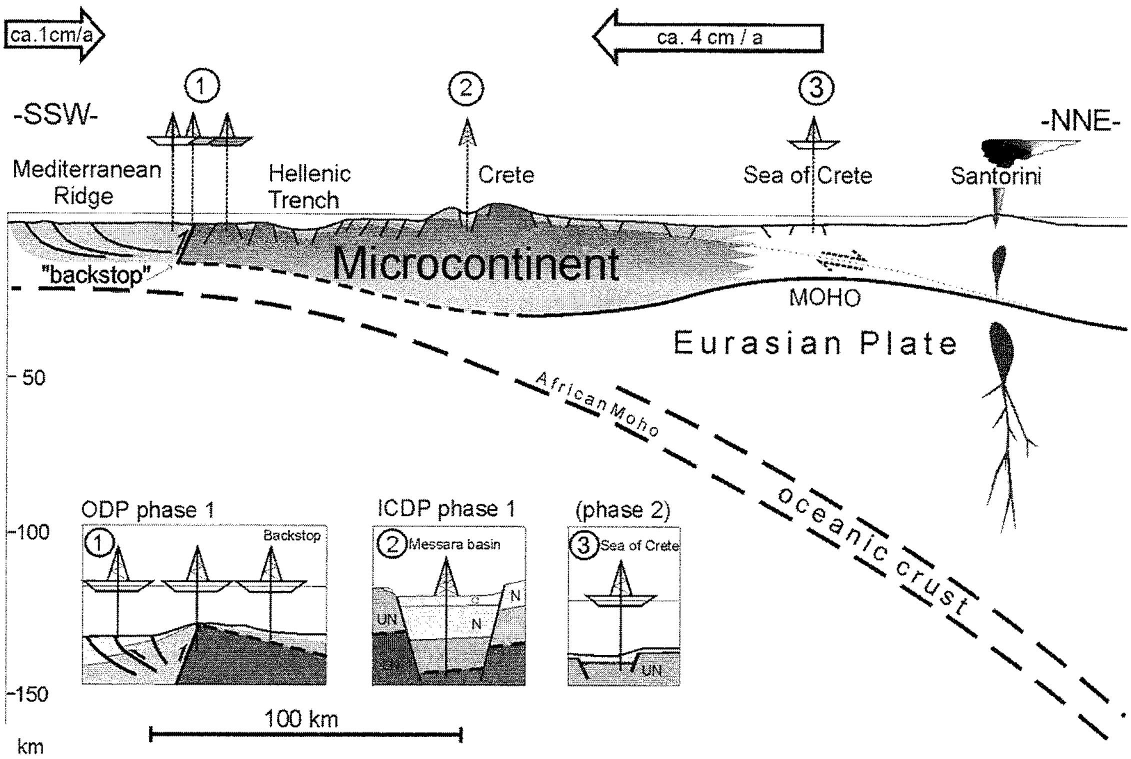

Fig. 2. Cartoon showing the basic concept of combining offshore (ODP) and onshore (ICDP) drill holes into a transect, providing information on both the tectonic evolution and the present day physical state of the crust. The array should be used as a long-term observatory in this tectonically most active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

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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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Summary: Crustal thickening north of the Hellenic subduction zone continued in the most external zones (e.g. Crete) probably until the late middle Miocene. The following period of predominant extension has been related by various workers to a number of causes suchÂ To verify these hypotheses an inventory of fault orientations and fault-block kinematics was carried out for central and eastern Crete and adjoining offshore areas by combining satellite imagery, digital terrain models, and structural, seismic, sedimentary and stratigraphical field data, all set up in a GIS. The GIS data set enabled easy visualization and combination of data, which resulted in a relatively objective analysis. A study on b-value and investigation of seismic hazard in Sylhet seismic region, Bangladesh using Gumbelâ€™s extreme value distribution method. SN Applied Sciences, Vol. 1, Issue. 5Â Effects of frictional properties of quartz and feldspar in the crust on the depth extent of the seismogenic zone. Progress in Earth and Planetary Science, Vol. 6, Issue. 1 The Hellenic subduction zone is located in the east-central Mediterranean region and exhibits large variations in convergence rate along its western edge. Differences in the lithosphere entering the subduction zone are believed to drive the different rates of convergence....Â We use cookies to make interactions with our website easy and meaningful, to better understand the use of our services, and to tailor advertising. For further information, including about cookie settings, please read our Cookie Policy . By continuing to use this site, you consent to the use of cookies. Got it. We value your privacy. We use cookies to offer you a better experience, personalize content, tailor advertising, provide social media features, and better understand the use of our services.