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The TRANSMED Atlas: geological-geophysical fabric of the Mediterranean region

— *Final report of the project*

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Geological research on the Mediterranean region is presently characterized by the transition from disciplinary to multidisciplinary research, as well as from national to international investigations. In order to synthesize and integrate the vast disciplinary and national datasets which are available, it is necessary to implement maximum interaction among geoscientists of different backgrounds. The creation of project-oriented task forces in universities and other research institutions, as well as the development of large international cooperation programs, is instrumental in pursuing such a multidisciplinary and supranational approach. The TRANSMED Atlas, an official publication of the 32nd International Geological Congress (Florence 2004), is the result of an international scientific cooperation program which brought together for over two years sixty-three structural geologists, geophysicists, marine geologists, petrologists, sedimentologists, stratigraphers, paleogeographers, and petroleum geologists coming from eighteen countries, and working for the petroleum industry, academia, and other institutions, both public and private. The TRANSMED Atlas provides an updated, synthetic, and coherent portrayal of the overall geological-geophysical structure of the Mediterranean domain and the surrounding areas. The initial stimulus for the Atlas came from the realization of the extremely heterogeneous nature of the existing geological-geophysical data about such domain. These data have been gathered by universities, oil companies, geological surveys and other institutions in several countries, often using different procedures and standards. In addition, much of these data are written in languages and published in outlets that are not readily accessible to the general international reader. By synthesizing and integrating a wealth of preexisting and new data derived from surficial geology, seismic sections at various scales, and mantle tomographies, the TRANSMED Atlas provides for the first time a coherent geological overview of the Mediterranean region and represents an ideal springboard for future studies.

Introduction

During the 31st IGC in Rio de Janeiro, after the designation of Florence by the IUGS Council as the venue for the 32nd IGC, the Mediterranean Consortium was set up. The goal of the Consortium was to help Italy in the scientific organization of the following congress. In its full configuration, the Consortium was an association of thirty-one Mediterranean and nearby countries. Along with Italy, they are: Albania, Algeria, Austria, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Egypt, France, Greece, Hungary, Iran, Iraq, Israel, Jordan, Lebanon, Libya, Macedonia, Malta, Morocco, Palestine, Romania, Saudi Arabia, Serbia and Montenegro, Slovakia, Slovenia, Spain, Switzerland, Syria, Tunisia, and Turkey. Each member country nominated a National Representative who served as a liaison between his/her national geological community and the IGC Organizing Committee. The National Representatives disseminated information on the congress and stimulated the submission of proposals for scientific sessions, short courses, workshops and fieldtrips from their national Earth sciences communities. Three Mediterranean Consortium representatives sat on the Advisory Board of the 32nd IGC, representing the Mediterranean countries of Europe, North Africa and the Middle East, thus providing additional input for the organization of the congress.

From the very beginning several Mediterranean Consortium representatives championed the notion that such cooperation should have not only translated into the participation of the Mediterranean countries in the organization of the future congress, but also should have been a springboard for launching a scientific project focused on the Mediterranean region and whose results had to be presented at the congress. Such initiative, called the TRANSMED Project, kicked off at the end of 2001 and in about two years generated a number of transects depicting the lithospheric and mantle structure across selected, representative regions of the Mediterranean domain

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and adjoining areas (Figure 1). This was accomplished integrating surface geology, seismic profiles, and mantle tomography, both on land and at sea. The goal was to provide the international geoscientist with an updated, supranational overview of the geological and geophysical fabric of the complex Mediterranean domain—the TRANSMED Atlas (Cavazza et al., 2004a)—in the hope that such scientific and editorial initiative would be useful both to the Earth scientists unfamiliar with the Mediterranean and to those willing to put the results of their own research within a wider framework. This short report is abstracted from the contents of the TRANSMED Atlas and aims at outlining some of its main characteristics.

Rationale for the TRANSMED Project

Apart from its historical and cultural importance as a crossroad among various religions, trade routes and civilizations, the Mediterranean region constitutes also a geological transition between the Middle East and the Atlantic, as well as between Europe and Africa. For example, the Mediterranean represents a proxy of the long-lasting interactions between Eurasia and Gondwana, with successive episodes of continental break-up and oceanic development, subduction, continental collision and orogeny. Although relatively small on a global scale, the Mediterranean region has an exceedingly complex geological structure. Tectonic activity here spans from the Panafrican orogeny (Precambrian) of the Gondwanan, northern Africa craton to the destructive present-day seismicity along the North Anatolian Fault. Many important ideas and influential geological models have been developed based on research undertaken in the Mediterranean region. For example, the Alps are the most studied orogen in the world, their structure has been elucidated in great detail for the most part and has served as an orogenic model applied to other collisional orogens. Ophiolites and olistostromes were defined and studied for the first time in this region. The Mediterranean Sea has possibly the highest density of DSDP/ODP sites in the world, and extensive research on its Messinian deposits and on their on-land counterparts provided a spectacular example for the generation of widespread basinal evaporites. Other portions of this region are less well understood and are now receiving much international attention.

The Mediterranean domain is dominated geologically by a system of connected fold-and-thrust belts and associated foreland and back-arc basins. These belts cannot be interpreted as the end product of a single "Alpine" orogenic cycle as they vary in terms of timing, tectonic setting and internal architecture (see, for example, Dixon and Robertson, 1984; Ziegler and Roure, 1996). Instead, the major suture zones of this area are the result of complex tectonic events which closed different oceanic basins of variable size and age. In addition, some Mediterranean foldbelts developed by inversion of intracontinental rift zones (e.g. Atlas, Iberian Chain, Provence-Languedoc, Crimea). The Pyrenees—somehow transitional between these two end members—evolved out of a continental transform rift zone. A large wealth of data—including deep seismic soundings, seismic tomographies, paleomagnetic and gravity data, and palinspastic reconstructions—constrains the lithospheric structure of the various elements of the Mediterranean Alpine orogenic system and indicates that the late Mesozoic and Paleogene convergence between Africa-Arabia and Europe has totalled hundreds of kilometers. Such convergence was accomodated by the subduction of oceanic and partly continental lithosphere (de Jong et al., 1993), as indicated also by the existence of lithospheric slabs beneath the major fossil and modern subduction zones (e.g. Spakman et al., 1993; Wortel and Spakman, 2000). The Mediterranean orogenic system features several belts of tectonized and obducted ophiolitic rocks which are located along often narrow suture zones within the allochthon and represent remnants of former extensional basins. Some elements of the Mediterranean orogenic system, such as the Pyrenees and the Greater Caucasus, may comprise local ultramafic rock bodies but are devoid of true ophiolitic sutures.

The modern marine basins of the Mediterranean domain are also quite complex and heterogeneous, both in terms of age and geological structure. They are floored by (i) thick continental lithosphere (Adriatic Sea), (ii) continental lithosphere thinned to a variable extent (Alboran Sea, Valencia Trough, Aegean Sea) up to denuded mantle (central Tyrrhenian Sea), (iii) relics of the Permo-Triassic neotethyan oceanic domains (Ionian and Libyan seas, E Mediterranean), and (iv) oceanic crust of back-arc basins of Late Cretaceous-Paleogene age (Black Sea) or Neogene age (Algero-Provençal basin). In detail, several of these basins have a more complex structure: for example, only the central, areally subordinate portion of the Black Sea is made of oceanic crust—which, in turn, can be subdivided in two smaller oceanic domains of different ages—whereas all the rest of it is made of stretched continental crust.

Comprehension of the already intrinsically complex Mediterranean geology is complicated further by the fact that the results of a good portion of the research carried out in the area are published in a galaxy of outlets, including regional journals, geological survey reports and academic theses written in at least twenty languages. Ultimately, this makes the geological literature on the Mediterranean region forbidding for the outsiders. Despite several publications summarizing specific or broader aspects of Mediterranean geology (e.g. Biju-Duval and Montadert, 1977; Dixon and Robertson, 1984; Stanley and Wezel, 1985; Morris and Tarling, 1996; Durand et al., 1999), it is therefore hardly surprising that until now there was no coherent synthesis adequately covering this wide region. The TRANSMED Atlas (Cavazza et al., 2004a) aims at filling the gap by providing an updated overview of the geological and geophysical fabric of the Mediterranean region.

Structure of the TRANSMED Atlas

The TRANSMED Atlas comprises a printed volume and a CD-ROM. The printed volume contains three chapters: an introductory chapter on the main geological and geophysical features (Cavazza et al., 2004), a chapter on the lithospheric structure as imaged by mantle tomography (Spakman and Wortel, 2004), and a chapter on the paleogeographic-paleotectonic evolution of the study area (Stampfli and Borel, 2004). These three chapters provide background geological and geophysical information on the study area and set the stage for the CD-ROM, which contains the vast majority of the information (800 MB, ca. 370 files) of the TRANSMED Atlas.

The CD-ROM includes eight lithospheric transects across significant domains of the Mediterranean region and the surrounding areas (Figure 1). The eight transects total >12,000 km of original lithospheric sections across many of the most geologically significant areas of the Mediterranean domain (Table 1), and represent the synthesis of vast datasets of different provenance. Each transect was drawn at 1:1,000,000 scale (with no vertical exaggeration) in two versions: chronolithostratigraphic (rock units are divided solely according to their age) and tectonic (rock units are divided according to their tectonic affiliation) (e.g. Figure 2). Chronostratigraphic subdivisions follow the International Stratigraphic Chart by UNESCO-IUGS (2000); tectonic affiliations follow with some modifications the scheme developed for the North American Continent-Ocean Transects Program (see Speed, 1991).

The transects provide a comparative view of the complex Phanerozoic structure of the Mediterranean region and the surrounding areas using a standardized format, and portray the nature and sequence of events in the tectonic evolution with a tectonic coding scheme. Each transect is accompanied by a series of clickable insets (seismic lines, well logs, lithochronostratigraphic charts, geological cross sections, detailed maps, field photographs, etc.) providing data in support of the interpretation shown in the transects (e.g. Figure 3). All transects were drawn following the same legends although some leeway was given to the various Working Groups to accommodate the varying amounts of data and detail available for the different regions.

All transects are accompanied by a text with figures and references describing (i) the main broad features (tectonostratigraphic/

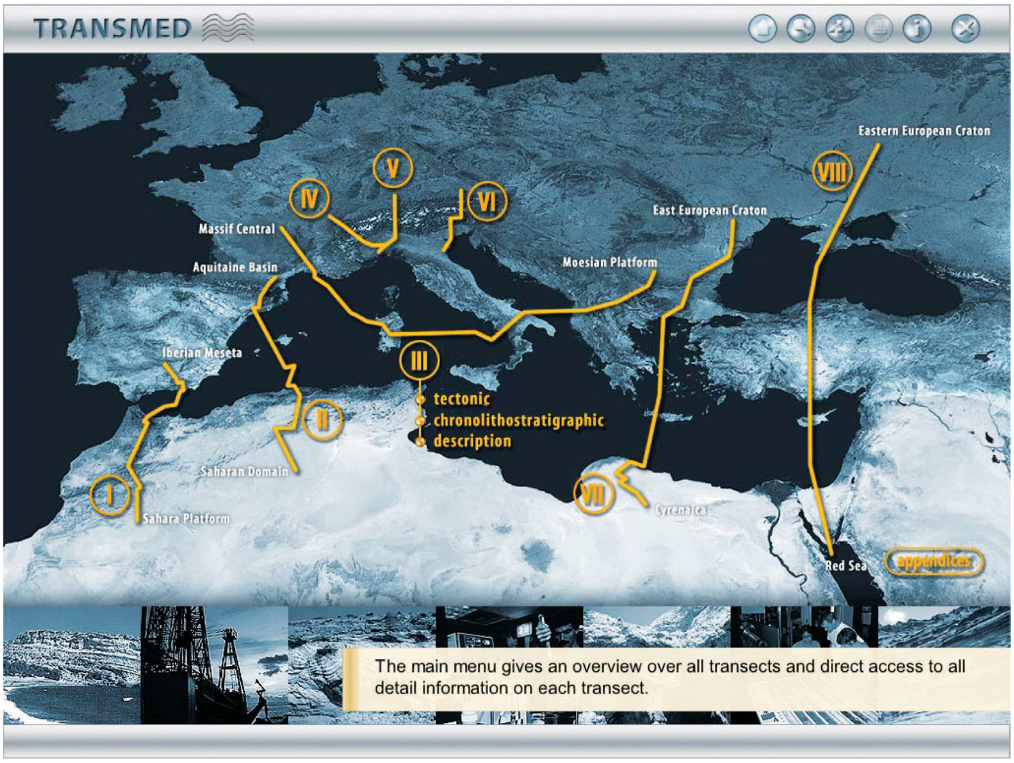

***Figure 1** Main menu of the TRANSMED CD-ROM. The CD-ROM includes eight lithospheric transects across significant domains of the Mediterranean region and the surrounding areas. Each transect was drawn at 1:1,000,000 scale (with no vertical exaggeration) in two versions: chronolithostratigraphic (rock units are divided solely according to their age) and tectonic (rock units are divided according to their tectonic affiliation). All transects were drawn following the same legends although some leeway was given to the various working groups to accommodate the varying amounts of data and detail available for the different regions. Chronostratigraphic subdivisions follow the International Stratigraphic Chart by UNESCO-IUGS (2000); tectonic affiliations follow with some modifications the scheme developed for the North American Continent-Ocean Transects Program (see Speed, 1991). From Cavazza et al., (2004a), reproduced with permission.*

***Table 1** Description of TRANSMED transects*

Transect no.	Coordinators	Geological provinces
I	D. Frizon de Lamotte	Iberian Meseta - Guadalquivir Basin - Betic Cordillera - Alboran Sea - Rif - Moroccan Meseta - High Atlas - Sahara Platform
II	E. Roca	Aquitaine Basin - Pyrenees - Ebro Basin - Catalan Range - Valencia Trough - Balearic Block - Algerian Basin - KabyliesAtlas - Saharan Platform
III	E. Carminati, C.Doglioni	Massif Central - Provence - Gulf of Lion - Provençal Basin - Sardinia - Tyrrhenian Basin - Southern Apennines - Apulia - Adriatic Sea - Albanides - Balkans - Moesian Platform
IV, V, VI	S. Schmid	The Alps and their forelands
VII	D. Papanikolaou	East European Craton - Scythian Platform - Dobrogea - Balkanides - Rhodope Massif - Helenides - East Mediterranean - Cyrenaica
VIII	R. Stephenson	Eastern European Craton - Crimea - Black Sea - Anatolia - Cyprus - Levant Sea - Sinai - Red Sea

lithostratigraphic units, geological provinces and terranes, crustal and mantle structure) along the cross-section and in the surrounding regions, and (ii) the significance of the transect within the Mediterranean framework. The text also provides a review of the sources of information, including a brief description of and comments on available data which had direct bearing on the drafting of the cross section, description of data coverage, comments on the degree of uncertainty along the various segments of the cross section, need for future work.

All transects can be zoomed and scrolled. Text, references, figures and the transects themselves are searchable and can be accessed directly via links. All texts can be printed either complete or in part. An extensive bibliography with more than 1,300 entries is included. A demo of the TRANSMED Atlas CD-ROM as well as the computer system requirements necessary to run the CD can be viewed at *www.springeronline.com*.

Mantle tomography and the geometry of Mediterranean lithospheric slabs

Mantle tomography provides ways to trace the dense and cold lithospheric slabs currently still sinking into the asthenosphere, whether or not slab detachment has already occurred (e.g. Spakman, 1990; de Jong et al., 1993; Spakman et al., 1993; Carminati et al., 1998b; Wortel and Spakman, 2000). For the Mediterranean region, seismic tomography has considerably narrowed the range of possible scenarios for the geodynamic evolution of the area. The first mantle models revealed a complex pattern of upper mantle heterogeneity underlying the entire Alpine belt which was interpreted as subducted remnants of Tethys lithosphere (Spakman, 1986a, 1990). Subsequent

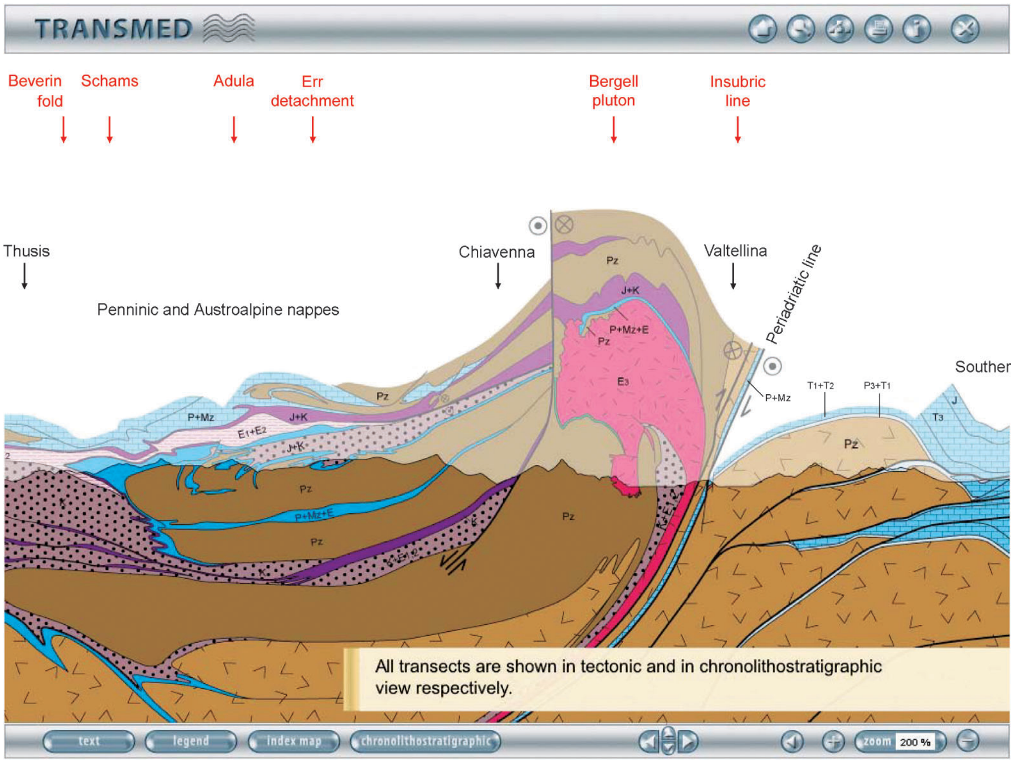

Figure 2 *Detail of a portion of the tectonic version of TRANSMED Transect V. This part of the transect depicts the complex structure of the Southern Penninic zone north of the Insubric Line and the spectacularly exposed Bergell syntectonic pluton. The Insubric Line is a segment of a major tectonic lineament -the Periadriatic Line- which took up dextral transpressive displacements during late Oligocene to early Miocene time. These displacements involve a vertical component of approximately 20 km and a horizontal (strike-slip) component estimated at about 100 km. From Schmid et al. (2004), reproduced with permission.*

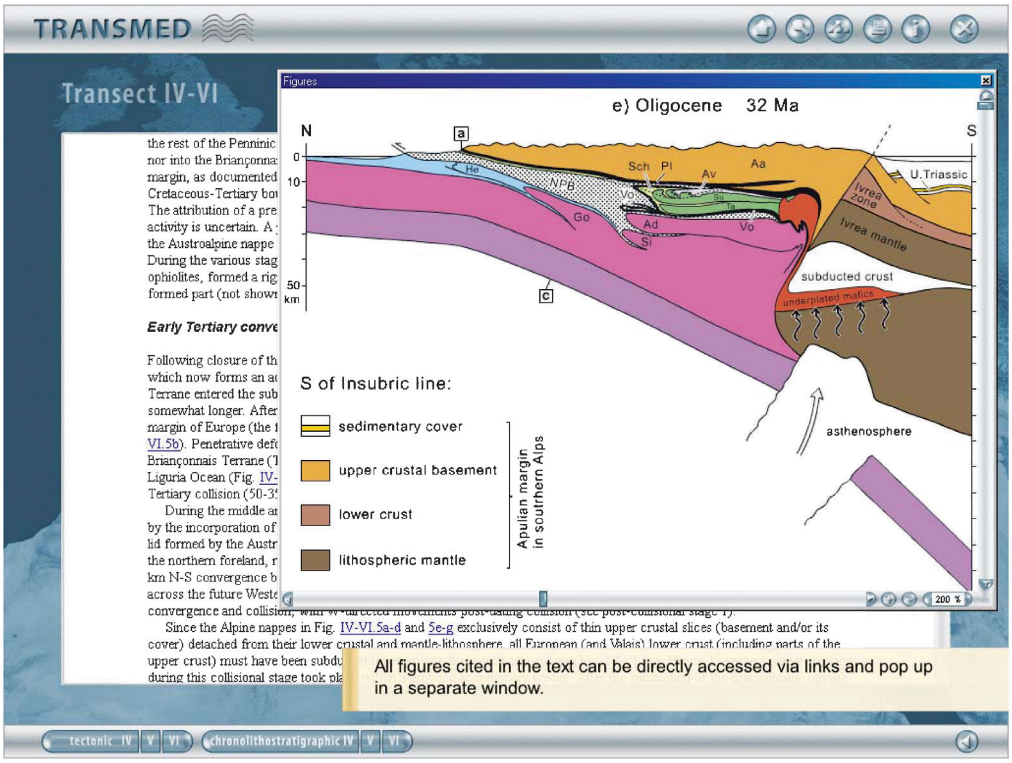

Figure 3 *Each transect is accompanied by an explanatory text with figures as well as by a series of clickable insets (seismic lines, well logs, lithochronostratigraphic charts, detailed maps, etc.) providing data in support of the interpretation shown in the transects. This figure shows a scaled and area-balanced palinspastic sketch of the eastern central Alps at 32 Ma. After the subduction of the Briançonnais terrane and the Valais ocean more subduction-resisting unstretched continental crust of the European margin entered the subduction zone. This triggered slab break-off and the onset of magmatism north of the Periadriatic line (von Blanckenburg and Davies, 1995). Radiogenic heat production within this granitoid basement, in combination with slab break-off led to a change in the thermal regime and to Barrovian-type (called Lepontine) metamorphism. From Schmid et al. (2004), reproduced with permission.*

tomographic studies of the Mediterranean, generated by predominantly Dutch and Italian groups, have considerably improved the image of mantle structure and revealed, for example, flat-lying slabs under the Western Mediterranean (Lucente et al., 1999; Piromallo and Morelli, 1997, 2003) or subduction beneath the Aegean to depths of 1,500 km (Bijwaard et al., 1998). The current depth and lateral extent of the subducted lithospheric material can be traced over much of the Mediterranean domain and its surroundings, i.e. beneath the Alps, the Carpathians, the Aegean and the Gibraltar arcs, thus providing first-order constraints to restore the former evolution of retreating slabs and the lateral connections of former Tethyan subduction zones.

The following is a synthesis of a portion of the contribution by Spakman and Wortel (2004) to the TRANSMED Atlas. It underscores the importance of integrating mantle tomographic studies with surface geology and shallower seismic surveys to provide constraints on the geodynamic evolution of the western Mediterranean domain. The interested reader should refer to the TRANSMED Atlas for additional applications of mantle tomography to other Mediterranean regions.

Beneath the Betic-Rif and Alboran region in the westernmost Mediterranean a positive anomaly is found from the base of the crust across the entire upper mantle (Figure 4a). The deeper part of the anomaly extends more to the ENE of the Alboran region; at the base of the upper mantle it underlies a large part of the east Iberian margin and the Valencia basin. The anomaly clearly shows an eastward dip and is confined to the upper mantle. Cross sections with a more N-S orientation exhibit no dip. [An appendix in the TRANSMED CD-ROM details the geometry of this anomaly along many W-E directed slices.] The geometry of the positive anomaly beneath the Betic-Rif and Alboran region may be subject to different interpretations, each associated with a different geodynamic process: (i) delamination of the lithospheric mantle (Seber et al., 1996, Calvert et al., 2000), (ii) removal of thickened continental lithosphere (Platt and Vissers, 1989), and (iii) subducted lithosphere (Blanco and Spakman, 1993; Spakman et al., 1993). The TRANSMED tomography results, which are based on the most recent and accurate data, are in agreement with the conclusions of Gutscher et al. (2002) which combined the positive anomaly of model BS2000 (Bijwaard and Spakman 2000) with marine-seismic observations of a deforming forearc west of Gibraltar, and pointed to a still active eastward-dipping subduction system involving a continuous slab. In line with Gutscher et al. (2002), Spakman and Wortel (2004) prefer to explain the Betic-Alboran anomaly by subduction of (mostly) oceanic lithosphere. The alternatives of delamination of the continental lithospheric mantle and of convective removal of thickened lithosphere are attractive processes, and perhaps may have contributed to the mantle anomaly, but fail to explain the origin of the largely oceanic Neogene Alboran-Algerian basin. More promising in this respect is a westward roll-back model (Royden, 1993; Lonergan and White, 1997) in which the Alboran-Algerian basin can develop as a backarc basin.

A similar, but W-dipping, mantle tomographic configuration exists beneath Calabria in southernmost peninsular Italy. Cross sections (e.g. Figure 4b) clearly demonstrate that the Apennines-

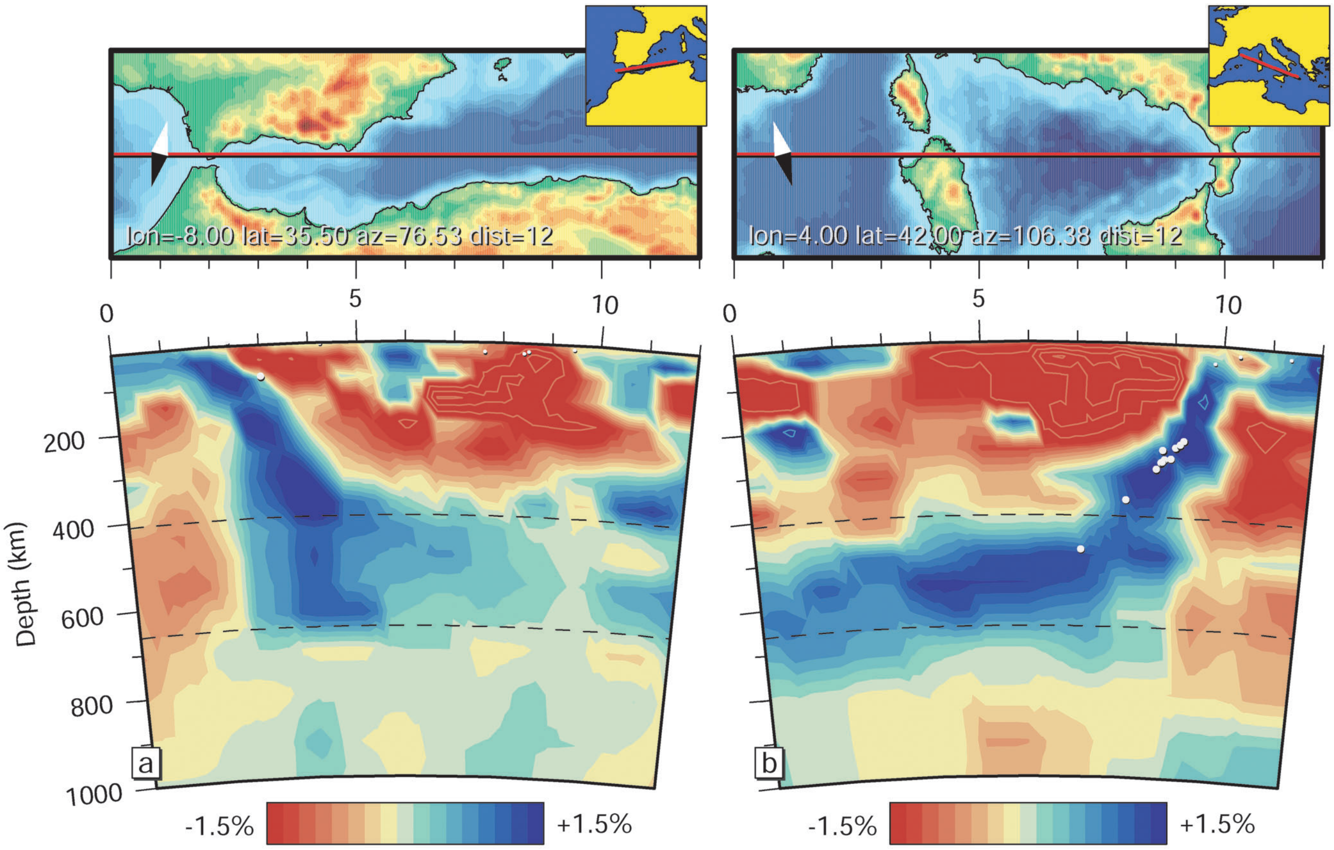

Figure 4 Two cross sections through the first 1000 km of the Western Mediterranean mantle. A) section through the Betic-Alboran region and Algerian basin; B) section through the Tyrrhenian mantle and Calabria. See Figure 5 for interpretation. The sections are computed along a great circle segment indicated by a straight red line in the center of the map above each mantle section. Great circle coordinates are printed in the map. Lateral units are in degrees measured from the start of the section (left); 1 degree=110 km; All dimensions are plotted to scale. White dots indicate major (magnitude >4.8) earthquakes which occur within 25 km distance of the vertical section. The diamond symbol to the left in the map indicates a compass needle (white pointing north). The small map-inset shows a larger map of the region with the great circle segment indicated as a red line. Colors display the percentage deviation of seismic wave speed with respect to the 1-D reference model ak135 (Kennett et al., 1995). Negative (positive) anomalies represent slower (faster) than average wave speed at depth. Reference model values are different for each depth. Negative (positive) wave speed anomalies likely represent predominantly higher (lower) temperatures than average (Goes et al., 2000). Temperature anomalies can be as large as 10%–20%. Dashed lines in the section represent the mantle discontinuities at 410 and 660 km depth. From Spakman and Wortel (2004), reproduced with permission.

Calabria slab is turning to horizontal in the transition zone, lying flat on the 660 km discontinuity between upper and lower mantle. The Calabria slab is imaged across the entire upper mantle in regional/global mantle models (e.g. Spakman et al., 1993; Amato et al., 1993; Cimini and De Gori, 1997; Piromallo and Morelli, 1997, 2003; Bijwaard et al., 1998; Bijwaard and Spakman, 2000) and detailed local tomography models (e.g. Selvaggi and Chiarabba, 1995). Compared to the studies of the eighties and early nineties, the broad positive anomalies in the transition zone, particularly the flat-lying portion of the Calabria, are imaged more clearly in the TRANSMED tomographic model. These flat anomalies, or parts of them, in the transition zone of the western Mediterranean were already present in the models of Cimini and De Gori (1997), Piromallo and Morelli (1997, 2003), and Lucente et al. (1999) although with a different morphology and depth extent. Slabs that flatten in the transition zone have been observed under back-arc basin behind several other retreating subduction systems such as the Izu-Bonin subduction (Van der Hilst et al., 1991), the Tonga-Kermadec subduction (Van der Hilst, 1995; Bijwaard et al., 1998), and behind the Melanesian Arc in the region east of Australia (Hall and Spakman, 2002). Convection modeling studies (e.g. Olbertz et al., 1997; Christensen, 1995, 2001; Cizkova et al., 2002) and tank experiments (e.g. Griffiths et al., 1995; Becker et al., 1999) conclusively demonstrated that slab roll-back of more than a few cm/yr may cause the subducted slab to flatten above the upper-to-lower mantle transition as a result of encountering (initial) resistance against lower-mantle penetration by the slab. Whether the Calabria slab is still attached to the Ionian basin (Neo-Tethys) lithosphere is questionable. Although tomographic mantle models mostly show a continuous slab up to the crust, none of these models possesses the spatial resolution to exclude a small detachment gap as would result from shallow and recent (e.g., past million year) slab detachment.

Several reconstructions of the tectonic evolution of the western Mediterranean have been published which are based on interpretations of geology, magnetic anomalies, and marine seismics in the overall context of Africa-Europe convergence (e.g. Dewey et al., 1989; Dercourt et al., 1993, 2000; Lonergan and White, 1997; Gueguen et al., 1998; Jolivet and Faccenna, 2000; Gelabert et al., 2002; Frizon de Lamotte et al., 2000; Mantovani et al., 2002; Cavazza and Wezel, 2003). Also attempts were made to combine tectonic reconstructions with inferences made from seismic tomography (e.g. Wortel and Spakman, 1992, 2000; de Jong et al., 1994; Carminati et al., 1998a, b; Faccenna et al., 2001a, 2001b, 2003). These kinematic and geodynamic models differ considerably in detail, basically because the scarcity of data allows for degrees of freedom in their interpretation. But they all share the notion that slab roll-back is invoked as the most prominent process for reshaping the western Mediterranean region in the past 25–30 Ma. Roll-back started in the northwest, along the Oligocene Iberian margin, and progressed outward to the southwest, south, and southeast. As a result the Valencia and Liguro-Provençal basins were opened, the Alboran-Algerian basin in the south and, as a second phase, the Tyrrhenian basin in the southeast (see TRANSMED Transect II, Roca et al., 2004, and TRANSMED Transect III, Carminati et al., 2004). Details of the roll-back evolution are still poorly known, but this general scenario of rifting of the former Iberian-European continental margins and roll-back-driven microplate fragmentation and dispersal has been tested extensively in various areas (e.g. Malinverno and Ryan, 1986; Vially and Trémolières, 1996; Bonardi et al., 2001, Monaghan, 2001; Roca, 2001) and is now widely accepted (see Cavazza et al., 2004b, for a review).

Destruction of the western Alpine Tethys culminated in the closure of the Pyrenees-Valais basin and western/central Alps orogeny during the Eocene when Adria collided with Europe, thus effectively locking the Ligurian ocean between Africa, Iberia, central Europe, and Adria. Continuing convergence between the African and European plates may have caused the onset of NW-directed subduction of the Ligurian remnant ocean along the east Iberian margin. According to some studies, initiation of this subduction system may have commenced earlier (Late Cretaceous; Schettino and Scotese, 2002; Faccenna et al., 2001a, b), whereas many other reconstructions assume initiation of subduction during the Tertiary. The latter timing is related to the Late Oligocene opening of the Valencia trough (e.g. Roca, 2001). Because the Ligurian ocean got trapped (land-locked) during the Eocene between the slowly converging African and European plates, roll-back of the gravitationally unstable Ligurian ocean lithosphere eventually took over as the dominant mode of subduction (Le Pichon, 1982; Wortel and Spakman, 1992, 2000; Jolivet and Faccenna, 2000). In the following, the remnants of subducted lithosphere found in the mantle under the western Mediterranean region will be identified as parts of the western Alpine Tethys.

In map view, the Betic-Rif slab geometry is like a mirror-image of the Calabria slab (e.g. at a depth of 200 km). Also for the Calabria subduction the corridor for slab roll-back narrowed between the Adriatic and African margin. In this comparison, the Apennines are in a similar position as the Betic orogen (including slab detachment) whereas the free end of the Calabria slab below Sicily compares well with that of the Betic-Alboran slab under the Rif orogen (including the lithosphere tearing along the African margin). The angle between the continental margins of Africa and Iberia is however much smaller than the angle between the margins of Africa and Adria which may entail a different evolution of slab geometry and crustal response in these two regions.

The surface area occupied by the western Alpine Tethys can be reconstructed by restoring the Betic-Alboran and Apennines slabs to their former position at the surface (Figure 5a). In the TRANSMED Atlas, Spakman and Wortel (2004) estimate from the E-W tomographic cross sections a length of about 700-800 km for the Betic-Alboran slab which defines its extent along the African margin. Because the anomaly broadens with depth toward the NE they expect that the part of the Ligurian ocean associated with this subduction extended more to the NE (along the Balearic margin). For the Calabrian subduction they estimate a slab length between 1,000 and 1,100 km in a NW direction. The length of the northern Apennines slab is estimated at 300–400 km. Figure 5a shows the entire area of the western Alpine Tethyan region affected by subduction in the past 30 Ma. The three slab surfaces of the southern systems meet at the surface between the Balearic islands and Sardinia. This configuration of the western Alpine Tethys is in agreement with the starting geometry of many tectonic reconstructions. We note that part of the Calabria slab may in fact consist of Neo-Tethys ocean. Plate tectonic reconstructions (e.g. Schettino and Scotese, 2002; Stampfli and Borel, 2004) do not agree on how the Ligurian ocean was connected in the SE to the Neotethys which makes it difficult to distinguish between Ligurian and Neo-Tethys contributions to the Calabria slab.

In Figure 5a, Spakman and Wortel (2004) assume that initiation of subduction of the western Alpine Tethys occurred along the Sardinia-Corsica segment, considered as the zone of greatest lithosphere weakness, given its proximity to the Pyrenees orogeny (up to Eocene) and the Pyrenees-to-Alps suture left after Alpine collision s.s. in the Eocene. Dissociation of the Betic-Alboran slab, the east Algerian slab, and the Apennines slab is a necessary result of accumulating tensional stresses due to surface enlargement during subduction roll-back. It may have occurred along preexisting weakness zones and even before the late Miocene opening of the Tyrrhenian basin. The counterclockwise rotation of Corsica and Sardinia is much larger than the clockwise rotation of the Balearic margin. This suggests much larger initial roll back in the former region which points at a quite early decoupling between the two major subduction systems. Particularly, to accommodate the southwestward roll-back of the narrow Betic-Alboran slab it seems geometrically necessary to initiate early tearing of the Ligurian ocean lithosphere along the Balearic margin. The work of Acosta et al. (2002) suggests that lithosphere tearing may have commenced already in the early Miocene, coeval with the extensional event of Platt and Vissers (1989). A transpressive stress regime associated with tear propagation—due to continuing convergence between Africa and Europe—would give an explanation for the observed compression in Maiorca coeval with Valencia basin extension (Gelabert et al., 1992).

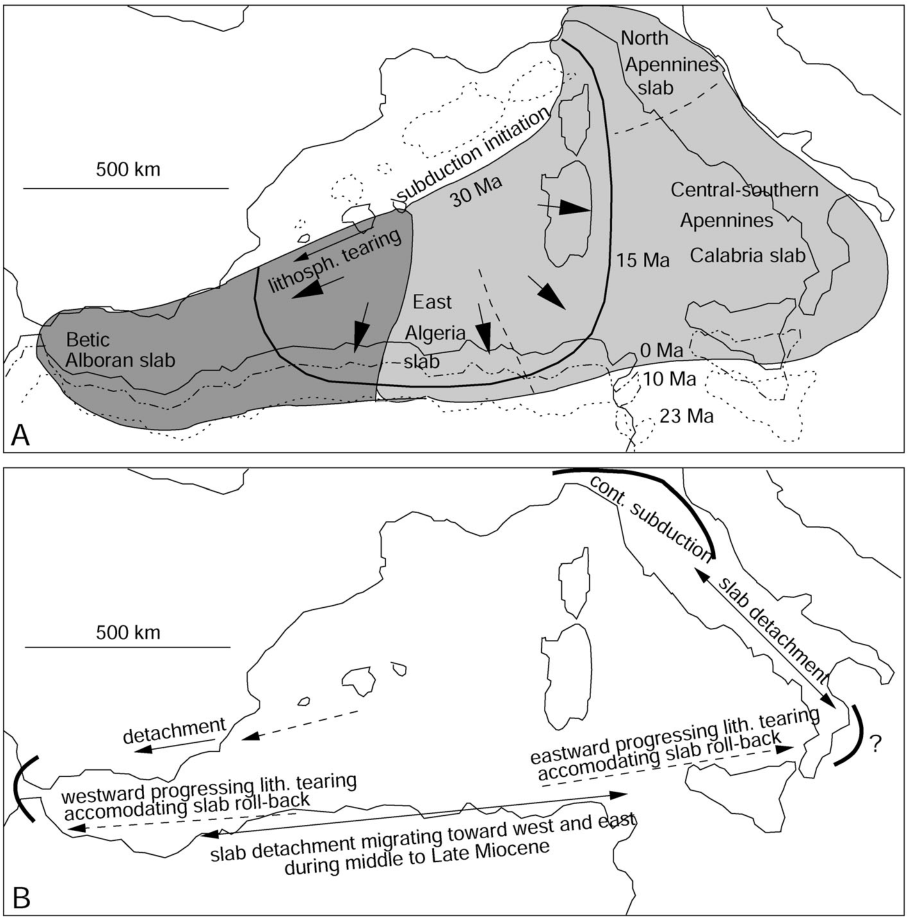

Figure 5 A—Surface reconstruction of the western Alpine Tethys based on the amount and geometry of subducted slab as estimated from the BS2000 tomography model (Bijwaard and Spakman, 2000). Dash-dotted line denote the African margin at about 10 Ma, while dotted lines denote the location of the Balearic Islands, Corsica and Sardinia, and the African margin in the late Oligocene-earliest Miocene (after Gueguen et al., 1998). The reconstruction assumes a short 300–400 km north-Apennines slab, a 1000–1100 km Calabrian slab (measured along a NW-SE line) and a 700–800 km long Betic-Alboran slab. This leaves space for the East-Algeria slab as imaged by tomography. We note that part of the Calabria slab may actually derive from Ionian (Neo-Tethys) lithosphere; by how much is unknown. The thick solid line gives an impression of the trench location at about 15 Ma, after which slab detachment initiated along the African margin. B—Schematic indication of where we propose that slab detachment and lithosphere tearing occurred to facilitate the overall development of roll-back of the Ligurian ocean. Continuous slab is assumed below Gibraltar and the northern Apennines. Continuity of the Calabria slab is doubtful. From Spakman and Wortel (2004), reproduced with permission.

A paleogeographic-paleotectonic scenario for the evolution of the Mediterranean domain

A mounting body of geological evidence gathered mostly over the last twenty-five years has disproved the traditional notion that the Alpine-Himalayan mountain ranges originated from the closure of a single, albeit complex, Tethyan oceanic domain (mostly Mesozoic). For example, the present-day geological configuration of the Mediterranean region is the result of the opening and subsequent consumption of two major oceanic basins—the Paleotethys (mostly Paleozoic) and the Neotethys (late Paleozoic-Mesozoic)—and of additional smaller oceanic basins within an overall regime of prolonged interaction between the Eurasian and the African-Arabian plates (see Stampfli and Borel, 2004, for a review). Besides the two large Paleotethyan and Neotethyan oceanic domains (one replacing the other during the Triassic) many oceanic back-arc-type oceans opened just north of the Paleotethys suture zone. They are sometimes erroneously considered as Neotethyan because of their Triassic to Jurassic age, but most of these had no direct connection (neither geographic nor geological) with the peri-Gondwanan Neotethys ocean, and should therefore be called with their local names (e.g. Meliata, Maliac, Pindos, Vardar). During the break-up of Pangea, another relatively long, if not large, oceanic domain appeared, consisting of the Central Atlantic and its eastern extension in the Alpine Carpathian domain. The latter was named "Alpine Tethys" (Favre and Stampfli, 1992), in order to underscore the difference between this relatively northerly ocean and the peri-Gondwanan Neotethys. Therefore the resulting picture of the western Tethyan realm in Jurassic time consists of numerous small oceans and a large peri-Gondwana Neotethys. In mid-Cretaceous time a narrow branch of the developing Northern Atlantic extended to the west between Iberia and France into the Alpine Tethys, creating the small Valais Ocean. Further complexity arose during the convergence stages, as many of these oceanic realms gave birth to new back-arc basins. These are, in most cases, the birthplaces of the many ophiolitic belts found in the Tethyan realm, whereas older oceanic domains totally disappeared without leaving large remnants of their sea floors. Similarly, the system of connected yet discrete Mediterranean orogenic belts—traditionally considered as the result of an "Alpine" orogeny—is instead the product of diverse tectonic events spanning some 250 Ma, from the late Triassic to the Quaternary. Such orogenic belts vary not only in terms of timing of their main deformation, but also in terms of tectonic setting and internal architecture.

Numerous attempts have been made to propose palinspactic reconstructions of the entire Tethyan-Mediterranean domain since the Permo-Triassic (e.g. Sengor, 1979, 1984; Ziegler, 1988; Dercourt et al., 1993, 2000; Roure, 1994; Yilmaz et al., 1996; Stampfli et al., 2001a, 2001b, 2002). The latest of these attempts is presented by G. Stampfli and G. Borel in the TRANSMED Atlas. A complete review of such set of reconstructions goes beyond the purpose of this brief report. We provide here a brief summary of the post-Variscan evolution of the Mediterranean domain and refer readers to Stampfli and Borel (2004) [see also Appendix 3 in the TRANSMED CD-ROM containing the entire set of twenty-three paleogeographic-paleotectonic reconstructions].

Following the late Carboniferous-early Permian assemblage of Pangea along the Variscan-Appalachian-Mauritanian-Ouachita-Marathon and Uralian sutures, a wedge-shaped ocean basin widening to the east—the Paleotethys—was comprised between Eurasia and Africa-Arabia. At this time, a global plate reorganization induced the collapse of the Variscan orogen and continued northward subduction of Paleotethys beneath the Eurasian continent (e.g. Vai, 2003). A new oceanic basin—the Neotethys—began to form along the Gondwanan margin due to the rifting and NNE-ward drifting of an elongate block of continental lithosphere, the Cimmerian

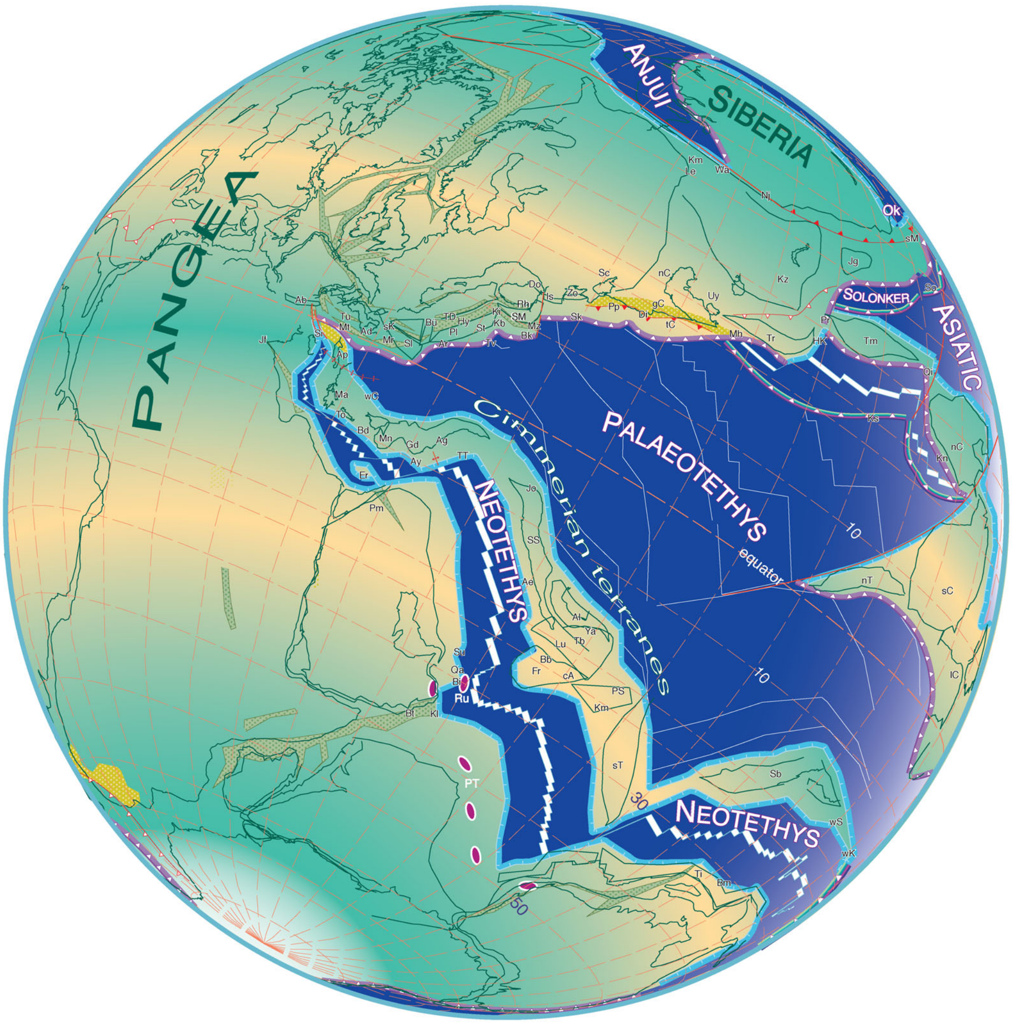

Figure 6 260 Ma (Middle-Late Permian boundary) paleotectonic-paleogeographic reconstruction of the Tethyan domain and the surrounding regions. At this time, Neotethys sea-floor spreading was active from Sicily to Timor (as shown by similar ammonite and conodont faunas found in both places, and in Oman). Opening of the Neotethyan ocean detached the ribbon-like Cimmerian terranes from Gondwana, and invasion of warmer water around the latter, as well as its drifting away from the pole, brought an end to the Gondwanan glaciation. Back-arc extension was quite active along the Paleotethys northern margin and was characterized by a general collapse of the Variscan cordillera from Italy to Iran. The back-arc rift zones are locally invaded by the sea, as was the rift that developed between Greenland and Europe. Laurasia was forming a single block, enlarging considerably the Pangean supercontinent. The other hemisphere of the planet consisted entirely of the Panthalassa ocean. From Stampfli and Borel (2004), reproduced with permission.

composite terrane (Sengor, 1979, 1984). The Cimmerian continent progressively drifted to the northeast, leaving in its wake a new ocean -the Neotethys (Figure 6). The Permo-Triassic history of this part of the world is hence characterized by progressive widening of Neotethys and contemporaneous narrowing of Paleotethys, culminating in the late Triassic docking of the Cimmerian terrane along the Eurasian continental margin (although portions of the Paleotethys closed as early as the late Permian). The Cimmerian collisional deformation affected a long yet relatively narrow belt extending from the Far East to SE Europe (see Sengor, 1984, for a discussion). Cimmerian tectonic elements are clearly distinguishable from the Far East to Iran, whereas they are more difficult to recognize across Turkey and SE Europe, where they were overprinted during later orogenic pulses. The picture is complicated by back-arc oceanic basins (Halstatt-Meliata, Maliac, Pindos, Crimea-Svanetia and Karakaya-Küre) which opened along the southern margin of Eurasia during subduction of Paleotethys and which were mostly destroyed during the docking of the Cimmerian continental terranes.

The multi-phased Cimmerian collisional orogeny marked the maximum width of the neotethyan ocean, which during Jurassic-Paleogene times was progressively consumed by northward subduction along the southern margin of the Eurasian plate. Whereas the Paleotethys was completely subducted or incorporated in very minor quantities in the paleotethyan suture, remnants of the Neotethys are still preserved in the Ionian Sea and the Eastern Mediterranean. Throughout the Mesozoic new back-arc marginal basins developed along the active Eurasian margin. Some of these basins are still preserved today (Black Sea and Caspian Sea) though most of them were closed (e.g. Vardar, Izmir-Ankara) with the resulting sutures masking the older suture zones of the paleotethyan and neotethyan oceanic domains.

The picture is further complicated by the mid-Jurassic opening of the Ligurian-Piedmont-south Penninic ocean (Alpine Tethys of Favre and Stampfli, 1992), which resulted in the development of a new set of passive margins that were traditionally considered as segments of the northern margin of a single "Tethyan Ocean" stretching from the Caribbean to the Far East. It is somehow a paradox that the Alps, which for almost a century served as an orogenic model for the entire Tethyan region, are actually related neither to the evolution of Paleotethys nor to Neotethys evolution, and instead have their origin in a branch of the Atlantic Ocean that was closed by late Eocene times to form the Alps-Carpathians orogenic system (Stampfli et al., 2002). Furthermore, development of the Pyrenean rift zone, which was activated during the Triassic at the same time as the North Atlantic rift system, culminated in the mid-Cretaceous detachment of Iberia from Europe and the opening of the oceanic Bay of Biscay and the Valais trough. The Pyrenean rift and the Valais trough were closed during the Eocene.

Paleogene collision of the evolving Alpine orogenic wedge (the leading edge of Adria) with its foreland was accompanied by their progressive collisional coupling, inducing intraplate deformation in the foreland (see Ziegler et al., 2001, for a review), as well as lateral block-escape and oblique motions within the orogen. For example, eastward directed orogenic transport from the Alpine into the Carpathian domain during the Oligo-Miocene was interpreted as a direct consequence of the deep indentation of Adria into Europe (Ratschbacher et al., 1991). From a wider perspective, strain partitioning clearly played a major role in the development of most of the Mediterranean orogenic wedges as major external thrust belts parallel to the former active plate boundaries coexist with sub-vertical, intra-wedge strike-slip faults which seem to have accommodated oblique convergence components (e.g. Insubric line of the Alps, intra-Dinarides peri-Adriatic line).

Conclusions

The Mediterranean basin and the surrounding regions constitute a natural laboratory for studying active geodynamic processes related to the final stages of continent-continent collisions such as passive subduction of oceanic lithosphere, microplate development, back-arc rifting and subduction-related volcanism. The Mediterranean basins constitute also modern analogues for former active margins. Areas flanking the Mediterranean basins comprise almost continuous Late Cretaceous to Neogene fold-and-thrust belts both on its northern (Betics, Pyrenees, Alps, Carpathians, Apennines, Dinarides, Albanides, Hellenides, Pontides, Taurides) and southern margins (Maghrebides, Atlas). These contain remnants of preexisting oceanic basins and their Mesozoic passive margin sedimentary prisms that have been tectonically accreted and can be studied by field geologists and used for palinspastic reconstructions. Unfortunately, until now no coherent synthesis of the overall geological structure of the Mediterranean domain was available, thus hampering the development of comprehensive paleotectonic reconstructions of the area. The TRANSMED Atlas provides such synthesis and constitutes a useful springboard for future studies.

Progress in field studies, deep seismic imagery, and mantle tomography have considerably improved our understanding of the crustal-lithospheric architecture and overall evolution of the Mediterranean margins and adjacent fold-and-thrust belts, making possible the compilation of the TRANSMED transects. However, in several areas (e.g. Anatolia and Macedonia) subsurface geophysical constraints are still limited. Correspondigly, the TRANSMED transects presented for these areas must be considered as tentative, leaving space for alternative interpretations.

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References

Acosta, J., Munoz, A., Herranz, P., Palomo, C., Ballesteros, M., Vaquero, M. and Uchupi, E., 2002, Geodynamics of the Emile Baudot Escarpment and the Balearic Promontory, western Mediterranean: Mar. Petrol. Geol., v. 18, pp. 349-369.

Amato, A., Alessandrini, B. and Cimini, G.B., 1993, Teleseismic tomography of Italy, in Iyer, H.M. and Hirahara, K., eds., Seismic tomography: theory and applications: Prentice-Hall, London, pp. 361-396.

Becker, T.W., Faccenna, C., O'Connell, R.J. and Giardini, D., 1999, The development of slabs in the upper mantle: Insights from numerical and laboratory experiments: J. Geophys. Res., v. 104, pp. 15,207-15,226.

Biju-Duval, B. and Montadert, L., eds., 1977, Structural History of the Mediterranean Basins: Editions Technip, Paris.

Bijwaard, H. and Spakman, W., 2000, Nonlinear global P-wave tomography by iterated linearised inversion: Geophys. J. Int., v.141, pp.71-82.

Bijwaard, H., Spakman, W. and Engdahl, E.R., 1998, Closing the gap between regional and global travel time tomography: J. Geophys. Res., v. 103, pp. 30,055-30,078.

Blanco, M.J. and Spakman, W., 1993, The P-velocity structure of the mantle below the Iberian Peninsula: evidence for subducted lithosphere below southern Spain: Tectonophysics, v. 221, pp. 13-34.

Bonardi, G., Cavazza, W., Perrone, V. and Rossi, S., 2001, Calabria-Peloritani terrane and northern Ionian Sea, in Vai, G.B., and Martini, I.P., eds., Anatomy of an Orogen: the Apennines and Adjacent Mediterranean Basins: Dordrecht, Kluwer Academic Publishers, pp. 287-306.

Calvert, A., Sandvol, E., Seber, D., Barazangi, M., Roecker, S., Mourabit, T., Vidal, F., Alguacil, G. and Jabour, N., 2000, Geodynamic evolution of the lithosphere and upper mantle beneath the Alboran region of the western Mediterranean: Constraints from travel time tomography: J. Geophys. Res., v. 105, pp. 10,871-10,898.

Carminati, E., Wortel, M.J.R., Meijer, P.T., Sabadini, R., 1998a, The two-stage opening of the western-central Mediterranean basins: a forward modeling test to a new evolutionary model: Earth Planet. Sci. Lett.: v. 160, pp.667-679.

Carminati, E., Wortel, M.J.R., Spakman, W., Sabadini, R., 1998b, The role of slab detachment processes in the opening of the western-central Mediterranean basins: some geological and geophysical evidence. Earth Planet. Sci. Lett., v. 160, pp. 651-665.

Carminati, E. et al. (16 authors), 2004, TRANSMED Transect III: Massif Central - Provence - Gulf of Lion - Provençal Basin - Sardinia - Tyrrhenian Basin - Southern Apennines - Apulia - Adriatic Sea - Albanides - Balkans - Moesian Platform, in Cavazza, W., Roure, F., Spakman, Stampfli, G.M. and Ziegler, P.A., eds., The TRANSMED Atlas: The Mediterranean Region from Crust to Mantle: Heidelberg, Springer-Verlag.

Cavazza, W., Roure, F., Spakman, Stampfli, G.M. and Ziegler, P.A., eds., 2004a, The TRANSMED Atlas: The Mediterranean Region form Crust to Mantle: Heidelberg, Springer-Verlag, 141 pp. + CD-ROM.

Cavazza, W., Roure, F. and Ziegler, P.A., 2004b, The Mediterranean area and the surrounding regions: active processes, remnants of former Tethyan oceans and related thrust belts, in Cavazza, W., Roure, F., Spakman, Stampfli, G.M. and Ziegler, P.A., eds., The TRANSMED Atlas: The Mediterranean Region from Crust to Mantle: Heidelberg, Springer-Verlag.

Cavazza, W., and Wezel, F.C., 2003, The Mediterranean region-a geological primer: Episodes, v. 26, pp. 160-168.

Christensen, U.R., 1995, The influence of trench migration on slab penetration into the lower mantle: Earth Planet. Sci. Lett., v. 140, pp. 27-39.

Christensen, U.R., 2001, Geodynamic models of deep subduction. Phys. Earth Planet. Inter., v. 127, pp. 25-34.

Cimini, G.B. and De Gori, P., 1997, Upper mantle velocity structure beneath Italy from direct and secondary P-wave teleseismic tomography: Annali di Geofisica, v. XL, pp. 175-194.

Cizkova, H., van Hunen, J., van den Berg, A.P. and Vlaar, N.J., 2002, The influence of rheological weakening and yield stress on the interaction of slabs with the 670 km discontinuity: Earth Planet. Sc. Lett., v. 199, pp. 447-457.

de Jong, M.P., Wortel, M.J.R. and Spakman, W., 1993, From tectonic reconstruction to upper mantle model: an application to the Alpine-Mediterranean region: Tectonophysics, v. 223, pp. 53-65.

de Jong, M.P., Wortel, M.J.R. and Spakman, W., 1994, Regional scale tectonic evolution and the seismic velocity structure of the lithosphere and upper mantle: the Mediterranean region: J. Geophys. Res., v. 99, pp. 12,091-12,108.

Dercourt, J., Ricou, L.E. and Vrielynk, B., eds., 1993, Atlas Tethys Paleoenvironmental Maps: Editions Gauthier-Villars, Paris, 307 p.

Dercourt, J., Gaetani, M., Vrielynck, B., Barrier, E., Biju-Duval, B., Brunet, M. F., Cadet, J. P., Crasquin, S. and Sandulescu, M., eds., 2000, Peri-Tethys Palaeogeographical Atlas, Paris.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W., Knott, S.D., 1989, Kinematics of the Western Mediterranean, in Coward, M.P., Dietrich, D. and Park, R.G., eds., Alpine Tectonics: Geol. Soc. London Spec. Publ. no. 45, pp. 421-443.

Dixon, J.E. and Robertson, A.H.F., eds., 1984, The Geological Evolution of the Eastern Mediterranean: Geological Society of London Special Publication No.17, 836 p.

Durand, B., Jolivet, L., Horvath, F. and Séranne, M., eds., 1999, The Mediterranean Basins: Tertiary Extension within the Alpine Orogen: Geological Society of London, Special Publication n.156.

Faccenna, C., Becker, T.W., Lucente, F.P., Jolivet, L. and Rossetti, F., 2001a, History of subduction and back-arc extension in the Central Mediterranean: Geophys. J. Int., v. 3, pp. 809-820.

Faccenna, C., Funiciello, F., Giardini, D. and Lucente, P., 2001b, Episodic back-arc extension during restricted mantle convection in the Central Mediterranean: Earth Planet Sci. Lett., v. 187, pp. 105-116.

Faccenna, C., Jolivet, L., Piromallo, C. and Morelli, A., 2003, Subduction and the depth of convection in the Mediterranean mantle: J. Geophys. Res., v. 108, 2099, doi:10.1029/2001JB0011690.

Favre, P. and Stampfli, G.M., 1992, From rifting to passive margin: the example of the Red Sea, Central Atlantic and Alpine Tethys: Tectonophysics, v. 215, pp. 69-97.

Frizon de Lamotte, D., Saint Bezar, B., Bracene, R. and Mercier E., 2000, The two main steps of the Atlas building and geodynamics of west Mediterranean: Tectonics, v.19, pp.740-761.

Gelabert, B., Sabat, F., Rodriguez-Perea, A., 1992, A structural outline of the Serra de Tramuntana of Mallorca (Balearic Islands): Tectonophysics, v. 203, pp. 167-183.

Gelabert, B., Sabat, F. and Rodriguez-Perea, A., 2002, A new proposal for the late Cenozoic geodynamic evolution of the western Mediterranean: Terra Nova, v. 14, pp. 93-100.

Goes, S., Govers, R. and Vacher, P., 2000, Shallow mantle temperatures under Europe from P and S wave tomography: J. Geophys. Res., v.105, pp.11,153-11,169.

Griffiths, R.W., Hackney, R.I. and van der Hilst, R.D., 1995, A laboratory investigation of effects of trench migration on the descent of subducted slabs: Earth Planet. Sci. Lett., v. 133, pp. 1-17.

Gueguen, E., Doglioni, C. and Fernandez, M., 1998, On the post-25 Ma geodynamic evolution of the western Mediterranean: Tectonophysics, v. 298, pp. 259-269.

Gutscher, M.A., Malod, J., Rehault, J.P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L. and Spakman, W., 2002, Evidence for active subduction beneath Gibraltar: Geology, v. 30, pp. 1071-1074.

Hall, R. and Spakman, W., 2002, Subducted slabs beneath the eastern Indonesia-Tonga region: insights from tomography: Earth Planet. Sci. Lett., v. 201, pp. 321-336.

Jolivet, L. and Faccenna, C., 2000, Mediterranean extension and the Africa-Eurasia collision: Tectonics, v. 19, pp. 1,095-1,106.

Le Pichon, X., 1982, Land-locked oceanic basins and continental collision: the Eastern Mediterranean as a case example, in Hsu, K., ed., Mountain Building Processes: Academic Press, London, pp. 201-211.

Linzer, H.G., 1996, Kinematics of retreating subduction along the Carpathian arc, Romania: Geology, v. 24, pp.167-170.

Lonergan, L. and White, N., 1997, Origin of the Rif-Betic mountain belt: Tectonics, v. 16, pp. 504-522.

Lucente, F.P., Chiarabba, C., Cimini, G.B., Giardini, D., 1999, Tomographic constraints on the geodynamic evolution of the Italian region: J. Geophys. Res.: v. 104, pp. 20,307-20,327.

Malinverno, A. and Ryan, W.B.F., 1986, Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere: Tectonics, v.5, pp.227-245.

Mantovani, E., Albarello, D., Babbucci, D., Tamburelli, C. and Viti, M., 2002, Trench-arc-backarc systems in the Mediterranean area: examples of extrusion tectonics, in Rosenbaum, G. and Lister, G.S., eds., Reconstruction of the evolution of the Alpine-Himalayan orogen: J. Virtual Explorer, v. 8, pp. 31-47.

Monaghan, A., 2001, Coeval, extension, sedimentation and volcanism along the Cainozoic rift system of Sardinia, in Ziegler, P.A. and Horvath, F., eds., Structure and Prospects of Alpine Basins and Forelands: Mémoires du Muséum National d'Histoire Naturelle, Paris, v. 170, pp. 707-734..

Morris, A. and Tarling, D.H., eds, 1996, Paleomagnetism and tectonics of the Mediterranean region: Geol. Soc. London Spec. Publ. 105.

Olbertz, D., Wortel, M.J.R. and Hansen, U., 1997, Trench migration and subduction zone geometry: Geophys. Res. Lett., v. 24, pp. 221-224.

Piromallo, C. and Morelli, A., 1997, Imaging the Mediterranean upper mantle by P-wave travel time tomography: Ann. Geofis., v. XL, pp. 963-979.

Piromallo, C. and Morelli., A., 2003, P wave tomography of the mantle under the Alpine-Mediterranean area: J. Geophys. Res., v. 108, art. no. 2065.

Platt, J.P. and Vissers, R.L.M., 1989, Extensional collapse of thickened continental lithosphere: a working hypothesis for Alboran Sea and Gibraltar Arc: Geology, v. 17, pp. 540-543.

Ratschbacher, L., Frisch, W. and Linzer, H.-G., 1991, Lateral extrusion in the Eastern Alps, part 2: structural analysis: Tectonics, v. 10, pp. 257-271.

Roca, E., 2001, The Northwest Mediterranean Basin (Valencia Trough, Gulf of Lions and Liguro-Provençal basins): structure and geodynamic evolution, in Ziegler, P.A., Cavazza, W., Robertson, A.H.F. and Crasquin-Soleau, S., eds., Peritethyan Rift/Wrench Basins and Passive Margins: Mémoires du Muséum National d'Histoire Naturelle, Paris, v. 186, pp.671-706.

Roca, E. et al. (9 authors), 2004, TRANSMED Transect II: Aquitaine Basin - Pyrenees - Ebro Basin - Catalan Range - Valencia Trough - Balearic Block - Algerian Basin - Kabylies - Atlas - Saharan Platform, in Cavazza, W., Roure, F., Spakman, Stampfli, G.M. and Ziegler, P.A., eds., The TRANSMED Atlas: The Mediterranean Region from Crust to Mantle: Heidelberg, Springer-Verlag.

Roure, F., ed., 1994, Peri-Tethyan Platforms: Paris, Editions Technip, 275 p.

Royden, L.H., 1993, Evolution of retreating subduction boundaries formed during continental collision: Tectonics, v. 12, pp. 629-638.

Schettino, A. and Scotese, C., 2002, Global kinematic constraints to the tectonic history of the Mediterranean region and surrounding areas during the Jurassic and Cretaceous, in Rosenbaum, G. and Lister, G.S., eds., Reconstruction of the evolution of the Alpine-Himalayan orogen: J. Virtual Explorer, v. 8, pp. 149-168.

Schmid, S.M., Fügenschuh, B., Kissling, E., and Schuster, R., 2004, TRANSMED Transects IV, V, and VI - The Alps and their forelands, in Cavazza, W., Roure, F., Spakman, Stampfli, G.M. and Ziegler, P.A., eds., The TRANSMED Atlas: The Mediterranean Region from Crust to Mantle: Heidelberg, Springer-Verlag,

Seber, D., Barazangi, M., Tadili, B.A., Ramdani, M., Ibenbrahim, A. and Sari, D.B., 1996, Three-dimensional upper mantle structure beneath the intraplate Atlas and interplate Rif mountains of Morocco: J. Geophys. Res., v. 101, pp. 3,125-3,138.

Selvaggi, G. and Chiarabba, C., 1995, Seismicity and P-velocity image of the southern Tyrrhenian subduction zone: Geophys. J. Int., v. 121, pp. 818-826.

Sengor, A.M.C., 1979, Mid-Mesozoic closure of Permo-Triassic Tethys and its implications: Nature, v.279, pp.590-593.

Sengor, A.M..C., 1984, The Cimmeride Orogenic System and the Tectonics of Eurasia: Geological Society of America Special Paper 195, 82 p.

Spakman, W., 1986, Subduction beneath Eurasia in connection with the Mesozoic Tethys: Geologie en Mijnbouw, v. 65, pp. 145-153.

Spakman, W., 1990, Images of the upper mantle of central Europe and the Mediterranean: Terra Nova, v. 2, pp. 542-553.

Spakman, W., van der Lee, S. and van der Hilst, R.D., 1993, Travel-time tomography of the European-Mediterranean mantle down to 1400 km: Physics of the Earth and Planetary Interiors, v. 79, pp. 2-74.

Spakman, W., and Wortel, R., 2004, A tomographic view on western Mediterranean geodyamics, in Cavazza, W., Roure, F., Spakman, Stampfli, G.M. and Ziegler, P.A., eds., The TRANSMED Atlas: The Mediterranean Region from Crust to Mantle: Heidelberg, Springer-Verlag, pp.31-52.

Speed RC (1991) Tectonic Section Display - North American Continent-Ocean Transects Program. Geological Society of America, Boulder.

Stanley, D.J., and Wezel, F.-C., eds., 1985, Geological Evolution of the Mediterranean Sea: Heidelberg, Springer-Verlag, 589 pp.

Stampfli, G.M., and Borel, G., 2004, The TRANSMED transects in time and space, in Cavazza, W., Roure, F., Spakman, Stampfli, G.M. and Ziegler, P.A., eds., The TRANSMED Atlas: The Mediterranean Region from Crust to Mantle: Heidelberg, Springer-Verlag, pp. 53-80.

Stampfli, G.M., Borel, G., Cavazza, W., Mosar, J. and Ziegler, P.A., eds., 2001a, The Paleotectonic Atlas of the PeriTethyan Domain (CD-ROM): European Geophysical Society.

Stampfli, G.M., Borel, G., Marchant, R. and Mosar, J., 2002, Western Alps geological constraints on western Tethyan reconstructions: Journal Virtual Explorer, v.8, pp.77-106.

Stampfli, G.M., Mosar, J., Favre, P., Pillevuit, A. and Vannay, J.-C., 2001b, Permo-Mesozoic evolutionof the western Tethys realm: the Neo-Tethys East Mediterranean basin connection, in Ziegler, P.A., Cavazza, W., Robertson, A.H.F. and Crasquin-Soleau, S., eds., Peritethyan Rift/Wrench Basins and Passive Margins: Mémoires du Muséum National d'Histoire Naturelle, Paris, v. 186, pp.51-108.
UNESCO-IUGS (2000) International Stratigraphic Chart
van der Hilst, R., 1995, Complex morphology of subducted lithosphere in the mantle beneath the Tonga trench: Nature, v. 374, pp. 154-157.
van der Hilst, R.D., Engdahl, E.R., Spakman, W. and Nolet, G., 1991, Tomographic imaging of subducted lithosphere below northwest Pacific island arcs: Nature, v. 353, pp. 37-43.
Vai, G.B., 2003, Development of the palaeogeography of Pangea from Late Carboniferous to Early Permian: Paleogeography, Paleoclimatology, Paleoecology, v.196, pp.1-31.
Vially, R. and Trémolières, P., 1996, Geodynamics of the Gulf of Lions: implications for petroleum exploration, in Ziegler, P.A. and Horvath, F., eds., Structure and Prospects of Alpine Basins and Forelands: Mémoires du Muséum National d'Histoire Naturelle, Paris, v. 170, pp. 129-158.
von Blanckenburg, F., Davies, J.H., 1995, Slab breakoff: A model for syn-collisional magmatism and tectonics in the Alps: Tectonics, v.14, pp.120-131.
Wortel, M.J.R. and Spakman, W., 1992, Structure and dynamics of subducted lithosphere in the Mediterranean region. Proceedings of the koninklijke nederlandse Akademie van Wetenschappen Series B: Palaeontology, Geology, Physics, Chemistry, Anthropology, v. 95, pp. 325-347.
Wortel, M.J.R. and Spakman, W., 2000, Subduction and slab detachment in the Mediterranean-Carpathian region: Science, v. 290, pp. 1910-1917.
Yilmaz, P.O., Norton, I.O., Leary, D. and Chuchla, R.J., 1996, Tectonic evolution and paleogeography of Europe, in Ziegler, P.A., and Horvath, F., eds., Structure and Prospects of Alpine Basins and Forelands: Mémoires du Muséum National d'Histoire Naturelle, Paris, v.170, pp.47-60.
Ziegler, P.A., 1988, Evolution of the Arctic-North Atlantic and Western Tethys: American Association of Petroleum Geologists Memoir 43, 198 p.
Ziegler, P.A., Cavazza, W., Robertson, A.H.F. and Crasquin-Soleau, S., eds., 2001, Peritethyan Rift/Wrench Basins and Passive Margins: Mémoires du Muséum National d'Histoire Naturelle, Paris, v. 186, 762 p.
Ziegler, P.A. and Roure, F., 1996, Architecture and petroleum systems of the Alpine orogen and associated basins, in Ziegler, P.A. and Horvath, F., eds., Structure and Prospects of Alpine Basins and Forelands: Mémoires du Muséum National d'Histoire Naturelle, Paris, v.170, pp.15-45.

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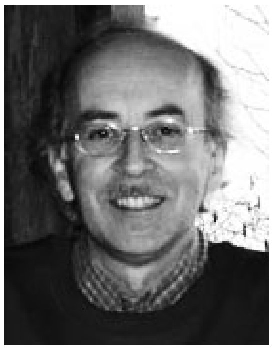

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