Tomographic View on Western Mediterranean Geodynamics

W. Spakman   and   M.J.R. Wortel

Chapter 2

A Tomographic View on Western Mediterranean Geodynamics

Wim Spakman - Rinus Wortel

Abstract

During the Cenozoic, the Western Mediterranean region has experienced a complex subduction history which involved the destruction of the Late Triassic/Jurassic Ligurian ocean and the West Alpine-Tethys. Lithosphere remnants of this evolution have been detected in the upper mantle by seismic tomography imaging. However, no general consensus exists on the interpretation of these remnants/slabs in the context of Ligurian ocean and West Alpine-Tethys subduction. In this paper we search for subduction remnants of the entire Cenozoic evolution in the recent global tomography model of Bijwaard and Spakman (2000) and compare these tomography results and our interpretations with those obtained in previous studies. Next, we present an analysis of imaged mantle structure in the context of the tectonic evolution of the Western Mediterranean during the Cenozoic. Our analysis leads to the following main results:

1) The identification of the remnant of the West Alpine-Tethys (Piedmont ocean) found at the bottom of the upper mantle under the Alps and northern Apennines region.

2) A surface reconstruction of the Ligurian ocean from subduction remnants found in the upper mantle under the Western Mediterranean.

3) The confirmation of the earlier propositions by Lonergan and White (1997) concerning slab roll-back and lithosphere tearing which led to two dominant Ligurian subduction systems: the Betic-Alboran subduction and the Apennines-Calabria subduction.

4) Propositions of a short (300-400 km) continuous north-Apennines slab and of slab detachment beneath the central-southern Apennines.

5) Slab detachment and lithosphere tearing are considered crucial processes for facilitating slab roll-back in the Western Mediterranean region.

6) A new kinematic model for slab roll-back in the Betic-Rif-Alboran region which involves slab detachment under the Betic, lithosphere tearing along the African margin, and which explains both the inferred slab geometry and the arcuate geometry of the Betic-Rif orogen.

2.1 Introduction

Seismic travel-time tomography is an imaging method which allows to construct three-dimensional (3-D) models of the Earth's internal structure from observations of seismic travel times (e.g. Spakman et al. 1993). Earth structure is obtained in terms of the propagation speed of seismic P- and/or S-waves. Seismic-wave speed is a material parameter which depends on local properties as temperature, pressure, and composition (e.g. Trampert et al. 2001). Thus, implicitly tomography delivers a snapshot of mantle dynamics. We note, however, that tomographic imaging generally provides a blurred view on Earth structure as a result of the combined influence of lack of observations, data errors, and theoretical and numerical approximations. Image blurring complicates the interpretation of a tomogram. Other factors that complicate interpretation are introduced by incomplete knowledge of how seismic wave speed relates to temperature and composition and by occasional degrees of freedom to explain the same image with different types of mantle processes. The latter basically derive from insufficient knowledge of, and/or constraints on, mantle dynamics and the crustal response to lithosphere processes (e.g. subduction, lithosphere delamination).

For the Alpine-Mediterranean region, seismic tomography has considerably narrowed the range of possible scenarios for the geodynamic evolution of the region. 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 tomographic studies of the Mediterranean, generated by predominantly Dutch and Italian groups, have considerably focussed 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, Wortel and Spakman 2003) or subduction beneath the Aegean to depths of 1,500 km (Bijwaard et al. 1998). In this paper we discuss recently obtained travel-time
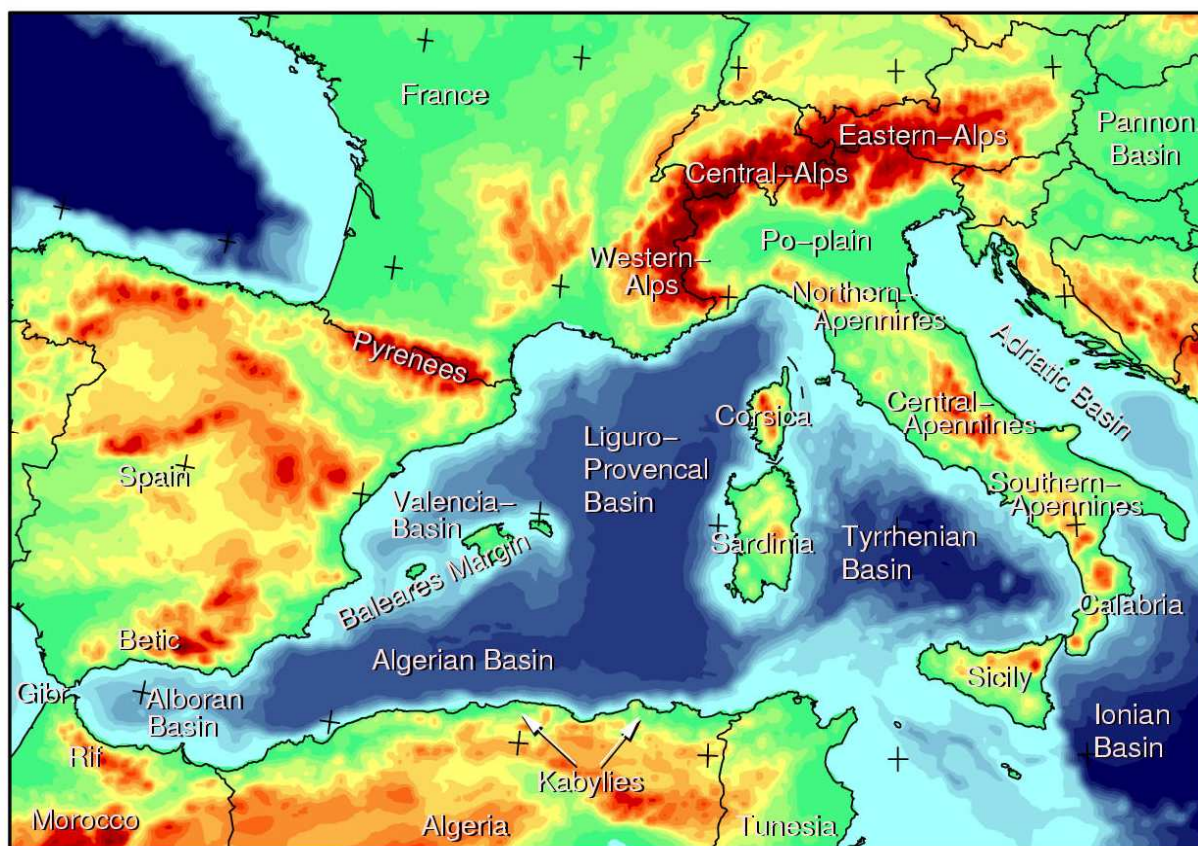
Fig. 2.1 The Western Mediterranean and surrounding regions. Indicated names are used in the text. For an introduction to the main geological features of the region, see Cavazza et al., this publication.

tomography results of the 3-D structure of the Western Mediterranean mantle (Figure 1). The results are extracted from the global-mantle model BS2000 of Bijwaard and Spakman (2000). Details on data analysis and tomographic method can be found in Spakman (1993), Spakman et al. (1993), Bijwaard et al. (1998), and Bijwaard and Spakman (2000). Some results of BS2000 concerning Mediterranean mantle structure were presented earlier (Wortel and Spakman 2000, 2001 (Erratum), Gutscher et al. 2002). We will analyse in detail what can be learned from imaged mantle structure to help unravel the complex geodynamics of the Western Mediterranean. Based on this new tomographic information we adapted some of our earlier interpretations. Furthermore, we can confirm, and in some cases refine, existing interpretations and we will also add some new results such as the identification of the West Alpine-Tethys slab (Piedmont ocean slab), a surface reconstruction of the Ligurian ocean, and a new qualitative reconstruction of the Betic-Alboran subduction history. In our analysis, we include inferences drawn from tectonic reconstructions of the Western Mediterranean, but stay relatively away from detailed comparisons with geology, in particular, timing of events. Rather we like to present, as the title of this contribution states, a tomographic view on Western Mediterranean mantle dynamics, leaving the test of our propositions to future research.

2.2 The global tomography model: BS2000

Model BS2000 (Bijwaard and Spakman 2000) is the successor of the BSE-model (Bijwaard et al. 1998). Both models result from a tomographic analysis of the global data set of 7.5 million P- and pP-phase delay times of Engdahl et al. (1998). They are determined as seismic wave-speed anomaly models with respect to the 1-D global reference model ak135 (Kennett et al. 1995). Furthermore, the models are based on exactly the same model parameterization. The basic difference results from the application of 3-D ray tracing and nonlinear inversion by a step-wise linearized approach (Bijwaard and Spakman, 1999, 2000). Nonlinear inversion is performed to account for the effects of ray bending caused by 3-D wave speed heterogeneity in the mantle and for the effects of an inadequate reference model. BS2000 is a model of the entire mantle based on a special cell-parameterization technique in which cell size is adaptive to the local data density (Spakman and Bijwaard 2001). Small cells are constructed in regions of high data density and larger cells elsewhere. This effectively allows for solving a tomographic inverse problem for the entire mantle while retaining resolution for the relatively small structural detail known from regional mantle studies (e.g. Spakman et al. 1993, Piromallo and Morelli, 1997, 2003). Figure 2 shows examples of the spatially variable cell parameterization of the Western Mediterranean mantle.

BS2000 results from a very large-size inverse

32

problem (about 400,000 model parameters) for which formal resolution analysis is computationally not feasible. An alternative and approximate method is to assess spatial resolution through sensitivity analysis with synthetic wave speed models (Spakman and Nolet 1988). Synthetic data are first computed by integrating a synthetic wave-speed anomaly model along the seismic ray paths of the real data. Usually some Gaussian noise is added and finally the synthetic data are inverted in the same way as the actual data. Qualitative inferences about model resolution are derived from the comparison between the synthetic model and its tomographic image. Examples are given in Figure 3 showing results of so-called spike- or block tests for synthetic blocks of 1.2 to 2.4 degrees in size, at different depths. Synthetic spike tests are conducted for a wide variety of block sizes ranging from 0.6 degrees to 6.0 degrees. This allows for investigating the potential for resolving both small and larger scale structure at specific locations in the tomographic model and reduces the risk of misinterpreting sensitivity test results (e.g. good recovery of detail does not imply good recovery of larger structures; see Leveque et al. 1993). Many examples of sensitivity tests are given in Appendix 1. The degree of recovery of a variety of synthetic patterns is used as a measure of confidence to engage interpretation of the actual tomogram.

Model BS2000 shows a complex and heterogeneous pattern of seismic wave-speed anomalies across the entire upper mantle beneath the Western Mediterranean. Generally, the imaged wave-speed heterogeneity becomes more smooth from the top of the mantle downward (see map view images of Figure 4). Amplitudes decrease from 3-4% in the upper 200 km to 1-1.5% at the base of the upper mantle. We deduce from sensitivity test results that the noted amplitude decrease with depth is real, although amplitudes may be underestimated on average. This was also found in other studies (e.g. Spakman et al. 1993, Piromallo and Morelli 2003). Sensitivity tests also indicate a general decrease in spatial resolution from, locally at best, 50 km in the first 100 km to 100-200 km in the mantle transition zone (410-660 km). For reasons of model comparison later in this paper, we note that, from a technical point of view, the regional mantle models of Spakman et al. (1993) and Piromallo and Morelli (1997, 2003) are closest to BS2000. The former work employs a spatially uniform parameterization with 0.8 degree cells and cell thicknesses similar to BS2000, whereas the latter uses a detailed node parameterization with a node distance of 0.5 degrees and 50 km node spacing in depth. This is comparable to using 0.25 degrees cells with thicknesses of 25 km (Spakman and Bijwaard 2001).

2.3 Interpretation of model BS2000 for the Western Mediterranean mantle

Our interpretations will concentrate on subduction of lithosphere. Previous tomographic studies have contributed strongly to unravelling the 3-D geometry of subducted slab in the region (e.g. Spakman 1986a, 1990, 1991, Spakman et al. 1993, Amato et al. 1993, 1998, Cimini and De Gori 1997, Piromallo and Morelli, 1997, 2003, Lucente et al. 1999). Model BS2000, however, allows to make new inferences on Mediterranean subduction systems. In tomography, subducted lithosphere translates into a positive (fast) wave-speed anomaly, predominantly, due to the temperature contrast between the cold slab and the warmer ambient mantle, whereas relatively warmer mantle regions lead to a negative (slow) wave-speed anomaly (e.g. De Jonge et al. 1994, Goes et al. 2000). We first discuss mantle structure in the eastern part of the region (Alps-Apennines-Calabria) and separately discuss imaged structure of the Betic-Alboran mantle. In the last part of this paper we analyse our findings in the context of the geodynamic evolution of the entire Western Mediterranean.

2.3.1 Alps, Apennines, and the Western Mediterranean

The tomographic image of the upper mantle of this region is very complex. The 3-D cartoon displayed in Figure 5 shows our schematization of the imaged positive mantle anomalies and summarizes our geodynamic interpretation. This cartoon can be verified against the imaged positive anomaly patterns as extensively displayed in map view sections (Figure 4), selected cross sections (Figures 6, 7, and 8) and cross sections presented in Appendix 2. To justify our choices leading to the geometric and geodynamic interpretation depicted in Figure 5, we start with a brief description (with some interpretation) of the larger scale patterns, followed by a comparison with related work.

Imaged   upper mantle structure

The positive anomalies found in the upper 150-200 km beneath the Alps and northern Po plain are dipping to the south, beneath the central Alps, and to the east-southeast below the western Alps. This is best shown in cross sections (Figure 8b and Appendix 2). This pattern is consistent with overriding of the European margin by the Adriatic plate. Beneath the northern Apennines (from Tuscany to the Po plain) positive anomalies shift westward with increasing depth, indicative of lithosphere subduction. Below 400 km this slab anomaly connects with a broad positive anomaly found in the upper mantle transition-zone (410-660 km). Under the central-southern Apennines only negative anomalies
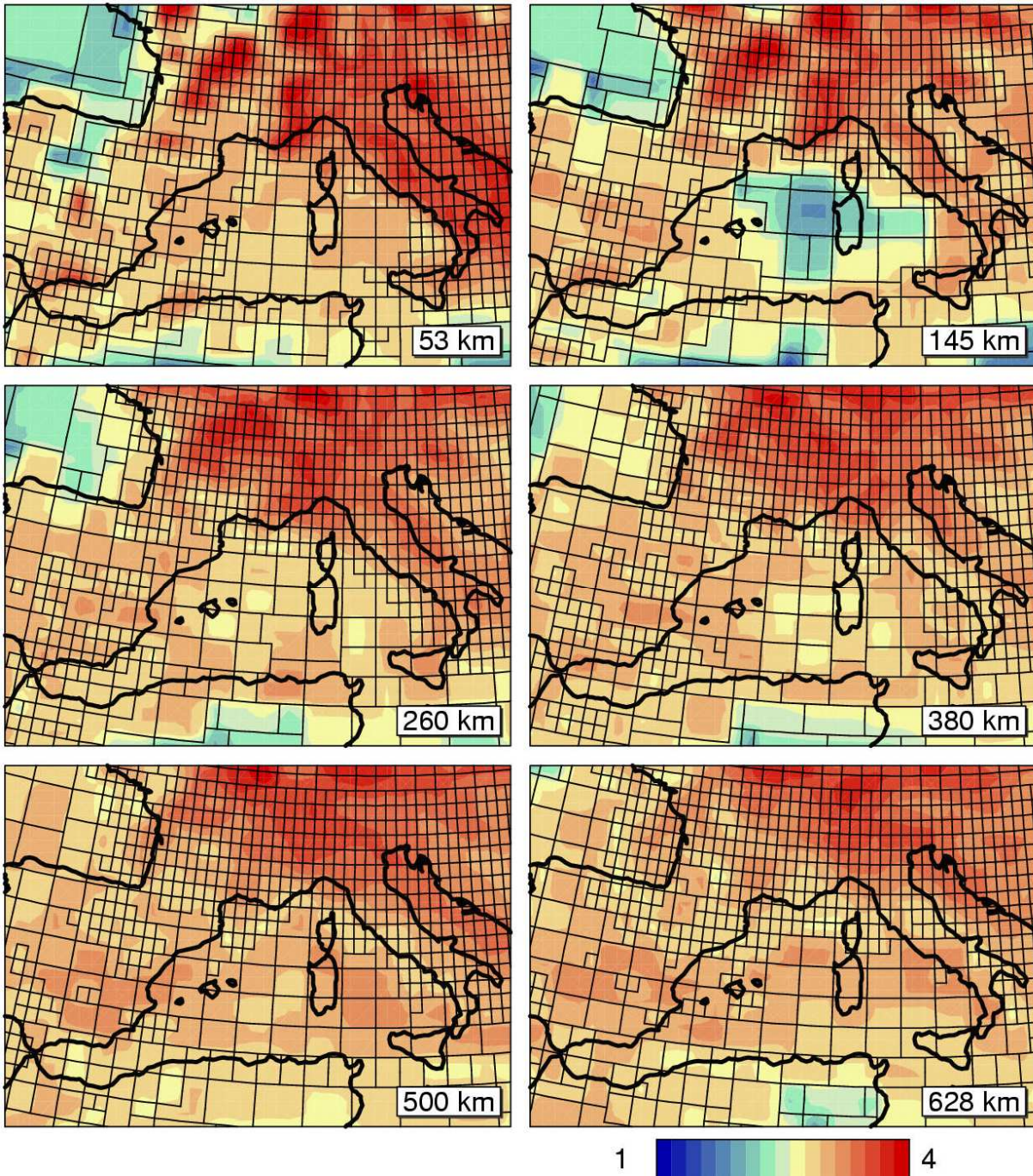
Fig 2.2 Cell hit count and model cell-parameterization at selected depths beneath the Mediterranean region. The smallest cells have lateral dimensions of 0.6 degrees. Lateral dimensions of larger cells are a multiple of 0.6 degrees.   The smallest cells have lateral dimensions of 0.6 degrees and thickness of 35 to 65 km increasing with depth, respectively. Larger cells are found below the sea areas and northern Africa where station and earthquake density is strongly reduced. Still, the 1.8*1.8 degree cells constructed at a depth of 628 km in the Western Mediterranen have a thickness of only 65 km. The color contouring quantifies the cell hit count, i.e. the number of rays passing through each cell. The color coding uses a 10-logarithm scale.The irregular cell grid is specifically designed to minimize hit-count differences between adjacent cells as well as possible. This is done in a self-adaptive way using a target hitcount of about 500 rays per cell in the upper mantle (see Spakman and Bijwaard, 2001, for details). This explains why cells of different volume have similar hit count. The smallest cells used in the grid construction procedure have dimensions of 0.6 degrees therefore their hit count can exceed the target value.
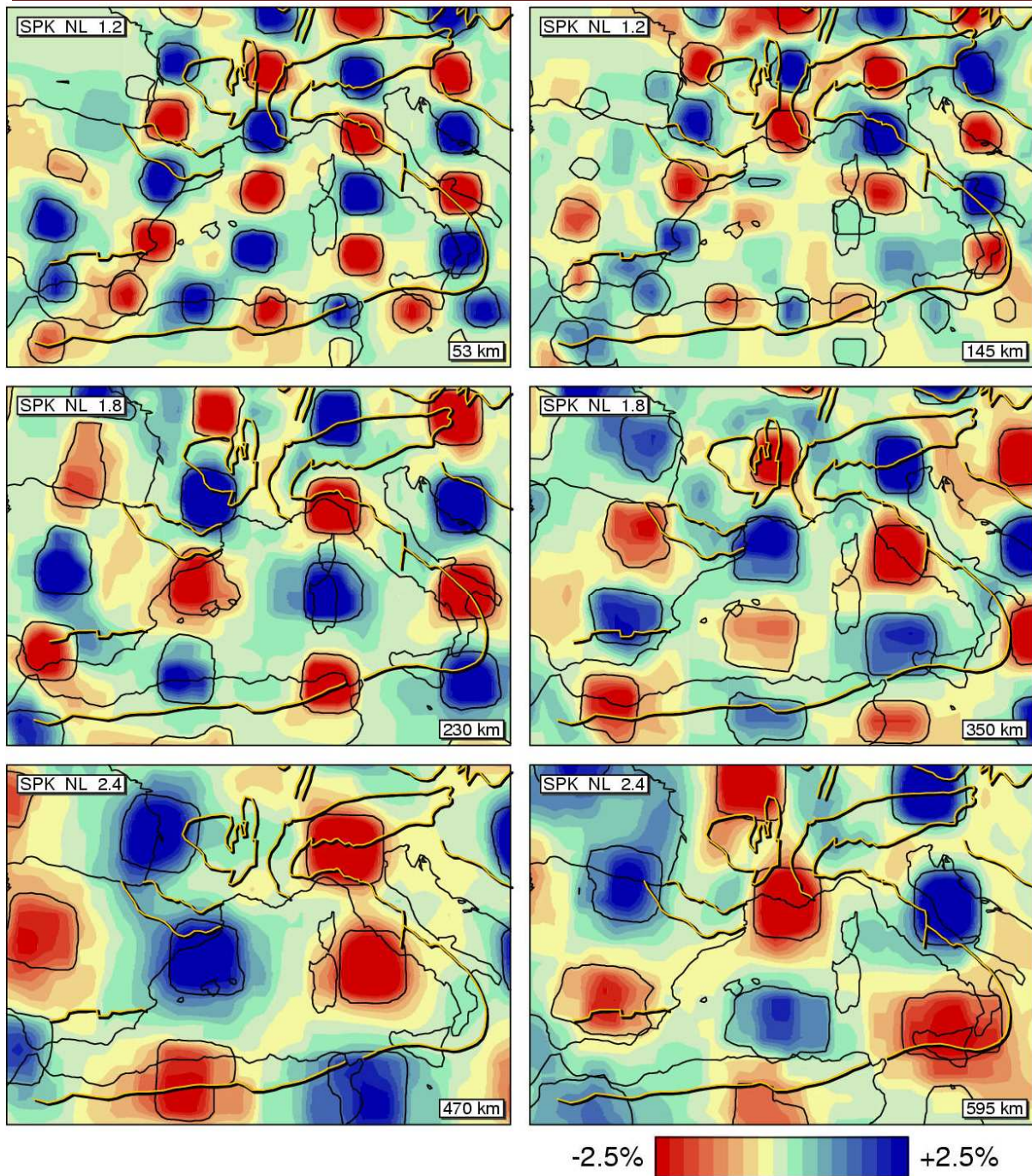
Fig. 2.3 1 Results of a sensitivity test for the recovery of a regular patterns of 1.2, 1.8, and 2.4 degree blocks at different depths in the upper mantle. Circular lines denote the location of the isolated synthetic blocks with an seismic wave-speed anomaly amplitude of +5% or -5% with respect to the 1-D reference model ak135 of Kennett et al. (1995). Between these blocks the synthetic anomaly is 0%. The colors denote the tomographic image of the synthetic block models. Comparison of "input" and "output" model leads to qualitative assessment of spatial resolution. The figure shows results for the Western Mediterranean taken from a global synthetic mantle model (model BS2000 is a *global* mantle model). The synthetic models are only constructed in regions where cell sizes of 1.2 (or 0.6), 1.8, or 2.4 degrees were permitted. This explains, e.g., the absence of synthetic blocks of 1.2 degree below the Western Mediterranean at 145 km depth. Lack of resolution can be detected where significant amplitudes occur between the blocks where block anomalies smear into the model. Generally the synthetic patterns are well recovered although with systematically smaller amplitudes than the input values.
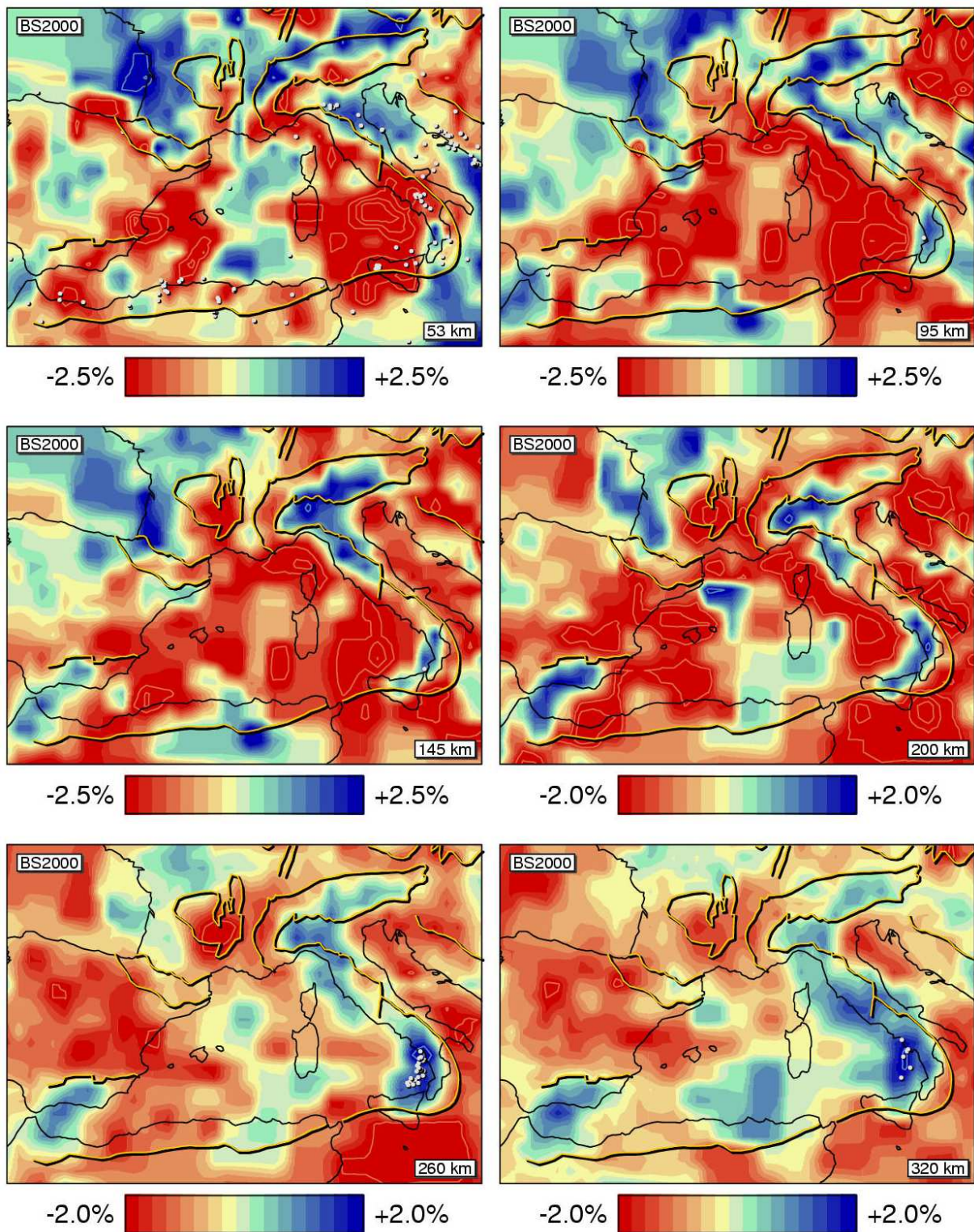
Fig. 2.4 1 Tomographic map view images at twelve selected depths for the upper 710 km of the Western Mediterranean and surrounding regions. Colors display the percentage deviation of seismic wave speed with respect to the 1-D reference model ak135 (Kennett et al. 1995). Negative (positive) anomalies 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%. In regions where imaged amplitudes are larger than the limits of the contouring scale, additional line-contours are plotted for every step in 1%-anomaly value. Shaded yellow lines indicate outlines of major tectonic features for reference. Capital letters A, B, C, D, at depths of 500 km, or larger label individual anomaly patterns for discussion in the text.
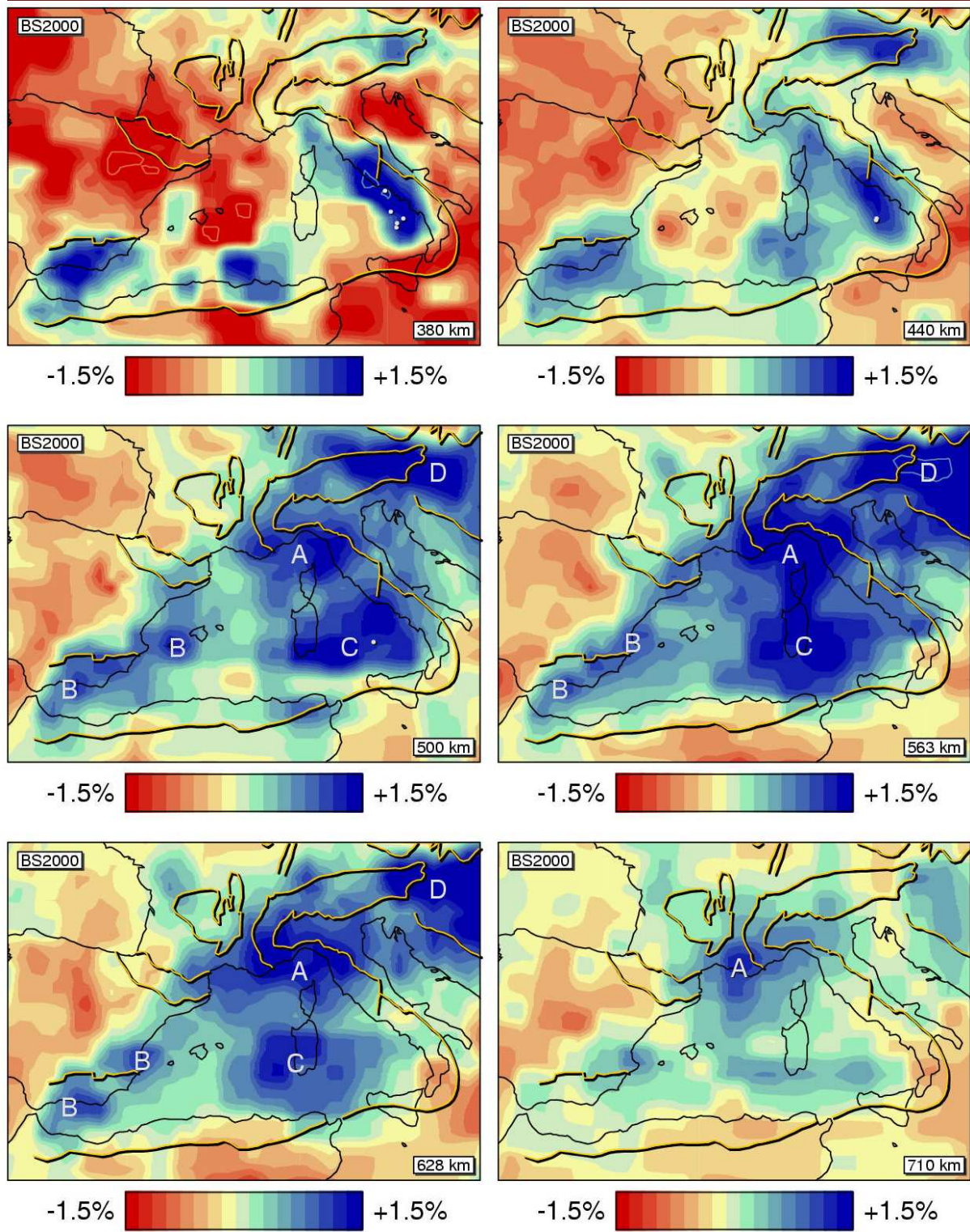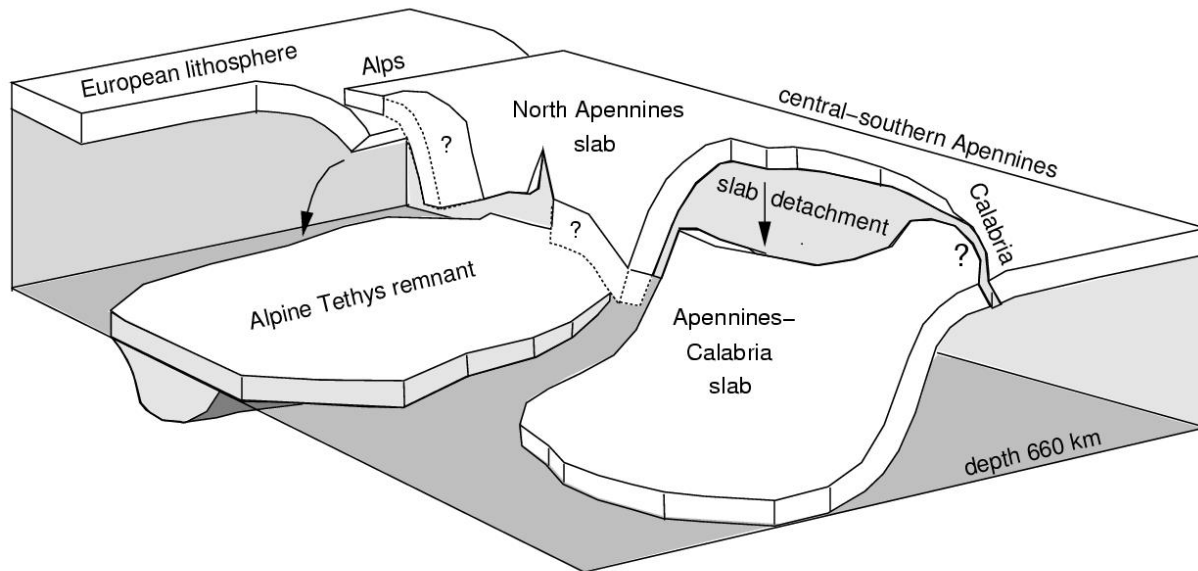
Fig. 2.4. *Continued*

Fig. 2.5.   Cartoon depicting our interpretation of the geometry and geodynamic significance of imaged upper mantle anomalies below the Alps, Apennines and the western Western-Mediterranean. See text for further information.

are found in the upper 200-250 km. Below this depth a long positive anomaly appears along the strike of the Apennines and connects to the south with the fast anomaly associated with the well-known Calabria subduction. Since their discovery (Spakman, 1986a, 1990), these positive anomaly structures have been equivocally attributed to subducted lithosphere. The patterns of relatively elongate wave-speed heterogeneity in the upper 400 km start to change in the transition zone (410-660 km). There, we distinguish four large positive anomalies (see Figure 4):

A) The broad positive anomaly found beneath the northern Italy/Adriatic region, the northwestern Mediterranean, southern France, and the Alps;
B) the Betic-Alboran anomaly which will be described later,
C) a broad anomaly found west of, and connected to, the subduction anomaly beneath the central-southern Apennines and Calabria, and
D) a broad anomaly imaged under the eastern-Alps and the Pannonian basin.

Note that anomaly **A** also attains significant amplitudes at the top of the lower mantle (710-810 km) while the other anomalies fade away. Under east Algeria we find a positive anomaly of varying amplitude which trends northward with increasing depth. In the transition zone, anomaly **C** also encompasses the deeper part of this east-Algeria anomaly. We observe no other (north-)dipping structures connected to the north-African margin. Sensitivity tests results (Figure 3, Appendix 1) indicate that the spatial resolution in the mantle under the African margin is sufficient to rule out the existence of such large positive anomalies.

Cross sections (Figure 6b, Appendix 2) clearly demonstrate that the Apennines-Calabria slab is turning to horizontal in the transition zone, lying flat on the 660 km discontinuity between upper and lower mantle. The flattening of this slab explains the sudden broadening of positive anomalies (anomaly **C**). The Calabria slab is imaged across the entire mantle beneath Calabria (Figure 6b). In contrast, sections across the central-southern Apennines (e.g. Figure 7a) demonstrate, as can also be observed in the map view images, that no positive wave speed connection exists between slab and Adriatic lithosphere at the surface. Westward subduction below the northern Apennines is imaged as continuous with the broad transition zone anomaly **A**. Compared to the images of flattening subduction below the southern Tyrrhenian we observe a distinct difference: The northern Apennine slab is almost centered above anomaly **A** (Figure 7b, Appendix 2) whereas the Apennines-Calabria slab is located to the side of its flat lying portion (anomaly **C**; Figures 6b, 7a, Appendix 2). Cross sections taken along strike of the Apennines (Figure 8 and Appendix 2) lend additional support for large structural differences between the Apennines-Calabria slab (to the right of the 8-degree tic mark), the northern Apennines slab (to the left of the 8-degree tic mark and found in the upper 300 km), and the broad anomaly **A** in the transition zone, suggesting that these anomalies result from (at least partly) a difference in geodynamic evolution.
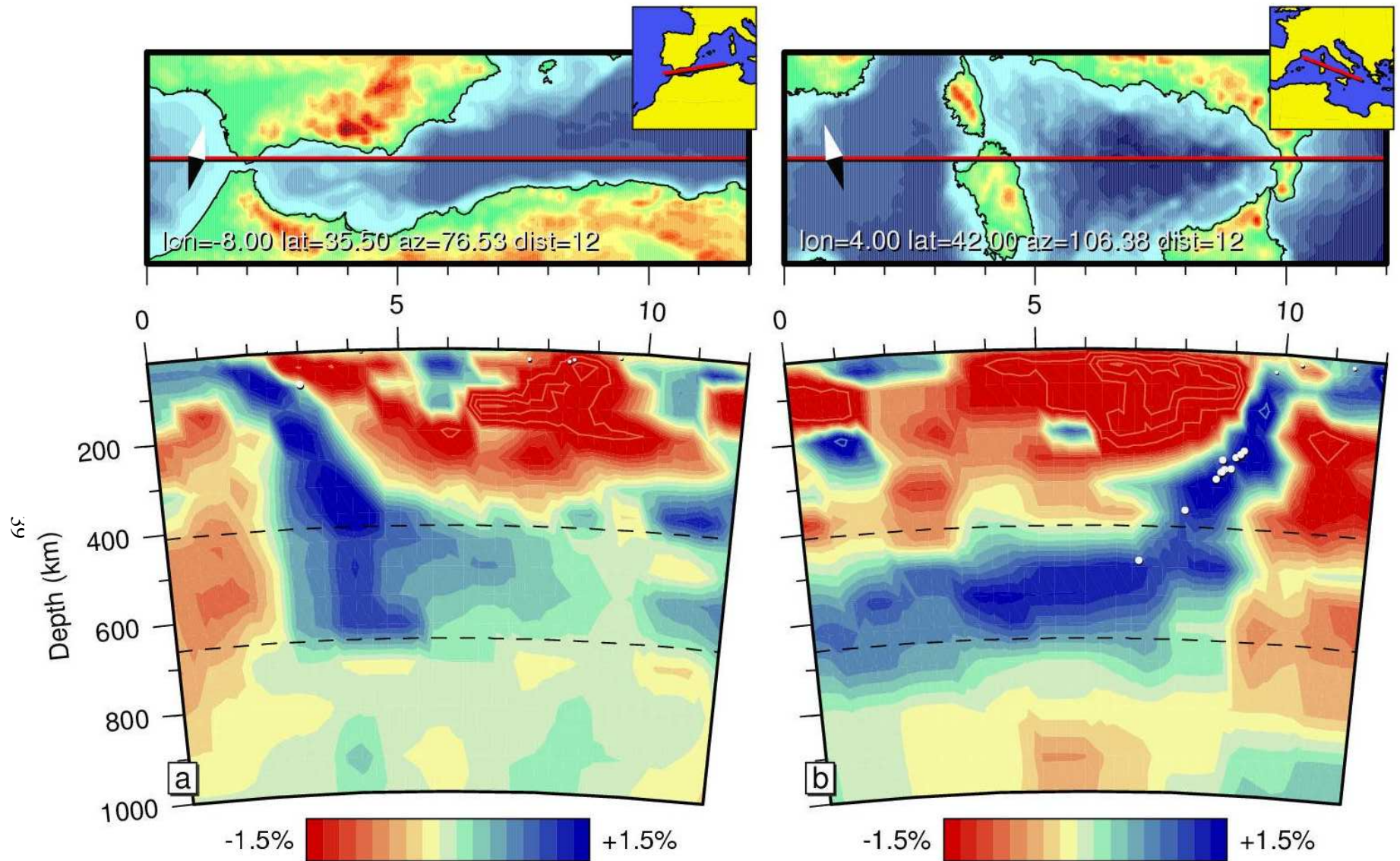
38

Fig 2.6. Two BS2000 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. 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. For color coding (and line contours) of the tomographic image see caption of Figure 4. Dashed lines in the section represent the mantle discontinuities at 410 and 660 km depth.
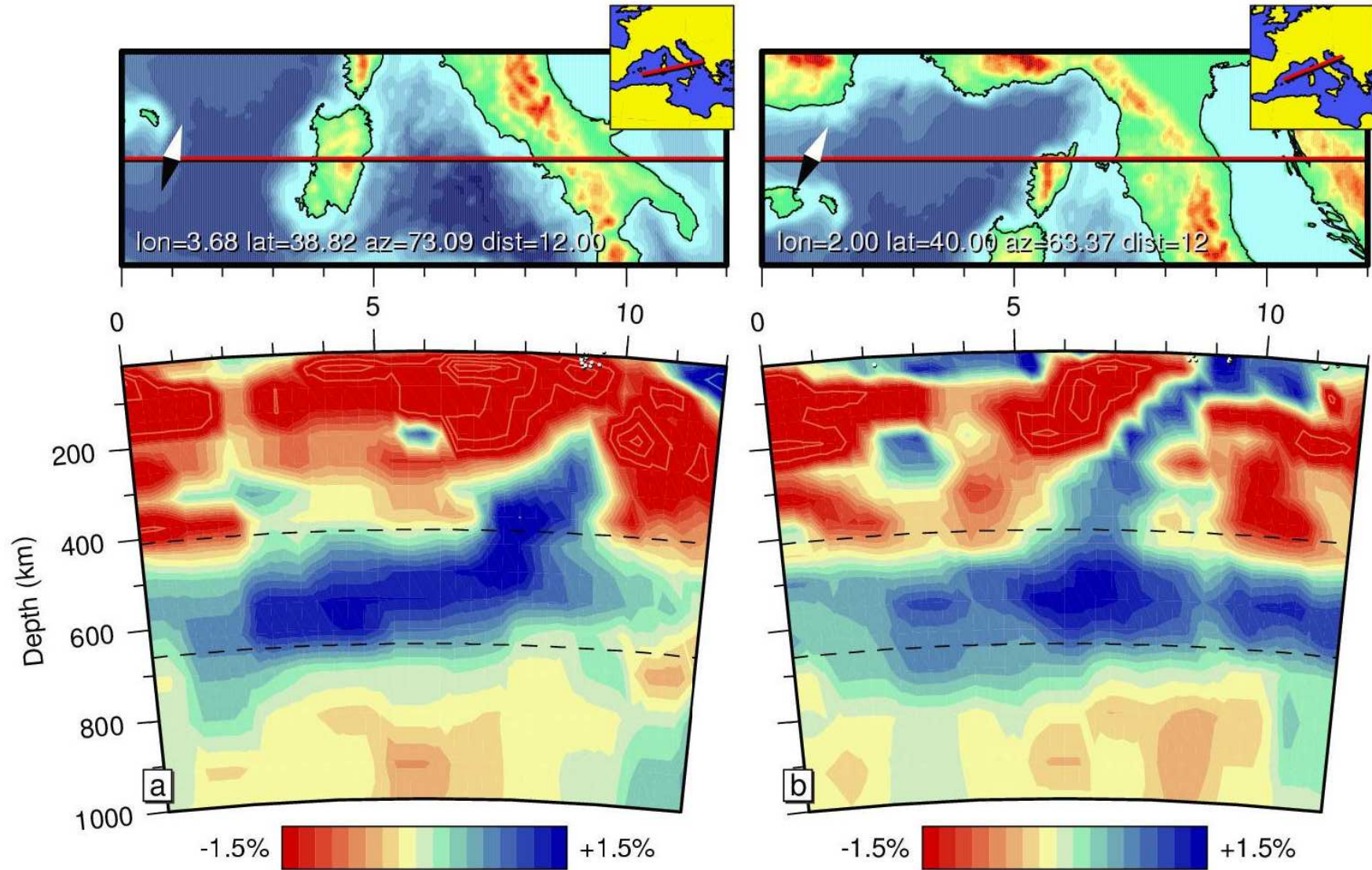
tFig. 2.7. . Two BS2000 cross sections through the first 1000 km of the Western Mediterranean mantle. A) section through the southern Apennines and Tyrrhenian basin; B) section through the northern Apennines and Liguro-Provencal basin. For further explanation see caption of Figure 6.
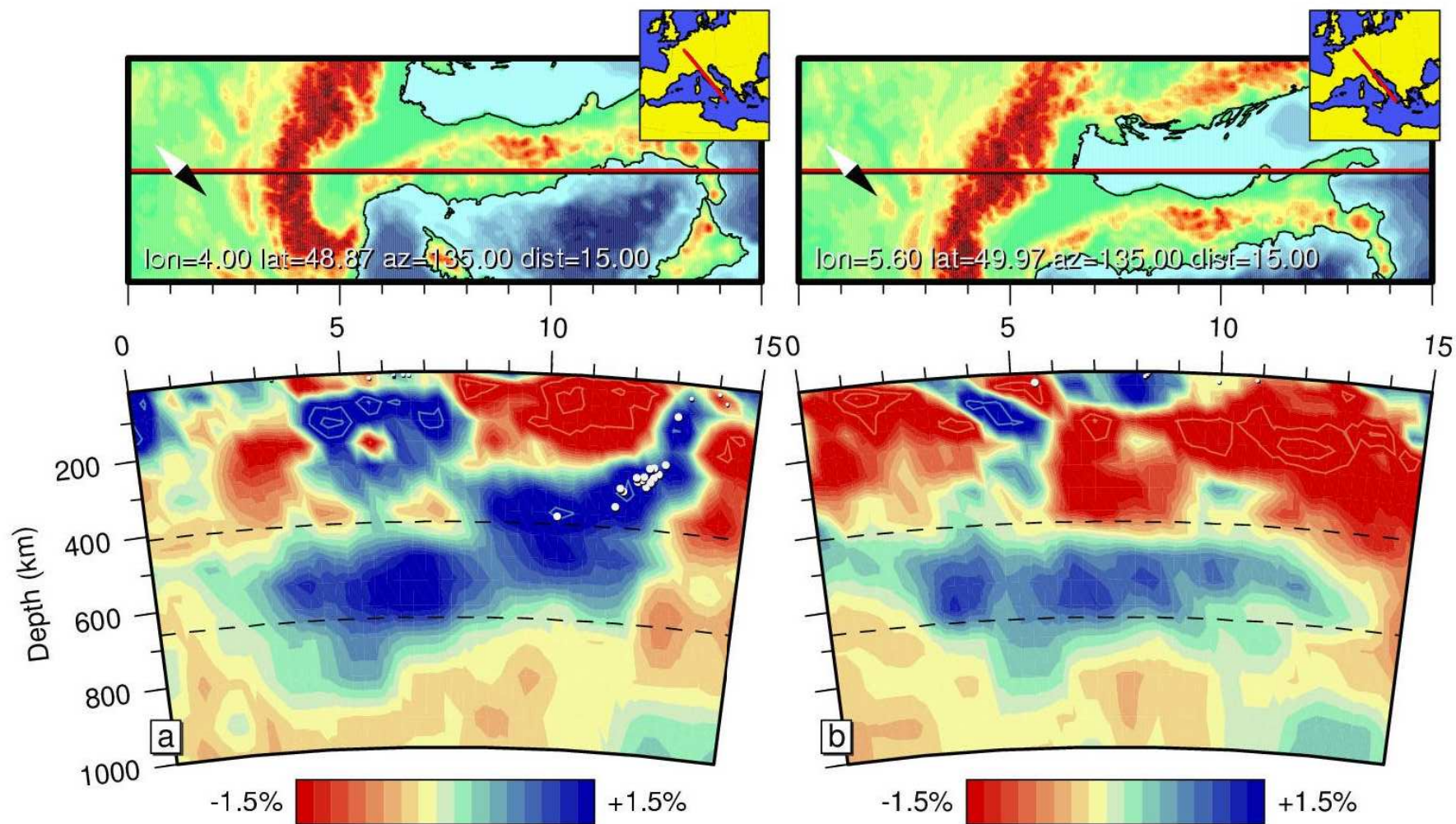
Fig. 2.8. Two BS2000 cross sections through the first 1000 km of the Western Mediterranean mantle taken along strike of the Italian Peninsula: A) section through western Italy and the central Alps; B) section through the Adriatic basin and the central-eastern Alps. For further explanation see caption of Figure 6.

Comparison with other tomographic work

The general patterns described above are broadly consistent with previous tomographic models which are based on inverting data from both regional and teleseismic earthquakes (Spakman 1991, Spakman et al. 1993, Piromallo and Morelli, 1997, 2003, Bijwaard et al. 1998). However, the more detailed morphology of imaged patterns still differs among the more recent models. The reason should be found in differences in data selection and processing, tomographic techniques and model parameterization, and inversion regularization, as discussed hereafter.

Alps

The S-dipping European lithosphere below the central Alps and ESE-dipping under the Western Alps is well known from interpretations of deep seismic sounding and geology (e.g Waldhauser et al. 1998, Schmid and Kissling 2000) and has - for the central Alps - also been inferred from mantle tomography (Spakman 1986b, Kissling 1993, Kissling and Spakman 1996). European plate geometry was similarly imaged in the models of Piromallo and Morelli (1997, 2003). We also find a clearly S-dipping European margin below the eastern Alps (Figure 8b, Appendix 2) which contrasts with the recent proposition of north dipping lithosphere along the Trans-Alp transect by Lippitsch et al. (2003). See also Transect VI of this publication.

Northern Apennines

The patterns imaged in the upper 250 km beneath the northern Apennines show subtle but important differences among models. Originally, Panza et al. (1980) discovered the deep lithospheric root beneath the northern Apennines from an analysis of surface waves. Spakman (1990) and Spakman et al. (1993) also imaged a root and observed that, similar to the central-southern Apennines, no positive wave speed connection exists between the Adriatic lithosphere and positive anomalies imaged deeper under this region. Beneath Tuscany the gap is smallest, only about 50 km wide (e.g. Figure 16 of Spakman et al. 1993). This pattern was adopted by Wortel and Spakman (1992) as the premise for their hypothesis of slab detachment under the entire Apennines and of lateral migration of a slab tear from north to south. Subsequent teleseismic tomography studies of the Italian peninsula (e.g. Amato et al. 1993, 1998, Cimini and De Gori, 1997, Lucente et al. 1999), however, showed continuous positive anomalies under the northern Apennines. The regional mantle models of Piromallo and Morelli (1997, 2003) exhibit local evidence for a continuous slab at the same location where Spakman et al. (1993) find the smallest gap. The model of Bijwaard et al. (1998) and BS2000 also possess evidence for a continuous positive anomaly in the upper 200 km (Figure 4, 7b, Appendix 2).

The differences between tomographic models concern the 50-km detail in the depth continuation of north-Adriatic lithosphere subduction. Mantle structure of this scale is at the current limit of model resolution and, even if resolved in some models, cell amplitude errors may still lead to unequivocal interpretations. All these factors of uncertainty have prompted Wortel and Spakman (2000, 2001) to put a question mark on their earlier suggestion regarding slab detachment in the northern Apennines.

Central-southern Apennines

A very consistent feature of regional and global tomography studies (Spakman 1991, Spakman et al. 1993, Piromallo and Morelli, 1997, 2003, Bijwaard et al. 1998) is a zone of negative wave-speed anomalies which is imaged in the top 200-250 km under the central-southern Apennines. A local teleseismic-tomography study (Cimini and De Gori, 2001) corroborate this result. We note, however, that teleseismic studies can produce quite different results for the same region. For instance, Lucente et al. (1999) find on average zero anomalies for the upper 170 km under the central-southern Apennines. Teleseismic tomography studies are intrinsically hampered by a poor depth resolution (only steeply emergent seismic rays are used) and, for the Italian region, by the fact that *relative* travel-time residuals are inverted. The latter implies that the average wave-speed anomaly for a particular depth is invisible, and thus a low or high wave-speed layer cannot be imaged properly.

Overall, results from independent studies mostly lend support for the case that no positive-anomaly connection exists between the Adriatic plate and the deeper positive anomaly imaged below 200-250 km. Proposed interpretations of this feature include (i) a slab window (absence of slab or subducted continental lithosphere; Amato et al. 1993); (ii) subduction of a promontory of continental lithosphere (Lucente et al. 1999, Lucente and Speranza, 2001); (iii) lithosphere attenuated by a hot asthenospheric wedge (Amato et al. 1993, Cimini and De Gori, 2001); (iv) deep (250 km) slab detachment (Lucente and Speranza, 2001), in which case the low velocities above 250 km depth are still assigned to subducted continental lithosphere; and (v) shallow slab detachment (Wortel and Spakman, 1992, 2000, Cimini and De Gori, 2001, Panza et al. 2002), in which case the low wave-speed anomaly represents mobile (asthenospheric) mantle.

Calabria

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, BS2000) 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 falt lying portion of the Calabria slab (Anomaly **C** in Figure 4), are imaged more clearly in the recent tomographic models. 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 as compared to our models BSE (Bijwaard et al. 1998) and BS2000.

2.3.2 The Betic-Rif and Alboran region

 Beneath the Betic-Rif and Alboran region a positive anomaly is found from the base of the crust across the entire upper mantle (Figure 4). 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. Figure 6a displays a W-E cross section through the anomaly which clearly shows an eastward dip and confinement of the anomaly to the upper mantle. Cross sections with a more N-S orientation exhibit no dip. Figures of Appendix 2 allow to follow this anomaly along many W-E directed slices.

        Previous tomographic studies, based on different tomographic approaches and data sets, have already imaged a positive anomaly in the upper mantle of the Betic-Rif/Alboran region. Blanco and Spakman (1993) and Spakman et al. (1993) find the anomaly from a depth of 200 km downward, whereas Seber et al. (1996), Bijwaard et al. 1998, and Calvert et al. (2000) image the anomaly locally from sub-Moho depth downward. The latter authors prefer a division into two separate bodies which however are not imaged in BS2000. Piromallo and Morelli (1997, 2003) find a positive anomaly connection below northern Morocco, but most of the positive anomaly is overlain by low wave-speed anomalies.

         Figure 9 shows a 3-D cartoon schematically depicting the geometry of the positive anomaly in model BS2000. Several options exist for its interpretation, 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). Gutscher et al. (2002) combined the positive anomaly of model BS2000 with marine-seismic observations of a deforming fore-arc west of Gibraltar. They propose a still active eastward-dipping subduction system involving a continuous slab. Blanco and Spakman (1993) and Spakman et al. (1993) proposed an interpretation of a completely detached slab because only low velocities were imaged above 200 km in their models. The recent tomography results, which are based on much more accurate data, weaken the basis for their detachment interpretation, at least where complete slab break-off is concerned.

2.4 Analysis: The geodynamic evolution of the Western Mediterranean

 Several detailed reconstructions of the tectonic evolution of the Western Mediterranean s.l. 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. Dercourt et al. 1986, Dewey et al. 1989, Lonergan and White 1997, Gueguen et al. 1998, Jolivet and Faccenna, 2000, Gelabert et al. 2002, Rosenbaum et al. 2002a, Frizon de Lamotte et al. 2000, Mantovani et al. 2002, Cavazza and Wezel 2002). Also attempts were made to combine tectonic reconstructions with inferences made from seismic tomography (e.g. Wortel and Spakman 1992, De Jonge et al. 1994, Carminati et al. 1998, Wortel and Spakman 2000, 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

Fig. 2.9. Cartoon displaying our interpretation of the 3-D geometry of imaged structure below the Betic-Rif-Alboran region. For more explanation see text.
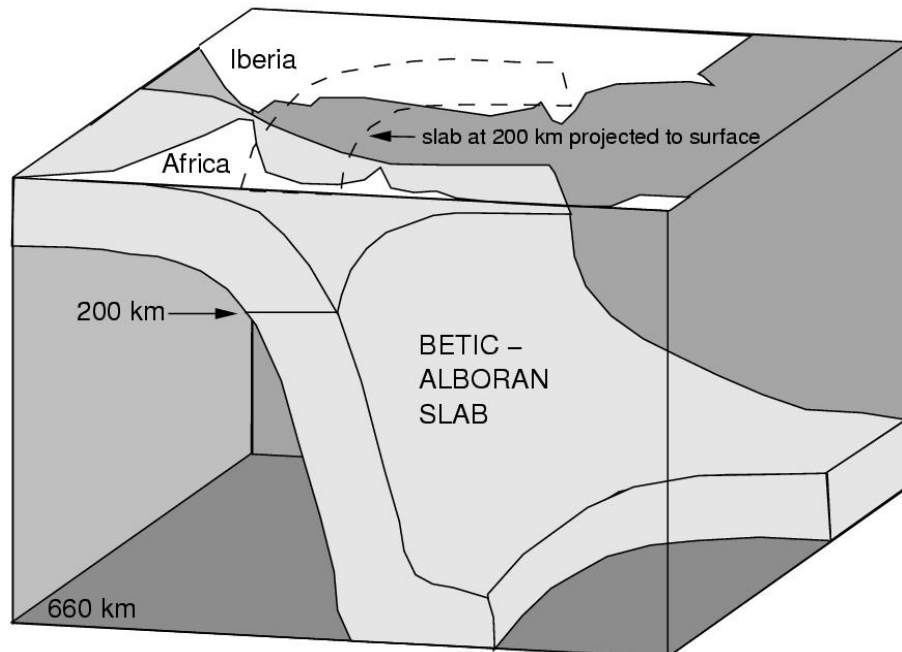
notion that slab roll-back is invoked as the most prominent process for reshaping the region in the past 25-30 Ma. Roll-back started in the northwest, along the Oligocene Iberian-margin, and progressed outward to the southwest, south, and southeast. As a result the Liguro-Provençal basin was opened in the central Western Mediterranean, the Alboran-Algerian basin in the south and, as a second phase, the Tyrrhenian basin in the southeast (see Transect III, this publication). Details of the roll-back evolution are still poorly known.

Most of the above cited kinematic and geodynamic models focus on the Cenozoic evolution. Reconstructions of the pre-Cenozoic evolution (e.g Stampfli and Borel 2002, Stampfli et al. 2002, Stampfli and Borel, this publ., Schettino and Scotese, 2002) show the origin of the oceanic areas that were involved in west Mediterranean and Alps subduction processess since the Mid-Cretaceous. Two small oceans bordered the south Iberian-European margin since the Late Triassic. To the southwest, the Ligurian ocean opened between Africa, Iberia, and Adria, as the result of a left-lateral transform motion between Iberia and Africa-Adria associated with the opening of the central Atlantic. The northern limit of the Ligurian ocean is assumed to be more or less in line with the North-Pyrenees fault system (Schettino and Scotese, 2002, Stampfli and Borel, this publ.). North-east of the Ligurian ocean, and north of the Adria block, the Alpine Tethys either already existed as the most western part of the Neo-Tethys (Schettino and Scotese, 2002), or was opened since the Late Triassic as a result of the same transform motion that caused the Ligurian ocean (Stampfli and Borel, this publ.). In both reconstructions, the Ligurian ocean connected in the north with the Alpine Tethys. Spreading in the Ligurian ocean came to a halt during the Early/Mid-Creteceous and the basin became incorporated as a passive embayment in the Iberia-Africa-Adria domain. Since the Mid-Cretaceous, this entire domain experienced a counter-clockwise rotation with respect to central Europe associated with the opening of the South Atlantic (e.g. Stampfli and Borel, this publ.). As a result of this motion the western Alpine-Tethys (Piemont/Valais ocean) was overrriden by the Adria block and perhaps also by the northern part of the Ligurian ocean. This convergence culminated in the closure of the Pyrenees-Valais basin and western/central Alps orogeny during the Eocene-Oligocene period when Adria collided with Europe.

Destruction of the western Alpine-Tethys effectively locked 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 ocean along the east Iberian margin. According to some studies initiation of this subduction system may have commenced earlier (Late Creteaceous; Schettino and Scotese, 2002, Faccenna et al. 2001a) whereas many other reconstructions assume initiation of subduction during the Tertiary. The latter timing is related to the Late Oligocene opening of the Valencia basin. 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 and Alps region will be identified as parts of the Ligurian ocean and of West Alpine-Tethys.

2.4.1 Tomographic evidence for slab roll-back

Seismic tomography has basically substantiated the presence of subducted lithosphere in the Western Mediterranean mantle and, importantly, has provided the missing evidence for slab roll-back by means of the observed flat-lying character of the Apennines-Calabria slab. 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. Griffitts et al. 1995, Becker et al. 1999) conclusively demonstrated that slab roll-back of more than a few cm/yr may cause 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.

2.4.2 Northern Apennines and Alpine -Tethys subduction

Below the Po plain and the northernmost Apennines, the southward underthrusting Eurasian plate meets with the westward dipping north-Apennines slab. The European margin may reach a depth of 200 km but is tomographically difficult to distinguish from the Adriatic plate under the Po plain. However, for the steeply dipping anomalies reaching a depth of 300 km beneath this region, close inspection of cross sections (Appendix 2) suggests the geometry of subducted/overridden Ligurian-Adriatic lithosphere which is strongly curving to the west below the Po plain and continues up to the Western Alps. In our cartoon (Figure 5) we indicate this interpretation with a question mark.

Slightly to the south-east, Lucente et al. (1999) and Lucente and Speranza (2001) propose the presence of a long (700 km) westward subducted slab below the northern Apennines (Tuscany). The Oligocene-to-present extension in the northern Liguro-Provençal basin amounts to only about 250 km (Faccenna et al. 2001a) and thus cannot explain the inferred slab length. Faccenna et al. (2001a) combine these inferences with the geological development of the north-east Iberian margin and propose that initiation of Ligurian ocean subduction dates back to about 80 Myr. The tomography results presented here

allow for different interpretations of the positive anomalies in the northern Apennines mantle. As noted in the first part of section 2.3.1, the top-400 km of the north-Apennines slab is nearly centered above the flat lying transition-zone anomaly **A** (Figure 4, 500 km depth). This peculiar geometry is well resolved (Appendix 1) and may suggest a lithosphere slab "plunging" into, and "feeding", a broad transition-zone anomaly where lithosphere material spreads in many directions. For several reasons, this interpretion is rather unrealistic. First, the rheological feasibility of such lateral flow in the transition zone is highly questionable. Secondly, the amount of subduction implied by the geometry of the slab and transition zone anomaly is much larger than 1000 km which by far exceeds the E-W extent of the northern part of the Ligurian ocean between Iberia and continental Adria in tectonic reconstructions of the past 100 Myr (e.g. Stampfi and Borel, this publ., Schettino and Scotese 2002).

An alternative explanation, which we prefer, is that the slab anomaly above the transition zone is actually unrelated to transition zone anomaly **A** described above. This interpretation allows for eastward overriding of the Ligurian-Adriatic lithosphere by only a few hundred km corresponding to a similar amount of opening of the northern Liguro-Provençal basin. We propose that anomaly **A** represents the remnant of the West Alpine-Tethys (or Piedmont ocean) and thus -as introduced earlier- results from S-dipping subduction below the Ligurian-Adria domain created by northward overriding of the Piedmont ocean by the Ligurian-Adria domain. This interpretation is consistent with the fact that anomaly **A** is partly found in the lower mantle which suggests a longer history than -for instance- the Apennines-Calabria subduction. Oligocene detachment of the West Alpine-Tethys slab under the Alps (Davis and Von Blanckenburg 1995) allowed it to sink further into the upper mantle and drape itself on the 660 km discontinuity. We note that the geometry of flat lying slabs can also result from a situation in which an oceanic basin is being actively overriden. We estimate the NS extent of Piedmont ocean to be between 500 and 600 km. Its EW extent has been a few hundred km larger. This interpretation of anomaly **A** implies that Europe has hardly moved with respect to the mantle during the second half of the Cenozoic and that flat-lying remnants of subducted slab can reside for 30 Myr or more in the upper mantle transition-zone. According to its position in the mantle, the Piedmont ocean may have existed in the region east of the Pyrenees upto and including the central Alps. We remark that remnants of subducted lithosphere with a coeval or even older subduction history have also been identified elsewhere in the mantle (e.g. Van der Hilst et al. 1997, Bijwaard et al. 1998, Van der Voo et al. 1999a,b, Hall and Spakman 2002).

In line with our interpretation of anomaly **A**, we interpret anomaly **D** (Figure 4) as the remnant of the east Alpine-Tethys of which the subduction history is quite different from the Piedmont ocean and specifically related to the evolution of the Austro-Alpine-Carpathian-Pannonian domain (e.g. Stampfli and Borel, this publ.). Last remnants of the East Alpine-Tethys were subducted during the Neogene (e.g. Wortel and Spakman 2000).

2.4.3 Slab detachment beneath the central-southern Apennines

Following our earlier propositions (Wortel and Spakman, 1992, 2000), we interpret the absence of cold (seismically fast) Adriatic lithosphere beneath the central and southern Apennines as a result of slab detachment. The lower seismic velocities imaged in the detachment zone result from inflow of hot mobile asthenosphere. Other interpretations have as common factor the subduction of the Adriatic continental lithosphere, or more specifically, the subduction of a promontory of continental lithosphere (Lucente et al. 1999, Lucente and Speranza, 2001). We see, however, no compelling reasons why such a promontory would exist or why subducted Adriatic continental/transitional lithosphere beneath the south-central Apennines should image as a slow wave-speed anomaly. In the north, continental Adriatic lithosphere images as fast at the surface and as a fast slab anomaly. Similarly, the overriden European continental lithosphere below the Alps is seismically fast.

The detachment hypothesis provides many testable predictions for surface development above the detachment zone and thus can be used as a working hypothesis to understand geological evolution (Wortel and Spakman, 1992, 2000, Davies and Von Blanckenburg 1995). These predictions concern for example vertical motions, and sedimentary depocenter formation and migration in central-southern Italy for which laterally migrating slab detachment provides a reasonable explanation (Van der Meulen et al. 1998, 2000). Furthermore, numerical modelling (Yoshioka and Wortel, 1995, Wong a Ton and Wortel, 1997) demonstrates that slab detachment and its lateral migration is a feasible process, particularly, in the late stage of subduction when continental lithosphere enters the trench. Modelling result by Van der Zedde and Wortel (2001) show that slab detachment can occur at shallow levels (e.g. Moho depth) and that inflow of hot asthenosphere and subduction wedge material can raise the geotherm considerably (creating slow seismic anomalies) to the point that the mantle and lower crust can start to melt. As noted by Wortel and Spakman (1992, 2000) and Davies and Von Blanckenburg (1995), slab detachment may cause a specific change in character of the geochemistry of volcano products from more subduction-related calc-alkaline to more alkaline (potassium enriched). Because of the geochemical complexity of volcanic rock in the region (e.g. Serri et al. 2001) interpretation is still controversial. For example, Doglioni et al. (1999) relate the high-potassium content to the subduction of Adriatic continental lithosphere (see Transect III, this publ.).

2.4.4 Calabria subduction

The detachment gap becomes smaller toward the Calabria arc. 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. Indicative for a continuous slab would be progressing slab roll back which can be expected because Ionian oceanic lithosphere is still found east of the trench. Wortel and Spakman (2000) argue on the basis of space geodetic observations of crustal motion that at present evidence for strong roll-back is absent. These observations show a distinct contrast between the speed of Aegean roll-back (about 3 cm/yr, Noomen et al. 1996, McClusky et al. 2000) and southern Apennines-Calabria-Sicily motion which more closely follows the motion of Africa (< 1 cm/yr) relative to the European plate (Noomen et al. 1996, Oldow et al. 2002). The observed small (<< 1cm/yr) eastward component of southern-Apennines motion (Oldow et al. 2002) cannot be uniquely attributed to roll back since it can also be explained by extrusion of a crustal block, as a result of continuing Africa-Europe convergence, above a detached-slab setting.

2.4.5 The north African margin

Below northern Sicily we find the free edge of the Apennines-Calabria slab. Tomography does not show subducted slab beneath the African margin except for a zone beneath east Algeria. This corresponds to the location where the Kabylies (derived from the Iberian margin) accreted around 15 Ma ago with the African margin (e.g. Frizon de Lamotte et al. 2000). Carminati et al. (1998) propose that vertical slab tearing, east of the Kabylies, initiated the last phase of slab roll-back which led to the opening of the Tyrrhenian basin. Detachment tearing of the slab along the African margin may have turned into a lithosphere (surface) tear-fault along the African margin propagating toward Sicily (Carminati et al. 1998, Wortel and Spakman 2000). Faccenna et al. (2001b) observed in tank experiments an acceleration of slab roll back after the slab starts to interact with the 660 km discontinuity. They propose that this interaction can explain the accelerated opening of the Tyrrhenian basin after an apparent stalling of the roll-back process. A combination of slab interaction with the 660 km discontinuity and slab rupture processes should be considered possible. Eastward migration of slab detachment [1] and lithosphere tearing explains why

tomography shows no north-dipping slab between east Algeria and Sicily. This development along the African margin is in line with the original suggestion made by Lonergan and White (1997): they propose that southward roll back of Ligurian ocean toward the African margin came to a halt in the middle Miocene after which plate rupture initiated below the African margin and progressed in two directions: to the east facilitating slab roll-back toward present-day Calabria (creating the Tyrrhenian basin), and to the west facilitating slab roll back toward Gibraltar (creating the Alboran-Algerian backarc basin) (Fig. 11).

Westward migrating slab-detachment below Algeria is proposed by Coulon et al. (2002) who observe a distinct change from calc-alkaline subduction-related arc volcanism (12-9 Ma) to more alkaline volcanism (4-0.8 Ma) with a distinct asthenospheric/plume contribution. Slab detachment along the entire African margin is in accord with the observation that this margin is under compression since the Pleistocene as a result of continuing Africa-Europe convergence (Frizon de Lamotte et al. 2000, Bracene and Frizon de Lamotte 2002). All of these observations are consistent with the fact that no north-dipping slab is found under the African margin (except locally below the east Algerian margin). Importantly, all geological interpretations invoke the presence of lithosphere slab below this margin at some period in the past. The subducted lithosphere, however, is now found at the base of the upper mantle and as dipping slabs at either extremity of the present Western Mediterranean.

2.4.6 Betic-Rif and Alboran region: I. Subduction and roll-back of predominantly oceanic lithosphere

In line with Gutscher et al. (2002) we prefer to explain the Betic-Alboran BS2000 anomaly by subduction of (mostly) oceanic lithosphere. The alternatives of convective removal of thickened lithosphere and of delamination of the continental lithospheric mantle 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 (which may include thinning of the continental Alboran microplate). Roll-back should have involved predominantly oceanic lithosphere because lithosphere delamination (or a convective removal mechanism) would have left at least the upper crust at the surface in the entire Alboran-Algeria basin, which is not observed. A slab retreating southward toward the African margin would provide an alternative for creating the Algerian basin. However, no north-dipping slab is observed with

---

[1] With slab detachment we mean lateral tearing of the subducted slab beneath depths of say 40-50 km along a more or less horizontal fault plane cutting the slab (see Wortel and Spakman 2000). Lithosphere tearing cuts the surface and propagates along a more vertical fault plane. The horizontal slab-detachment fault can turn into a vertical lithosphere fault and visa versa. This depends for instance on the development of the angle between the strike of the roll-back system and the local

strike of the continental margin; perpendicular strikes would favor lithosphere tearing whereas a parallel strike would favor detachment.

tomography. Instead the prime candidate to fuel regional geodynamics is found below the Betic-Rif region, which in fact implies that a northward dipping slab, creating the Algerian basin, may have eventually rolled westward.

For the sake of clarity we emphasize that, as for the Apennines subduction systems, the Betic-Alboran slab does not result from west-east convergence between plates but should be viewed as unstable lithosphere sinking *passively* into the mantle (with possible south- and westward components of retreat) and being replaced at the surface by a back-arc basin which may contain continental fragments (Alboran microplate). Delamination of continental mantle (Seber et al. 1996, Calvert et al. 2000) may start to get involved in the subduction process in its advanced stage when slab roll-back has reached the present Betic-Rif region. This depends on the distribution of oceanic and continental lithosphere in the region between Africa and Iberia. Recent paleogeographic reconstructions (Rosenbaum et al. 2002b; Stampfli and Borel, this publ; Schettino and Scotese, 2002) all suggest that, since about 150 Myr, at least a small stripe (less than 200 km) of Ligurian ocean lithosphere separated Iberia and Africa until it became involved in the Betic-Alboran subduction. Still, at present continental lithosphere may also be involved by delamination in the roll-back process.

Many arguments for slab roll-back in the Alboran region are given by Lonergan and White (1997) and will not be repeated here. We like to add the following inferences which are all in line with a model of WSW directed slab retreat and consistent with observed mantle structure. 1) The conspicuous arcuate geometry of the slab anomaly in the upper few hundred kilometers (particularly around a depth of 200 km) is quite similar to that of the retreating Calabria slab. 2) Platt et al. (2003) demonstrate that, in the Middle-Miocene, the Alboran domain was at least about 250 km to the ESE of its present position with respect to Iberia and 200 km to the ENE of its present position with respect to the African margin. They suggest that convergence of the Alboran Domain with Iberia and Africa results from lithosphere roll-back in a westerly direction (coeval with Africa - Iberia convergence in a roughly NNW direction). The WNW convergence of the Alboran domain with Iberia proves to be about perpendicular to the arcuate geometry of the slab anomaly imaged at a depth of 200 km (Figure 4). 3) Duggen et al. (2003) combine the evidence for an east-dipping Betic-Alboran slab (Gutscher et al. 2002) with the spatial-temporal evolution of calc-alkaline to alkaline volcanism in the Betic-Rif / Alboran region. They propose to explain their observations by a model of westward slab retreat which invokes lithosphere rupture along the north African and Betic-Balearic margin allowing for inflow of asthenospheric mantle in the lithosphere tear-zones. 4) From detailed marine-seismic

observations and the geology of the Balearic margin, Acosta et al. (2002) infer southeast migration of the Alboran microplate during the Late Oligocene and Miocene and opening of the Alboran-Algeria basin behind it, while in the north the Valencia basin is opening and the Balearic islands undergo clockwise rotation. Also, these authors report a transition from calc-alkaline to alkaline volcanism pointing at early slab detachment or southwestward lithosphere tearing along the Balearic margin.

Tectonic reconstructions place Betic-Alboran fragments in the Oligocene Balearic margin (e.g. Lonergan and White 1997, Rosenbaum et al. 2002A, Stampfli and Borel, this publ.) implying at least 400 km of westward transport to the present Betic-Rif system. The Early-Miocene orogenic collapse event of Platt and Vissers (1989) occurred along the Balearic margin where it evolved in a tectonic environment of WSW directed slab roll-back which was likely accommodated by SW propagating slab detachment or lithosphere tearing. Although more research needed, lithosphere tearing may cause considerable subsidence (juxtaposed to uplift at the other side of the lithosphere tear) and may allow for exhumation of mantle rock (Ronda peridotite) along the lithosphere tear (Duggen et al. 2003). These observations along the Balearic margin are consistent with the absence of a north (or south) dipping slab under this margin, and with the observed east-dipping Betic-Alboran slab found to the southwest.

2.4.7 Betic-Rif Alboran region: II. Development of arc geometry and subduction roll-back

The shape of the Betic-Alboran slab, e.g. at a depth of 200 km, correlates quite conspicuously with the asymmetry in arcuate shape between the Betic and Rif orogens - the Betic orogen being much larger than the Rif orogen - and with the spatial distribution of Neogene volcanism (e.g. Lonergan and White 1997). The reconstruction of Betic-Rif shortening by Platt et al. (2003) leads to shortening directions roughly perpendicular to the slab (as imaged at 200 km depth). These observations point at a possible relation between the shape of the slab and the (creation of) arcuate geometry of the Betic-Rif orogen. Duggen et al. (2003) propose that part of the Iberian continental lithosphere, attached to the Ligurian ocean, delaminated in the roll-back process in the Late Miocene. In this case, at least the top part of the slab (e.g. from 145 to 250-300 km) could consist of delaminated lithosphere. In map view (Figure 4), the arcuate geometry of the slab can more or less be followed with increasing depth from which we infer that it rather is a deep feature of the slab, independent of lithosphere delamination. In the following, we will relate this feature to the evolution of the roll-back process.
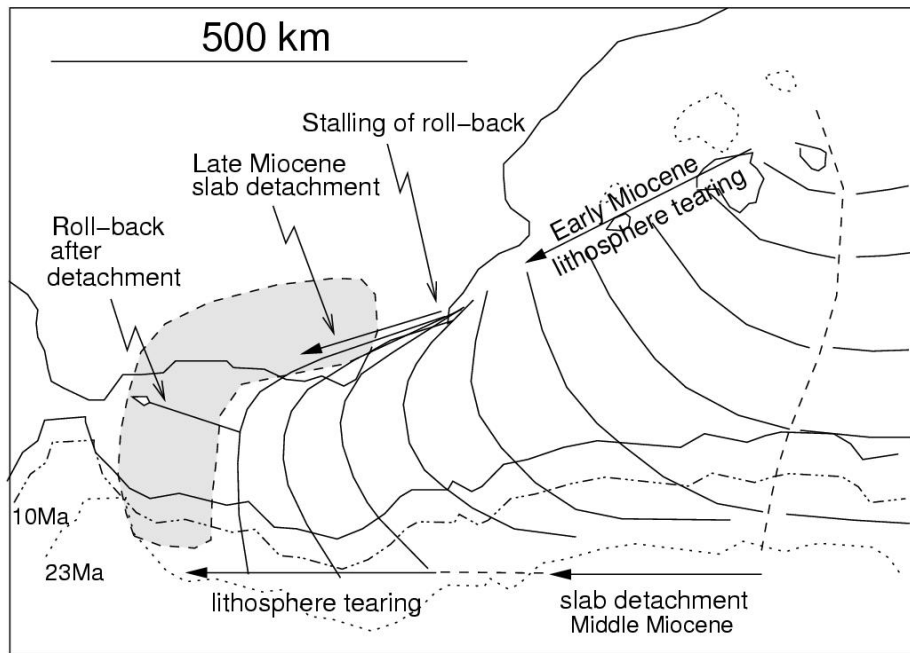
Fig. 2.10. Kinematic evolution of slab roll-back in the Betic-Rif-Alboran region. Grey shaded area gives the present location of the Betic-Alboran slab at a depth of 200 km (compare to Figure 4). The location of the African margin is denoted by dashed/dotted lines for 10 and 23 Ma ago (after Gueguen et al. 1998). The dashed line on the right indicates the outline of that part of the Ligurian ocean that rolled-back to form the Betic-Alboran slab (see Figure 11). Curved lines denote the location of the subduction trench through time, starting at the Balearic islands and ending at the time of slab detachment under the Betic (Late Miocene). Initially, south- and southwest-ward roll-back moved the trench in a roughly SW direction while slab bending progressed. Lithosphere tearing along the Balearic margin in a WSW direction occurred already in the Early Miocene and facilitated slab roll-back. During the Middle Miocene the trench reached the African margin in the south after which slab detachment initiated and migrated to the west along the African continental margin. This lithosphere rupture facilitated the westward turning of the roll-back system. When the angle between trench and margin became large enough, slab detachment evolved into lithosphere tearing along the African margin eventually leading to a margin-perpendicular trench (slab). Along the Balearic margin, lithosphere tearing came to a halt at some time during the Middle-Early Miocene perhaps as the combined effect of 1) encountering a southward-directed turn in the continental Iberian-Balearic margin, i.e. a strong narrowing of the Africa-Iberia corridor (see Bos et al. 2003 for an analogous situation in the Taiwan region), 2) and of faster slab roll-back to the south. The trench rotated and turned parallel to the Iberian margin while lithosphere tearing and faster roll-back along the African margin continued. Such a slab-bending process seems necessary to facilitate subduction to pass through the narrow corridor between Africa and Iberia and basically caused the present-day geometry of the slab as imaged at 200 km depth. When the trench became more or less parallel to the Iberian margin, Early-Miocene slab detachment allowed the slab to tear away and deflect under the Betic by which it facilitated the last phase of roll-back to the west, leading to the geometry as imaged by tomography.

Slab roll-back can transport continental fragments over large distances (e.g. Betics, Corsica-Sardinia, Kabylies, Calabria, Alboran microplate) but does not necessarily imply the building of mountain belts. Special circumstances are needed, for instance effects of continental margin geometry or continental margins entering the trench, to lead to orogenic activity. The BS2000 results show that the slab is located only slightly under the Rif margin whereas it largely underlies the Betics (e.g. at a depth of 200 km). The Rif orogen is created at the location where the African margin turns toward a NW strike (Figure 1), thus, where westward slab roll-back (accommodated by E-W lithosphere tearing) would start to involve the continental margin (and possibly lithosphere delamination). The slab's north-south extent is narrowing in the top 200 km toward Gibraltar. At 200 km depth, the slab width along strike is 400 +/- 50 km wheras Africa and Iberia have been separated by a much smaller distance. We suggest that the strong curvature of the slab at 200 km depth is the result of the narrow(ing) corridor between the African and Iberian margins. Along the African margin roll-back is more advanced toward the west, as reflected by the position of the slab under the Rif orogen compared to that below the Betic Cordillera. Lithosphere tearing has accommodated faster westward roll-back along the African margin whereas roll-back / lithosphere tearing was inhibited or stalled temporarily against the Betic margin. This leads to an evolution of trench positions as depicted qualitatively in Figure 10. In the late Miocene, detachment below the eastern Betics, possibly involving continental lithosphere, must be invoked to allow the slab to deflect to its position under the Betic region. Slab detachment under the Betics is consistent with the noted trends from calc-alkaline to alkaline volcanism and the recent uplift of Neogene basins along the Betic margin (e.g. Lonergan and White

48

1997, Duggen et al. 2003). The position of the slab under

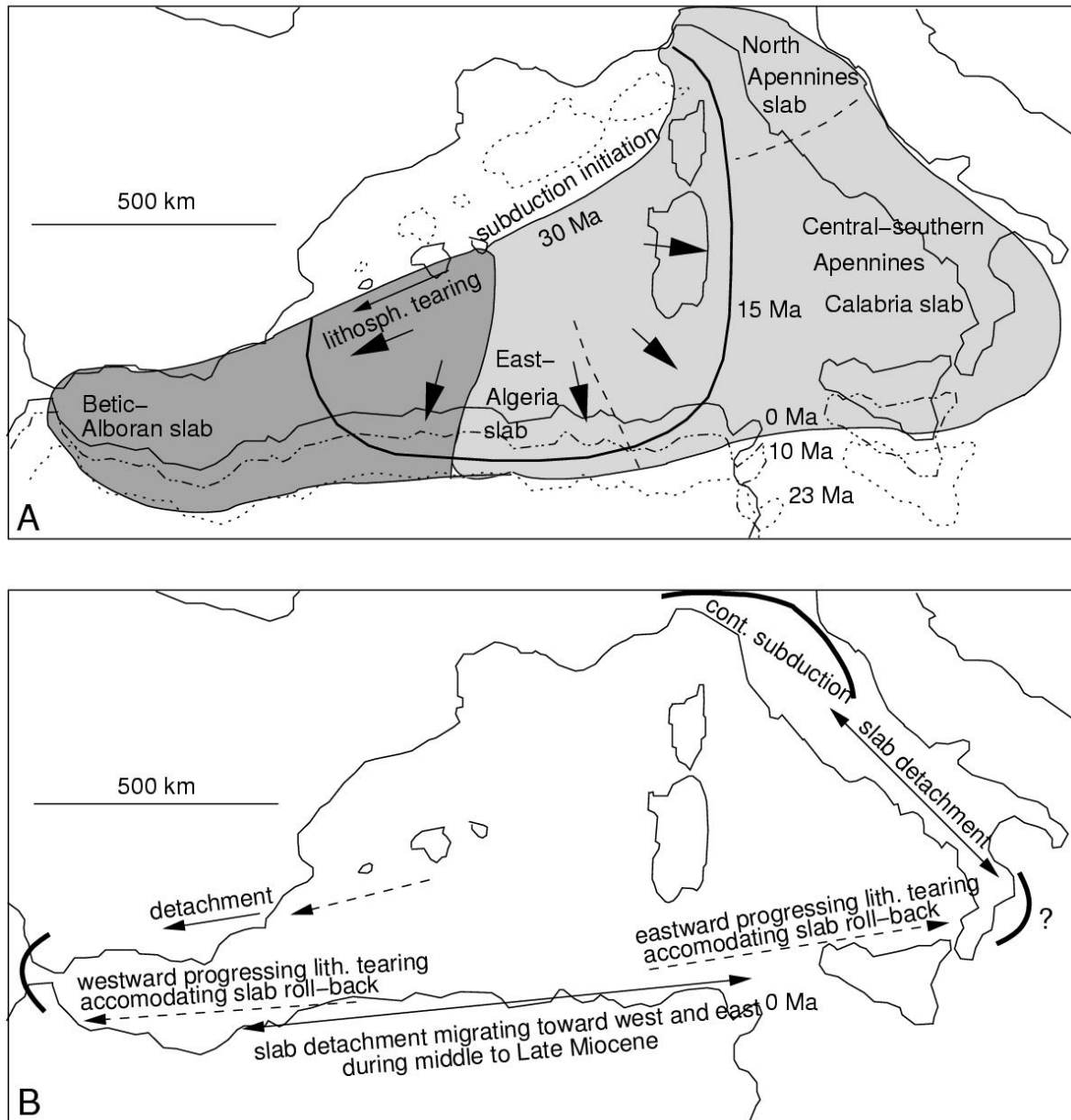Calabria subduction the corridor for slab roll-back

Fig. 2.11.   Surface reconstruction of the Ligurian ocean based on the amount and geometry of subducted slab as estimated from the BS2000 tomography model. 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 remnant of the West Alpine-Tethys (anomaly A; Figure 4) is not used for this reconstruction. 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.

the African margin is consistent with small, but continuing, NNW-directed motion of Africa.

Lastly, we remark that, 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

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 both regions.

2.4.8 Synthesis of tomographic constraints on the geodynamic evolution of the W Mediterranean region

The surface area occupied by the Ligurian ocean can be reconstructed by restoring the Betic-Alboran and Apennines slabs to their former position at the surface (Figure 11a). We 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 we 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 we estimate a slab length between 1000 and 1100 km in a NW direction. This is shorter than the estimate of 1200 km of Faccenna et al. (2001a) which is based on the tomographic model of Lucente et al. (1999). The difference is related to our interpretation of the flat lying anomaly **A** (West Alpine-Tethys) which we do not incorporate in the length estimate. With these estimates, space is left in the surface reconstruction for the east Algeria slab. The length of the northern Apennines slab we estimate to be between 300 and 400 km. Figure 11a shows the entire area of the Ligurian ocean region affected by subduction in the past 30 Myr. The three slab surfaces of the southern systems meet at the surface between the Balearic islands and Sardinia. This configuration of the Ligurian ocean is in agreement with the starting geometry of many tectonic reconstructions. We note that the transition zone anomaly **A** is not needed for this reconstruction. This also attests for its different origin independent of Ligurian ocean subduction. We also note that part of the Calabria slab may in fact consist Neo-Tethys ocean. Plate tectonic reconstructions (e.g. Stampfli and Borel, this publ., Schettino and Scotese, 2002, Rosenbaum et al. 2002) do not agree on how the Ligurian ocean was connected in the SE to the Neo-Tethys ocean which makes it difficult to distinguish between Ligurian and Neo-Tethys contributions to the Calabria slab.

In figure 11a we assume that initiation of Ligurian ocean subduction occurred along the Sardinia-Corsica segment which we consider to be the zone of greatest lithosphere weakness considering 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 counter-clockwise 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 southeastward roll-back of 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 Majorca coeval with Valencia basin extension (Gelabert et al. 1992).

In Figure 11b, we schematically indicate the consequences of slab retreat for the development of slab detachment below the north African margin developing into propagating lithosphere tearing in the west and east (as suggested earlier by Carminati et al. 1998 for the eastern segment and by Duggen et al. (2003) for the Betic-Alboran region). Beneath Gibraltar and the northern Apennines the slabs are assumed to be continuous as evidenced by continuing fore-arc deformation (Gutscher et al. 2002, Lucente and Speranza 2001, Carminati et al. 2003).

2.5 Summary

Our interpretation of Western Mediterranean mantle structure leads to a surface reconstruction of the Ligurian ocean prior to its subduction which is in good agreement with the starting configuration of many independent tectonic reconstructions of the Western Mediterranean. The Betic-Alboran and Apennines-Calabria subduction are the two governing systems in the geodynamic evolution of the Western Mediterranean during the last 30 Myr. An unknown part of the Calabria slab may derive from subducted Ionian (Neo-Tethys) lithosphere.

Large scale roll-back, as evidenced by tomography, must be invoked to explain the present location of the subducted slabs. Southward roll-back of the Ligurian ocean reached the African-Maghrebian margin, at least in its central portion (Kabylies in Algeria). Because no N-dipping slabs are imaged beneath either side of this region, slab detachment and/or lithosphere tearing along the African margin must have assisted the slabs in retreating toward their present position. This independently confirms the original suggestion by Lonergan and White (1997).

Following our earlier work (Carminati et al. 1998) we stress the important role of lithosphere rupture (i.e. slab detachment or lithosphere tearing) in the more detailed, late stage, development of slab roll-back in the Western Mediterranean. In particular, we propose that lithosphere rupture is a key element in the evolution of Betic-Alboran slab roll-back toward the present-day

Betic-Rif region and in linking slab geometry with the geometry of the Betic-Rif orogenic belt. Lithosphere delamination may also have played a role in the latest development of this region, but this process is not considered important for the overall evolution of the westernmost Mediterranean at large.

We consider the large transition zone anomaly beneath the Alps, southern France and northern Italy as the remnant of the West Alpine-Tethys (Piedmont ocean) and the transition anomaly under the E-Alps and Pannonian basin as the remnant of the east Alpine-Tethys. This interpretation implies that during the second half of the Cenozoic the European plate was relatively stationary with respect to the base of the upper mantle. Importantly, the West Alpine-Tethys anomaly is not required for the surface reconstruction of the Ligurian ocean.

We propose a relatively short (300-400 km) and continuous northern Apennines slab which may strongly curve to the west beneath the Po plain. With this interpretation we depart from our earlier suggestion of slab detachment below the northern Apennines (Wortel and Spakman 1992) but are in contrast with the long slab suggested by other researchers (e.g. Lucente et al. 1999, Piromallo and Morelli 2003). A short north-Apennines slab is sufficient to explain the opening history of the northern Liguro-Provençal basin.

The negative anomalies found to depths of 200 km under the central-southern Apennines are attributed to slab detachment, which remains in line with our earlier propositions (Wortel and Spakman 1992, 2000). The Calabria slab, although imaged up to the crust, may have recently detached. We have refined the proposition of Blanco and Spakman (1993) and Spakman et al. (1993) for complete slab detachment of the Betic-Alboran slab: a continuous slab is proposed below the Gibraltar region (Gutscher et al. 2002) and slab detachment is confined to the central-eastern Betic region and probably occurred during the Late Miocene (Duggen et al. 2003).

Acknowledgements

References

Acosta J, Munoz A, Herranz P, Palomo C, Ballesteros M, Vaquero M, Uchupi E (2002) Geodynamics of the Emile Baudot Escarpment and the Balearic Promontory, western Mediterranean, Mar Petrol Geol, 18 (3):349-369

Amato A, Alessandrini B, Cimini GB (1993)Teleseismic tomography of Italy, In: Iyer HM, Hirahara K, Seismic tomography:theory and applications, Prentice-Hall, London, pp 361-396

Amato A, Margheriti L, Azzara R, Basili A, Chiarabba C, Ciaccio MG, Cimini GB, Di Bona M, Frepoli A, Lucente FP, Nostro C, Selvaggi G (1998) Passive seismology and deep structure in central Italy, Pure Appl Geophys 151 (2-4):479-493

Becker TW, Faccenna C, O'Connell RJ, Giardini D (1999) The development of slabs in the upper mantle: Insights from numerical and laboratory experiments, J Geophys Res, 104 (B7):15207-15226

Beghein C, Resovsky JS, Trampert J , P and S tomography using normal-mode and surface waves data with a neighbourhood algorithm, Geophys J Int, 149, (3), 646-658, 2002

Bijwaard H, Spakman W (1999) Fast kinematic ray tracing of first and later arriving global seismic phases, Geophys J Int, 139:359-369

Bijwaard H, Spakman W (2000) Nonlinear global P-wave tomography by iterated linearised inversion, Geophys J Int, 141:71-82

Bijwaard H, Spakman W, Engdahl ER (1998) Closing the gap between regional and global travel time tomography, J Geophys Res, 103L:30,055-30,078

Blanco MJ, Spakman W (1993) The P-velocity structure of the mantle below the Iberian Peninsula: evidence for subducted lithosphere below southern Spain, Tectonophysics, 221:13-34

Bos AG, Spakman W, Nyst MCJ (2003) Surface deformation and tectonic setting of Taiwan inferred from a GPS velocity field, J Geophys Res, 108 (B10):art no 2458

Bracene R, de Lamotte DF (2002) The origin of intraplate deformation in the Atlas system of western and central Algeria: from Jurassic rifting to Cenozoic-Quaternary inversion, Tectonophys, 357 (1-4):207-226

Calvert A, Sandvol E, Seber D, Barazangi M, Roecker S, Mourabit T, Vidal F, Alguacil G, 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, 105:10,871-10,898

Carminati E, Doglioni C, Scrocca D (2003) Apennines subduction-related subsidence of Venice (Italy), Geophys Res Lett, 30 (13):art no 1717

Carminati E, Wortel MJR, Spakman W, Sabadini R (1998) The role of slab detachment processes in the opening of the western-central Mediterranean basins: some geological and geophysical evidence, Earth Planet Sc Lett, 160:651-665

Cavazza W, Wezel FC (2002) The Mediterranean region-a geological primer, Episodes, 26(3)

Christensen UR (1996) The influence of trench migration on slab penetration into the lower mantle, Earth Planet Sc Lett, 140 (1-4):27-39

Christensen U, (2001) Geodynamic models of deep subduction, Phys Earth Planet Inter, 127 (1-4):25-34

Cimini GB, De Gori P (1997) Upper mantle velocity structure beneath Italy from direct and secondary P-wave teleseismic tomography, Ann Di Geofisica, Vol XL:175-194

Cimini GB, De Gori P (2001) Nonlinear P-wave tomography of

subducted lithosphere beneath central-southern Apennines (Italy), Geophys Res Lett, 28 (23):4387-4390

Cizkova H, van Hunen J, van den Berg AP, Vlaar NJ, (2002) The influence of rheological weakening and yield stress on the interaction of slabs with the 670 km discontinuity, Earth Planet Sc Lett, 199 (3-4):447-457

Coulon C, Megartsi M, Fourcade S, Maury RC, Bellon H, Louni-Hacini A, Cotten J, Coutelle A, Hermitte D (2002) Post-collisional transition from calc-alkaline to alkaline volcanism during the Neogene in Oranie (Algeria): magmatic expression of a slab breakoff, Lithos, 62 (3-4):87-110

Davies JH, Von Blanckenburg F (1995) Slab breakoff - a model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens, Earth Planet Sc Lett, 129 (1-4):85-102

De Jonge MR, Wortel MJR, Spakman W (1994) Regional scale tectonic evolution and the seismic velocity structure of the lithosphere and upper mantle: the Mediterranean region, J Geophys Res, 99:12091-12108

Dercourt J, Zonenshain LP, et al. (1986) Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias, Tectonophysics, 123:241-315

Dewey JF, Helman ML, Turco E, Hutton DHW, Knott SD (1989) Kinematics of the Western Mediterranean, In: Cowar MP, Dietrich D, Park RG (Eds), Alipne Tectonics, Geol Soc Spec Publ 45 pp 421-443

Doglioni C, Harabaglia P, Merlini S, Mongelli F, Peccerillo A, Piromallo C (1999) Orogens and slabs vs. their direction of subduction, Earth Sc Rev, 45 (3-4):167-208

Duggen S, Hoernle K, van den Bogaard P, Rupke L, Morgan JP (2003) Deep roots of the Messinian salinity crisis, Nature, 422 (6932):602-606

Engdahl ER, van der Hilst R, Buland R (1998) Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, B Seismolog Soc AM, 88 (3):722-743

Faccenna C, Becker TW, Lucente FP, Jolivet L, Rossetti F (2001a) History of subduction and back-arc extension in the Central Mediterranean, Geophys J Int, (3):809-820

Faccenna C, Funiciello F, Giardini D,Lucente P (2001b) Episodic back-arc extension during restricted mantle convection in the Central Mediterranean, Earth Planet Sc Lett, (1-2):105-116

Faccenna C, Jolivet L, Piromallo C, Morelli A (2003) Subdcution and the depth of convection in the Mediterranean mantle, J Geophys Res, 108 (B2), 2099, doi:10.1029/2001JB0011690

Frizon de Lamotte D, Saint Bezar B, Bracene R (2000) The two main steps of the Atlas building and geodynamics of the Western Mediterranean, Tectonics, 19 (4):740-761

Gelabert B, Sabat F, Rodriguez-Perea A (1992) A structural outline of the serra de tramuntana of mallorca (balearic islands), Tectonophys, 203 (1-4):167-183

Gelabert B, Sabat F, Rodriguez-Perea A (2002) A new proposal for the late Cenozoic geodynamic evolution of the western Mediterranean, Terra Nova, 14 (2):93-100

Goes S, Govers R, Vacher P (2000) Shallow mantle temperatures under Europe from P and S wave tomography, J Geophys Res, 105:11153-11169

Griffiths RW, Hackney RI, Van der Hilst RD (1995) A laboratory investigation of effects of trench migration on the descent of subducted slabs, Earth Planet Sc Lett, 133 (1-2):1-17

Gueguen E, Doglioni C, Fernandez M (1998) On the post-25 Ma geodynamic evolution of the western Mediterranean, Tectonophys, 298, (1-3):259-269

Gutscher MA, Malod J, Rehault JP, Contrucci I, Klingelhoefer F, Mendes-Victor L, Spakman W (2002) Evidence for active subduction beneath Gibraltar, Geology, 30 (12):1071-1074

Jolivet L, Faccenna C (2000) Mediterranean extension and the Africa-Eurasia collision, Tectonics, 19 (6):1095-1106

Hall R, Spakman W (2002) Subducted slabs beneath the eastern Indonesia-Tonga region: insights from tomography, Earth Planet Sc Lett, 201 (2):321-336

Kennett BLN, Engdahl ER, Buland R (1995) Constraints on seismic velocities in the earth from travel-times, Geophys J Int 122 (1):108-124

Kissling E (1993) Deep-structure of the alps - what do we really know, Phys Earth Planet Inter, 79 (1-2):87-112

Kissling E, Spakman W (1996) Interpretation of tomographic images of uppermost mantle structure: Examples from the western and central Alps, J Geodynamics, 21:97-111

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

Leveque J-J, Rivera L, Wittlinger G (1993) On the use of the checkerboard test to assess the resolution of tomographic inversions, Geophys J Int 115:313-318

Lippitsch R, Kissling E, Ansorge J (2003) Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography, J Geophys Res, 108 (B8), art no 2376

Lonergan L, White N (1997) Origin of the Betic-Rif mountain belt, Tectonics, 16 (3):504-522

Lucente FP, Chiarabba C, Cimini GB, Giardini D (1999) Tomographic constraints on the geodynamic evolution of the Italian region, J Geophys Res, 104 (B9):20307-20327

Lucente FP, Speranza F (2001) Belt bending driven by lateral bending of subducting lithospheric slab: geophysical evidences from the northern Apennines (Italy), Tectonophys, 337 (1-2):53-64

Mantovani E, Albarello D, Babbucci D, Tamburelli C, Viti M (2002) Trench-Arc-BackArc Systems in the Mediterranean area: Examples of Extrusion Tectonics, In:Rosenbaum G, Lister GS (Eds), Reconstruction of the evolution of the Alpine-Himalayan orogen, J Virtual Explorer, 8, pp131-147

McClusky S, Balassanian S, Barka A, et al. (2000) Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus, J Geophys Res, 105 (B3):5695-5719

Noomen R, Springer TA, Ambrosius BAC, Herzberger K, Kuijper DC, Mets GJ, Overgaauw B, Wakker KF, Crustal deformations in the Mediterranean area computed from SLR and GPS observations, J Geodyn 21 (1):73-96

Olbertz D, Wortel MJR, and Hansen U (1997)Trench migration and subduction zone geometry, Geophys Res Lett, 24:221-224

Oldow JS, Ferranti L, Lewis DS, Campbell JK, D'Argenio B, Catalano R, Pappone G, Carmignani L, Conti P, Aiken CLV (2002) Active fragmentation of Adria, the north African promontory, central Mediterranean orogen, 30 (9):779-782

Panza GF, Mueller S, Calcagnile G (1980) The gross features of the lithosphere-asthenosphere system in Europe from seismic surface waves and body waves, Pure Appl Geophys, 118:1209-1213

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

Panza GF, Pontevivo A, Chimera G, Raykova R, Aoudia A (2002) The lithosphere-asthenosphere: Italy and

surroundings, Episodes, 26(3):169-174

Piromallo C, Morelli A (2003) P wave tomography of the mantle under the Alpine-Mediterranean area, J Geophys Res, 108 (B2):art no 2065

Platt JP, Vissers RLM, Extensional collapse of thickened continental lithosphere - a working hypothesis for the Alboran sea and Gibraltar arc, Geology, 17 (6):540-543

Platt JP, Allerton S, Kirker A, Mandeville C, Mayfield A, Platzman ES, Rimi A (2003) The ultimate arc: Differential displacement, oroclinal bending, and vertical axis rotation in the External Betic-Rif arc, Tectonics, 22 (3):art no 1017

Rosenbaum G, Lister GS, Duboz C (2002a) Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene, In: Rosenbaum G, Lister GS (Eds), Reconstruction of the evolution of the Alpine-Himalayan orogen , J Virtual Explorer, 8, pp 107-126

Rosenbaum G, Lister GS, Duboz C (2002b) Relative motions of Africa, Iberia and Europe during Alpine orogeny, Tectonophys, 359 (1-2):117-129

Royden LH (1993) Evolution of retreating subduction boundaries formed during continental collision, Tectonics, 12 (3):629-638

Schettino A, 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, Lister GS (Eds), Reconstruction of the evolution of the Alpine-Himalayan orogen , J Virtual Explorer, 8, pp 149-168

Schmid SM, Kissling E, (2000) The arc of the western Alps in the light of geophysical data on deep crustal structure, Tectonics, 19, 62-85

Seber D, Barazangi M, Tadili BA, Ramdani M, Ibenbrahim A, Sari DB (1996) Three-dimensional upper mantle structure beneath the intraplate Atlas and interplate Rif mountains of Morocco, J Geophys Res, 101, 3125-3138

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

Serri G, Innocenti F, Maretti P (2001) Magmatism from Mesozoic to Present: petrogenesis, time-space distribution and geodynamic implication, In:Vai GB, Martini IP (Eds), Anatomy of an orogen: the Apennines and adjacent basins, Kluwer Academic Publ, Dordrecht, pp 77-104

Spakman W (1986a) Subduction beneath Eurasia in connection with the Mesozoic Tethys, Geologie en Mijnbouw 65:145-153

Spakman W (1986b) The upper mantle structure in the Central European-Mediterranean region, In: Freeman R, Mueller S, Giese P (Eds), European Geotraverse (EGT) Project, the central segment, European Science Foundation, Strassbourg, pp 215-222

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

Spakman W (1991) Delay time tomography of the upper mantle below Europe, the Mediterranean, and Asia Minor, Geoph J Int, 107:309-332

Spakman W (1993) Iterative strategies for nonlinear travel-time tomography using global earthquake data, In: Iyer HM, Hirahara K, Seismic tomography: theory and applications, Prentice-Hall, London, pp 190-226

Spakman W, Bijwaard H (2001) Optimization of cell parameterization for tomographic inverse problems, Pure and Applied Geophysics, 158:1401-1423

Spakman W and G Nolet (1988) Imaging algorithms, accuracy and resolution in delay time tomography, In: Vlaar NJ, Nolet G, Wortel MJR, Cloetingh SAPL (Eds), Mathematical Geophysics: a survey of recent developments in seismology and geodynamics, Reidel, Dordrecht, pp 155-188

Spakman W, Van der Lee S, van der Hilst RD (1993) Travel-time tomography of the European-Mediterranean mantle down to 1400km, Phys Earth Planet Inter, 79:3-7

Stampfli GM, Borel GD, Marchant R, Mosar J (2002) Western Alps geological constraints on western Tethyan reconstructions, In: Rosenbaum G, Lister GS (Eds), Reconstruction of the evolution of the Alpine-Himalayan orogen, J Virtual Explorer, pp 77-106

Stampfli GM, Borel GD (2002) A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons, Earth Planet Sc Lett, 196 (1-2):17-33

Trampert J, Vacher P, Vlaar N (2001) Sensitivities of seismic velocities to temperature, pressure and composition in the lower mantle, Phys Earth Planet Int, 124 (3-4):255-267

van der Hilst R (1995) Complex morphology of subducted lithosphere in the mantle beneath the Tonga trench, Nature, 374 (6518):154-157

van der Hilst RD, Engdahl ER, Spakman W, Nolet G (1991) Tomographic imaging of subducted lithosphere below northwest Pacific island arcs, Nature, 353:37-43

van der Hilst RD, Widiyantoro S, Engdahl ER (1997) Evidence for deep mantle circulation from global tomography, Nature, 386:578-584

van der Meulen MJ, Meulenkamp JE, Wortel MJR (1998) Lateral shifts of Appennine foredeep depocentres reflecting detachment of subducted lithosphere, Earth Planet Sc Lett, 154:203-219

van der Meulen MJ, Buiter SJH, Meulenkamp JE, Wortel MJR (2000) An Early Pliocene uplift of the central Apenninic foredeep, and its geodynamic significance, Tectonics, 19:300-313

Van der Voo R, Spakman W, Bijwaard H, (1999a) Mesozoic subducted slabs under Siberia, Nature, 397:246-249

Van der Voo R, Spakman W, Bijwaard H (1999b) Tethyan subducted slabs under India, Earth Planet Sci Lett, 171:7-20

van de Zedde DMA, Wortel MJR (2001) Shallow slab detachment as a transient source of heat at mid-lithospheric depths, Tectonics, 20:868-882

Waldhauser F, Kissling E, Ansorge J, Mueller S (1998) Three-dimensional interface modelling with two-dimensional seismic data: the Alpine crust-mantle boundary, Geophys J Int 135 (1):264-278

Wong A Ton SYM, Wortel MJR, Slab detachment in continental collision zones: an analysis of controlling parameters, Geophys Res Lett, 24:2095-2098

Wortel MJR, Spakman W (1992) Structure and dynamics of subducted lithosphere in the Mediterranean region, Proc Kon Ned Akad v Wetensch, 95: 325-347

Wortel MJR, Spakman W (2000) Subduction and slab detachment in the Mediterranean-Carpathian region, Science, 290:1910-1917

Wortel MJR, Spakman W (2001) Subduction and slab detachment in the Mediterranean-Carpathian region (vol 290, pg 1910, 2000), Science, 291:437-437 (erratum)

Yoshioka S, Wortel MJR, (1995) Three-dimensional numerical modeling of detachment of subducted lithosphere, J Geophys Res, 100:20223-20244

Appendix 1:

This appendix contains seven figures summarizing the results of sensitivity tests for different synthetic models. See Section 2 and the caption of Figure 3 for general information. Inspect Figure 4 for cell dimensions as constructed for model BS2000 in the upper mantle below the Western Mediterranean. See Spakman and Nolet 1988, Spakman et al. 1993, and Leveque et al. 1993 for more information on sensitivity analysis with synthetic models.
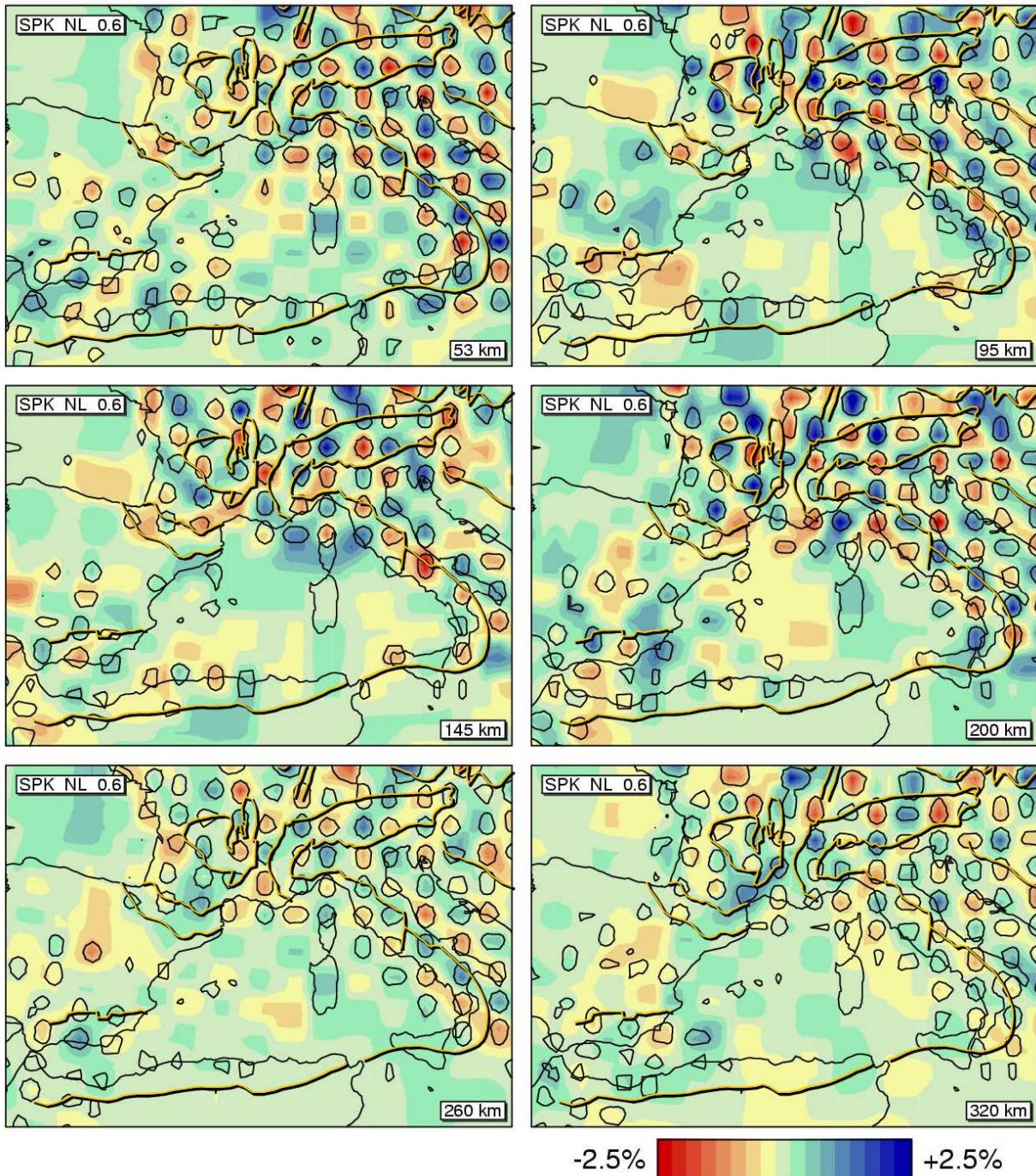

Figure 2.A1.1 Spike test for block size of 0.6 degrees and about 50 km thickness in the upper 300 km. Note that the BS2000 model does not possess these cell dimensions directly below the Western Mediterranean basins. Generally the sensitivity for "60km"-detail is good below the land areas. The amplitude response decreases with increasing depth but note that the pattern is still reasonably well recovered at 320 km although the individual blocks are below the limit of being resolved

54
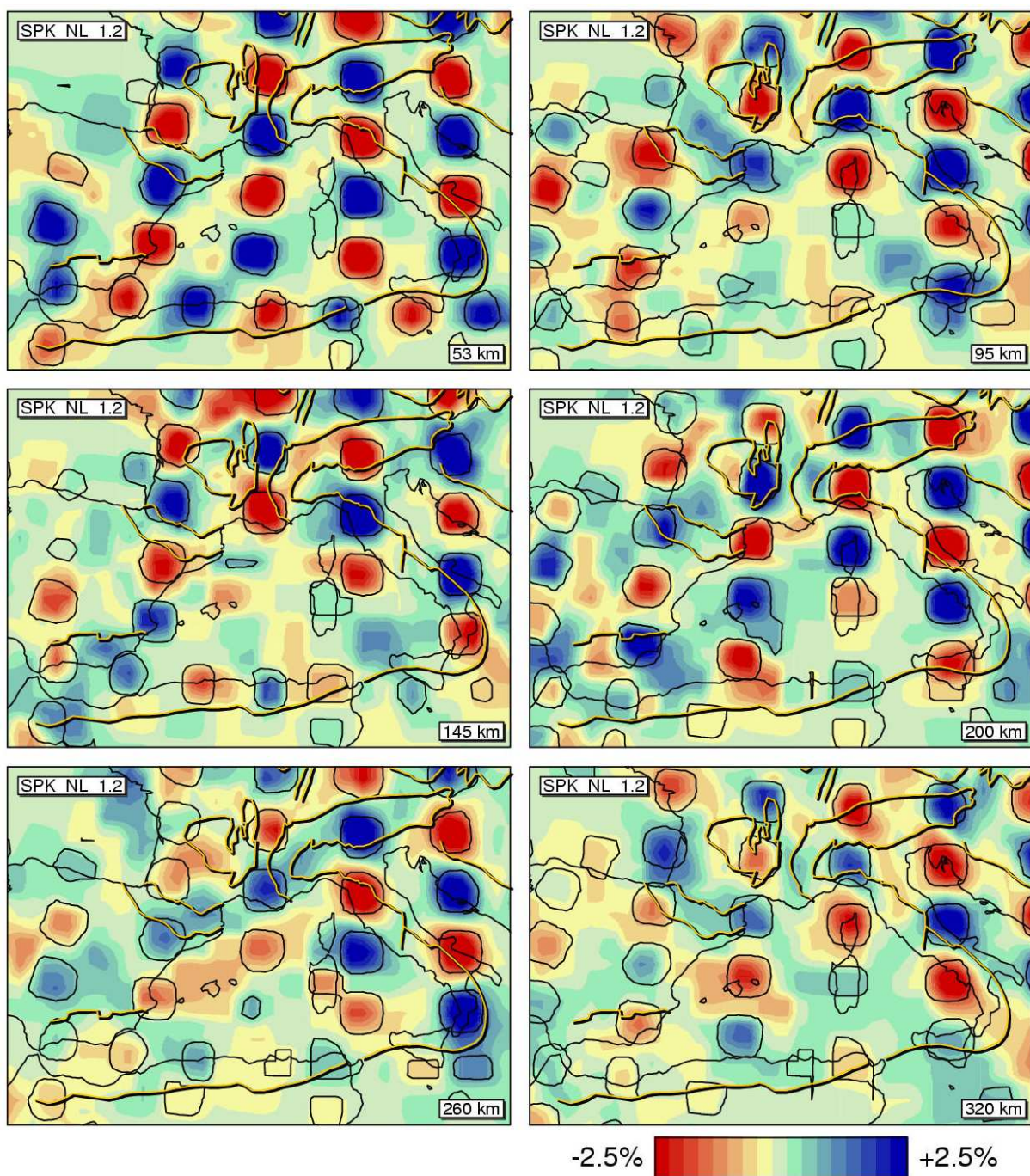
Fig. 2. A1.2   Spike test for block size of 1.2 degrees and about 50 km thickness in the upper 710 km. As for the 0.6 degree cells, the 1.2 degree cells are not constructed everywhere in the BS2000 model. Note that where 0.6 degree cells are used in the BS2000 model, we can perform a sensitivity test for 1.2 degree structure. With increasing depth, the sensitivity for 1.2 degee (50 km thick) detail decreases, although it stays good below the European land areas and the Adriatic. Below the Western Mediterranean detection of this "detail" is highly variable with position in the mantle. Specifically, this "detail" is difficult to image in the westernmost Mediterranean and under Iberia.
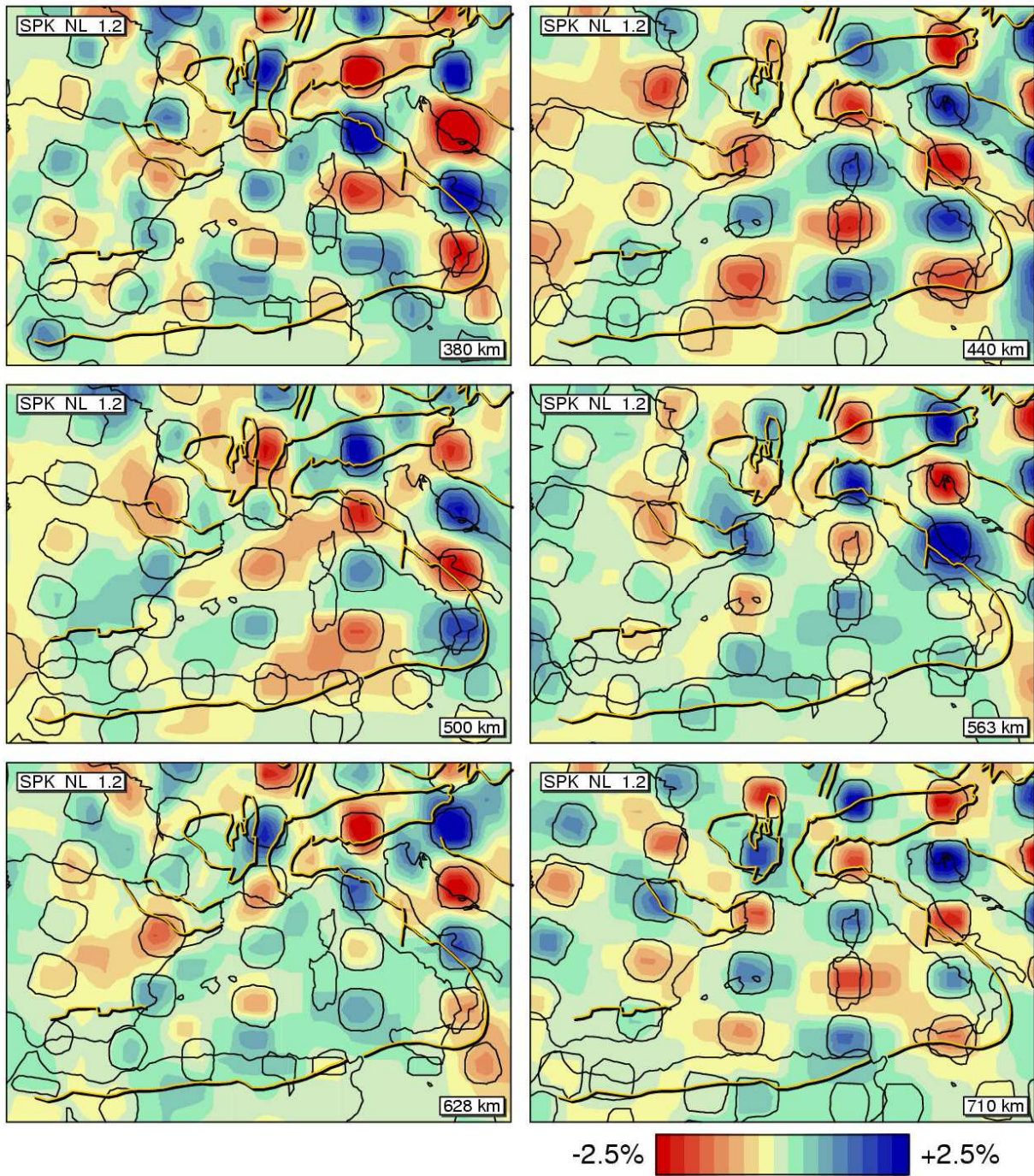
Fig. 2. A1.2 *Continued*

56
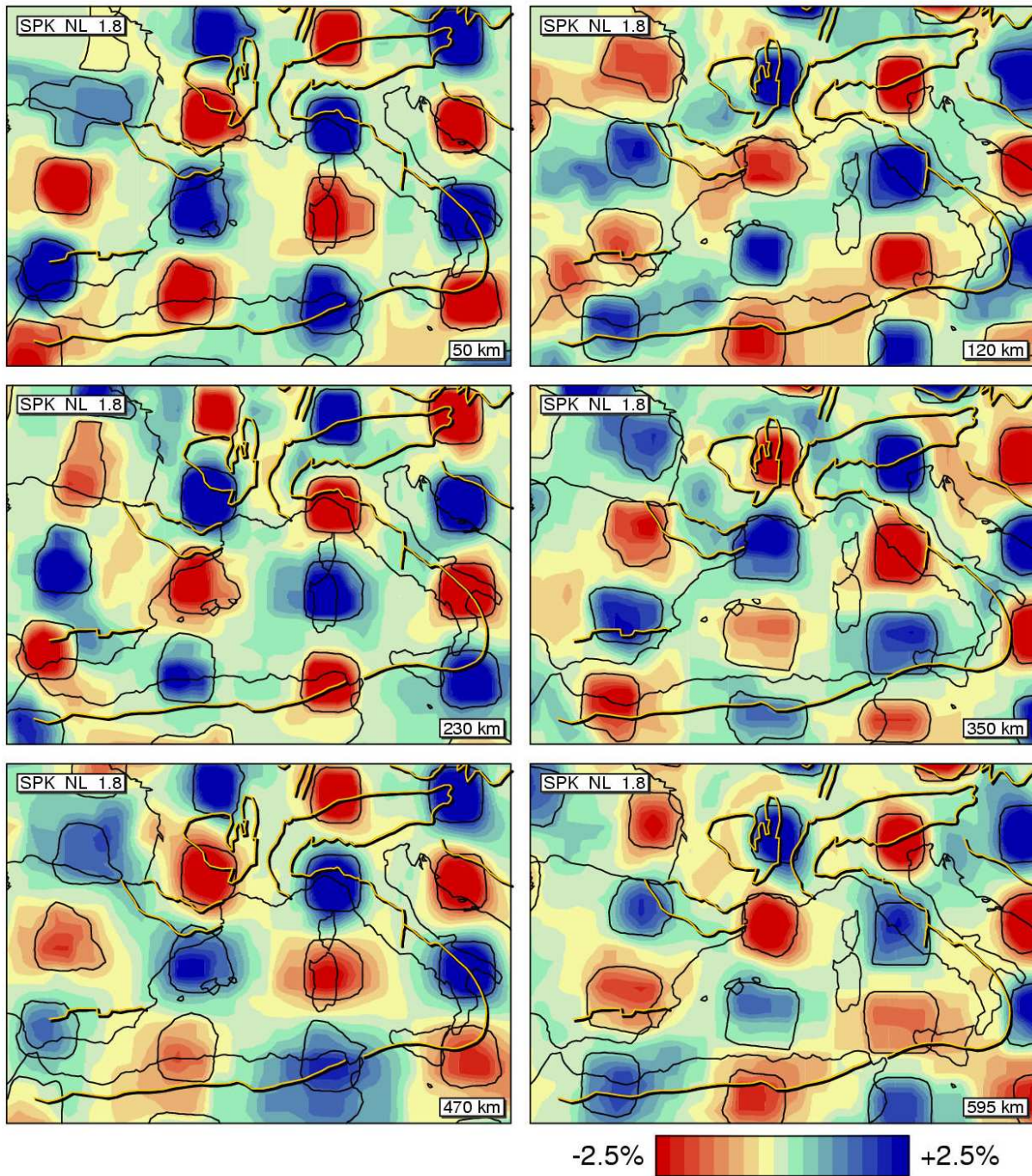
Fig 2.A1.3 Spike test for block size of 1.8 degrees and about 100 km thickness in the upper 710 km. This "detail" is very well recoverable in the synthetic test, although not perfect. But it is sufficient to interpret mantle anomalies such as the Betic-Alboran slab
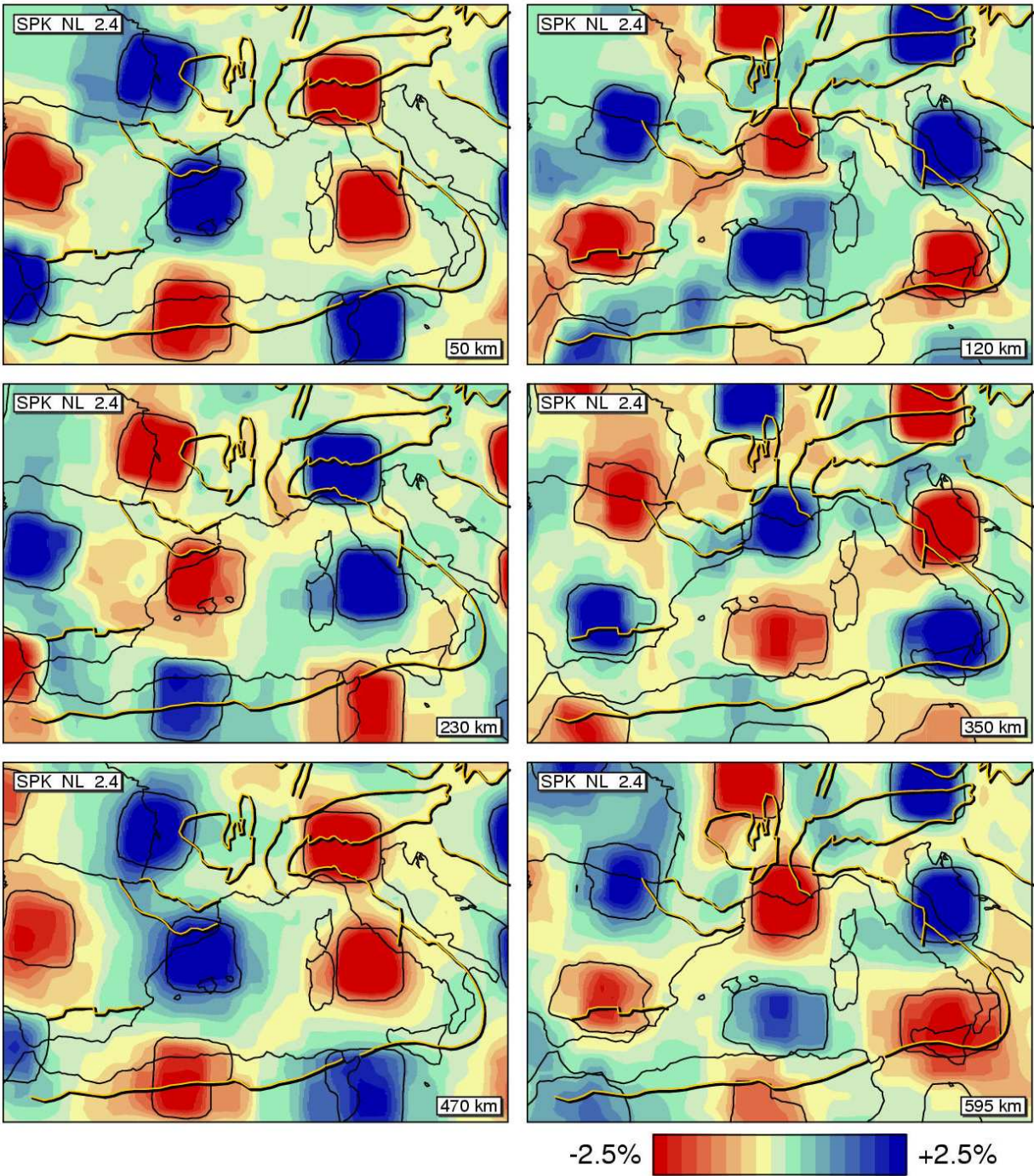
Fig. 2. A1.4 Spike test for block size of 2.4 degrees and about 120 km thickness in the upper 710 km. This "detail" is generally well recovered. Some anomaly smearing occurs, particularly, in locations where the sensitivity for smaller scale detail is reduced.
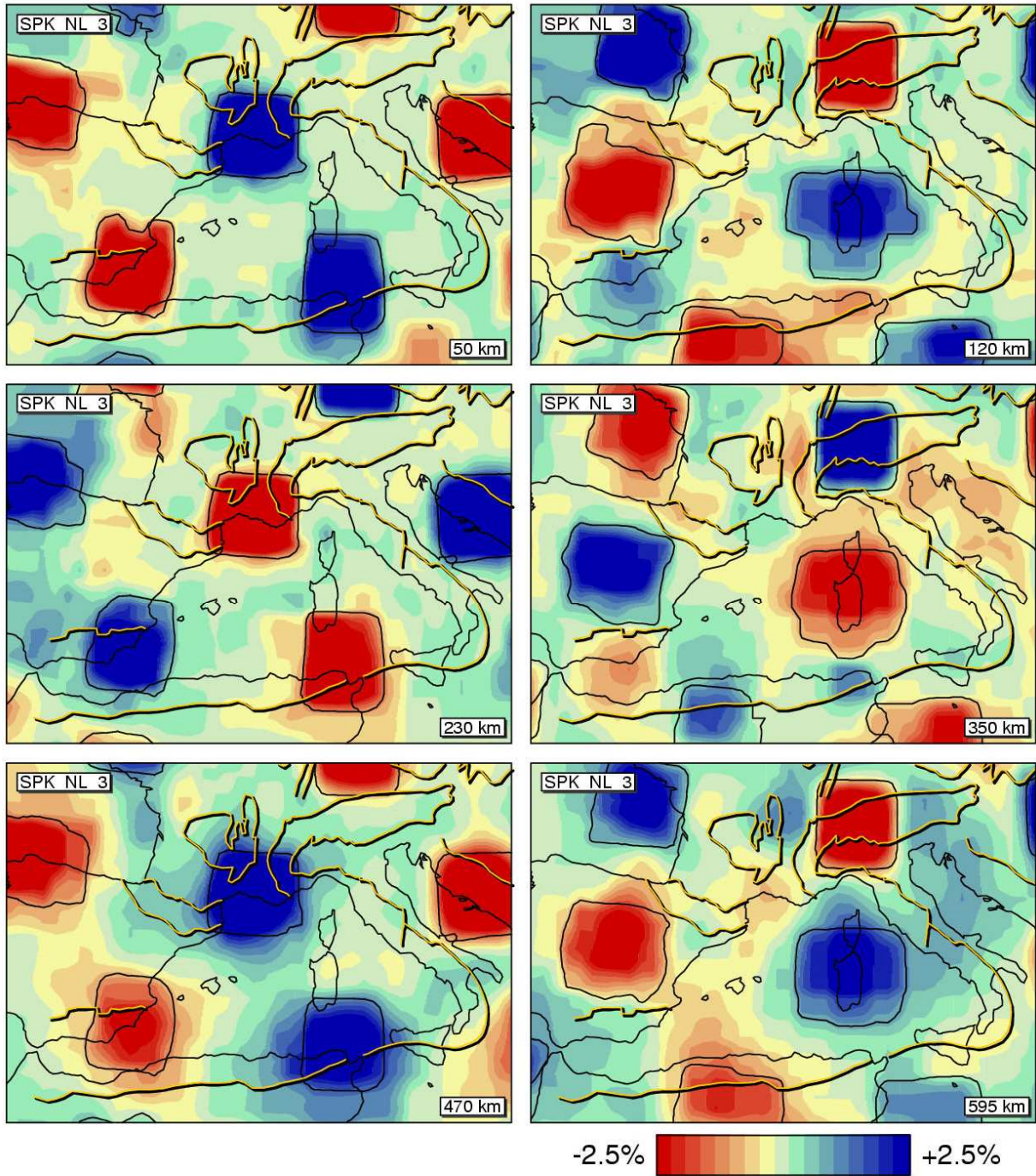
Fig. 2.A1.5 Spike test for block size of 3.0 degrees and about 120 km thickness in the upper 710 km. Similar to the 2.4-degree blocks, 3.0 degree structures are generally well recovered.
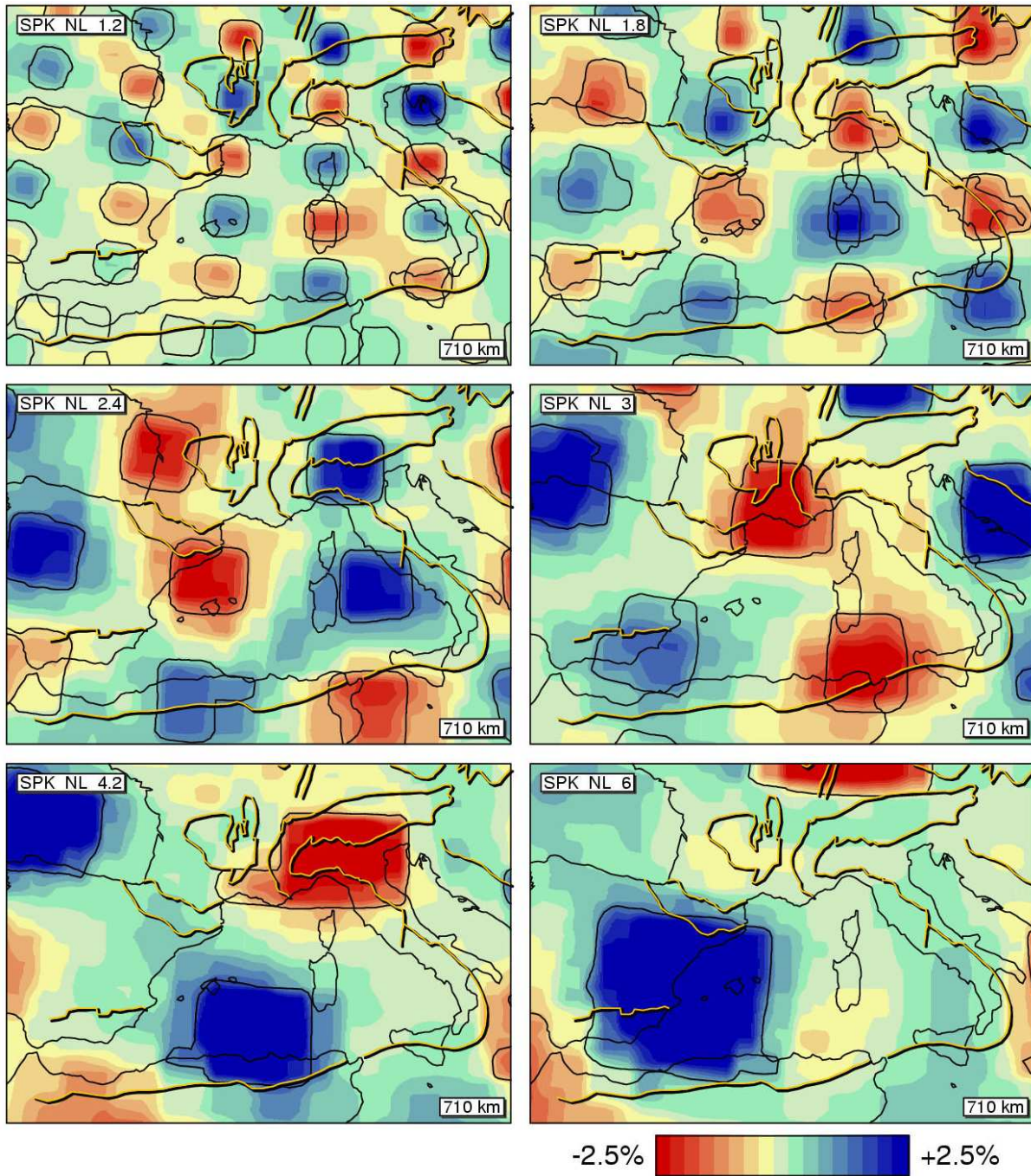
Fig. 2.A1.6 The sensitivity for different scales of detail at a depth of 710 km (uppermost lower mantle). Note that the penetration of the West Alpine-Tethys anomaly (anomaly A) is well detectable.

Appendix 2:

Three sets of upper-mantle cross sections (Figure A2.2, 2.3, and 2.4) are presented, each sweeping in detail across the BS2000 model (see Figure A2.1 for general locations). For description of the layout of cross sections see the caption of Figure 6. All cross section are plotted to scale. Small tics along the vertical axis are plotted at every 100 km of depth increase; large tic at 500 km. Along the horizontal axis small tics are placed at every 1 degree (110 km) and large tics at every 5 degrees. Above each of the cross sections a small map is plotted for geographical reference with Figure A2.1. Anomalies are labelled with the following letters: B=Betic-Alboran slab; Al=East Algeria slab; C=Calabria slab; A=West Alpine-Tethys remnant; Ad= northern Apennines subduction of oceanic-to-continental lithosphere; D=positive anomaly related to the Eastern-Alps-Dinarides-Pannonian system, interpreted as a remnant of the East Alpine-Tethys (not discussed in detail in this paper); Eu= European continental lithosphere.
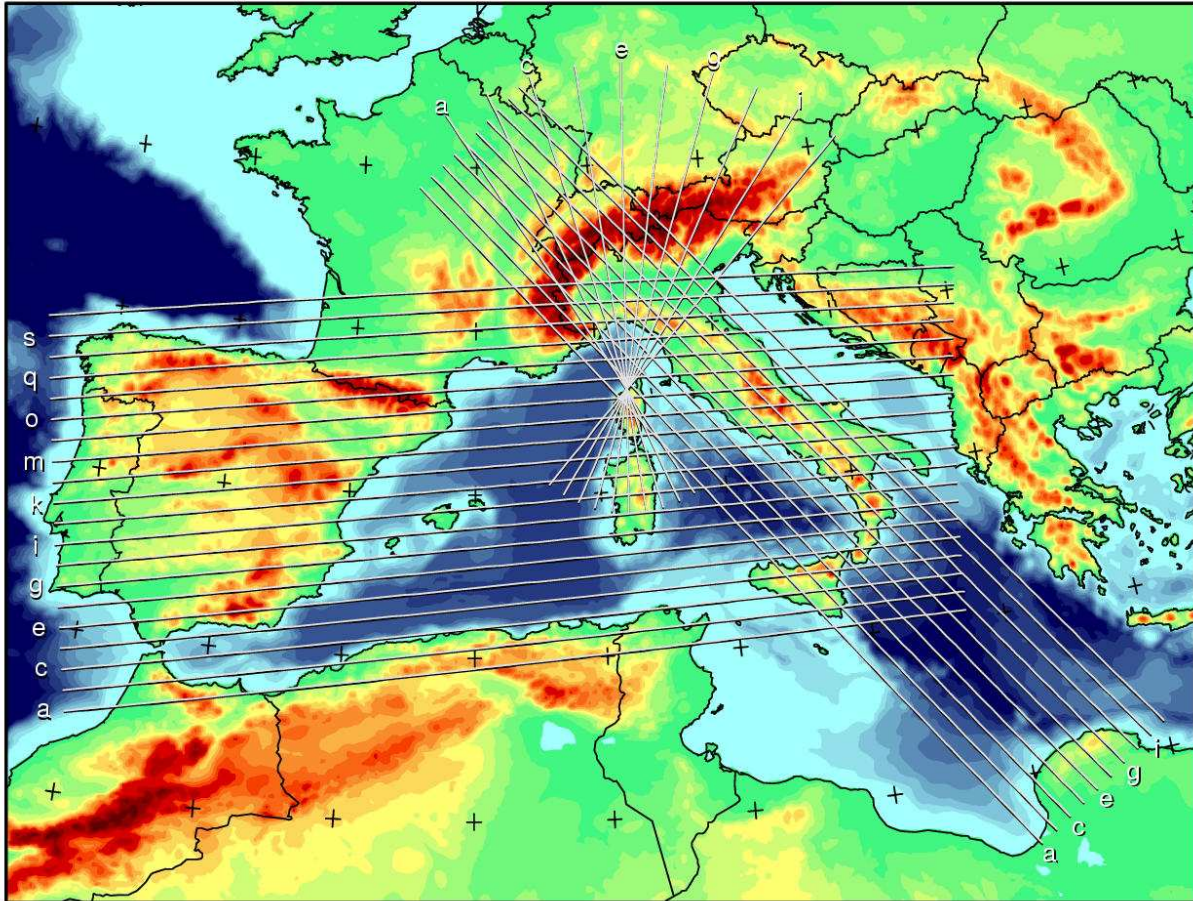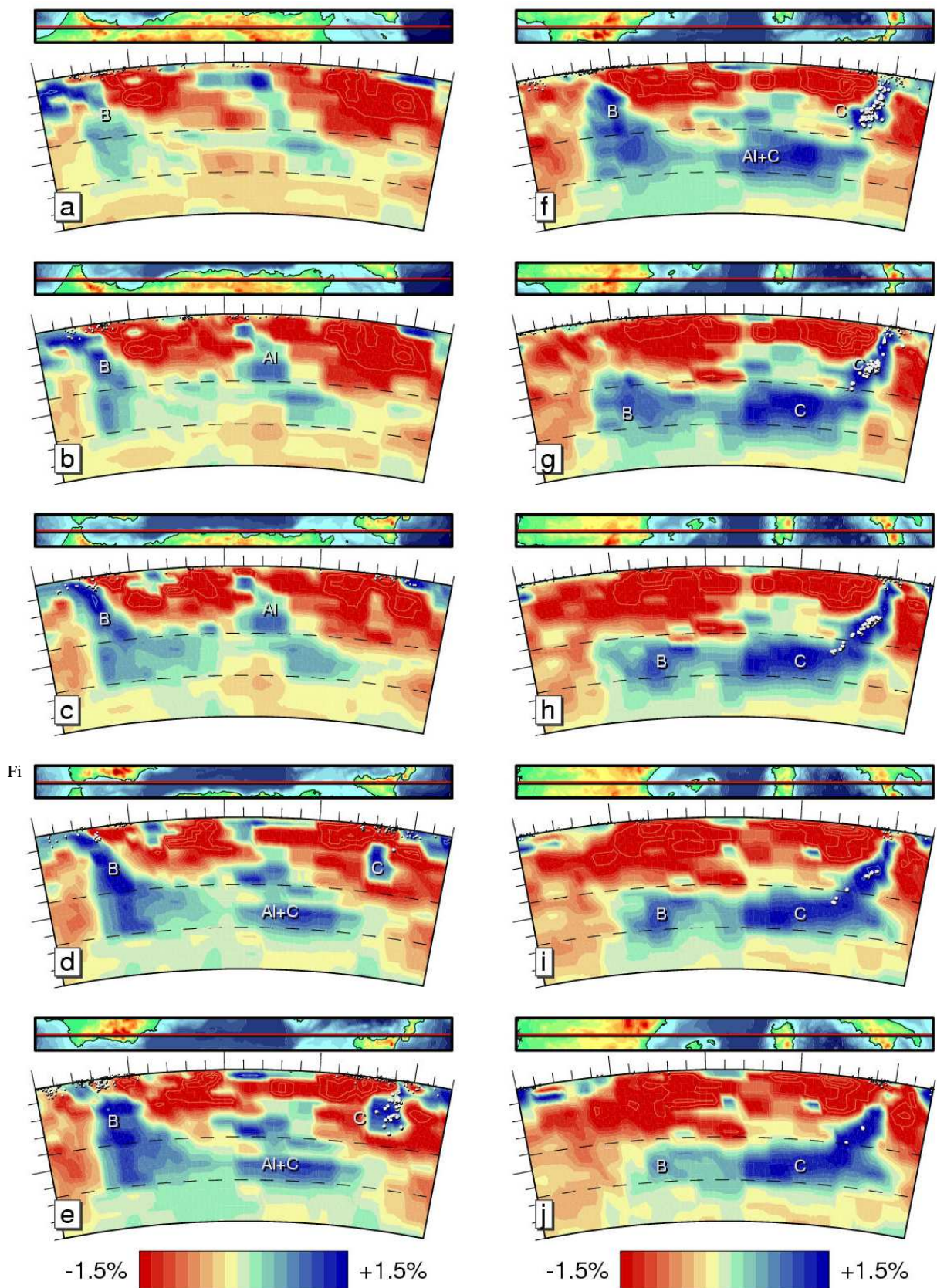
Fig 2. A2.2   A sweep of 20 West-East parallel sections across the Western Mediterranean from the African margin (a) to southern France-Alps (t). See for reference the labeling in Figure A2.1.
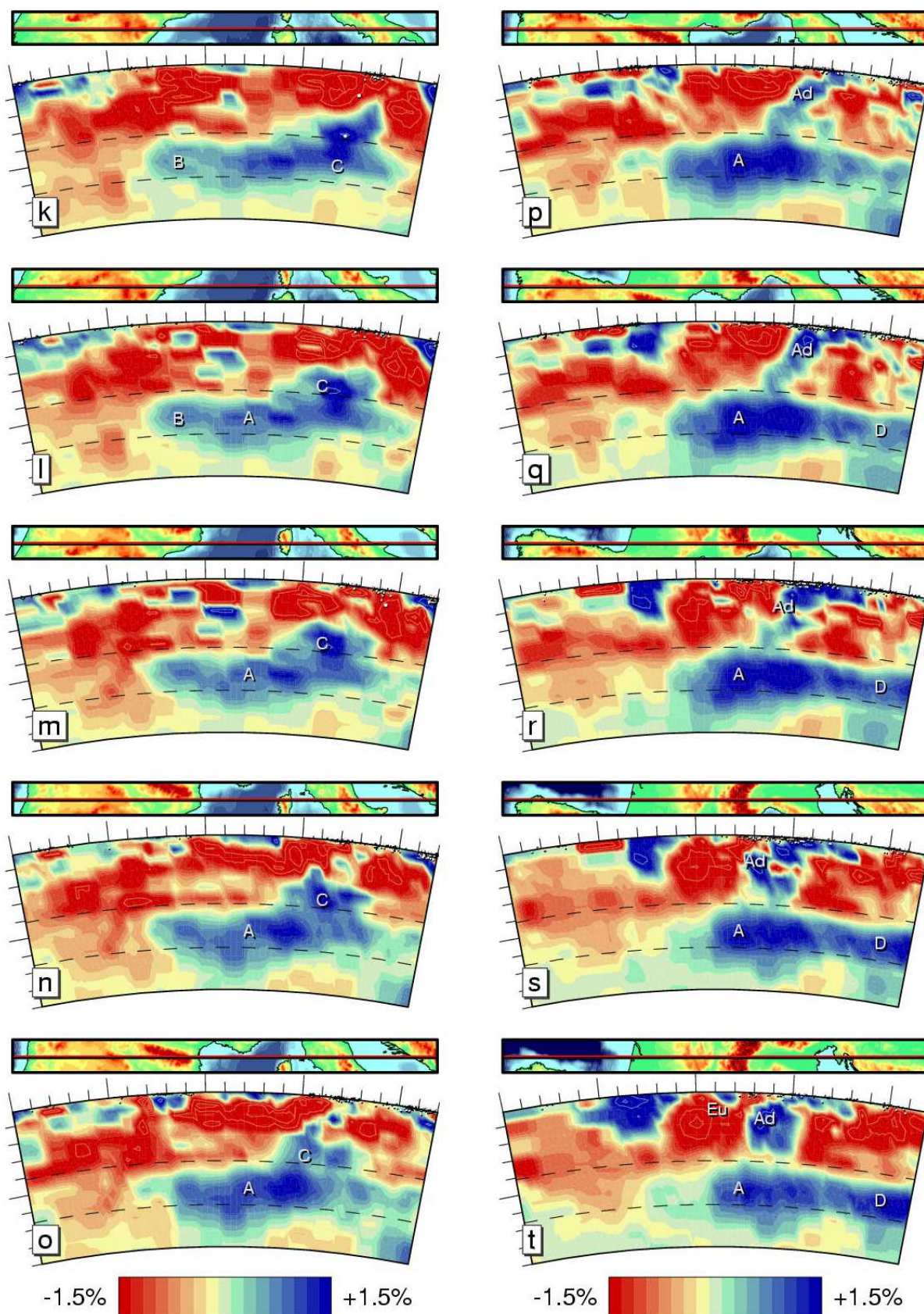
62

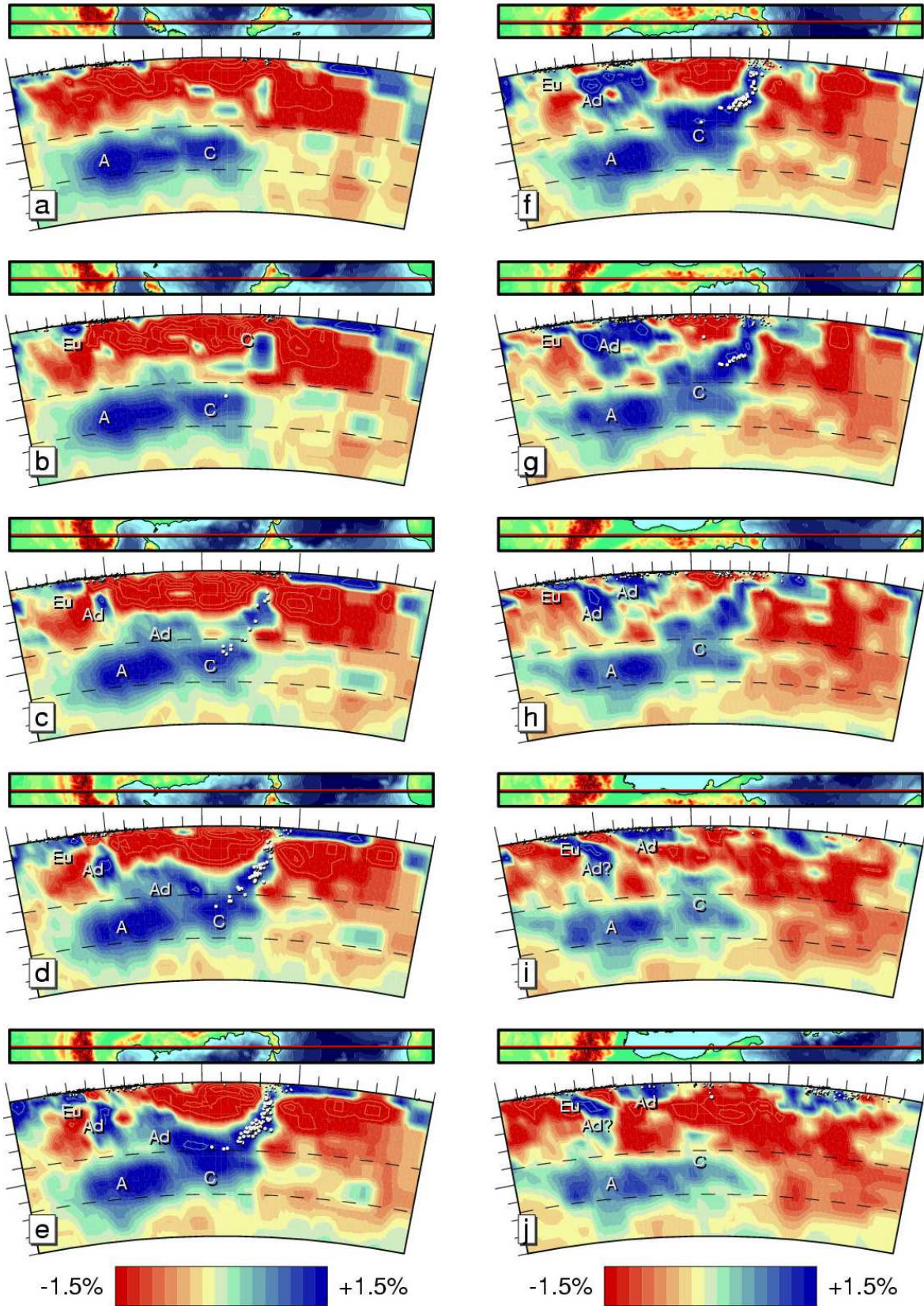-1.5%   +1.5%   -1.5%   +1.5%

Fig. 2. A2.2 *Continued*

Fig. 2. A2.3 A sweep of 10 NW-SE parallel sections across the Alps-Apennines-Tyrrhenean region. See for reference the labelling in Figure A2.1.
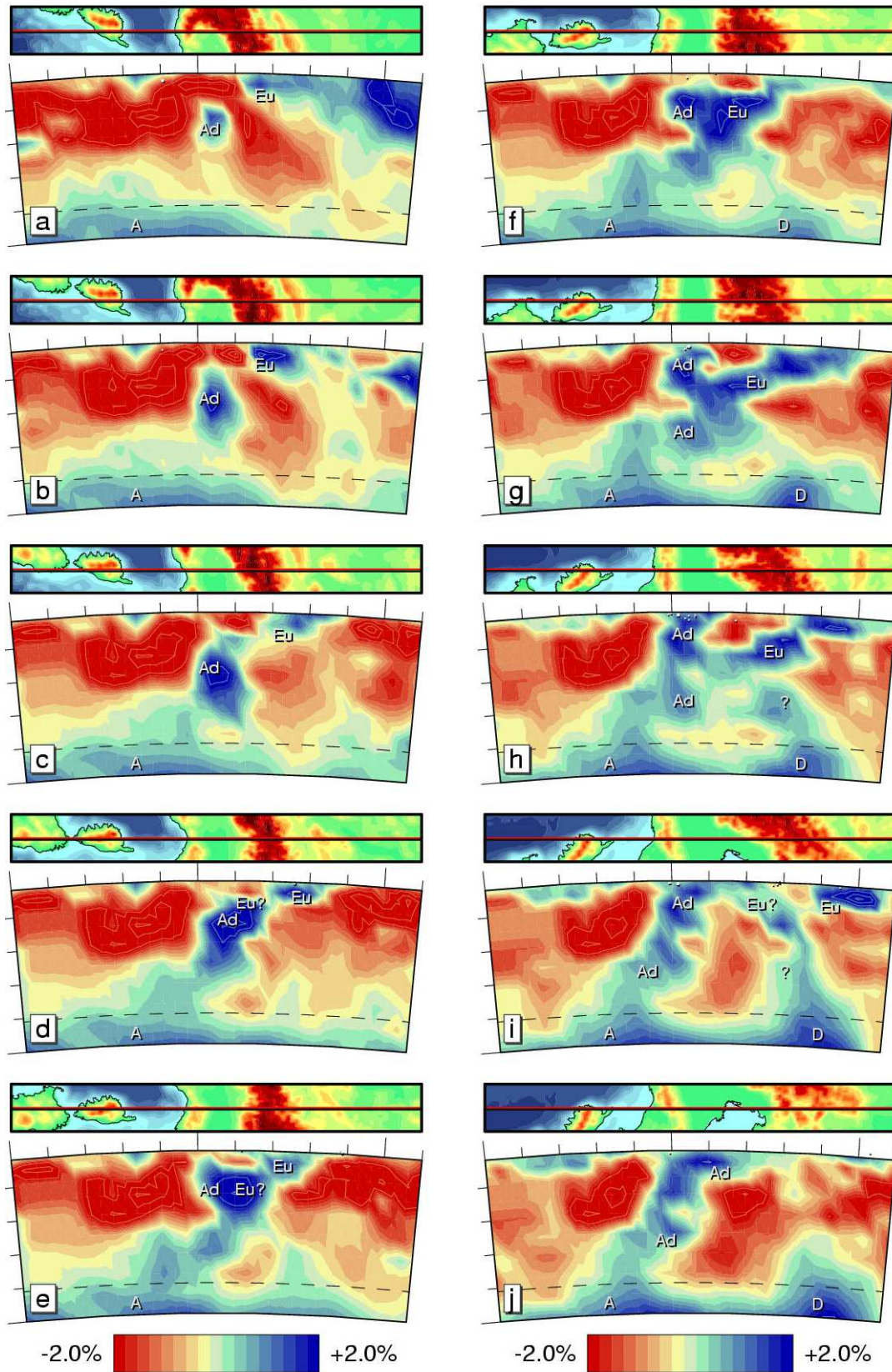
64

Fig. 2. A2.4 1 sections across the Alps, Po-plain and northernmost Apennines. See Figure A2.1 for labeling