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THE CRUST-MANTLE BOUNDARY IN THE LIGURIAN AREA: GEOLOGICAL AND GEODYNAMIC IMPLICATIONS

Abstract. The configuration of the crust-mantle boundary in the transition zone between the Western Alps and the Northern Apennines is examinated. Some recent Moho contour maps are discussed from a geological standpoint, and their paleogeographic and geodynamic implications are considered. It is assumed that three principal Moho surfaces exist in the examined area. Most authors agree that two of them (the European and Adriatic Mohos) belong to the pre-collisional Europe and Adria continental plates, while the appurtenance of the third ("Ligurian-Tuscan" Moho) is debated. On the basis of various arguments, the present work suggests that the Ligurian-Tuscan Moho should be considered as forming part of the Adria Moho. The deepest surface is the Europe Moho, which generally dips to the E under the Ligurian-Tuscan Moho. The Adria Moho (locally called Po Plain-Adriatic Moho) dips to the W or to the SW under the Ligurian-Tuscan Moho, which is the shallowest crust-mantle boundary. The overlap of the Ligurian-Tuscan Moho on the Adriatic one is considered to be a major intracontinental embrication, which is connected chronologically and dynamically to the Oligo-Miocene opening of the Ligurian-Balearic basin (in turn linked to the counterclockwise rotation of the Corso-Sardinian block) and to the subsequent Mio-Pliocene opening of the Tyrrhenian basin. The opening process has been accompanied either by crustal attenuation or by the creation of a new, oceanic type crust, hence generating new Moho surfaces (Ligurian-Balearic and Tyrrhenian) which replace the older ones (European and Adrian, respectively). Two SW-trending crustal sections of the Maritime Alps and Corsica-Tuscany regions illustrate the two alternative geodynamic models that may explain the structural evolution of the area.

INTRODUCTION

The transition zone between the Alps and the Apennines in Liguria is tectonically very complex. Moreover its outcrops are very limited because, to the north, they are buried beneath the Po Plain deposits, while to the south they disappear beneath the Ligurian Sea.

This complexity also involves the crust-mantle boundary surface which seems rather fragmented, as the latest Moho contour maps show. The most remarkable features of the Moho in the Maritime Alps-Corsica-Northern Apennines area are a) the presence of different Moho fragments with, in some cases, partially overlapping edges; and b) the post-collisional modifications of the Alpine setting caused by asthenosphere upliftings connected to the opening of the Ligurian-Balearic and Tyrrhenian basins. Owing to the above, problems arise in restoring the original connections between the different Moho surfaces and in ascribing them to the Europe or Adria plates.

The complex overlap of different Moho fragments implies important mantle involvement in the orogenetic process. Therefore the geodynamic study of the transition zone between the Western Alps and the Northern Apennines requires an examination of the deep structures. For this reason the most recent reconstructions of the Moho structure will be briefly reviewed; apart from geophysical data, only the relevant geological implications will be considered. Moreover, some regional geological aspects that condition the geophysical interpretation will be discussed

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in the light of some recent geodynamic models.

GEOLOGICAL SETTING

The area shown in Fig. 1 focuses on the link between the Western Alps and the Northern Apennines, i.e., between two chains whose main structuration is assumed to have been accomplished a) at different times (Cretaceous-Eocene and Miocene-Present, respectively) and b) with opposite directions of tectonic transport. In fact, closer inspection shows that the present structural setting is the result of several tectonic events distributed over a time span covering the Cretaceous-Present interval.

The building of the Western Alpine chain began in the Cretaceous period with an eastward-dipping subduction process, which progressively consumed the Piemont-Ligurian oceanic basin and finally led, during Late Eocene times, to the Europe-Adria continental collision. As a consequence, structural vergences and nappe translation were directed towards the outer sectors, which in the area of Fig. 1 are represented by the Dauphinois-Provençal foreland.

In the Maritime Alps, surface geology only shows that the Alpine deformation involved rock sequences from the European continental margin and Piemont-Ligurian ocean. But it is probable that the Adria western edge - now buried at some depth - was also deformed, exactly as occurred in the more northern sector, where the Sesia-Lanzo Zone crops out. By the end of Eocene times, this complex nappe system was to a greater or lesser extent backthrust, because of the identation of Adria into the European continent (Vanossi et al., 1986).

During Oligo-Miocene times, this pattern was modified by crustal deformations leading to the opening of the Balearic-Ligurian basin and to the related counterclockwise rotation of the Corsica-Sardinia block. In particular, the Pennidic domain - formerly running in a southwestern direction from the Alps to Corsica - was rotated and shifted eastward to its present N-S trend.

Since very Early Miocene times, the Corsica-Sardinia rotational process has produced NE-verging structures on both oceanic (Ligurian) units and the underlying Adria continental margin ones (Tuscan units).

Subsequent (Late Miocene to Present) Northern Apennines history seems complicated by the co-existence of two, possibly independent, and not strictly contemporaneous, processes: 1) an isostatic re-adjustment of the chain, which produces - on both sides - gravity-driven structures moving along intra-crustal detachment surfaces (Carmignani and Kliegfield, 1990); and 2) the opening of the Tyrrhenian basin, again by means of a sinistral rotation; this induces further compressional structures at the Apenninic front and, at the same time, extensional basins in the rear, on the Tyrrhenian side, which overprint and disrupt older, nearly homoaxial belts.

The sinistral rotations related to the opening of the Balearic-Ligurian and Tyrrhenian basins and giving rise to the Northern Apennines orogenesis also affect the Maritime Alps sector E of the NW-directed Sanremo-Cuneo belt (Vanossi et al., 1993).

Thus, it appears that a wide area comprising part of the European margin (namely the Maritime Alps, Corsica and Sardinia), Piemont-Ligurian oceanic units and Adria elements, having already been deformed by Alpine events, is again involved in deformational processes during the N-Apennines orogenesis. On land, the present eastern and western surface boundaries of this peculiar link zone, characterized by the overprinting of "Apenninic" structures on older "Alpine" ones, may be located respectively along the Villalvernia-Varzi and Ottone-Levanto lines (Elter and Pertusati, 1973) and the Sanremo-Cuneo belt.

CONFIGURATION OF THE CRUST-MANTLE BOUNDARY

The above framework, mainly inferred from surface geology, necessarily involves the whole crust and upper mantle; it therefore becomes important to check if the present attitude and location of the Moho discontinuity are consistent with this framework.

Research on the depth and geometry of the crust-mantle boundary in the Liguria region

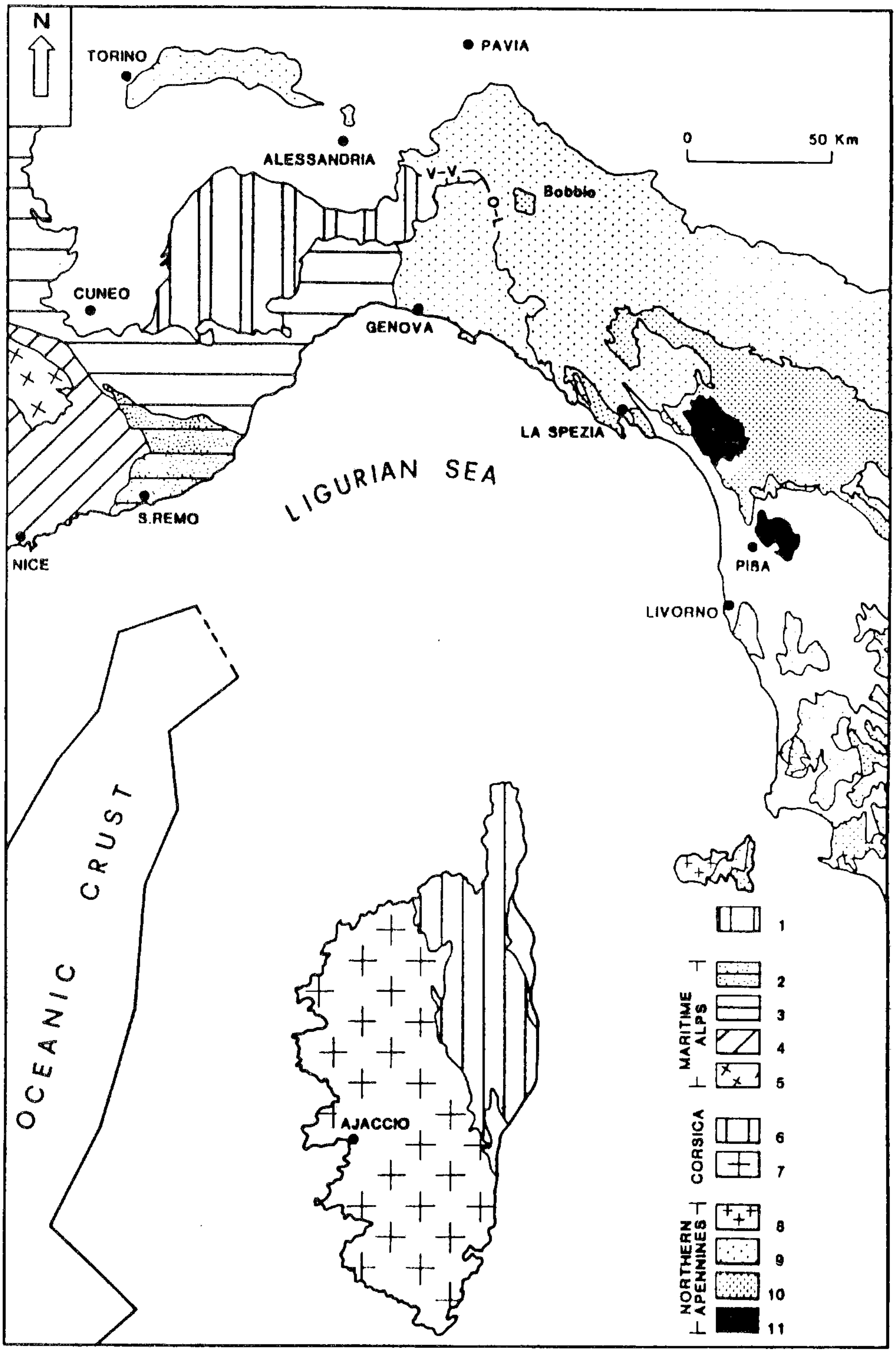

Fig. 1 - Tectonic sketch map of the Maritime Alps-Northern Apennines-Corsica area (simplified from Consiglio Nazionale delle Ricerche, 1990). 1) Ligurian-Piemont Tertiary Basin; 2) Helminthoid Flysch zone; 3) Penninic domain of Western and Maritime Alps; 4) Dauphinois-Provençal zone; 5) Argentera massif; 6) Alpine Corsica; 7) Pre-Alpine Corsica; 8) Tertiary plutonic body; 9) Ligurian and Sub-Ligurian Units; 10) Tuscan Units; 11) Tuscan metamorphic Units. Blank: principal Pliocene-Quaternary outcrops. V-V: Villalvernia-Varzi Line; O-L: Ottone-Levanto Line. Boundary of the oceanic crust in the Ligurian Sea from Burrus (1984).

and surrounding areas (Western Alps and Northern Apennines) has been greatly enhanced by the European Geotraverse Project (EGT) carried out in recent years (1983-1990). Numerous contour maps of the Moho discontinuity have been published, providing a variety of data and interpretations.

Some maps distinguish different Moho surfaces according to their paleogeographic appurtenance and the nature of their respective crusts (oceanic; continental, normal or thinned); these maps also show the local overlaps. Other maps indicate only the shallowest Moho surface without any specification.

The following review cannot be considered complete and exhaustive. Only a few of the most significant proposed interpretations are examined, and solely the geological implications of these have been considered, in the light of current knowledge about the region and the most accredited geodynamic models.

To make the comparisons clearer, the different types of Moho are named after their surface region (Po Plain, Ligurian, Tuscan Moho etc.).

In particular, "Ligurian Moho" refers to the continental crust-mantle boundary under the greater part of the Liguria region (i.e. under the Ligurian Alps and the north-western edge of the Apennines), the westernmost sector of the Po Plain and the north-eastern sector of the Ligurian Sea.

This definition does not apply to the western part of the Ligurian Sea, where the boundary is between mantle and oceanic crust: here the Moho has been called "Balearic-Ligurian Moho". Moreover it should be remembered that a) "European Moho" refers to the continental crust-mantle boundary in the pre-collisional European continental plate; and b) "Po Plain-Adriatic Moho" (or, simply, "Adriatic Moho") indicates the crust-mantle limit under most of the Po Plain area as well as under the Emilia-Romagna, Marche and Adriatic Sea regions; this Moho represents the crust-mantle boundary in the pre-collisional Adria continental plate.

From Mostaanpour's (1984) map (Fig. 2a) the existence of a deeper European Moho dipping under the Adriatic Moho may be inferred. In the Western Alps and in the zone between Corsica and Tuscany, the first dips to the E; in the Ligurian Alps and in the Ligurian Sea it undergoes a pronounced torsion and displays an overall northern dip. It is uplifted to a depth of 15 km under the Ligurian sphenocasm, while under the Tuscan Apennines and the Western Alps it reaches a depth of 50 km. The Po Plain-Adriatic Moho has a minimum depth of 20 km (in the north-eastern sector of the Ligurian Sea) and deepens to 36 km (under the Po Plain). In eastern Liguria and in the Northern Apennines it dips to the NE, while in the Ligurian and Western Alps it bends and dips to the E and SE. It is uplifted in Tuscany, in Latium and in the Tyrrhenian Sea.

From Giese's (1985) map (Fig. 2b), threee types of Moho can be identified: European, Ligurian-Tuscan and Po Plain-Adriatic. The European Moho is the deepest, and in the Western Alps it dips under the others to the E, to a depth of from about 30 to 60 km; in the Ligurian Alps it undergoes a torsion and dips to the N. Under the crustal thinning of the Ligurian sphenocasm it is considerably uplifted. The Ligurian-Tuscan Moho is the shallowest; it dips NE to a depth of 20 to 35 km. Under the Western Alps it bends to the E. The Po Plain-Adriatic Moho is little represented: under the central-western Alps it dips NNW to a depth of 45 to 65 km. Under the Po Plain and in the Northern Apennines it dips WNW under the Ligurian-Tuscan Moho.

Nadir (1988) distinguishes (Fig. 2c) between a European, Po Plain-Adriatic and Ligurian Moho. The European Moho is the deepest and dips under the Po Plain-Adriatic Moho and the Ligurian Moho. In the Western Alps it dips to the E, but in the Ligurian Alps it undergoes a torsion and dips to the N. It is 40 to 55 km deep. The Ligurian Moho is the shallowest and overlaps the European and Po Plain Mohos. In Liguria it dips N to a depth of 20 to 30 km. Near the Western Alps it bends and dips to the E. In general, the Po Plain-Adriatic Moho dips to the S under the Ligurian Moho and is about 35-45 km deep. In the Western Alps it bends to the E, overlapping the European Moho. Buness (1992) identifies (Fig. 2e) a European Moho and a Po Plain-Adriatic Moho which is considerably fragmented. In the Western Alps the European Moho is the deepest (33-55 km) and dips to the E under the Po Plain-Adriatic

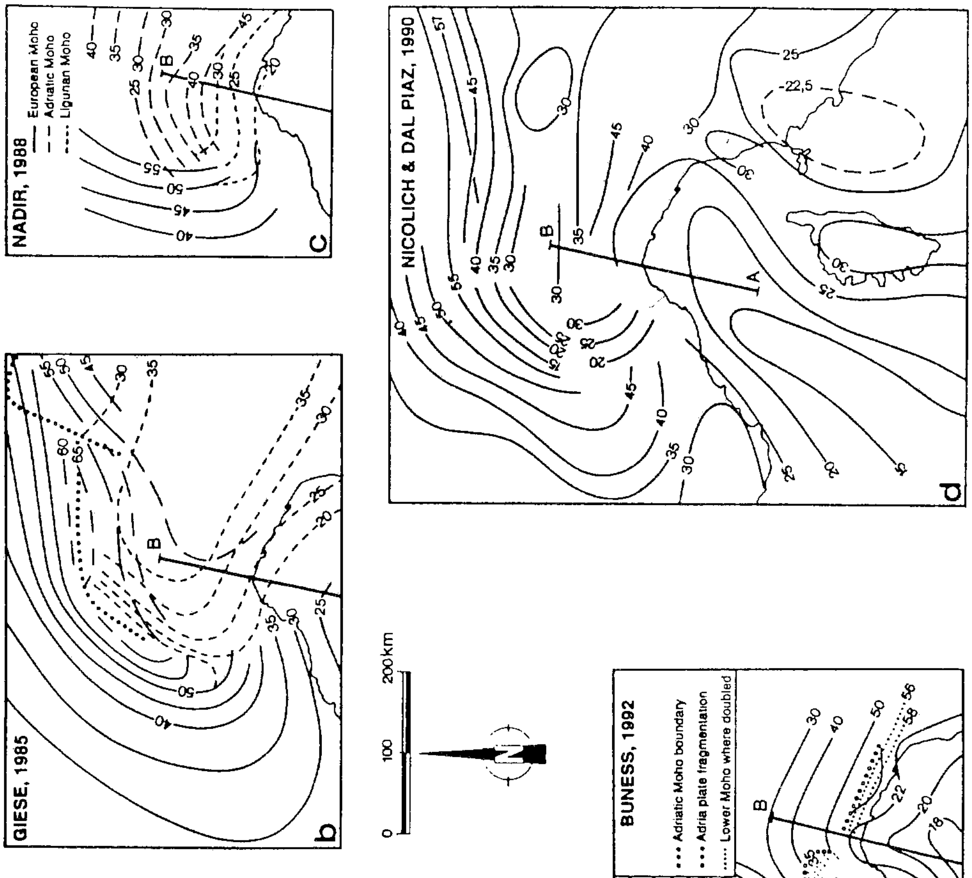

Fig. 2 - Moho contour maps from different Authors (simplified). The positions of crustal sections (Fig. 3) are shown. In part b the dotted line represents the Insubric Line; Giese has not given a name to the different types of isobath; see text for a possible interpretation.

Moho. In western Liguria it gradually bends, dipping to the N. It is notably uplifted under the Ligurian Sea to a depth of 18 to 20 km. In the Po Plain the Adriatic Moho dips SW to a depth of 30 to 58 km. In eastern Liguria it dips under a shallower Moho that is apparently a continuation of the Ligurian sphenocasm's Moho and the European Moho. In the Western Alps it dips E-SE.

Scarascia et al. (1992) distinguish (Fig. 2f) between a European Moho, a Po Plain-Adriatic Moho and an oceanic and crustal thinned Moho (Ligurian, Tuscan and Perityrrhenian). The European Moho is the deepest and dips to the E. It is indicated as far as the western boundary of Tuscany, with a depth of 25 to 60 km. The Po Plain-Adriatic Moho dips to the S (Po Plain) and W (Northern Apennines) under a thinned crust, to a depth of 30 to 45 km. The third type of Moho refers to thinned crust and oceanic crust of neo-formation. It extends from the Ligurian sphenocasm as far as eastern Liguria, Tuscany and the Tyrrhenian Sea. It is the shallowest and has a depth of 15 to 27 km.

In the other maps examined, the different types of Moho are not distinguished. Only the most superficial Moho is represented.

Nevertheless, from Nicolich and Dal Piaz's (1990) map (Fig. 2d), it is possible to infer that the European Moho is the deepest. In the Western Alps it dips E under the Po Plain-Adriatic crust, to a depth of about 30 to 55 km; in the Ligurian Alps it bends gradually and dips to the N. In the southern Po Plain the Adriatic Moho dips S, to a depth of 30 to 45 km, under the Moho in eastern Liguria, which seems to be a continuation of the Ligurian sphenocasm's Moho. The Moho under Liguria dips to the E, and near the Po Plain can be connected to the Adriatic Moho. The Moho under the Ligurian sphenocasm, Tuscany, the Tyrrhenian and Adriatic Seas, and the central part of the Po Plain is uplifted.

INTERPRETATION OF THE CRUST-MANTLE BOUNDARY

The above interpretations of the crust-mantle boundary reveal certain points in common and some significant differences.

In general, there is a high degree of consensus about the geometry of the European Moho, at least in the Western and Ligurian Alps: it is the deepest crust-mantle boundary and dips to the E under the Adriatic Moho (see also Roure et al., 1990); and it bends near the Ligurian Alps, where it dips to the N. Some authors identify the European Moho as being under a shallower crust-mantle boundary as far east as the western margin of Tuscany.

Apart from differences in depth, the Adriatic Moho's geometry in the Po Plain is similar in almost all the maps considered; the dip is generally to the S or SW except near the Western Alps, where it is to the E.

Furthermore, all the authors show the Moho as being uplifted under the Ligurian sphenocasm, the Tyrrhenian Sea, Tuscany and Latium.

The greatest differences concern the interpretation of the Moho under the Ligurian-Tuscan area. This is a belt trending (N) NW-(S) SE which is geographically interposed between the western and eastern sectors that are characterized by the European and Adriatic Mohos, respectively. The boundaries of this central belt are differently interpreted by the authors.

Some (e.g. Buness, 1992; Scarascia et al., 1992) propose that the Ligurian-Tuscan Moho continues westward and joins the Balearic-Ligurian Moho; others (Giese, 1985; Mostaanpour, 1984; Nadir, 1988) assume that the Balearic-Ligurian Moho belongs to the uplifted European Moho and that it is overlapped by the Ligurian-Tuscan Moho.

The eastward connection between the Ligurian Moho and the Po Plain-Adriatic Moho is also differently interpreted in the maps considered; many of the authors show the Ligurian Moho as overlapping the Adriatic Moho (Giese, 1985; Nadir, 1988; Nicolich and Dal Piaz, 1990; Buness, 1992; Scarascia et al., 1992), while others (e.g. Mostaanpour, 1984) indicate their substantial continuity.

In spite of the asthenosphere uplift (connected to the opening of the Ligurian-Balearic and

Tyrrhenian basins), which has modified and in part obliterated the relationships between the European and Adrian Mohos, some arguments lead to the conclusion that the Ligurian-Tuscan Moho belongs to the Adria plate.

1) Many authors (Mostaanpour, 1984; Nadir, 1988; Giese, 1985) indicate the continuity of the Ligurian-Tuscan Moho with the Adriatic Moho near the Western Alps, or else show a fragmentation within the Adria plate in the same area.

2) Almost all the examined maps indicate the same Moho surface under both eastern Ligurian and Tuscany; if this is the case, it must belong to the Adria plate, because the units that outcrop in Tuscany - apart from epidermal Ligurian nappes - are made from Adria's continental crust. Moreover, the Ligurian Moho is set by some authors (Giese, 1985; Nicolich and Dal Piaz, 1990) under the Bobbio window, which is the northernmost outcrop of the Tuscan units from under the Ligurian nappes (Fig. 1).

3) The crustal thinning which occurred between Corsica and Provence, and which was followed by the opening of the Ligurian sphenocasm and by the emplacement of oceanic crust, is connected to the European mantle uplift. In fact, along the sphenocasm's longitudinal axis, between Corsica and Provence, the Moho surface gradually deepens on both sides, joining the Western Alps Moho to the NW and the Sardo-Corsican Moho to the E-SE (Mostaanpour, 1984; Giese, 1985; Buness, 1992).

The hypothesis of the continuation of the oceanic (Balearic-Ligurian) Moho under the Ligurian Alps contrasts with the surface geological data. First, the northern edge of the new oceanic crust ends at the latitude of Nice (Burrus, 1984); second, the surface extensional phenomena north of this latitude do not seem prominent enough to account for a deep-seated rifting phase, accompanied by pronounced crustal thinning in central-eastern Liguria. Since the hypothesis of the landward prosecution of the sphenocasm's Moho is not consistent with surface geological data, the Ligurian Moho should be regarded as a fragment of Adria's Moho.

4) If, as recent CROP-ECORS results clearly indicate (Roure et al., 1990), the Late Eocene tectonic phase produced a deep-seated E-NE dipping collisional belt, marked by Moho duplication, then to the SW of this belt, only the Europe lower plate's Moho was present in Early Oligocene times and, likewise, to the E-NE, only the Adria upper plate's Moho existed.

In respect of this three-fold partition, the subsequent uplifts connected with the opening of the Ligurian and Tyrrhenian basins may have occurred either under the Europe or Adria plates, or under the duplicated collisional zone.

In the first and second cases the paleogeographic appurtenance of the present Moho is obvious; in the third case the shallower crust-mantle boundary (Ligurian Moho) necessarily belongs to the upper Adria plate, while the deeper one pertains to Europe.

The following additional remarks should help to clarify the above conclusions.

In sectors where the present crust still adheres to the mantle that existed at the end of the Alpine collision, the Moho surface corresponds to an old boundary that has not been modified by subsequent events; the Moho can be named Europe-Moho or Adria-Moho, according to its appurtenance.

On the contrary, where the crust-mantle boundary has been modified by LID uplift processes (active or passive) that have been accompanied by crustal extension and, probably, by crust-mantle detachments, the Moho represents a "new" boundary, because the crust and mantle that are now in contact are not the same as were in contact at the end of the meso-Alpine collision.

The distinction between new and old Moho is easy to make when there has been new crust emplacement (e.g., Ligurian-Balearic basin). It is more difficult when there has only been crustal thinning; in fact, the thinning might have also involved the uppermost mantle, and the detachment plane might run inside the mantle itself. In this case, the present Moho would simply be the old surface that has been antiformally bent, and has therefore reached a shallower emplacement.

The denomination of these new Moho surfaces is simply a matter of terminology; what seems to be important for the reconstruction of the geodynamic evolution is the identification of the old Moho's appurtenance in the areas where it has been replaced by a new Moho.

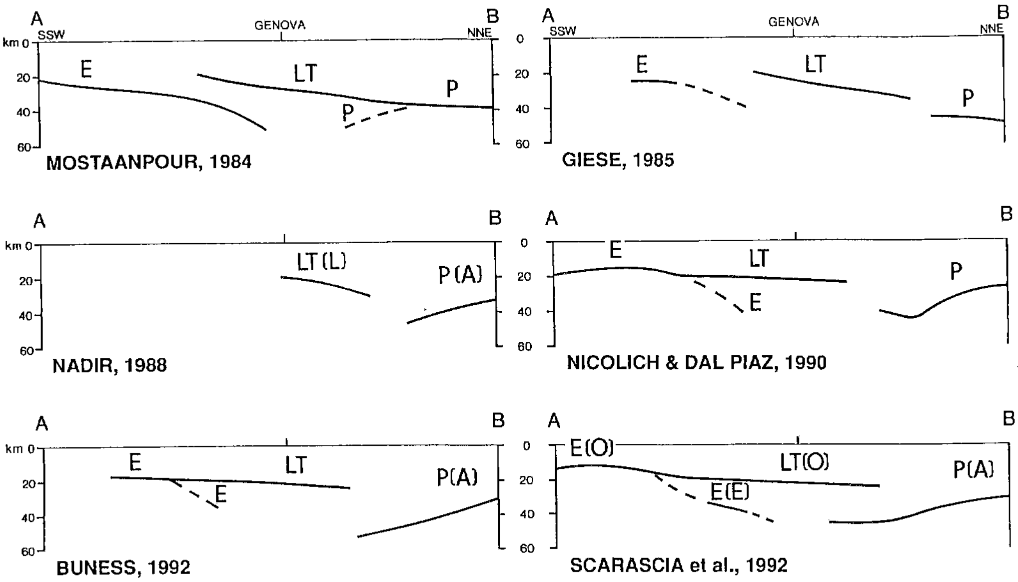

Fig. 3 - Crustal sections between Milan and the Ligurian Sea drawn on the basis of the Moho contour maps of Fig. 2. Each of the Moho segments is labelled following the Author's - between brackets - and/or our interpretation (dashed lines: added hypothetical segments).
Moho segments (see text for explanation): A) Adriatic; E) European; L) Ligurian; LT) Ligurian-Tuscan; O) Oceanic and thinned crust; P) Po Plain-Adriatic.

In this sense, we would suggest that the new Moho under the Ligurian-Balearic basin replaced the old European crust-mantle boundary; and that the Moho under central-eastern Liguria, the Tyrrhenian Sea, Tuscany and Latium is the Adria plate's Moho which, depending on the site, has been either deformed or replaced by a new surface.

In the light of the above statements, Fig. 3 presents different versions of a NNE-SSW crustal section between Milan and the Ligurian Sea; the sections have been drawn on the basis of the Moho contour maps discussed above. We have ascribed each of the different Moho segments to either the European, Adrian or Ligurian-Tuscan Moho; moreover, in order to outline better our interpretation, some hypothetical segments have been added.

KINEMATIC EVOLUTION

As previously mentioned, the Adria continental plate reached its position on the European one during the Late Eocene collision, while the Ligurian-Tuscan crust was overthrust on the Po Plain-Adriatic one later. As many authors have pointed out (see Vanossi et al., 1993 and refs. therein), this is proved by both geometric and chronological evidence.

Indeed, the overall geometric pattern indicates a mechanical - hence kinematic - link between the opening of the Ligurian basin, the Sardo-Corsican block rotation and the contractional structures in the Apennine chain involving Adria's crust.

Chronological data support this view. The rifting phase which precedes the Sardo-Corsican rotation began during (probably Early) Oligocene times (Cherchi and Montadert, 1982; Mosna et al., 1990). The first tectonic-metamorphic Apennine-verging phase affecting Tuscan units occurred during Late Oligocene or Early Miocene times, depending on which datings are chosen (Carmignani et al., 1978; Kliegfield et al., 1986; Ciarapica and Passeri, 1992; Costa et al., 1992; Deino et al., 1992). Accounting for unavoidable uncertainties about datings, extensions in the west (possibly somewhat older) and contractions in the east may be assumed to be roughly contemporary.

As recently discussed and proposed (Vanossi et al., 1993), it seems possible to summarize the event sequence in Liguria and adjoining regions from Late Eocene onwards, as follows:

By the end of Eocene times (about 34 Ma), the collision and welding of the Europe and Adria continental plates had occurred along the Alpine chain. As a consequence, the European crust was thrust under Adria's (Roure et al., 1990); backthrusting (i.e., E- or NE-verging structures) affected the European epidermal crust and overprinted older, foreland-directed deformations. It is possible (even probable) that during this phase NE-verging structures also developed in Ligurian oceanic units (see also Elter and Marroni, 1992); in our opinion, the same event should not be excluded even for some marginal, now buried, Adria (Tuscan) units.

A very relevant question, not yet answered, is how far eastward the European plate's margin extends under Adria's plate. As already mentioned, on Letz's (1978), Mostaanpour's (1984) and Scarascia et al.'s (1992) maps the European Moho is drawn as far as western Tuscany.

The Oligocene period began with a widespread extensional event (Dal Piaz, 1976; Laubscher, 1988), which produced the Sardo-Corsican rift system (Cherchi and Montadert, 1982), as well as the grabens on the southern margin of the Ligurian-Piemont Tertiary Basin (Lorenz, 1986) and the peri-Adriatic magmatic activity (Dal Piaz and Venturelli, 1985).

From Late Oligocene to Early Miocene (19 Ma) the opening of the Ligurian basin developed; its progressive widening was accompanied by a sinistral rotation around a pole which might be located near Alessandria. The roto (-translational) motion affected both some European sectors and the adjacent Adria northwestern indenter. The rotated European lithosphere is represented not only by the Sardo-Corsican block, but also by the area of the Maritime Alps which is located east of the Argentera massif. As a consequence, the southwestern Alpine arc underwent an accentuation. Depending on the shape of the rotating zone and on location and direction of its margins with respect to the rotation pole, compressional or transpressive structures were generated inside the rotating block and in adjoining areas.

Leaving aside the structures in the Southern and Western Alps, it is worthwhile drawing attention to the NE-verging compressional structures which developed in Monferrato, the Ligurian-Piemont Tertiary Basin, the Po Plain subsurface and the Northern Apennines. The latter, in particular, would have been accompanied, within the Adria continent, by lithosphere deformation, which would have led to a major duplication (Ligurian-Tuscan crust and mantle on top of Po Plain-Adriatic ones).

From the late Miocene times onwards, besides the already-mentioned possible (isostatic?) uplift of the Apenninic chain's axial part, the progressive opening of the Tyrrhenian basin began.

This occurred by means of a sinistral roto (-translational) mechanism whose effects were similar to those of the former Ligurian opening. This time, the rotation pole might possibly be located near Savigliano, west of Alessandria. Inside Adria, the process was accompanied by further NE-directed tectonic embrications both in the upper crust and along the Ligurian-Tuscan/Po Plain-Adriatic blocks' boundary. Extensional phenomena occurred more or less contemporarily in the rear of the Apenninic chain, i.e., on its Tyrrhenian side. They are documented by the graben systems which are parallel to the chain axis, and by neogenic-Quaternary volcanism.

TWO ALTERNATIVE GEODYNAMIC MODELS

Within the area shown in Fig. 1, the geodynamic system during Oligocene times is marked by two chronologically related processes: extension in the west (Ligurian sphenocasm) and contraction in the east, where the Ligurian-Tuscan crust is thrust over the Po Plain-Adriatic one.

Depending on the model assumed (collisional mechanism along a W-dipping, eastern subduction zone, or western asthenosphere uplift-related extensional mechanism), one of the two processes may be considered as being the cause or the effect of the other.

In the first model the Balearic-Ligurian basin would be considered as a back-arc basin, where the subduction-related extension favours the emplacement of new oceanic crust.

However some problems arise when considering the location and age of the subduction plane. Affinities between Ligurian-Tuscan and Po Plain-Adriatic crusts (chpat. 4) indicate that crustal duplication was achieved within the Adria continent; hence, the subduction would be an ensialic process, i.e., a mechanism whose effectiveness is questionable. Moreover, crustal characteristics in the area between Corsica and Tuscany (Letz, 1978; Morelli and Nicolich, 1990; Boccaletti et al., 1990) do not show the existence of a Paleogenic, W-dipping subduction plane east of Corsica; on the contrary, as already mentioned, the Corsican continental crust seems to extend eastward as far as the western margin of Tuscany. Finally, contractions in the subduction zone (i.e., in the Apenninic chain) would be older than extensions in the Ligurian sphenocasm; but, as already mentioned, the available datings for the beginning of both these processes, though not definitive, seem to indicate that extensions may have preceded compressions.

For the sake of simplicity, the second hypothesis has been referred to as the "asthenosphere uplift" model. In fact, the following interplay of events should be considered:

The meso-Alpine collision should naturally be followed by pattern rearrangement. This might initially involve a pause in plate motion and, hence, induce a stress field which aids the emplacement of peri-Adriatic magmatic bodies and, more generally, favours extensional phenomena; isostatic re-adjustments of the collisional chain may also occur. All these events may be accompanied by some asthenosphere uplift. Soon afterwards, the plates' relative motion would start again; the N (or NW) -directed push of the Adria indenter, being oblique to the pre-existent collisional belt, would give rise to a roto (-translational) opening of the Balearic-Ligurian basin (Tapponier et al., 1986; Waters, 1990; Vegas, 1992) and asthenosphere passive uplift. Once initiated, the uplift may actively contribute to the further asymmetric opening of the basin; this mechanism, in turn, would generate NE-directed compressions inside the Adria plate, and crustal duplication (Ligurian-Tuscan crust on top of Po Plain-Adriatic crust) may occur along a deep-seated overthrust surface (see also Locardi, 1998; Nicolich, 1989).

The subsequent opening of the Tyrrhenian basin might be imputed to a similar sequence of events (Lavecchia and Stoppa, 1989).

The geodynamic processes in the above two models are substantially different; nevertheless, from a purely geometric standpoint they only imply a different configuration for the deeper parts of the intra-mantle surfaces of motion. This is shown in Fig. 4, which presents two almost parallel, SW-striking, cross-sections of the Maritime Alps and Corsica-Tuscany regions, respectively (left: "subduction" model; right: "asthenosphere uplift" model).

Maritime Alps cross-section

In the "subduction" model (Fig. 4a) events would have developed as follows:

During the Oligo-Miocene period, after an initial, widespread, extensional phase, an intra-Adrian, ensialic, W-dipping subduction plane *(sb)* has driven the Po Plain-Adriatic crust under the Ligurian-Tuscan one. Following the back-arc basin model, subduction within the Adrian lithosphere is coupled to extension of the European lithosphere, which, in turn, is accompanied by a sinistral rotation. Rotation is performed both by ductile deformation and by intra-crustal thrust planes. Along one of these planes, shown in Figs. 4a and 4a', a European upper crust slice is transported onto the Adrian lithosphere (Reutter et al., 1978; see also Buness and Giese, 1990 and Buness, 1992).

During the Late Miocene-Present period, while the Tyrrhenian basin begins to open, the deeper part of the subduction plane *sb* shifts to a new, steeper position *(sb')*. This change may correspond either to progressive rotation, as suggested by Laubscher et al. (1992), or to deactivation of the former *sb* plane and its replacement by a new *sb'* surface. In the latter case, the area between the *sb* and *sb'* planes would obviously be occupied by the Adria mantle, while under the alternative assumption, the European mantle and/or asthenosphere would be expected to fill that space.

In Fig. 4a' the post-collisional pattern is assumed to be triggered by asthenosphere uplift, which is coupled to a detachment master fault; this allows the European crust to be extended. The deeper part of the detachment plane might correspond to the former Europe-Adria collisional

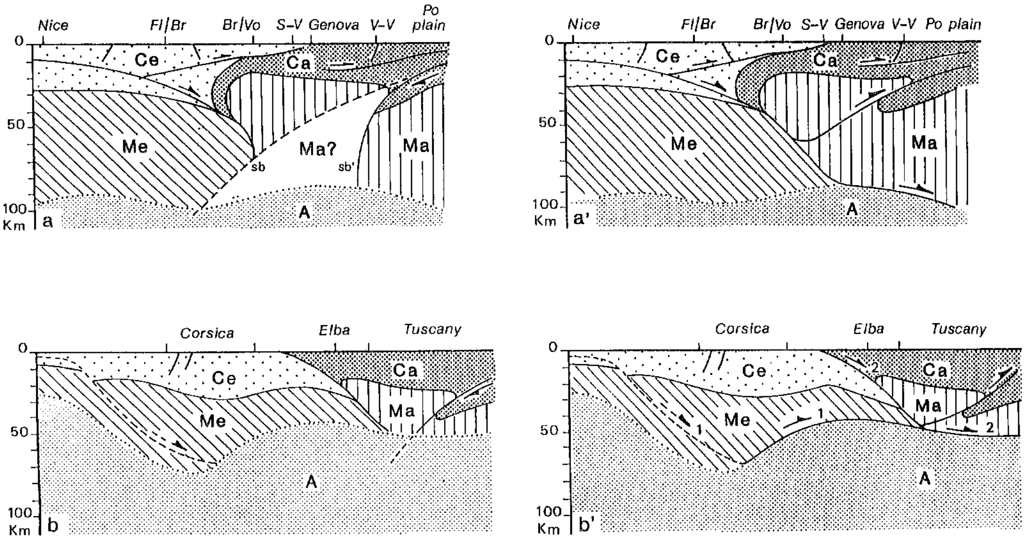

Fig. 4 - Comparison between "subduction" (left) and "asthenosphere uplift" (right) models, by means of two almost parallel, NE-striking cross-sections of the Maritime Alps (above) and Corsica-Tuscany (below) regions. Fl/Br: Helminthoid Flysch/Briançonnais-Piemont Zone boundary. Br/Vo: Briançonnais-Piemont Zone/Voltri Group boundary. S-V: Sestri-Voltaggio Zone. V-V: Villalvernia-Varzi Line. A: asthenosphere. Me, Ma: Europe and Adria plate mantles, respectively. Ce, Ca: Europe and Adria continental crust, respectively, also including slabs from the formerly interposed Piemont-Ligurian oceanic basin. Data on crust thickness from Morelli and Giese (1985) (western sector) and from Nadir (1988) (eastern sector). Lithosphere thickness from Consiglio Nazionale delle Ricerche (1990).

surface (negative inversion tectonics). The related sinistral rotation brings the Ligurian-Tuscan lithosphere on top of the Po Plain-Adriatic one. This process can be considered as an intra-Adria indentation along a deep-seated overthrust surface, which joins the detachment master fault. The subsequent asthenosphere uplift along the Tyrrhenian belt induces further indentation and, at shallower levels, foreland-directed transport of Apennine thrust sheets.

Corsica-Tuscany cross-section

In both models (Figs. 4b and 4b') a hypothetical normal fault has been drawn west of Corsica, for the sole purpose of pointing out the extension which is related to mantle uplift under the Ligurian Sea.

In Fig. 4b intra-Adria subduction causes the extension of the European crust and, hence, mantle uplift. It should be noted that while in the Maritime Alps the subduction plane runs east of the north-western prolongation of the Tyrrhenian mantle uplift, at a more southern latitude it seems to be positioned just above the uplift: the cause-effect connection between these processes therefore becomes less easy to explain.

The only graphical change in fig. 4b' concerns the "subduction" surface, which is now connected with the lithosphere/asthenosphere boundary. In this model, Oligo-Miocene extension would create a detachment fault (arrow 1) within the Europe plate. In response to the rotational process, a deep-seated overthrust surface, joining the detachment fault, would subsequently be generated within the Adria plate. During the Tyrrhenian extension, a new detachement fault overprinting the meso-Alpine Europe-Adria collisional belt (arrow 2), would become active. A comparison between Figs. 4a' and 4b' shows that in the "asthenosphere uplift" model, the extension-related detachment faults which allow the roto (-translational) motions are oblique to the plate boundaries; such faults would have been reactivated only locally be negative inversion tectonic processes.

Finally, whatever model is considered, it is worth noting that the intra-Adria "subduction" (or "overthrust") W-dipping surface, and the vertical plane containing the axis of the maximum

Tyrrhenian uplift, converge NW-ward and diverge SE-ward; and towards the SE the amounts of crustal contraction and extension also increase. Hence, apart from cause-effect mutual relationships, the existence of a chronological and genetic link between these two mechanisms should be inferred.

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