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A crustal-scale cross-section of the south-western Alps combining geophysical and geological imagery

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ABSTRACT

A geotransect across the south-western Alps from the Pelvoux Massif (external French Alps) to the Dora-Maira massif (internal Italian Alps), through the Monviso ophiolitic complex, was investigated in the framework of the 'Géo-France 3D Alpes' programme. A new interpretative crustal-scale section across the south-western Alps is proposed, combining geological and geophysical 2D/3D data. The Apulian mantle (i.e. the Ivrea body) might be divided into two rigid pieces separated by the downward prolongation of the Penninic frontal thrust. These mantle indenters drive the decoupling of the European crust. Beneath the high to ultra-high pressure metamorphic nappes, the deep structure results from the stacking of crustal slices extracted from the European lithosphere. The proposed structural model provides a basis for discussing the evidence of the crustal-scale partitioning of the current strain pattern as well as the location of the seismicity.

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Introduction

The alpine belt is one of the most intensively studied orogenic domains in the world. However, its general 3D lithospheric and crustal geometries remain poorly constrained. By the 1980s, the deep structure of the north-western Alps was imaged by a French–Italian project (ECORS-CROP Deep Seismic Sounding Group, 1989). Different interpretations of this 190-km-long profile are available (Nicolas *et al.*, 1990; Polino *et al.*, 1990; Roure *et al.*, 1990, 1996; Tardy *et al.*, 1990; Ménard *et al.*, 1991; Burov *et al.*, 1999; Schmid and Kissling, 2000).

Most of them agree on a first-order geometrical interpretation characterized by the following features:

1. predominant western vergence of the major thrusts, with a component of back-thrusting in the internal zones;
2. underthrusting of the European margin beneath the Apulian plate;
3. development of large crustal flakes that may include mantle slices;
4. distinctive geometry of the internal zones, in which widespread high to ultra-high pressure metamorphic units built a strongly deformed accretionary wedge resting on the subducted European lithosphere.

In the south-western Alps, new information on the lithospheric structure was obtained in the framework of the 'Géo-France 3D Alpes' programme. They include: tectonic constraints, lithological, petrological and geochronological data that help to define the main tectono-metamorphic gaps along the geotransect; 2D/3D geophysical data, including local earthquake tomography (Paul *et al.*, 2001) and gravity modelling (Masson *et al.*, 1999; Vernant *et al.*, 2002).

Geological outline and evolution of the south-western Alps

The western Alps underline the boundary between Europe and Africa plates (e.g. Dal Piaz *et al.*, 1972). In the south-western Alps (Fig. 1), the orogenic arc derives mainly from the Piedmont-Ligurian ocean and its north-western European margin (Lemoine *et al.*, 1986). Collisional structures resulted from the rotational indentation of Europe by the Adria promontory (Tapponnier, 1977; Vialon *et al.*, 1989; Collombet *et al.*, 2002). Available geological, stratigraphic and geochronological constraints suggest the following evolution.

1. Late Cretaceous to Early Eocene oceanic subduction followed by continental subduction of the European margin giving rise to high to ultra-high pressure metamorphism (e.g. Duchêne *et al.*, 1997) and building of the Queyras-Monviso accretionary wedge (Blake *et al.*, 1995; Agard *et al.*, 2001; Lombardo *et al.*, 2002; Schwartz, 2002).
2. Oligocene continental collision during which shortening concentrated in front of the Adria promontory. This resulted in the thrusting of the internal zones upon the external alpine domain along the Penninic frontal thrust, and new deformation in the Queyras-Monviso wedge.
3. Neogene to present-day strain partitioning (Fig. 2) with general shortening in the external arc, widespread extension in the internal zones and inversion of the Penninic frontal thrust as an extensional detachment (Sue and Tricart, 1999). Extension resulted in a dense normal fault network overprinting the compressional structures (Sue and Tricart, 2003).

The main geological units along the geotransect

The map and the sections in Fig. 3a and b illustrate the main geological units along the geotransect. The proximal palaeo-European margin (Helvetic-Dauphinois domain) is represented by the Pelvoux external crystalline massif, a piece of the European continental crust composed of Palaeozoic magmatic and metamor-

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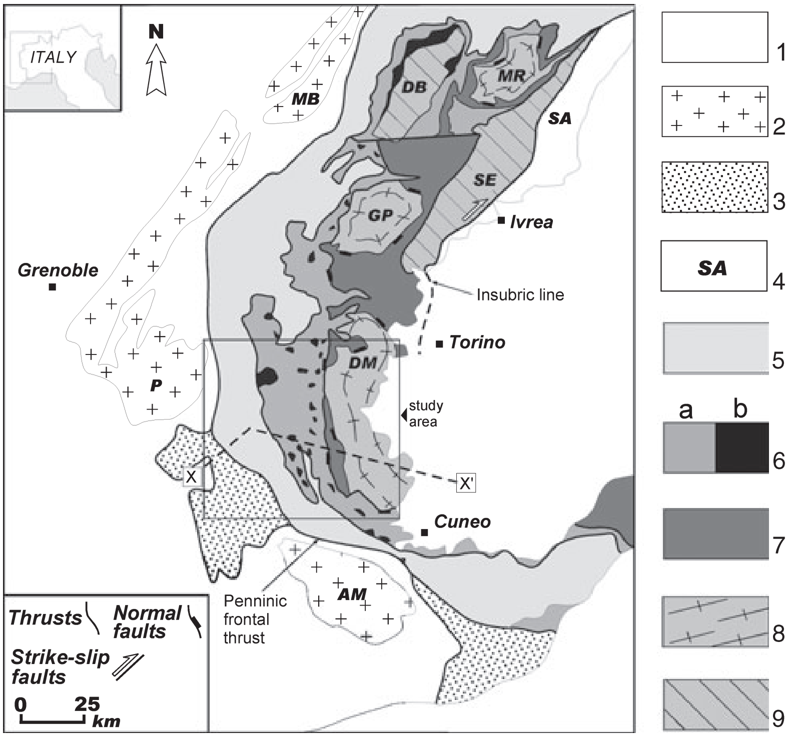

Fig. 1 Simplified tectonic map of the western Alps. The interpretative structural cross-section of Fig. 4 is indicated (XX′). Alpine external arc and Apulian interland with: (1) Helvetic-Dauphinois domain and Po plain sediment; (2) external crystalline massif (AM, Argentera-Mercantour; P, Pelvoux; MB, Mont Blanc); (3) Heminthoid flysch nappes; (4) South-Alpine zone, Alpine internal arc with: (5) Briançonnais zone; (6) Blueschist facies Piedmont zone [(a) Schistes lustrés; (b) ophiolites]; (7) eclogite facies Piedmont zone; (8) internal crystalline massif (DM, Dora-Maira; GP, Gran Paradiso; MR, Monte Rosa); (9) Austroalpine units (SE, Sesia; DB, Dent Blanche).

phic rocks, and by Mesozoic to Cenozoic sediments of the subalpine fold–thrust belt. Along its eastern fringe, late Eocene–early Oligocene turbidites were deposited in a flexural basin in relation with the westward thrusting of the internal Alps onto the external domain along the Penninic frontal thrust. The Dauphinois zone corresponds to a thin-skinned and also basement-involved fold–thrust belt, with west or south-west vergence (Butler *et al.*, 1986; Gratier *et al.*, 1989; Vialon *et al.*, 1989). Many thrusts correspond to inversion of pre-orogenic normal faults (DeGraciansky *et al.*, 1989). Still-active compression leads the uplift of external crystalline massifs. In a more internal position with respect to these massifs, the Penninic frontal thrust was reactivated as a normal fault in connection with general extension in the Alpine internal arc (Sue and Tricart, 2003; Fig. 2).

The Briançonnais zone mainly displays late Palaeozoic to Mesozoic sediments and pre-Alpine basement rocks (Ambin massif and Acceglio zone). A remarkable nappe stack involves the pre-, syn- and post-rift Tethyan sediments originating from a stretched margin (e.g. Claudel and Dumont, 1999). This stack of cover nappes was shortened during the Oligocene and, being a mechanically contrasted multilayer, gave rise to regional west- and east-verging folds and associated thrusts. The latter are known as the Briançonnais backfolds and backthrusts and correspond to the present-day alpine fan-shaped structure (Tricart, 1984) metamorphosed under greenschist facies conditions (Goffé *et al.*, 2004; with references therein). A dense, regional-scale fault network attests to a Neogene to present-day radial extension (Sue and Tricart, 2003). The Briançonnais basement consists of pre-Alpine magmatic and metamorphic rocks. Its Permo-Carboniferous sedimentary cover is strongly re-worked during Alpine orogeny. The metamorphic evolution of these basement slices, where upper blueschist and/or eclogite facies conditions have been deciphered (Goffé *et al.*, 2004), contrasts with the evolution of the cover nappe pile. These significant metamorphic gaps are consistent with the existence of severe tectonic decoupling between the Briançonnais units. For example, the Acceglio zone is regarded as a low-angle extruded unit, bounded to the west by a normal fault and to the east by an inverse fault, within the overlying Piedmont Schistes lustrés of Queyras (Caby, 1996).

The composite Piedmont zone comprises the Queyras Schistes lustrés complex, the Monviso and Rocciavré ophiolic complexes. The Queyras Schistes lustrés derived from Mesozoic oceanic sediments (Lemoine and Tricart, 1986). These sediments were strongly deformed and metamorphosed during alpine subduction and they outcrop today as foliated and polydeformed calcschists enclosing boudinaged decametre-to-kilometre-sized ophiolitic bodies. At the regional scale, the main structure is a pile of thrust sheets imbricated within an accretionary wedge during the Palaeogene. This pile has undergone repeated and severe refolding under metamorphic conditions grading up eastwards from blueschist to blueschist–eclogite transitional facies (Goffé *et al.*, 2004). The latter represent major remnants of the Tethyan oceanic lithosphere that were strongly deformed and metamorphosed under eclogite facies conditions (Lombardo *et al.*, 1978; Lardeaux *et al.*, 1987; Rubatto and Hermann, 2003) during the Eocene (Monié and Philippot, 1989; Duchêne *et al.*, 1997). Contrasted eclogitic conditions (e.g. Schwartz *et al.*, 2000) indicate that the Monviso massif is composed of imbricated units. The Monviso eclogites are separated from the Dora-Maira massif by a ductile normal fault (Blake and Jakyo, 1990; Philippot, 1990; Schwartz *et al.*, 2001). Situated in the lowermost structural position in the

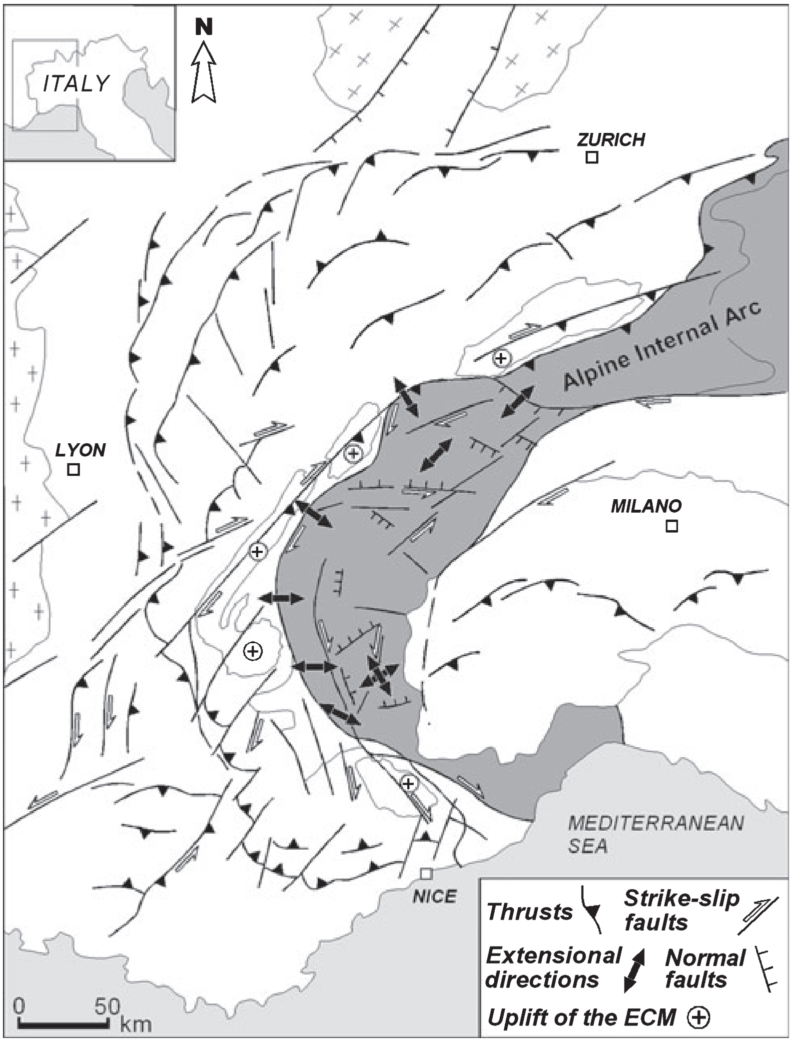

Fig. 2 Neogene to ongoing strain pattern in the Alps. At the crustal scale, the deformation is partitioned with an important shortening in Alpine external arc and Apulian interland associated with the uplift of the external crystalline massifs. On the other hand, Alpine internal arc (heavy grey) is affected by a generalized transtensive deformation.

studied transect, the Dora-Maira massif corresponds to a stack of more or less deeply subducted continental basement slices involved in a 'dome-like' structure (Michard *et al*., 1993). Here again, significantly contrasted metamorphic conditions have been inferred (Chopin *et al*., 1991; Henry *et al*., 1993; Compagnoni and Rolfo, 2003). Quartz-bearing eclogite facies rocks outcrop at the top of the Dora-Maira dome and overlie a coesite-bearing eclogitic unit. This pile of thin (<1 km) high to ultra-high pressure metamorphic units overlies the lowermost Pinerolo-Sanfront blueschist bearing unit along a thrust contact. The latter unit is similar, with respect to the lithologies, structural position and metamorphic evolution, to the Briançonnais basement slices (Vialon, 1966; Michard, 1967).

An interpretative crustal-scale cross-section of the south-western Alps

Figure 4 represents an interpretative crustal-scale section across the south-western Alps including the South-Alpine crust which is here covered by the Po plain sediments. As mentioned above, this section integrates near-surface structures (Fig. 3) and seismic tomography (Fig. 5). The following constraints have guided our interpretation:

1. the nature of the geophysical 'Ivrea body', generally interpreted as a piece of Apulian upper mantle, recognized through local earthquake tomography and gravity modelling;
2. the subdivision of the Ivrea body into upper and lower sub-units;
3. the extension at depth of the thick slice of eclogitized ophiolites of the Monviso massif;
4. the necessity of an effective decoupling between the Alpine external and internal arcs in order to account for the present-day strain partitioning;
5. the diversity of tectonic contacts involving reactivated ductile thrusts, ductile to brittle normal faults or a combination of both normal (at the top) and inverse faults (at the bottom) compatible with tectonic extrusions;
6. the occurrence at the bottom of the nappe pile (i.e. beneath the ultra-high pressure unit) of crustal slices derived from the European margin (Acceglio, Pinerolo units) and metamorphosed under blueschist facies conditions.

In this new proposed cross-section, the prominent geological features are as follows.

1. The existence of a slice of cold and rigid mantle of Apulian origin at 8–10 km depth beneath the Dora-Maira massif. This mantle body is truncated by a system of deeply rooted vertical faults and is decoupled in two main pieces at depth by a gently dipping fault interpreted as an in-depth extension of the Pennic frontal thrust.
2. The two Apulian mantle pieces acted as distinct indenters and drove the decoupling of the European crust. The upper mantle indenter, still attached to the Alpine high-pressure orogenic wedge, represents a 'pop up' structure in the core of the Alpine internal arc. This upper mantle indenter was, at least partly, responsible for the doming of the Dora-Maira massif. The lower indenter, still in the position of 'mantle backstop' with respect to the European crust, is

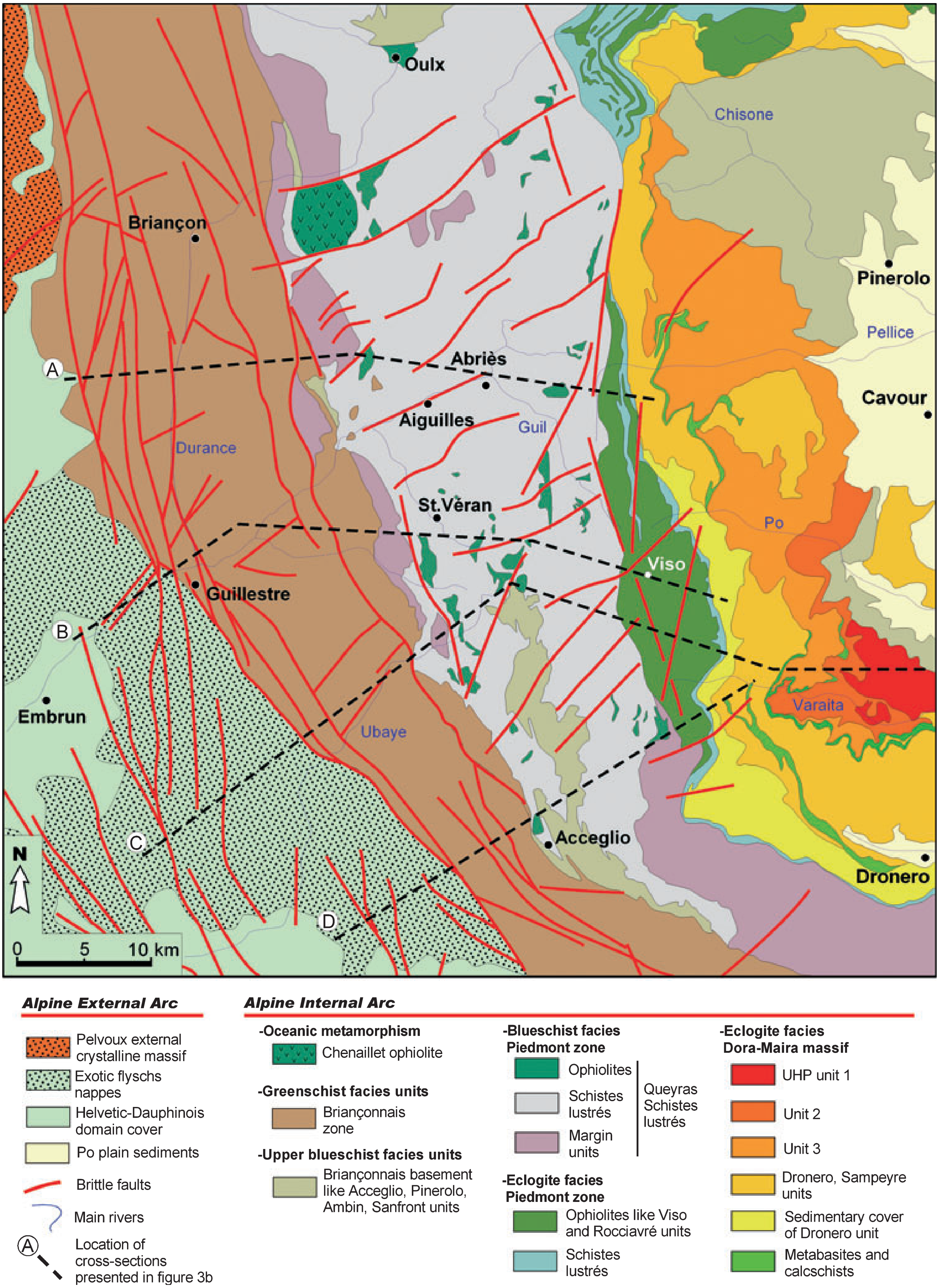

Fig. 3 Main geological units along the studied transect (modified after Bigi *et al.*, 1990; Gidon *et al.*, 1994): (a) geological map; (b) cross-sections.

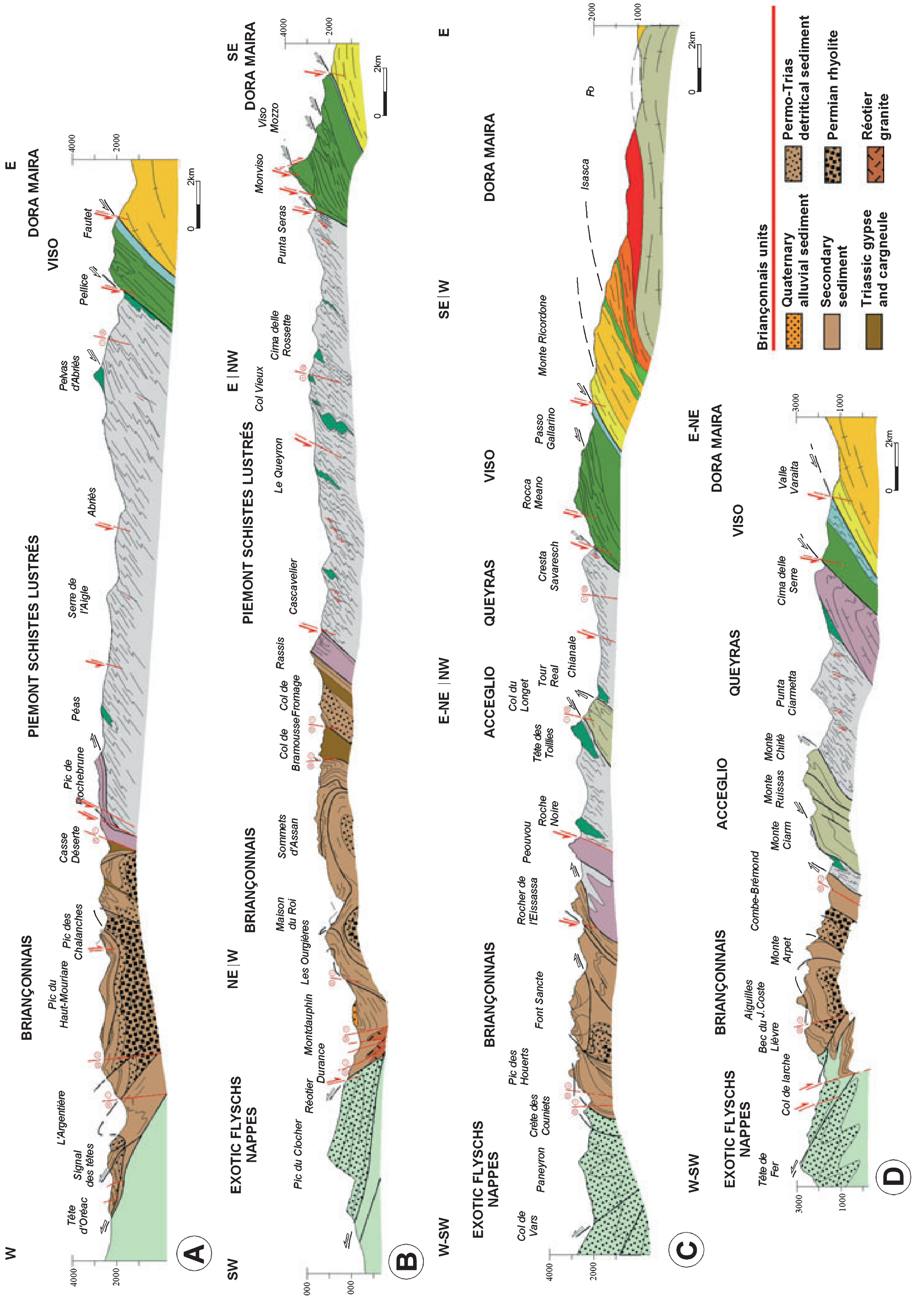

Fig. 3 *Continued.*

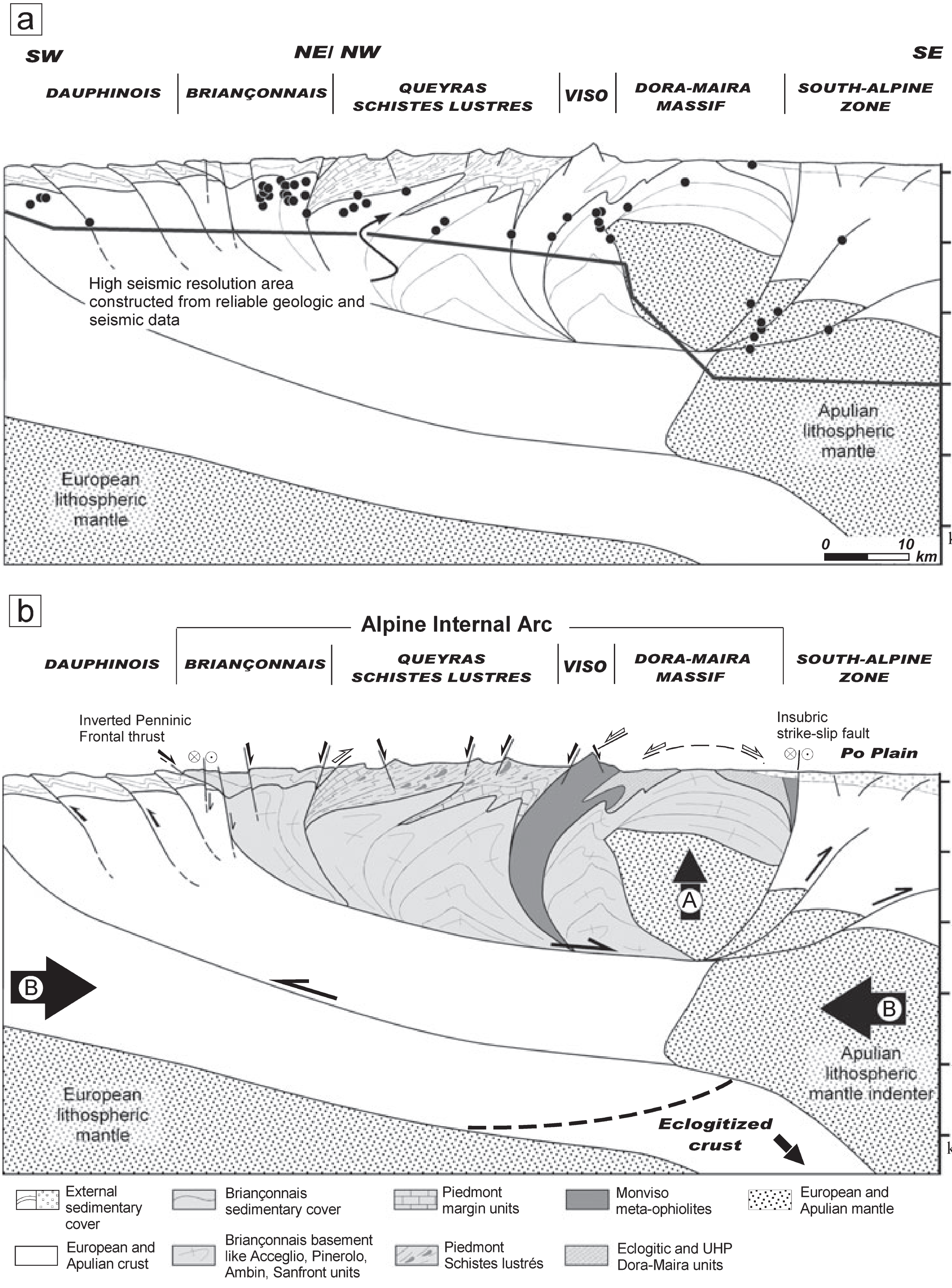

Fig. 4 Interpretative crustal-scale cross-section of the south-western Alps. (a) Cross-section showing the high seismic resolution area with the localization of earthquake hypocentres (black circles) with respect to the main geological and tectonic boundaries. (b) Cross-section with the main geological units and kinematics indicators, the upper part of the Apulian mantle (arrow A) acts as an indenter and the lower part (arrow B) transfers the compression onto the external arc (European foreland).

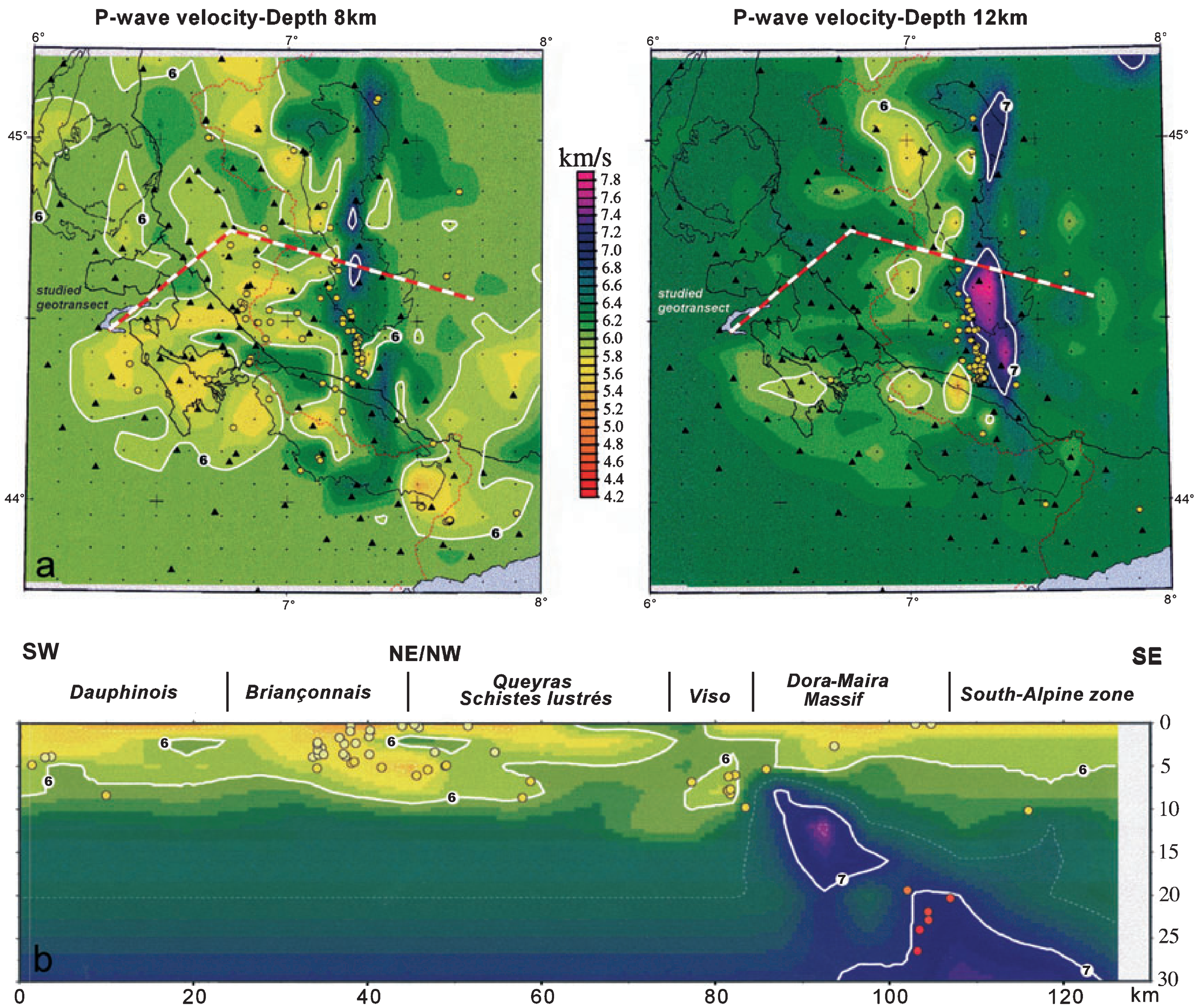

Fig. 5 Three-dimensional Vp model computed from direct inversion of local earthquake traveltimes (after Paul *et al.*, 2001). Black triangles: station location; circles: hypocentres located in a 5-km-thick depth slice. (a) Map view slices at 8 and 12 km depth; (b) cross-section, along the studied geotransect.

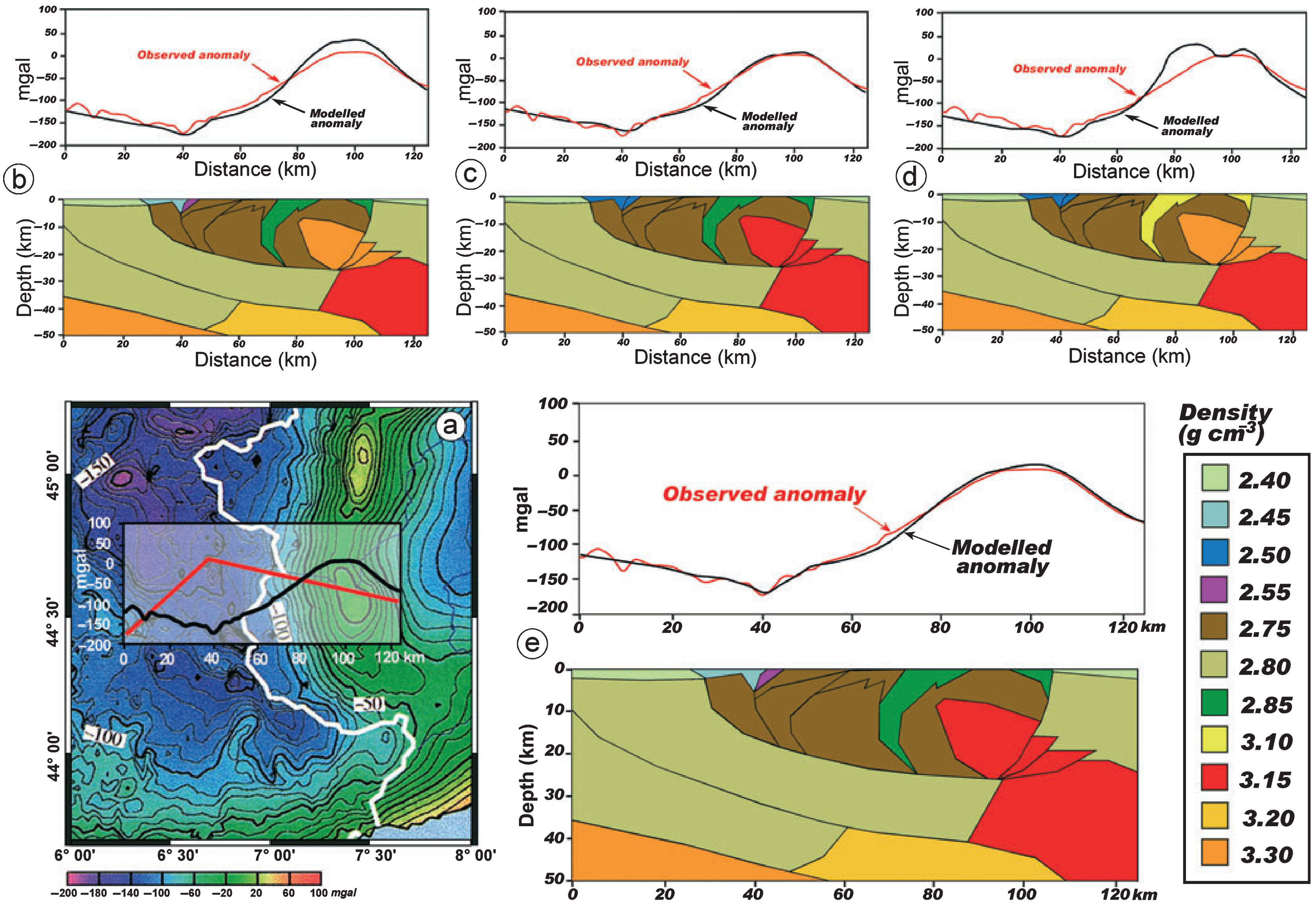

Fig. 6 Models of the gravity effect calculated for the interpretative cross-section. Three models with different rock density values are presented. The model showing the best fit between the observed and the modelled anomaly is presented in the enlarged picture. The studied geotransect (red line) is located on the Bouguer gravity map of Masson *et al.* (1999). The black line represents the gravity profile along the geotransect.

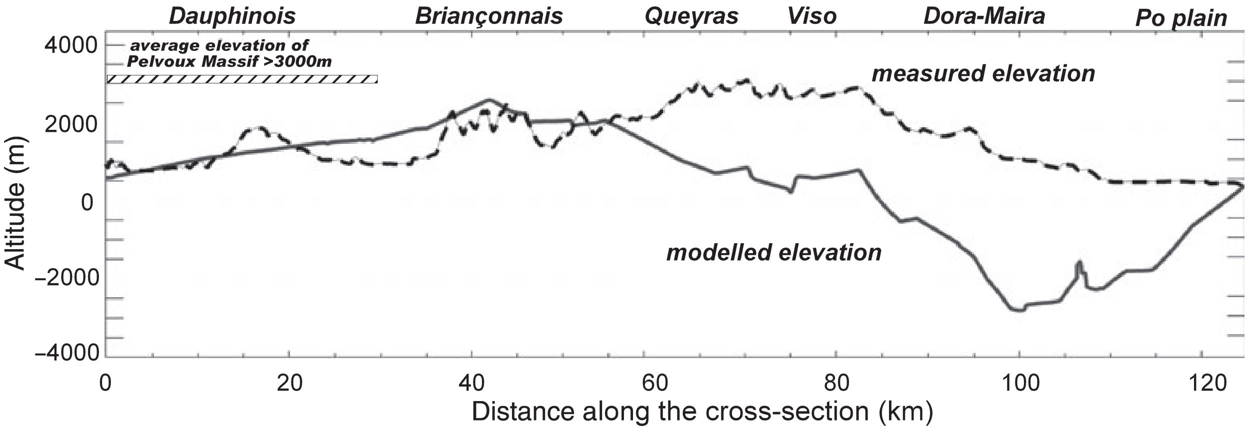

Fig. 7 Comparison between the topography computed assuming local isostasy and a density of 3.4 g cm^{-3} for the asthenosphere and the observed topography along the studied geotransect. The average elevation of the Pelvoux massif is indicated in the Dauphinois zone. See the large modelled depression below the Piedmont zone, inconsistent with the measured elevation.

currently pushing the basement of the external alpine arc towards the west.

3 The Monviso eclogitized ophiolites, which are plunging down to 20 km depth below the Queyras Schistes lustrés.

4 The deep architecture of the belt is characterized by the stacking of crustal slices extracted from the European lithosphere. These slices should be regarded as duplexes of European crust. Some of them (Acceglio zone) acted like tectonic extrusions within the overlying Queyras Schistes lustrés.

Discussion and conclusion

In order to test this new interpretative crustal-scale cross-section, we developed a gravity model by the conversion of the seismic/structural data into an 'a priori' density model (Fig. 6b–e) in order to confront with the Bouguer gravity map (Fig. 6a). We used rock density calculations of Bousquet *et al.* (1997) that take into account the progressive phase transitions in metamorphic rocks and are in good agreement with the measured densities of natural or experimental rocks representative of upper crust, lower crust and upper mantle. The best fit between the modelled and the measured gravity anomalies is obtained with the following assumptions (Fig. 6).

1 The density for the Apulian mantle is fixed at 3.15 g cm^{-3} and not in the range 3.20–3.30 g cm^{-3}. This is in agreement with the shallow position of this mantle, especially the uppermost mantle indenter, which is probably composed of plagioclase-bearing peridotites and/or partly hydrated peridotites.

2 The density for the Monviso meta-ophiolitic massif is assumed to be 2.85 g cm^{-3}, i.e. less than 3 g cm^{-3} that is commonly accepted for mafic eclogites. This is explained by the amount of serpentinites outcropping in this massif (Lombardo *et al.*, 1978) and by the degree of retrogression of the mafic eclogites under blueschist and/or greenschist metamorphic facies (Lardeaux *et al.*, 1987; Schwartz *et al.*, 2000).

In our model, and as suggested by different authors (Bousquet *et al.*, 1997; Henry *et al.*, 1997), the Alpine crustal root is eclogitized and thus may stay in gravitational equilibrium in the mantle. Moreover, an interpretative crustal-scale section, consistent with entire set of geophysical constraints, implies a crustal wedge composed of a significant amount of stacked crustal slices with densities in the range of 2.75–2.80 g cm^{-3}, and thus metamorphosed under blueschist or greenschist facies conditions. If accepted, the proposed structural model allows an interpretation of the tectonic significance of the regional seismicity. The Briançonnais seismic arc (Rothé, 1941; Thouvenot, 1996) should be related to the regional network of normal faults and locally associated strike–slip faults, developed during the Neogene to present-day extension (Sue and Tricart, 2003). The Piedmont seismic arc (Thouvenot, 1996) is controlled by the position of the two main mechanical heterogeneities (i.e. rigid bodies) in the Piedmont zone, the upper mantle indenter (mantle pop up) and the Monviso eclogitized ophiolites. Indeed, earthquake hypocentres are mainly localized at the boundaries between the European crustal duplex and the Apulian rigid mantle or the Monviso massif. The Padane seismic arc (Thouvenot, 1996) should be related to the inverse fault system and associated strike–slip faults which account for the present-day shortening of the Apulian lithosphere. All these observations are compatible with a strong control of the present-day stress field by the crustal structure of the belt.

The subdivision of the Ivrea body is still a matter of debate (Ménard and Thouvenot, 1984; Nicolas *et al.*, 1990; Tardy *et al.*, 1990; Schmid and Kissling, 2000; Paul *et al.*, 2001). Our model supports such an interpretation with a sharp structural contrast on both sides of the Penninic frontal thrust. To the East of the Penninic frontal thrust, the present-day extension is widespread, while westward crustal shortening is still active. The shortening tectonic regime is related to the lower mantle indenter which transfers the compression to the external Alpine basement. This lower mantle backstop is still pushing the European crust westwards and thus leads to the development of a thrust and fold system in the external part of the arc.

The location of the crust/mantle boundary at a depth of 8–10 km beneath the Dora-Maira massif should have a strong effect on the topography of the south-western Alps. The topographic effect of the density model presented in Fig. 6e is calculated in an isostatic model with a compensation surface fixed at 100 km depth (Fig. 7). The modelled topography is not consistent with the observed one, particularly in the internal Alpine arc. Indeed, the predicted elevation of the internal Alps should be lower than that observed, especially for the Dora-Maira massif. Thus, to account for the present-day high elevation of the Piedmont zone, tectonic forces should be dominant with respect to gravitational forces, reinforcing the idea that the upper mantle indenter tectonically maintains the internal zones, and enhancing the observed extension in the Alpine internal arc (Sue and Tricart, 2003).

Clearly, our structural model should be tested using permanent GPS data. Preliminary data have been obtained for horizontal displacements in the western Alps; they are consistent with the extension in the internal alpine arc (Calais *et al.*, 2000; Sue *et al.*, 2000), but there is no clear evidence for active convergence in the Alpine belt (Calais *et al.*, 2002). Only a better knowledge of the 3D lithospheric structure of the western Alps, combined with more continuous GPS measurements, could constrain a dynamic model for this belt.

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