Zeitschrift: Eclogae Geologicae Helvetiae
Herausgeber: Schweizerische Geologische Gesellschaft
Band: 90 (1997)
Heft: 2

Artikel: Local earthquake tomography of the southern part of the Ivrea body, North-Western Italy
Autor: Solarino, Stefano / Kissling, Eduard / Cattaneo, Marco
DOI: https://doi.org/10.5169/seals-168165

0012-9402/97/020357-08 $1.50 + 0.20/0
Birkhäuser Verlag, Basel, 1997

Eclogae geol. Helv. 90 (1997) 357–364

Local earthquake tomography of the southern part of the Ivrea body, North-Western Italy[1]

STEFANO SOLARINO[2], EDUARD KISSLING[3], MARCO CATTANEO[2] & CLAUDIO EVA[2]

Key words: Ivrea body, seismic tomography, Moho, European plate, Adriatic plate, local earthquakes

ABSTRACT

The so-called "Ivrea body" in the Western Alps is a complex of high-density, high-velocity, and high-magnetic susceptibility rocks of lower crustal and possibly upper mantle origin. This study presents a seismic tomographic image of the southernmost part of the Ivrea body by means of local earthquake seismic tomography. Similar to earlier geological and geophysical models for the northern Ivrea zone, the results of this study on the southernmost part of the Ivrea body support the model of a ca. 20 km thick high-velocity plate dipping towards East. With a dip of only 40°–45°, however, this plate is far less steep than in the northern parts of the Ivrea zone. Toward its southern end, the bottom of the high-velocity Ivrea body shallows from 30 km or more to only 10 km before ending at about 44.3° North. Our results suggest no current connection of the southernmost Ivrea body with the lower Alpine or Adriatic lower crust nor with the present-day Adriatic mantle lithosphere.

ZUSAMMENFASSUNG

Der Ivrea-Körper in den Westalpen ist ein Komplex von Gesteinen mit hoher Dichte, hoher seismischer Geschwindigkeit und hoher magnetischer Suszeptibilität. Er entstammt der unteren Kruste und möglicherweise dem oberen Mantel. Die vorliegende Arbeit zeigt ein tomographisches Bild des südlichsten Teiles des Ivrea-Körpers, erstellt mit Hilfe seismischer Tomographie von lokalen Erdbeben. Ähnlich wie frühere geologische und geophysikalische Modelle im nördlichen Teil der Ivrea-Zone unterstützen die Resultate im Süden das Modell einer etwa 20 km dicken Platte mit hoher seismischer Geschwindigkeit, welche gegen Osten abtaucht. Mit einem Abtauchwinkel von 40–45° ist die Platte aber viel weniger steil als im nördlichen Teil der Ivrea-Zone. Gegen ihr südliches Ende wird die Untergrenze des Körpers untiefer, sie steigt von 30 km und mehr bis 10 km und endet auf etwa 44.3° Nord. Unsere Resultate lassen vermuten, dass keine durchgehende Verbindung des südlichen Ivrea-Körpers zur alpinen oder adriatischen Unterkruste besteht und ebensowenig zur heutigen adriatischen Mantel-Lithosphäre.

Introduction

The so-called geophysical "Ivrea body" (Wagner & Müller 1984) is one of the most intriguing structures of western Alpine lithosphere. This complex of high-density, high-velocity and high-susceptibility rocks outcrops in the Ivrea-Verbano zone (Zingg et al. 1990; Burollet et al. 1992) and exhibits a positive gravity effect of some 180 mgals (Kissling 1984) that equals the negative gravity effect of the Alpine crustal root in amplitude (Fig. 1 and 2). Recent tectonic work on the northern end of the zone Ivrea-Verbano (Schmid et al. 1987; Zingg et al. 1990; Schmid et al. 1995) linked the near-surface geometry of the Ivrea body to late Alpine tectonics and, in particular, to movements along the Insubric line and shed light on the tectonic evolution of the Ivrea body. The southern parts of the Ivrea body, however, are covered by some 500 meters of Tertiary sediments of the Po Plain (Bigi et al. 1990) and, therefore, can only be studied by geophysical methods.

In the past decades, the deep structure of the Alps has been intensively probed by various geophysical methods with the aim to illuminate the three-dimensional (3-D) lithospheric structure of the Alpine orogen (for a review of the geophysical methods and of the general Alpine lithospheric structure see Kissling 1993). So far, though, the deep Ivrea body has evaded definition of its precise 3-D geometry. In particular, its relation to the Adriatic block and to the western Alpine orogen remains speculative and – due to lack of high-resolution seismic data – it is not known whether the zone Ivrea-Verbano includes pieces of Pre-Alpine or more recent Moho-layers (Berckhemer 1968, Schmid et al. 1987, Brodie & Rutter 1987). Based on a review of geophysical, petrological and geological models, Menard & Thouvenot (1987) point out that three different geophysical Ivrea bodies seem to exist. More likely, the Ivrea body exhibits different images which simply depend on

[1] Contribution no. 873 Institute of Geophysics, ETH Zürich
[2] DiSTer, Dipartimento di Scienze della Terra, Universita degli studi di Genova, Viale Benedetto XV, I-16132 Genova
[3] Institute of Geophysics, ETH-Hönggerberg, CH-8093 Zürich

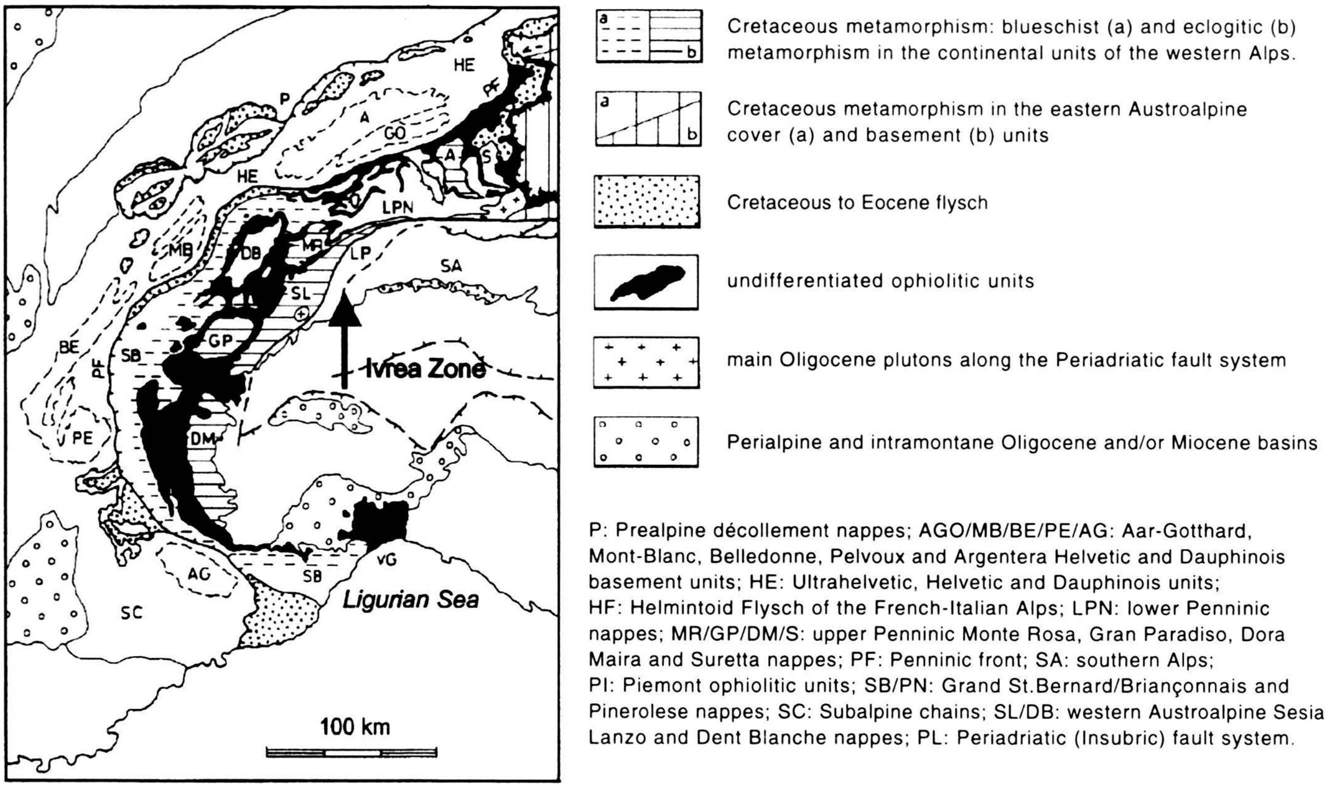

Fig. 1. Geologic map of the Alps after Polino et al. (1990). Ivrea area is marked by an arrow.

the petrophysical parameters (density, susceptibility, seismic velocity) that determine the models.

Solarino et al. (1996) recently carried out a detailed teleseismic tomographic study in north-western Italy and summarized large-scale lithospheric and upper mantle structures in the Western Alps down to a depth of 300 km. Solarino et al. (1996) and Cattaneo & Eva (1990) interpreted their tomographic results such as to suggest a connection between the high-velocity Ivrea body with the Adriatic upper mantle. Their interpretation corresponds with earlier speculations about a possible continuation of the Adriatic seismic Moho within the shallowing Ivrea body and about a possible outcrop of a seismic Moho in the northern zone Ivrea-Verbano (Berckhemer 1968; Brodie & Rutter 1987). With wavelengths of 10 km or more, however, teleseismic tomography cannot resolve details of the 3-D crustal structure. Only the general shape of a large-scale structure such as the Ivrea body (see Bouguer gravity map, Fig. 2) may be determined. Thus, more detailed modeling of the Ivrea body geometry by a high-resolution 3-D seismic method such as seismic tomography using local earthquake data is required.

The area around Cuneo is one of the seismically most active regions in the Western Alps (Fig. 3). Since 1982 the seismological service in Genova (DiSTer) has run a network of a few dozen seismic stations in north-western Italy (Solarino 1994). In the present study we use the data collected by this network in order to produce a detailed 3-D image of the crustal structure of the southern end of the Ivrea body by local earthquake seismic tomography. The results provide a basis for discussing the relation of the Ivrea body to the Western Alpine and Adriatic crustal blocks.

Method and data

The inversion of local earthquake data involves the simultaneous location of the earthquakes while inverting for a 3-D velocity field. Precise location of earthquakes and high-resolution crustal tomography requires 3-D ray tracing. Several methods and techniques (Aki & Lee 1976; Thurber 1983; Kissling 1988) have been proposed to solve the inverse tomographic problem for local earthquake data. Though different in their approaches, the fully iterative 3-D methods of Thurber (1983) and Kissling (1988) yield identical tomographic results in optimal cases (Kissling et al. 1994). In this study we apply the methodology by Thurber (1983) because the inverse problem is small enough in order to be successfully handled by the iterative routine SIMULPS (Eberhart-Philips 1986), and because this routine includes an algorithm that searches for the 3-D ray path. This latter option is of obvious importance in the

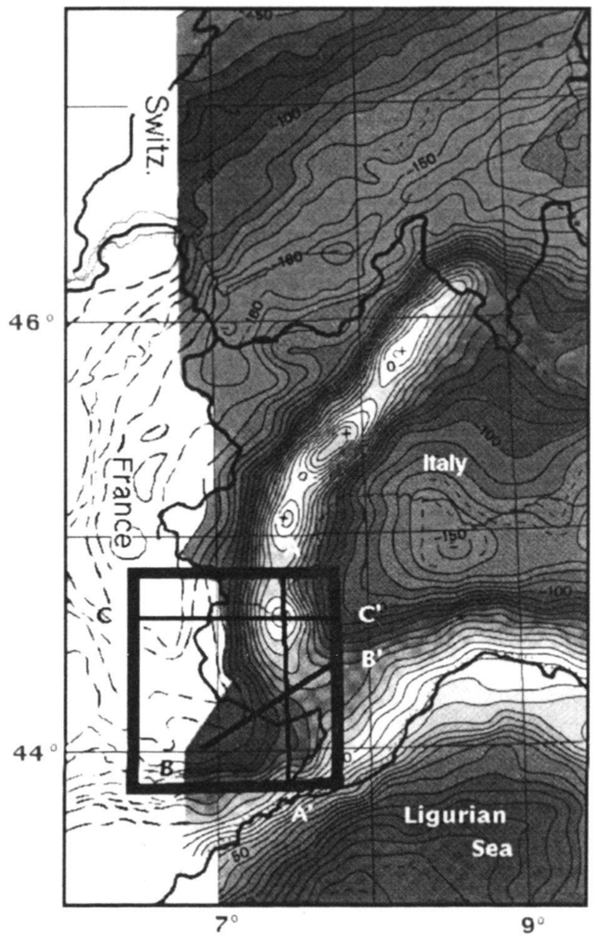

Fig. 2. Bouguer gravity map (Klingele et al. 1992) of the European Geotraverse (Blundell et al. 1992) with area of tomographic study (box) superimposed.

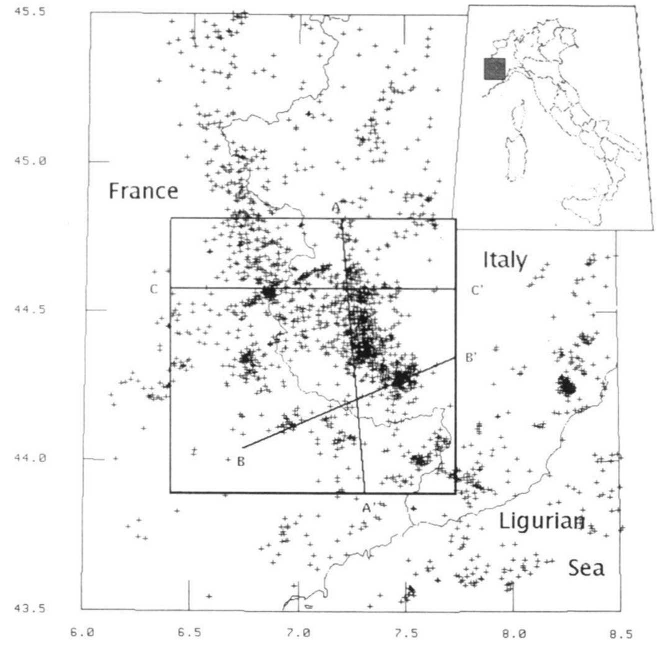

Fig. 3. Epicenter distribution in NW Italy for period 1982 to 1993 as registered by the seismological service in Genova (DiSTer) and neighbouring seismological centers. Study area of approximately 100 km by 100 km in vicinity of Cuneo is marked by box.

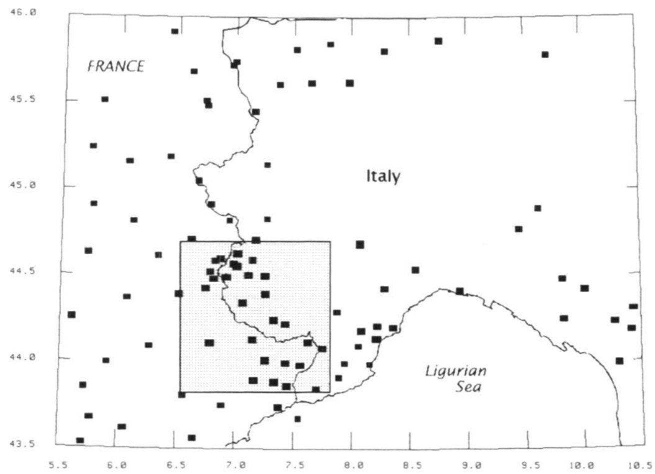

Fig. 4. Station distribution in NW Italy.

case of the Ivrea body where the lateral velocity gradient might locally exceed the vertical velocity gradient.

The 3-D seismic velocity structure is represented by a grid with variable spacing. The velocity at any point is determined by linear interpolation among the velocity values of the surrounding grid points (Eberhart-Philips 1986). The approximative 3-D ray tracing algorithm (ART) by Thurber (1983) involves two steps: first an initial pseudo-ray path of least travel time is selected from a suite of circular arcs connecting the source and the receiver. Subsequently, an iterative 3-D velocity dependent on purely geometrical bending mechanism is applied to the selected arcuate path in order to better approximate a true ray path.

The process of deriving 3-D velocity structure from local earthquake travel time data involves solving a non-linear inverse problem. The solution is approximated by iteratively seeking solutions to a linearized inverse problem where the 3-D velocity field is replaced by a perturbation model relative to an a priori known initial reference model. The choice of the initial reference model for local earthquake tomography is crucial for 3-D tomographic results (Kissling et al. 1994). Recently, Kissling et al. (1995) presented a so-called "Minimum 1-D model" for the area of Cuneo in the Western Alps. We use this

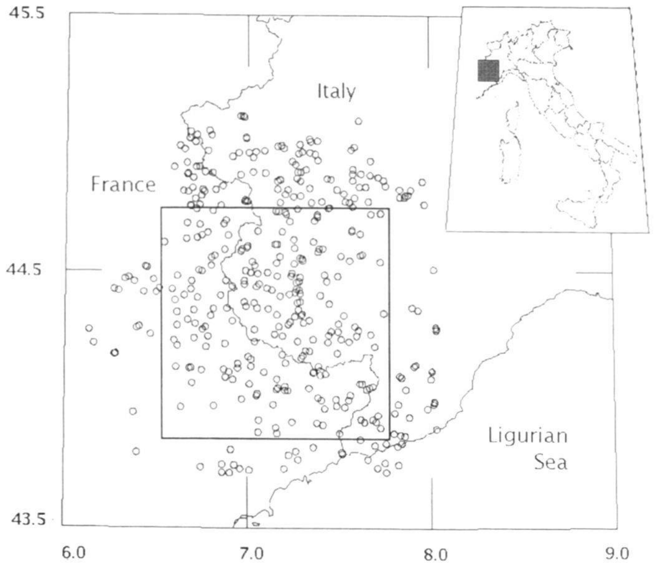

Fig. 5. Epicentral distribution of 600 earthquakes in Cuneo area selected for 3-D tomographic inversion (see text).

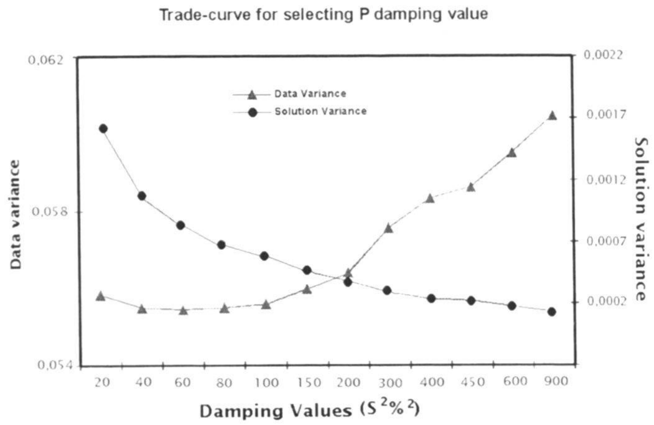

Fig. 6. Selection of appropriate damping parameter for tomographic inversion (see text).

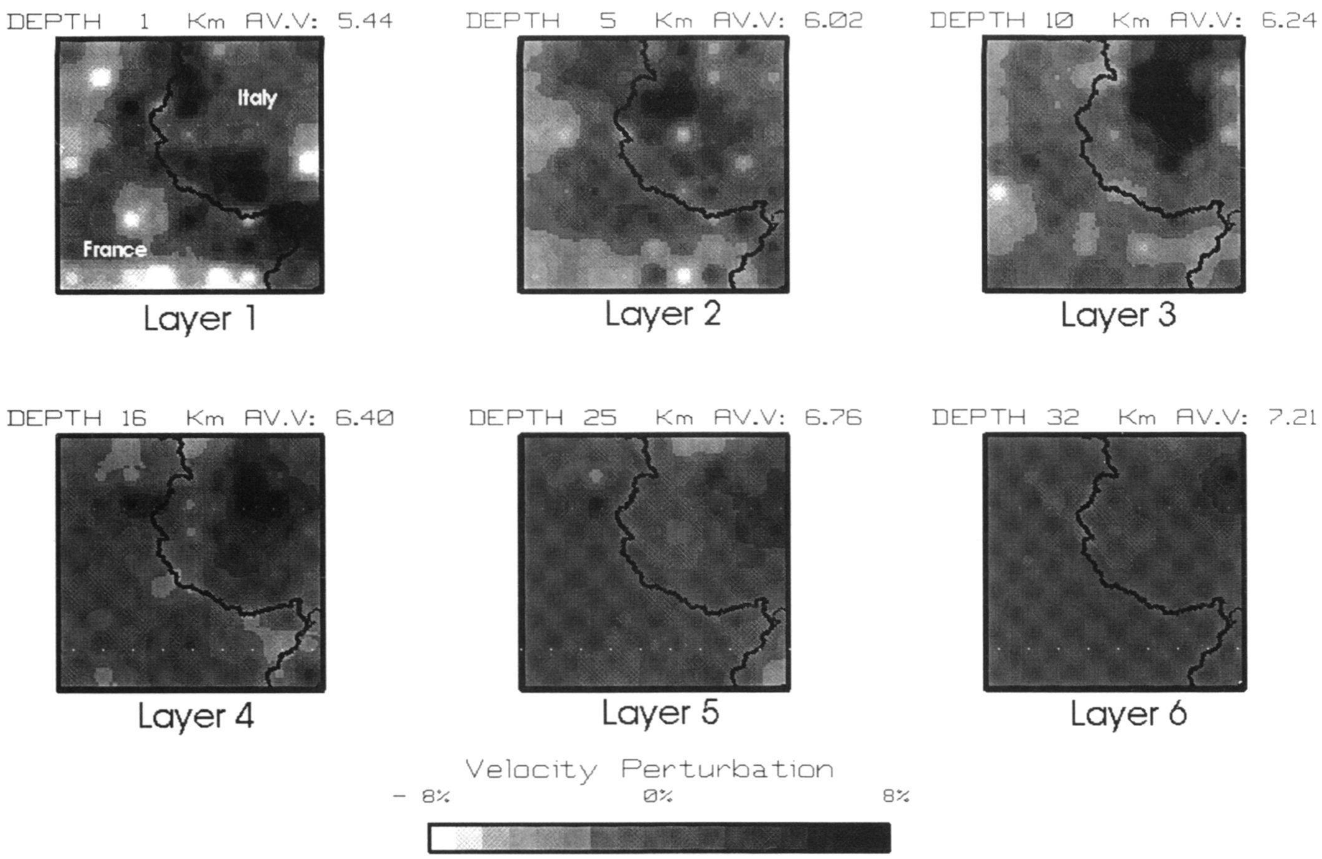

Fig. 7. Results of tomographic inversion of selected local earthquake data in map view for six layers from top (upper left) to bottom (lower right) of 3-D model. Av.v.: averaged velocity for each layer in Km/s.

model with 7 crustal layers, an average crustal velocity of 6.5 km and a Moho depth of 38 km as our initial reference model for seismic tomography.

During the period 1982–1993 the seismological service in Genova (DiSTer) and neighbouring seismological centers recorded several thousands of events up to magnitude 3.8 in northwestern Italy (Fig. 3) on their permanent and temporary seismic networks (Fig. 4). The station coverage is not homogeneous nor does it completely cover the Western Alpine area, although it is rather dense in the area of the southern end of the Bouguer gravity anomaly associated with the Ivrea body (see Fig. 2). Within the area of this study around Cuneo, 600 events in the depth range from the surface down to 30 km were selected (Fig. 5) with a total of 9412 P- and 8701 S-wave observations from stations shown in Figure 4. Selection criteria were a minimal number of 8 P-wave observations and a gap smaller than 180° (which means that the epicenter must lie within the station network).

Underdetermination of the inverse tomographic problem is commonly treated by application of damped least squares where the damping parameters relate to data and model variance (Ellsworth 1977; Menke 1984). In this study P- and S-wave damping parameters for the iterative inverse process have been selected using an approach by Eberhart-Phillips (1986), where the best damping value is defined by greatly reducing residual data variance while only moderately increasing solution variance. Appropriate damping values of 140 ($s^2\%^2$) for P and 280 ($s^2\%^2$) for S are derived from the results of single-step inversions with fixed hypocenters for a damping ranging from 20 to 900 (see Fig. 6).

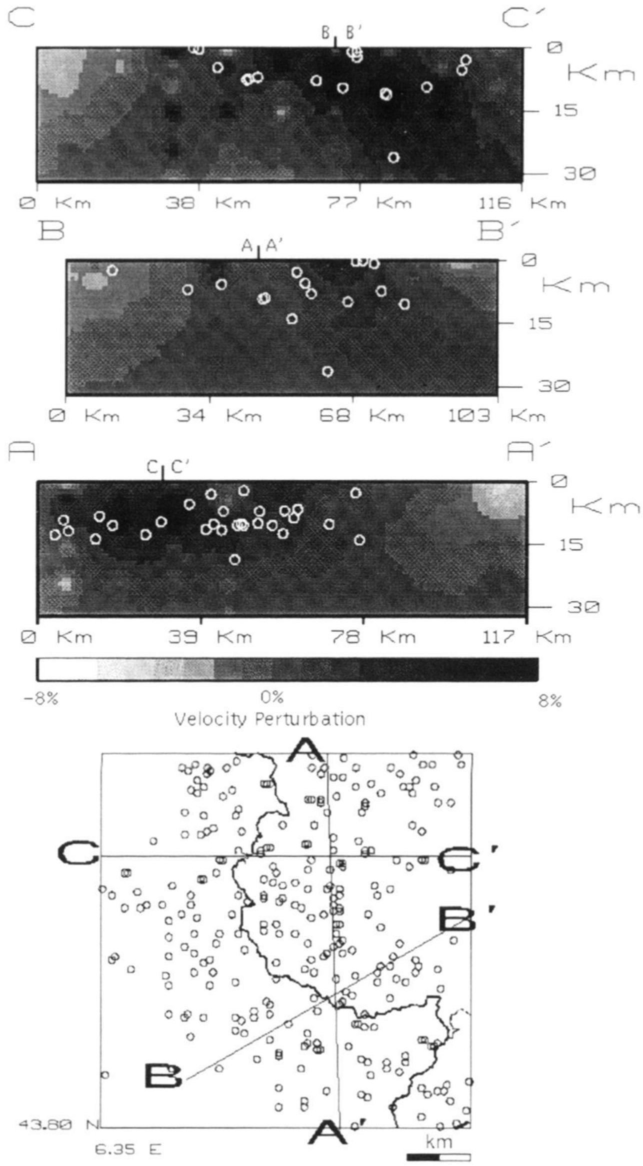

Fig. 8. Three vertical cross sections displaying results of tomographic inversion of selected local earthquake data. For geographical location of cross sections see figure 2. White circles denote hypocenters located within 5 km of profile.

Tomographic results

The 3-D P-wave velocity structure (Fig. 7, 8 and 9) results from 3 iterations simultaneously inverting for velocity and hypocentral parameters. S-wave observations have been used to constrain the hypocentral part of the inverse problem by S-P travel times with a constant Poisson's ratio of 1.73. The overall variance reduction was 50% from an initial value, as calculated for the Minimum 1D model, of 0.099 (sec^2). Ray coverage for the Cuneo area is uniformly good for a depth range from 5 km to 25 km only. Due to uneven distribution of stations and hypocenters, ray coverage in the top layer is heterogeneous and the resolution in the bottom layer is generally poor.

Not surprisingly, the 3-D velocity structure in the crust below Cuneo area is dominated by the Ivrea body, which appears as a high-velocity zone in the depth range from 7 km to 20 km in the north-eastern quadrant (Fig. 7). The average P-wave velocity of 7 km/s found in this zone corresponds well with velocities derived by earlier refraction seismic experiments on the Ivrea body (Ansorge 1968; Berckhemer 1968; Nadir 1988). Within layers 2, 3 and 4 (depth range from 5 km to 16 km) no further strong lateral velocity anomalies seem to be present in this part of the Western Alpine crust.

In Figure 8, the general shape of the Ivrea body as an east dipping plate (W-E cross section C-C', Fig. 2 and 8) and the southern end of this high-velocity body (N-S cross section A-A', Fig. 8, at about profile distance 60 km) are easily recognized. A series of W-E cross sections (Fig. 9) reveal the shallowing of the bottom of the high-velocity zone from 30 km or more in the north to less than 10 km in the center of the study area. Figure 10 shows a schematic summary of the 3-D geometry.

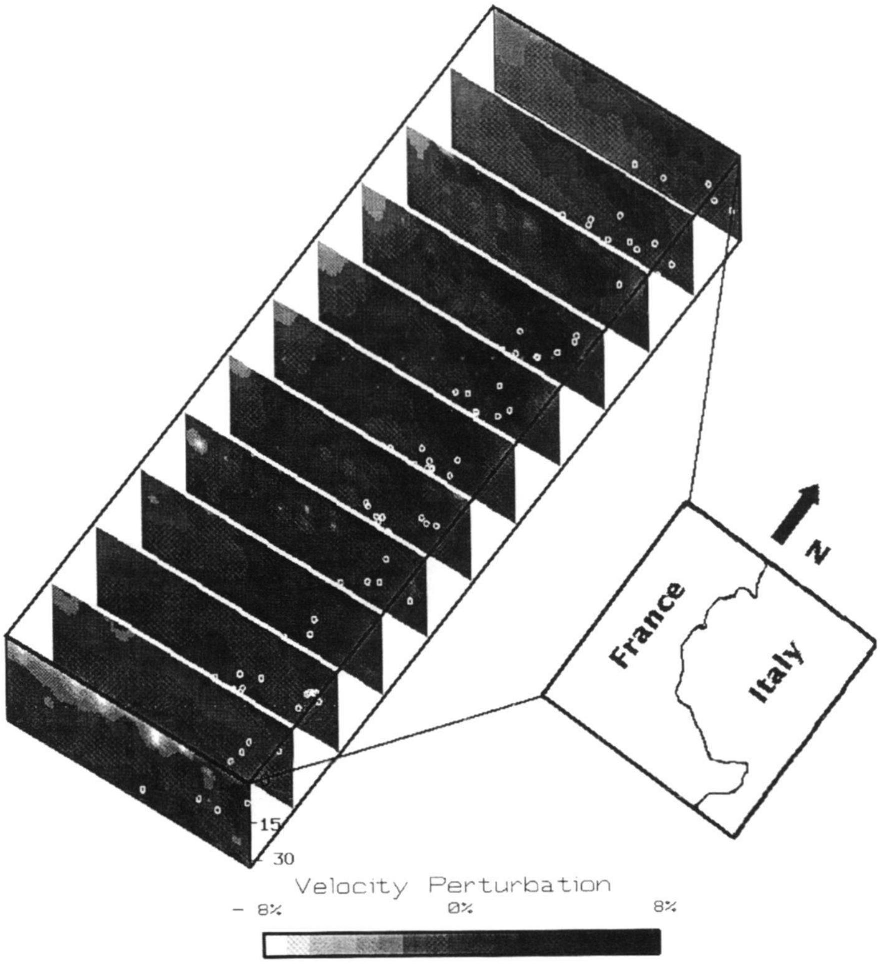

Fig. 9. Perspective view of series W-E cross sections through 3-D tomographic model.

The tomographic results of this study indicate that the southern Ivrea body is an approximately 20 km thick plate dipping east at an angle of about 45°. While this plate reaches from the surface to depths below the studied volume in the northern part of the Cuneo area, the southern end of the Ivrea body is characterized by shallowing of the bottom of this plate (Fig. 10).

Discussion and conclusions

For deeper layers, the use of stations outside the Cuneo area increases the ray coverage and cross firing. Projection of anomalous velocities from outside the study area into the 3-D model is minimal for those layers containing many well-locatable hypocenters. With only a few earthquakes below 30 km depth, however, the results for layer 6 (Fig. 7, lower right corner) are less reliable than in the case for the upper layers, due to potential leakage problems (smearing effects as a result of few cross firing). Reliable results are obtained for layers 2 through 5 (depth range of 5 km to 25 km).

Due to reduced cross firing, i.e., smaller numbers of crossing ray paths, resolution in bordering layers is generally not as good as in the interior of the model. As a result of uneven station and epicenter distributions the resolution in the top layer (Fig. 7, upper left corner) of our model varies from poor to fair. The narrow zone of strongly reduced P-wave velocity along the southern bounds of the model, and in particular, the single-block anomalies in the first layer are probably artifacts, poorly resolved, and should be disregarded. The high-velocity anomaly in the SE corner of the first layer possibly reflects high-velocity rocks associated with the Argentera massif, although the geometry of this anomaly is poorly resolved. In order to better define the near-surface velocity structure of this area, high-resolution controlled-source seismology data need to be acquired.

The geographical location and the shape, for upper crustal material, of the exceptionally high-velocity anomalies (up to 8–9%), in layers 3 and 4 (Fig. 7, upper right and lower left corner, respectively) coincide with the very strong positive gravity anomaly associated with the Ivrea body (Fig. 2). This is a clear

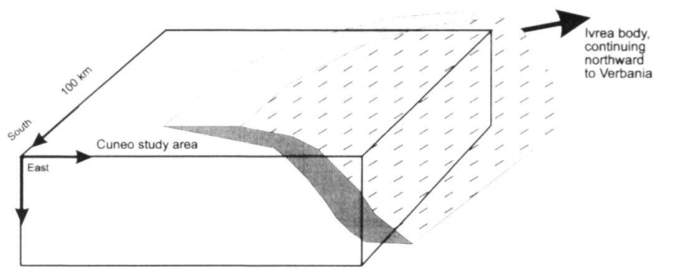

Fig. 10. Schematic 3-D model of the southernmost part of Ivrea body as interpreted from tomographic results.

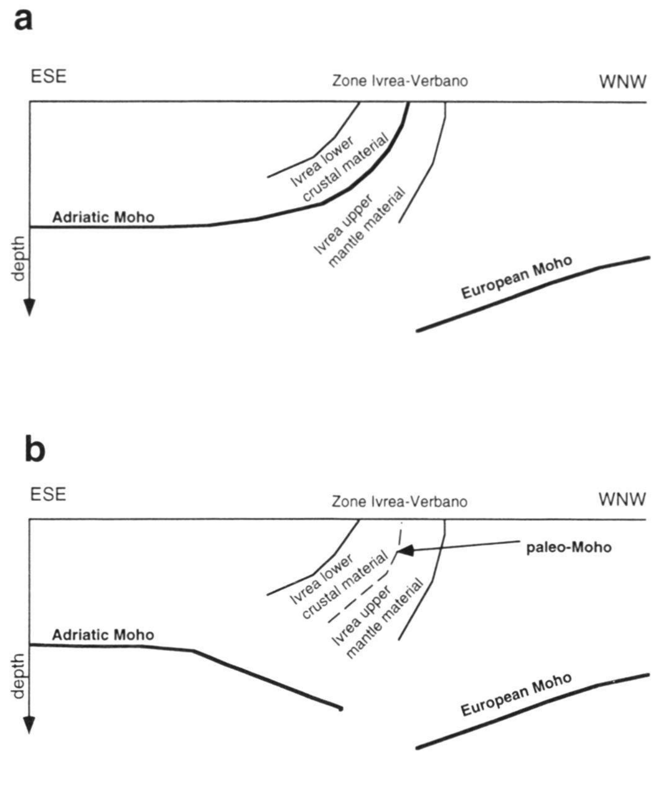

Fig. 11. Cartoon illustrating the possible relation between Ivrea body, Adriatic Moho and Adriatic upper mantle. a: present Adriatic Moho outcropping in Ivrea zone, b: outcropping paleo-Moho in Ivrea zone disconnected from present-day Adriatic Moho

indication that the tomographically determined high-velocity body beneath the Dora Maira (Bigi et al. 1990) reflects the southernmost part of the geophysical Ivrea body which continues toward north beyond our study area (Fig. 10). In their reviews, Menard & Thouvenot (1987) and Kissling (1993) concluded that the apparent discrepancies between magnetic, gravimetric and seismic Ivrea models were probably due to insufficiencies in the geophysical methods. Our results document the potential of seismic tomography using local earthquake data to illuminate and outline complex 3-D subsurface structure. We have imaged the high-velocity, high-density Ivrea body as an approximately 20 km thick plate dipping at an angle of about 40° to 50° to the E. At its southern end, the bottom of this plate shallows from deeper than 30 km depth to less than 10 km depth (Fig. 10). The zone of high seismic activity in the Cuneo region (Fig. 3) roughly correlates with the high-velocity Ivrea body.

The tomographic results reported in this study are in general agreement with earlier findings and further constrain the geometry of the Ivrea body at its southern end. Our tomographic results outline the 3-D geometry of the geophysical Ivrea body at depth and may provide new arguments to the discussion about a possible Moho outcrop within the zone Ivrea-Verbano (see, f.e., Brodie & Rutter 1987; Zingg et al. 1990). If the high-density, high-velocity Ivrea body would be in direct contact with the present-day Adriatic uppermost mantle and if the present seismic Adriatic Moho could be shown to shallow from beneath the Po plain toward the west and within the Ivrea body, the zone Ivrea-Verbano would most likely represent a cross-section of lower continental crust and upper mantle separated by a young seismic-petrologic Moho (see Fig. 11a). On the other hand, the interpretation of an outcropping paleo-Moho (Zingg et al. 1990) would be more likely, if the Ivrea body could be shown to be separated from the present-day Adriatic mantle and if the Adriatic Moho could be continuously traced beneath the Ivrea body (Fig. 11b).

Based on a review of controlled-source seismic data, Kissling (1993) argues that, in its northern part the Ivrea body overlies an offset seismic Moho while at its southern end the Ivrea gravity anomaly extends into an area, where a smooth transition between the European and Adriatic Moho at approximately 40 km to 35 km depth, respectively, is suggested. Our tomographic results clearly show a shallowing of the high-velocity Ivrea body at its southernmost end (Fig. 10) where the Ivrea body overlies an Adriatic middle crust of normal seismic velocity. Further to the North and partly still within our small area of study, the Ivrea body reaches from a few hundred meters below the surface down to lower crustal depths and possibly even across the present Adriatic seismic Moho. Results of teleseismic tomography may be interpreted to show a direct connection between the Adriatic mantle and the high-velocity Ivrea body in its central part (Solarino et al. 1996), though the resolution of this kind of data is insufficient to clearly resolve such details.

The 3-D geometry of the southernmost end is not representative for the Ivrea body in its northern parts. Bigi et al. (1990) propose a tectonic line (Fig. 1, southward continuation of the Insubric line) cutting from NW to SE across the Ivrea gravity anomaly beneath the Po plain sediments (compare with Bouguer gravity map, Fig. 2). However, the coincidence of the gravity anomaly with the high-velocity seismic anomaly in the upper crust and the shape of the gravity anomaly (Fig. 2) prohibit a large offset of the southernmost part from the main

Ivrea body, although a vertical displacement may not be ruled out. Whatever the exact shape and depth extent of the central and northern part of the Ivrea body might be, our tomographic results clearly show the southernmost part of the high-density, high-velocity Ivrea body confined to upper crustal levels in an area where the present-day Adriatic seismic Moho is subhorizontal at about 35 km depth. Thus, our results favor the interpretation by Zingg et al. (1990) that a paleo-Moho with no contact to the present-day Adriatic Moho is outcropping in the zone Ivrea-Verbano.

Acknowledgments

This study is part of a PhD thesis (by S.S.) supported by Universita' degli Studi di Genova. We thank R. Freeman for helpful suggestions. We greatly profited and thankfully acknowledge the thourough reviews by S. Schmid (Basel) and W.L. Ellsworth (Menlo Park). We are indebted to E. Eva (Genova) for her precious cooperation. This work has partly been supported by the Swiss National Science Foundation project no. 21-37661.93.

REFERENCES

AKI, K. & LEE, W.H.K. 1976: Determination of three-dimensional velocity anomalies under a seismic array using first P-arrival times from local earthquakes, 1, A homogeneous initial model. J. Geophys. Res. 81, 4381–4399.

ANSORGE, J., 1968: Die Struktur der Erdkruste an der Westflanke der Zone von Ivrea. Schweiz. mineral. petrogr. Mitt. 48, 247–254.

BERCKHEMER, H. 1968: Topographie des «Ivrea-Körpers», abgeleitet aus seismischen und gravimetrischen Daten. German Research Group for Explosion Seismology. Schweiz. mineral. petrogr. Mitt. 48, 235–246.

BIGI, G., CASTELLARIN, A., COLI, M., DAL PIAZ, G.V., SARTORI, R., SCANDONE, P. & VAI, G.B. 1990: Progetto finalizzato geodinamica: structural model of Italy. Scientific Coordination and Editing: BIGI, G., COSENTINO, D., PAROTTO, M., SARTORI, R. & SCANDONE, P. Consiglio Nazionale delle Ricerche, 1983. S.E.L.C.A., Florence, 1990.

BLUNDELL, D., FREEMAN, R. & MUELLER, ST. (eds), 1992: A Continent Revealed, The European Geotraverse, Cambridge Univ. Press, Cambridge UK.

BRODIE, K.H. & RUTTER, E.H. 1987: Deep crustal extensional faulting in the Ivrea Zone of Northern Italy. Tectonophysics 140, 193–212.

BUROLLET, P., DAL PIAZ, G.V., FRANKE, W. & TRÜMPY, R. 1992: Atlas map 1: Tectonics. In: A Continent Revealed, The European Geotraverse. (Ed. by BLUNDELL, D., FREEMAN, R. & MUELLER, ST.) Cambridge Univ. Press, Cambridge UK.

CATTANEO, M. & EVA, C. 1990: Propagation anomalies in Northwestern Italy by inversion of teleseismic residuals. Terra Nova 2, 577–584.

EBERHART-PHILIPS, D. 1986: Three-dimensional velocity structure in northern California coast ranges from inversion of local earthquakes. Bull. Seismol. Soc. Am. 76, 1025–1052.

ELLSWORTH, W.L. 1977: Three-dimensional structure of the crust and mantle beneath the island of Hawaii. Ph.D. thesis, Mass. Inst. of Technol., Cambridge.

KISSLING, E. 1984: Three-dimensional gravity model of the northern Ivrea-Verbano zone. In: Geomagnetic and Gravimetric Studies of the Ivrea Zone. (Ed. by J.-J. WAGNER & ST. MUELLER) Matér. Géol. Suisse, Géophys. 21, 55–61.

– 1988: Geotomography with local earthquake data. Rev. Geophys. 26, 659–698.

– 1993: Deep structure of the Alps – what do we really know? Phys. Earth Plan. Int., 79, 87–112.

KISSLING, E., ELLSWORTH, W.L., EBERHART-PHILLIPS, D. & KRADOLFER, U. 1994: Initial reference models in local earthquake tomography. J. Geophys. Res. 99, 19635–19646.

KISSLING, E., SOLARINO, S. & CATTANEO, M. 1995: Improved seismic velocity reference model from local earthquake data in northwestern Italy. Terra Nova 7, 528–534.

KLINGELÉ, E., LAHMEYER, B. & FREEMAN, R. 1994: Atlas map 9: Gravity Anomaly Map: Bouguer Anomalies. In: A Continent Revealed, The European Geotraverse. (Ed. by BLUNDELL, D., FREEMAN, R., & MUELLER, ST.), Cambridge Univ. Press, Cambridge UK.

MÉNARD, G. & THOUVENOT, F. 1987: Coupes équilibrées crustales: méthodologie et application aux Alpes occidentales. Geodinamica Acta (Paris) 1, 35–45.

MENKE, W. 1984: The resolving power of cross-borehole tomography. Geophys. Res. Lettr. 11, 105–108.

NADIR, S. 1988: Structure de la croute continentale entre les Alpes occidentales et les Alpes Ligures et ondes S dans la croute continentale a l'ouest du Bassin de Paris. Ph.D. thesis, Univ. Paris VII.

POLINO, R., DAL PIAZ, G.V. & GOSSO, G. 1990: Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny in the Alps. In: Deep structure of the Alps. (Ed. by ROURE, F., HEITZMANN, P. & POLINO, R.). Soc. Géol. de France Mém. 156, Soc. Géol. de Suisse Mém. 1, Soc. Geol. Italiana, Vol. spec. 1, 345–367.

SCHMID, S.M., ZINGG, A. & HANDY, M. 1987: The kinematics of movements along the Insubric Line and the emplacement of the Ivrea Zone. Tectonophysics 135, 47–66.

SCHMID, S.M., FROITZHEIM, N., KISSLING, E., PFIFFNER, A. & SCHOENBORN, G. in press: Integrated geophysical-geological transect and tectonic evolution of the eastern Central Alps. In: Deep structure of Switzerland, NFP20 Atlas (Ed. by LEHNER, P. et al.), Kümmerly & Frey, Bern, Switzerland.

SOLARINO, S. 1994: Tomografia Sismica su Strutture crostali e Lito-Astenosferiche dell'Italia Nord Occidentale. Ph.D. thesis, University of Genova, Italy.

SOLARINO, S., SPALLAROSSA, D., PAROLAI, S., CATTANEO, M. & EVA, C. 1996: Lithoasthenospheric structures as inferred by teleseismic waves tomography. Tectonophysics 260/4, 271–290.

THURBER, C.H. 1983: Earthquake locations and three-dimensional crustal structure in the Coyote Lake area, central California. J. Geophys. Res. 88, 8226–8236.

WAGNER, J.J. & MUELLER, S. (eds.) 1984: Geomagnetic and gravimetric studies of the Ivrea zone. Mat. Géol. Suisse, Géophysique 21, Kümmerly & Frey, Bern, Switzerland.

ZINGG, A., HANDY, M., HUNZIKER, J.C. & SCHMID, S.M. 1990: Tectonometamorphic history of the Ivrea Zone and its relationship to the crustal evolution of the Southern Alps. Tectonophysics 182, 169–192.

Manuscript received December 6, 1995
Revision accepted March 3, 1997