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# First seismic evidence for continental subduction beneath the Western Alps

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## ABSTRACT

**The first discovery of ultrahigh-pressure coesite in the European Alps 30 years ago led to the inference that a positively buoyant continental crust can be subducted to mantle depth; this had been considered impossible since the advent of the plate tectonics concepts. Although continental subduction is now widely accepted, there remains debate because there is little direct (geophysical) evidence of a link between exhumed coesite at the surface and subducted continental crust at depth. Here we provide the first seismic evidence for continental crust at 75 km depth that is clearly connected with the European crust exactly along the transect where coesite was found at the surface. Our data also provide evidence for a thick suture zone with downward-decreasing seismic velocities, demonstrating that the European lower crust underthrusts the Adriatic mantle. These findings, from one of the best-preserved and long-studied ultrahigh-pressure orogens worldwide, shed decisive new light on geodynamic processes along convergent continental margins.**

## INTRODUCTION

The subduction of the continental lithosphere in the mantle has long been considered as unlikely because of the positive buoyancy of the continental crust (McKenzie, 1969). The first conclusive evidence in support of burial (and exhumation) of the continental crust to depths >90 km was provided by the discovery of coesite-bearing metamorphic rocks in the Dora Maira massif of the Western Alps (Chopin, 1984). Since then, even though similar outcrops of exhumed high-pressure to ultrahigh-pressure (HP-UHP) rocks have been recognized worldwide (Guillot et al., 2009), direct seismic evidence for subduction of the continental crust in the mantle of the upper plate is rare (Roecker, 1982; Sippl et al., 2013; Schneider et al., 2013). Such conclusive seismic evidence for the burial of the European crust below the Adriatic mantle is lacking for the Alpine belt.

The Alpine belt resulted from the collision of the European plate with the Adriatic microplate in the Paleogene Period. Its curve-shaped western termination is where the concept of continental subduction was defined. The Western Alps are the only continental UHP orogen worldwide that has preserved in full the metamorphic, structural, and stratigraphic record of subduction and exhumation, and for which plate motion constraints are also available (Malusà et al., 2011).

Traveltime tomography studies at regional and global scales have revealed high-velocity anomalies in the Alpine upper mantle that were interpreted as traces of subducting slabs (Piromallo and Morelli, 2003; Lippitsch et al., 2003). There is, however, no direct evidence relating to the nature of these slabs (continental or oceanic), and the debate has focused on comparisons between the lengths of the high-velocity slabs and the estimated amount of convergence at the trench (Piromallo and Faccenna, 2004). None of the controlled-source seismic experiments carried out in the Alps (Fig. 1) have succeeded in imaging the European continental crust subducting in the Adriatic upper mantle. For example, the ECORS-CROP wide-angle experiment imaged the European Moho at a maximum depth of 55 km beneath the internal zones (ECORS-CROP Deep Seismic Sounding Group, 1989). The lack of direct evidence for the presence of the Adriatic mantle above the deep European Moho led to contrast-

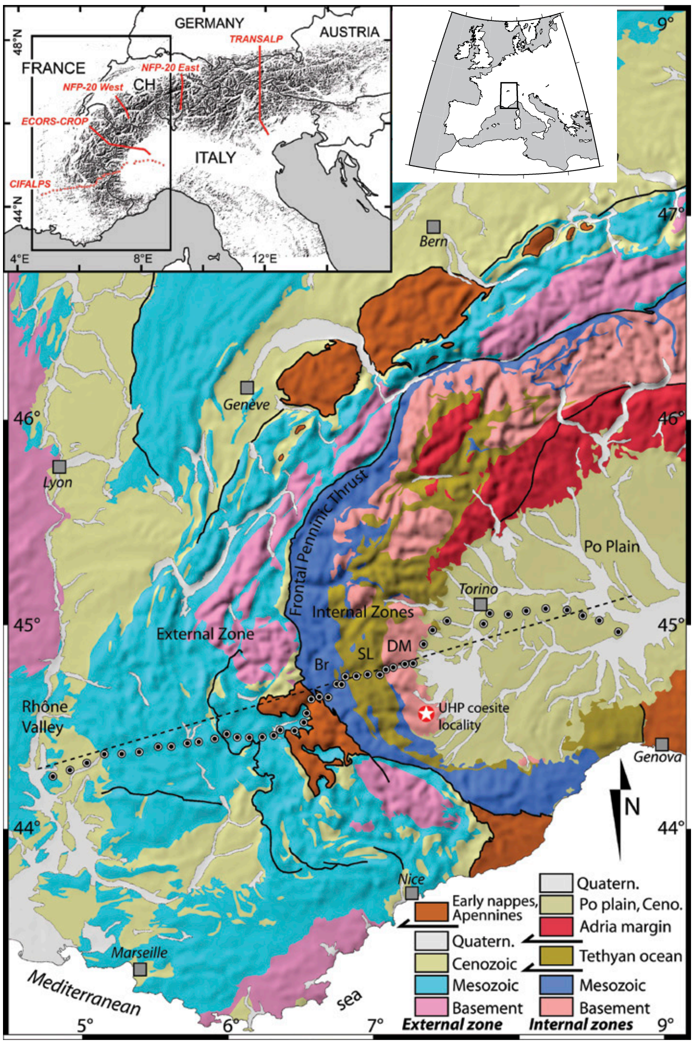


**Figure 1. Location of the seismic array on a geological map of the Western Alps. Black circles show seismic stations; dashed line is reference profile used in projections. Large inset: Locations of the previous main seismic experiments in the Alps. Small inset: Location of the study area. CH—Switzerland; UHP—ultrahigh pressure; NFP—Nationales Forschungsprogramm (Swiss National Science project); CIFALPS—China-Italy-France Alps seismic survey; Br—Briançonnais; DM—Dora Maira; SL—schistes lustrés; Quatern.—Quaternary; Ceno.—Cenozoic.**

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ing interpretations of the seismic data (Nicolas et al., 1990; Schmid and Kissling, 2000). Thirty years after the discovery of coesite (Chopin, 1984), we present here the first seismic evidence for the subduction of the European crust in the Adriatic mantle beneath the Dora Maira massif.

## SEISMIC IMAGING

The China-Italy-France Alps seismic survey (CIFALPS) was the first passive seismic transect to crosscut the entire orogen across the Dora Maira massif (Fig. 1). Temporary broadband seismic stations (n = 46) were deployed along a linear WSW-ENE transect with spacing from 5 km in the central part, where the ECORS-CROP reflection profile failed to image the European Moho (Nicolas et al., 1990), to 10 km at each end (Fig. 1). The stations were operated from July 2012 to September 2013.

To image the crustal structures along the profile, we used the P receiver function technique that enhances P to S (Ps) converted waves on velocity interfaces beneath an array in the records of teleseismic earthquakes (Langston, 1979). A radial receiver function was computed for each three-component record of a distant earthquake by deconvolution of the vertical component from the radial. This processing removes the earthquake source signature and travel-path effects from the source to beneath the recording station. The time delay between the converted P to S wave and the direct P wave is proportional to the depth of the converting interface and the average velocity structure above it. The receiver function records were stacked and migrated from time to depth using the common conversion point (CCP; Zhu, 2000) method to produce a depth section of Ps converted phases along the profile (details on the method are provided in the GSA Data Repository[1]). Because the polarity of the converted signal depends on the sign of the velocity change, interfaces with velocity increases with depth are easily discriminated from those with velocity decreases.

In the CCP image of Figure 2, the European Moho is continuously traced as a strong-amplitude positive-polarity converted phase (Fig. 2B, black line) that dips gently to the east-northeast from ~35 km at the western end of the profile, to ~40 km beneath the Frontal Penninic thrust (Fig. 2E). The amplitude of the Moho conversion weakens beneath the internal zones, while its southeastward dip increases from <5° to >20°. A weak but reliable conversion from the European Moho reaches a maximum depth of 75 km beneath the Dora Maira massif and the westernmost Po Plain, in continuity with the Moho converted phase of the external zone (Fig. 2B). This feature is clearer using receiver functions from events with east-northeast backazimuths, due to the amplification of the Ps converted phases for waves that propagate in the updip direction (Fig. DR3 in the Data Repository).

A thick spot of Ps conversions with negative polarity (Fig. 2B, dashed line) and strong amplitudes is present between 20 km and 60 km depth beneath the Dora Maira massif and the westernmost Po Plain. This is located above the weak positive conversion of the European Moho and below the strong shallow positive signals that coincide with the Bouguer anomaly high (Fig. 2A, red curve) associated with the so-called Ivrea body (Closs and Labrouste, 1963). The spatial coincidence between the Bouguer anomaly high and the 10–15 km depth of these positive Ps phases led us to interpret them as the image of the top of the Ivrea body. Because early seismic studies reported high velocities (Vp = 7.4 km $s^{-1}$) at 10 km depth in the Ivrea body (Closs and Labrouste, 1963), these Ps phases were interpreted as a slice of Adriatic mantle at the upper crustal depth (Nicolas et al., 1990). The shallow positive Ps phases at 10–15 km depth are likely to have been generated by the downward velocity increases from the crustal rocks of the Dora Maira massif to the Ivrea body mantle slice.

At greater depths, the CCP section shows a thick set of Ps conversions of negative polarity that correspond to downward velocity decreases between the Ivrea body mantle slice on top and the European lower crust underneath. Our CCP image thus provides evidence for an inverted Moho structure (Bostock et al., 2002). Similar strongly dipping structures with a negative Ps phase on top of a positive Ps phase have been interpreted as evidence for subduction of the continental lower crust (Schneider et al., 2013; Chevrot et al., 2015). In the Alps, our images are the first compelling evidence for continental subduction of the European lithosphere (lower crust and uppermost mantle) within the Adriatic mantle.

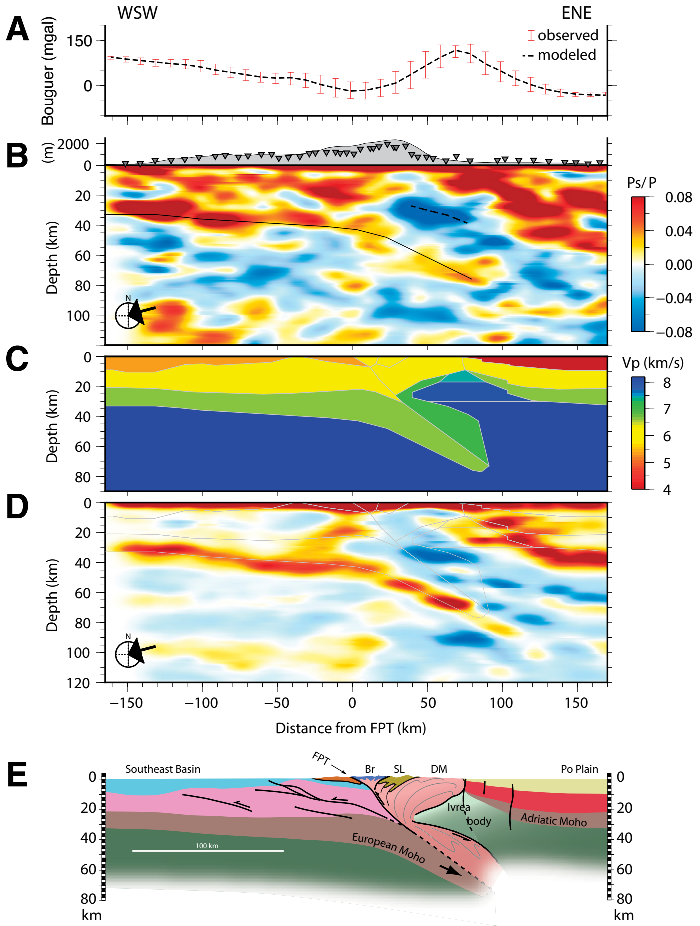


**Figure 2. Common conversion point (CCP) migrated depth section projected onto the reference profile (Fig. 1). A: Observed (for details, see the Data Repository [see footnote 1]) and modeled (as indicated) Bouguer gravity anomaly. B: CCP depth section computed from teleseismic events in the northeast quadrant. Positive and negative Ps phases are shown in red and blue, respectively, according to color scale (right). Continuous black line is the European Moho. Dashed black line is the inverted Moho. Topography (gray-filled curve) and station locations (black inverted triangles) are shown at top. C: Preferred two-dimensional velocity and gravity model. Density scale is proportional to the velocity (Vp) scale (Fig. DR4; see footnote 1). D: Synthetic CCP depth section computed for the preferred model and northeast backazimuths. The layer boundaries of the input model are shown (light gray lines). E: Interpretation of the crustal-scale geological cross section, using the same color legend as in Figure 1. Arrows in B and D indicate range of event backazimuths (28°–118°) used in CCP stacking. Br—Briançonnais; DM—Dora Maira; FPT—Frontal Penninic thrust; SL—schistes lustrés.**

## INTERPRETATION

Our receiver function section is, however, different from images recorded in other mountain belts. While relatively thin strips of negative Ps phases parallel to the Moho conversion are a signature of continental subduction in the Pamir and Pyrenees (Schneider et al., 2013; Chevrot et al.,

[1]GSA Data Repository item 2015276, details on the methods and on the interpretative model, Figures DR1–DR5, and Tables DR1 and DR2, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

2015), we observe a broad blue spot (Fig. 2B) that is 70 km wide and 40 km thick. The broad set of negative conversions results from interactions of the incident wave with a wide and thick wedge between the subducted European lower crust and the Adriatic Moho. Thus, we interpret the blue spot in Figure 2B as the image of the thick suture zone between Europe and Adria, which includes the former accretionary wedge, HP-UHP exhumed slices of European lower crust, the serpentinite channel, and the hydrated mantle wedge that includes the Ivrea body (Malusà et al., 2011; Lardeaux et al., 2006).

## BUILDING AND TESTING THE DENSITY-VELOCITY INTERPRETATIVE MODEL

The simplest explanation for the thick blue spot in Figure 2B is a set of Ps conversions on multiple interfaces with downward velocity decreases. To test this hypothesis, we computed synthetic receiver functions in two-dimensional forward models of the lithospheric structure (for details on the method, see the Data Repository). The CCP depth section provides basic elements on the geometry of the main layer boundaries and the velocity contrasts (e.g., European Moho, top of Ivrea body, inverted Moho). Additional data on the crustal structure that were available along our profile and in neighboring regions were used to better constrain the geometry of a set of possible two-dimensional models.

In the internal Alps, we built our crustal model based on the results of the 1958–1960 seismic experiments in the western Alps (Closs and Labrouste, 1963), and the local earthquake tomography (Paul et al., 2001), complemented by the sequential inversion of the local earthquake travel-times and gravity anomaly (Vernant et al., 2002) of the GeoFrance-3D experiments. Since the 1960s (Closs and Labrouste, 1963), we have known that the shallowest part of the Ivrea surface (i.e., the top surface of the Ivrea body) is located at 10 km depth and x = 70–80 km along our profile. At this depth, the P-wave velocity measured by refraction in the Ivrea body was 7.4 km $s^{-1}$. The shape of the Ivrea body in our model mimics the shape of the high-velocity–high-density body imaged along an east-west profile located slightly south of our array (Vernant et al., 2002). To account for a likely velocity increase with depth in the Ivrea body (due to a likely decrease in the volume ratio of serpentinite to peridotite), we divided the body into two parts at an arbitrary depth of 17 km. The lower boundary of the Ivrea body, which corresponds to the transition from serpentinized peridotite to peridotite, was set at 30 km in depth. This is both the depth of the Adriatic Moho to the north-northeast (see the Data Repository) and the average depth of the inverted Moho in the CCP section to the west-southwest. The geological input to the final interpretative model was also important (Figs. 2C and 2E), and in particular the locations where the HP–UHP metamorphic rocks cropped out at the surface.

After constructing the model geometry (for information on the western and eastern parts of the model, see the Data Repository), density contrasts were adjusted to fit the observed Bouguer anomaly (Fig. DR4; Table DR2). We computed synthetic receiver functions for a large set of models, which were processed to obtain the CCP depth-migrated stacks.

## DISCUSSION AND CONCLUSIONS

Our preferred two-dimensional model and the corresponding CCP section are shown in Figures 2C and 2D. The assumption that underpins this model is that a broad east-west–elongated body of hydrated mantle akin to the Ivrea body indents a thick wedge of HP-UHP metamorphosed European crust of lower velocity that crops out in the Dora Maira massif. The lower boundary of the Ivrea body roughly corresponds to the center of the observed blue spot of negative conversions (Fig. 2B). This boundary with the downward velocity decrease produces a negative Ps phase, which combines with the deeper downward velocity decreases at the top of the European lower crust, to generate a thick stripe of negative signal. This two-dimensional model reproduces the major features of the observed CCP section much better than a model with a homogeneous high-velocity mantle wedge (Fig. DR5). The broad set of negative conversions is most likely to be the image of a thick subduction complex with, from top to bottom, the Ivrea body of hydrated mantle, a thick slice of metamorphosed HP-UHP rocks of European origin, and the European lower crust. Figure 2E shows the crustal-scale cross section of the southwestern Alps that we propose, based on the interpretation of our seismic data and geological data (Handy et al., 2010, and references therein).

The Ps converted phases at a maximum depth of 75 km that are connected with the European Moho are the deepest Moho signature recognized in the Alps. The conversion on the strongly dipping European Moho has a weaker amplitude in the observations than in the synthetics, which might be due to the onset of eclogitization of the lower crust at depths >40 km (van Keken et al., 2011). This amplitude change is beneath the Frontal Penninic thrust, in a location similar to the abrupt disappearance of the reflective lower crust (and Moho reflection) in the ECORS-CROP section (Nicolas et al., 1990). This coincidence suggests that the lack of reflected signals from the deep crust beneath the internal zone in the ECORS-CROP section is due to a change in the intrinsic properties of the European Moho rather than to a signal penetration problem.

Picking the lower boundary of the thick set of negative Ps phases as the top of the subducted European crust provides a maximum estimate of 10–20 km for the thickness of the subducted crust (Fig. 2B). The thickness of the normal European crust in the foreland is 30 km (Waldhauser et al., 1998); therefore, either a significant part of the initial crust has not subducted, and/or the crust involved in the subduction was previously thinned at the continental margin (Manatschal, 2004).

The suture zone between the top of the subducted lower European crust and the Adriatic Moho is 40 km thick and is characterized by negative Ps converted phases that are indicative of downward decreasing velocities from the Ivrea body on top, to the European lower crust beneath. In our model, the Ivrea body is divided into two parts, with velocities and densities corresponding to peridotite with 60% serpentinite in the upper part, and peridotite with 30% serpentinite in the lower part (Reynard, 2013) (Table DR2). In the space between the bottom of the Ivrea body and the top of the subducted lower crust, a correct fit to the seismic data requires a P-wave velocity of peridotite with 45% serpentinite. We, however, favor the hypothesis of a thick wedge of HP-UHP metamorphic rocks that is more consistent with the volume of the subduction complex exposed at the surface (Fig. 1) and with the geometry predicted by thermomechanical models of Alpine-type orogens (Jamieson and Beaumont, 2013). The connection established between the best-preserved surface outcrop of UHP metamorphic rocks and the seismic image of subducted continental lithosphere with a crust-mantle boundary at 75 km depth provides decisive proof of the concept of continental subduction.

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**Notes**