Seismic evidence for continental subduction beneath the Western Alps

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Abstract

The occurrence of continental ultra-high pressure metamorphic minerals such as coesite in continental collision belts implies that continental crust was buried to mantle depths as large as 100 km in spite of its positive buoyancy. In the Western Alps, where coesite was first discovered, seismic imaging however failed to provide direct evidence for deep subduction of continental crust. Here, we use new seismic data showing that the European Moho continuously extends to a maximum depth of 80 km 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, proving that the European lower crust underthrusts the Adriatic mantle. Our observations support the geodynamic model that the Alps is a subduction belt with a thick suture zone that was generated by the subduction and exhumation of the European continental margin, followed by indentation of the Adriatic metamorphic wedge.

One sentence summary: We provide the first seismic evidence for subduction of the European continental crust in the Adriatic mantle in the region where the concept of continental subduction was defined.

Main text

The subduction of continental lithosphere in the mantle has long been considered as unlikely because of the positive buoyancy of continental crust (*1*). The first conclusive evidence in support of the burial (and exhumation) of continental crust to depths larger than 90 km was provided by the discovery of coesite-bearing metamorphic rocks in the Dora Maira massif of the Western Alps (*2*). Since then, even though similar outcrops of exhumed high-pressure to ultra-high pressure (HP-UHP) rocks have been recognized worldwide (*3*), direct seismic evidences for subduction of continental crust in the mantle of the upper plate remain rare (*4-6*). Such conclusive seismic evidence for the burial of European crust below the Adriatic mantle is lacking for the Alpine belt.

The Alpine belt results from the collision of the European plate with the Adriatic microplate in early Tertiary times. Its curved-shaped western termination is the place where the concept of continental subduction was defined. Compared to other major mountain belts such as the Himalaya or the Andes, the Alps are special in that HP-UHP rock exposures represent half of the belt width (Fig. 1), suggesting that the records of subduction processes are exceptionally well preserved. A number of travel-time 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 (*7*, *8*). There is however no direct clue on the nature of these slabs (continental or oceanic) and the debate has focused on comparisons between the length of the high-velocity slabs and estimated amounts of convergence at the trench (*9*). None of the controlled-source seismic experiments carried out in the Alps (Fig. 1) 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 (*10*). The lack of direct evidence for the presence of Adriatic mantle above the deep European Moho led to contrasting interpretations of the seismic data (*11*, *12*). Thirty years after the discovery of coesite (*2*), we here present the first seismic evidence for the subduction of European crust in the Adriatic mantle beneath the Dora Maira massif.

We used data of a new, dense, 350-km long seismic transect crosscutting the entire orogen across the Dora Maira massif (Fig. 1; supplementary text S1). 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 the array in records of teleseismic earthquakes (supplementary text S1). Receiver function records are stacked and migrated from time to depth using the common conversion point method (hereafter referred to as CCP) to produce a depth section of Ps converted phases along the profile (supplementary text S2). As the polarity of the converted signal depends on the sign of the velocity change, interfaces with velocity increase with depth are easily discriminated from those with velocity decrease.

In the CCP image of Fig. 2, the European Moho is continuously traced as a strong amplitude positive-polarity converted phase (of red color) dipping gently to the ENE from ~35 km at the western end of the profile, to ~40 km beneath the Frontal Penninic thrust (FPT). The amplitude of the Moho conversion weakens beneath the internal zones while its southeastward dip increases from less than 5° to more than 20°. A weak but reliable conversion from the European Moho shows up down to a maximum depth of 80 km beneath the Dora Maira massif and westernmost Po plain in continuity with the Moho converted phase of the external zone (Fig. 2). This feature is clearer in Fig. 2d using receiver functions from events with east-northeast backazimuths due to the amplification of Ps converted phases for wave propagating in the updip direction (supplementary text S3). Beneath the Po plain, strong reverberations within the shallow low-velocity layers contaminate the Adriatic Moho signal (Fig. 2c). Comparing our CCP image to additional geophysical data including gravity modelling, however, allows us to pick the Adriatic Moho with some confidence (supplementary text S4). The Adriatic Moho can be roughly traced at ca. 20-35 km depth beneath the Po plain.

A thick spot of Ps conversions with negative polarity (blue color in Fig. 2c) and strong amplitudes shows up between 20 and 60 km depth beneath the Dora Maira massif and the westernmost Po plain. It is located above the weak positive conversion of the European Moho and below strong shallow positive signals that coincide with the Bouguer anomaly high (red curve in Fig. 2a) associated with the so-called “Ivrea body” (*13*). The spatial coincidence with the high Bouguer anomaly, 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. As early seismic studies reported high velocities (Vp=7.4 km.s^{-1}) at 10 km depth in the Ivrea body (*13*), it has been interpreted as a slice of Adriatic mantle at upper crustal depth (*11*). The shallow positive Ps at 10-15 km depth are likely generated by the downward velocity increase from the crustal rocks of the Dora Maira massif to the Ivrea body mantle slice. At greater depths, the CCP section displays a thick set of Ps conversions of negative polarity corresponding to downward velocity decreases between the Ivrea body mantle slice on top and the European lower crust at the bottom. Our CCP image thus provides evidence for an “inverted Moho” (*14*). Similar strongly dipping structures with a negative Ps on top of a positive one were interpreted as evidences for subduction of continental lower crust (*3*, *15*). In the Alps, our image is the first compelling evidence for continental subduction of the European lower crust within the Adriatic mantle.

Our receiver-function section is however different from images recorded in other mountain belts. While rather thin stripes of negative Ps phases parallel to the Moho conversion are the signature of continental subduction in the Pamir and the Pyrenees (*3*, *15*), we observe a broad blue spot 70 km wide and 40 km thick (Fig. 2c and supplementary Fig. S3). The broad set of negative conversions results from the interaction of the incident wave with a wide and thick wedge in-between the subducted European lower crust and the Adriatic upper mantle. Thus, we interpret the blue spot of Fig. 2c as the image of the thick suture zone between Europe and Adria including the former accretionary wedge, HP-UHP exhumed slices of European lower crust, the serpentinite channel and the hydrated mantle wedge including the Ivrea body (*16*, *17*).

The simplest explanation for the thick blue spot 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 (Supplementary text S4). The CCP depth section provides basic elements on the geometry of the main layer boundaries and velocity contrasts. Additional data on the crustal structure available along our profile and in neighbouring regions were used to better constrain the geometry of a set of possible 2-D models (Supplementary text S4). Then, density contrasts were adjusted to fit the observed Bouguer anomaly (*18*). Finally, we computed synthetic receiver functions for a large set of models, which were processed to obtain CCP depth migrated stacks.

Our preferred 2-D model (Fig. 2d) and the corresponding CCP section are displayed in Fig. 2e. The assumption underpinning 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, which outcrops 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. This boundary with downward velocity decrease produces a negative Ps phase, which combines with the deeper downward velocity decrease at the top of the European lower crust to generate a thick strip of negative signal. This 2-D model reproduces the major features of the observed CCP section. We tested another model with a homogeneous high-velocity mantle wedge that does not fit with our observations (Fig. S6). This comparison proves that multiple interfaces between layers with downward velocity decreases are required to explain the thick inverted Moho observed in our CCP section. They are most likely 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.

Fig. 2f shows the interpreted crustal-scale cross-section of the southwestern Alps that we propose based on the schematic crustal model of Fig. 2d. This model results from the picking of velocity boundaries in the CCP section, crosschecked with seismic (Fig. 2b) and gravity modelling. The geological data have been of decisive input in the interpreted section of Fig. 2f (*19*).

The converted phases at a maximum depth of 80 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 weaker amplitude in the observations than in the synthetics, which may be due to onset of eclogitization of the lower crust at depths greater than 40 km (*20*). This amplitude change is located beneath the FPT, in a similar location as the abrupt disappearance of the reflective lower crust (and Moho reflection) in the ECORS-CROP section (*11*). This coincidence suggests that the lack of reflected signals from the deep crust beneath the internal zone in the ECORS-CROP section is rather due to a change in the intrinsic properties of the European Moho than to a signal penetration problem.

We picked the lower boundary of the thick set of negative Ps phases as the top of the subducted European crust (Fig. 2c). This provides a maximum estimate of 10 to 20 km for the thickness of the subducted crust. As the thickness of the 'normal' European crust in the foreland is 30 km (*21*), either a significant part of the initial crust is not subducted, and/or the crust involved in the subduction was previously thinned at the continental margin (*22*).

The suture zone between the top of the subducted lower European crust and the Adriatic Moho is 40-km thick and characterized by negative converted phases indicative of downward decreasing velocities from the Ivrea body on top to the European lower crust at the bottom. In our model, the Ivrea body is divided in 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 (*23*). 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 P-wave velocity of peridotite with 45% of serpentinite. We however favor the hypothesis of a thick wedge of HP-UHP metamorphic rocks which is more consistent with the volume of the subduction complex exposed at the surface (Fig. 1), and with the geometry predicted by thermo-mechanical models of Alpine-type orogens (*24*).

References and Notes

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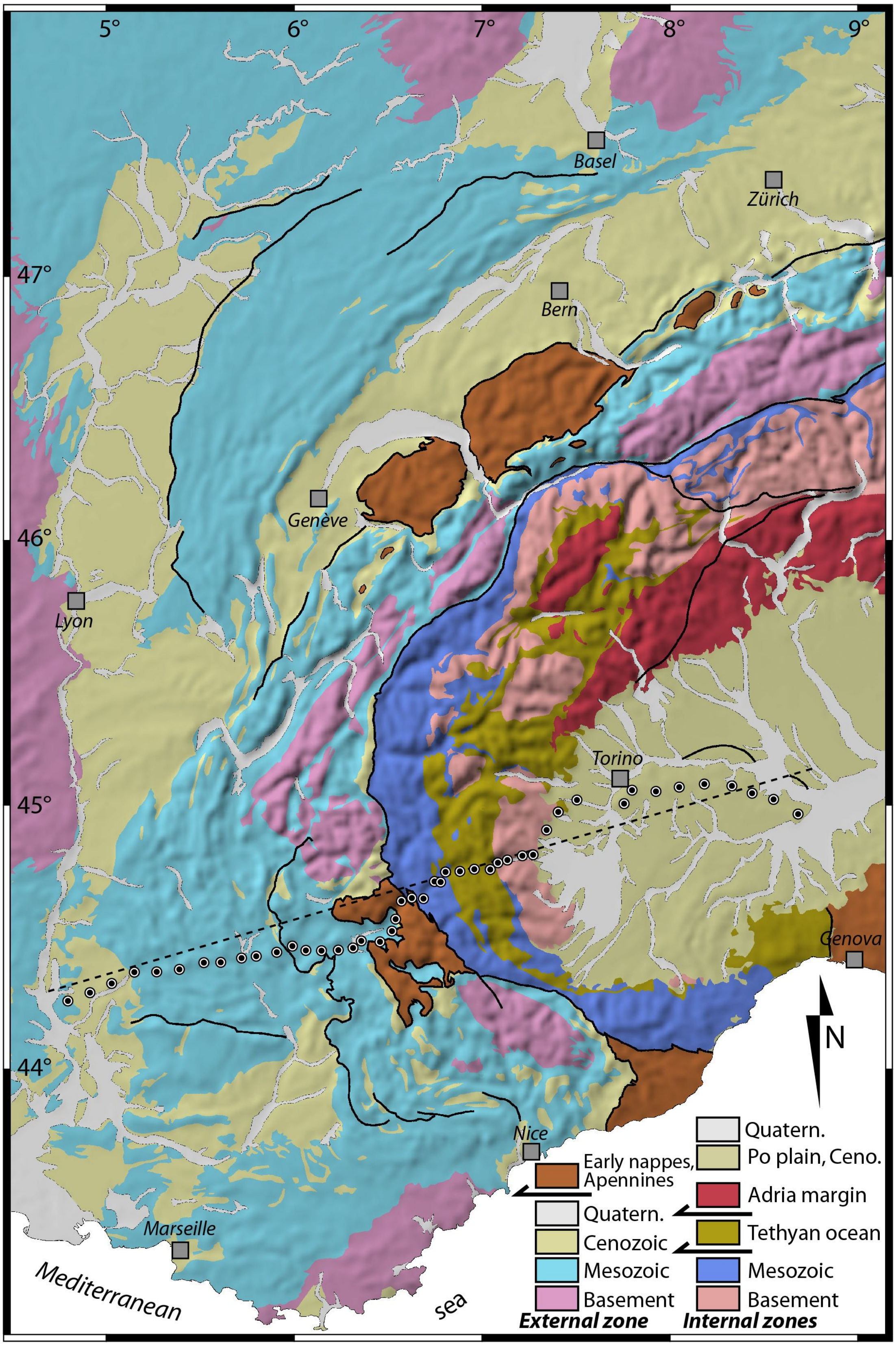

Fig. 1. Location of the seismic array on a geological map of the Western Alps.

Seismic sections shown as black circles. The dash line is the N73° reference profile used in projections.

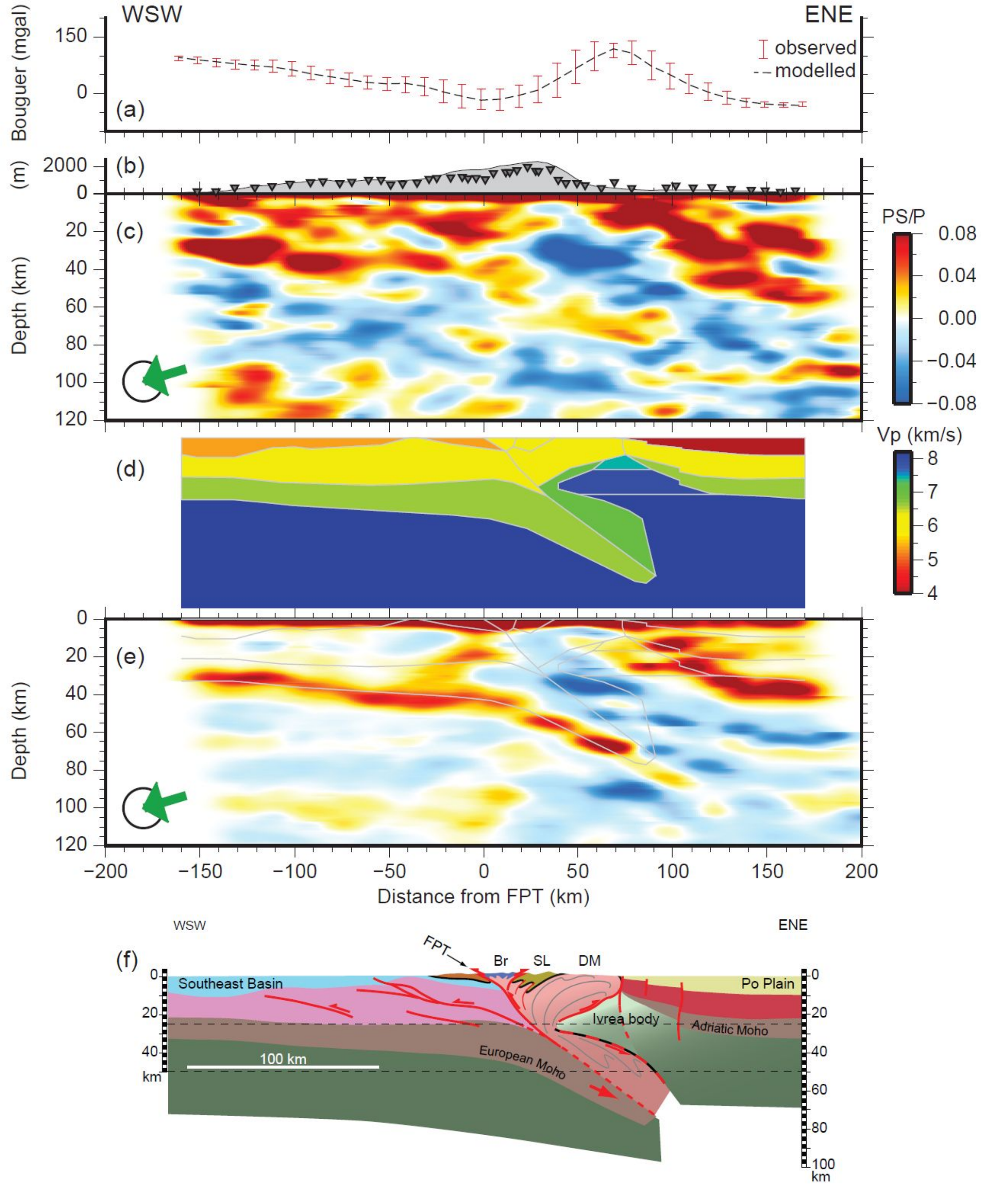

Fig. 2. Common-conversion-point (CCP) migrated depth section projected onto the reference profile (Fig. 1). (a) Bouguer gravity anomaly (*18*). (b) Topography and station locations. (c) CCP depth section computed from teleseismic events in the NE quadrant (backazimuths 28° - 118). Positive and negative Ps phases are shown in red

and blue colors, respectively. (d) Preferred 2-D velocity and gravity model. (e) Synthetic CCP depth section computed for the preferred model and NE backazimuths. The layer boundaries of the input model are plotted as light grey lines. (f) Interpretative crustal-scale cross-section. Br: Briançonnais; DM: Dora Maira; FPT: Frontal Penninic Thrust; SL: Schistes lustres.