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Mapping the Moho of the Western Alps by wide-angle reflection seismics

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Abstract

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A new picture of the Moho beneath the Western Alps could be obtained using wide-angle reflection seismic data. This picture, in addition to its increased sharpness, clearly shows how the Moho deepens down to the root zone of the chain (55 km). A 25–30 km deep reflector with upper mantle characteristics is discovered under the Briançonnais zone where it overlies the autochthonous Moho. This unit does not seem to connect to the so-called "Ivrea body", situated much shallower and farther into the chain. It supports a hypothetical flaking of the European lithosphere beneath the Western Alps. Farther east, the Moho beneath the Po Plain is clearly mapped too, with a crustal thickness increasing in steps from 25 to 35 km. This P-wave Moho picture is compared with an S-wave picture, and major differences appearing in the middle crust are discussed. Finally, the seismic response of the Moho is investigated, and is shown to be shifted towards low frequencies in the inner zones of the chain. This could partly explain why the ECORS–CROP vertical seismic line, equipped with high-frequency geophones, faltered over the identification of the deep Alpine Moho.

Introduction

Any tectonic process is likely to leave imprints on the Moho boundary since it is, beyond doubt, the major seismic marker in the continental lithosphere. The seismic characteristics of that interface, and also its position, topography, smoothness and continuity are amongst many keys that help to unravel the regional geodynamical evolution. Recent evidence indicates that, at least for extensional areas in a high heat-flow context, the Moho may migrate, flatten and re-adjust to restore a kind of lateral homogeneity. What happens in regions of tectonic convergence, such as those of recent orogenes, still has to be demonstrated.

In the Western Alps, the broad lines of the deep structure were already drawn more than two decades ago (Closs and Labrouste, 1963; Choudhury, Giese and de Visintini, 1971; Perrier, 1973; Giese and Prodehl, 1976; Miller, Müller and Perrier, 1982). Despite the scarcity of the data, tentative isobath charts of the Moho were sketched (Perrier, 1973; Giese and Prodehl, 1976), showing a smooth Moho dipping gently from the periphery towards the inner zones. The root zone— the zone of maximum crustal thickness— was found be-

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neath the Briançonnais, with depths between 45 and 60 km.

Of course, that pioneering work was carried out against a gravimetric background. The gravity high which underlines the limit between the Alps and the Po Plain from Locarno to Cuneo did capture the attention of geophysicists long before any deep seismic measurements could be made (Niggli, 1946). Thus the detection by the early profiles of the so-called "Ivrea body"—anomalous upper mantle—actually emerged as the corroboration of gravity evidence. Neither the top depth of this shallow mafic and ultramafic structure, nor its velocity of 7.4 km/s, which was estimated in the assumption of horizontal layering, could be reliably documented.

The experiment

Our attempt at a seismic cross-section of the lithosphere of the Western Alps was stimulated by the need to obtain preliminary data in order to prepare the layout of a vertical reflection profile through the Alps, subsequently referred to as the ECORS–CROP line (Etude de la Croûte Continentale et Océanique par Réflexion et Réfraction Sismiques and Crosta Profunda). This French–Italian program, completed in 1986, continues the efforts to adapt the lithospheric studies the vertical seismic profiling method widely used in oil prospecting (Barazangi and Brown, 1986a, b; Matthews and Smith, 1987), but with further difficulties caused by extreme crustal heterogeneity, strong dips and considerable crustal thicknesses (Bayer et al., 1987; ECORS–CROP Working Group, 1988).

The experiment designed in 1985, although with a much looser spatial resolution, used a wide-angle profiling method (Hirn et al., 1980, 1984a, b), specifically aimed at the Moho and deep reflective levels. One-ton charges were detonated at five places (Fig. 1) and more than 60 autonomous recorders equipped with low-frequency geophones (1–2 Hz) were spread out for each shot, with a 4–5 km interval between the sensors. About two-thirds of these sensors recorded the shots along fan profiles; the remaining third was laid out along in-line profiles from the shotpoint up to 150 km to the northeast (the local strike of the Alpine arc), in order to control the velocity–depth distribution in the upper crust.

This paper is mainly concerned with the fan data. To benefit from the theoretical maximum of the amplitude reached by interface reflections at critical distance and beyond, i.e. when total reflection occurs, the radii of the fans were chosen to sample deep reflectors in the 30–60 km depth range. Moreover, because the Moho depth was expected to increase under the inner parts, we consequently increased the radii of the fans from 90 km up to 130 km. The shortest radius—only 40 km—was selected in the Ivrea zone where shallow reflectors were expected. An average 4 km station spacing along fans allows the reflectors to be sampled at every 2 km (mirror points shown as open triangles in Fig. 1).

As the determination of the average crustal velocity would need reflections from a flat Moho to be observed along in-line profiles over a very large distance, we chose to compare our wide-angle reflection data with the vertical reflection data of the ECORS–CROP seismic profile (ECORS–CROP Working Group, 1988) in the external zone, where the Moho is supposed to be well-defined and almost flat. It yielded a value of at least 6.25 km/s, which was taken as the mean crustal velocity in the computation of the depth cross-sections. The absence of clear vertical reflections from the Moho in the Vibroseis data beneath the more internal zones prevents a direct comparison with wide-angle data farther east. Thus, the average crustal velocity is not necessarily constant across our sections. Since we actually measure the travel-times of the reflected wave at large distances, the depth values which can be derived should be varied by up to 5% if the velocity is changed locally by up to 2% (e.g. a depth of 37 km with a 6.25 km/s mean crustal velocity is changed to 34.8 km with a 6.1 km/s velocity). Larger changes, i.e. outside the 6.1–6.4 km/s range, are unlikely to occur, if our knowledge of the mean velocity in the European continental crust is correct.

The Moho topography

The fan data are displayed as two pseudo-cross-sections of the Alpine chain showing the

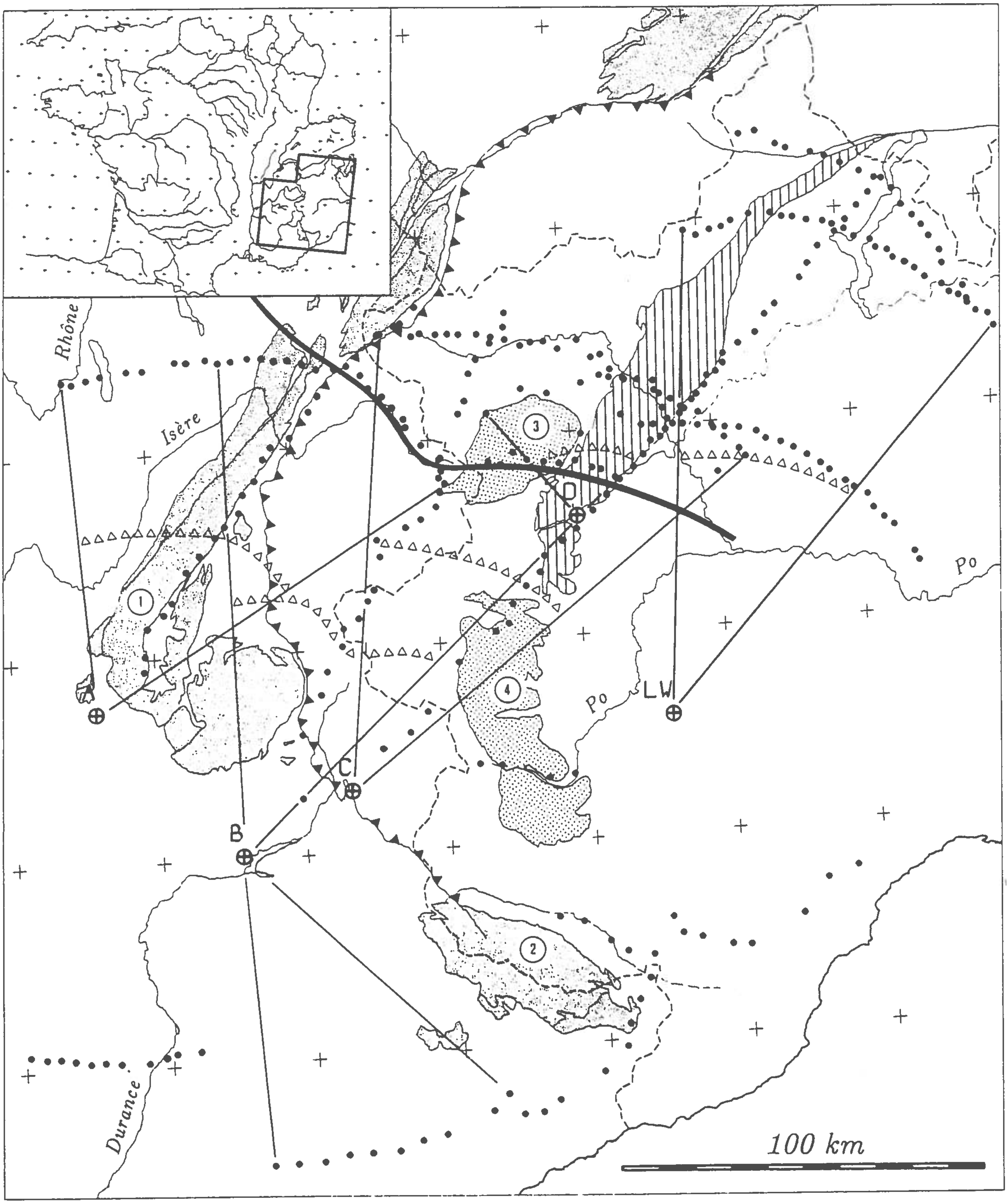

Fig. 1. Position map of the fan layout. Most shotpoints were recorded by stations (full circles) deployed along longitudinal profiles and fans. Open triangles indicate reflection points for the five fans used to build up Fig. 2. Shaded area—external crystalline massifs (*1*—Belledonne, *2*—Argentera); dotted area—internal crystalline massifs (*3*-Gran Paradiso, *4*—Dora Maira); hatched area—Sesia-Lanzo unit. The Penninic frontal thrust is identified by solid triangles. ECORS-CROP vertical reflection profile shown as a heavy line.

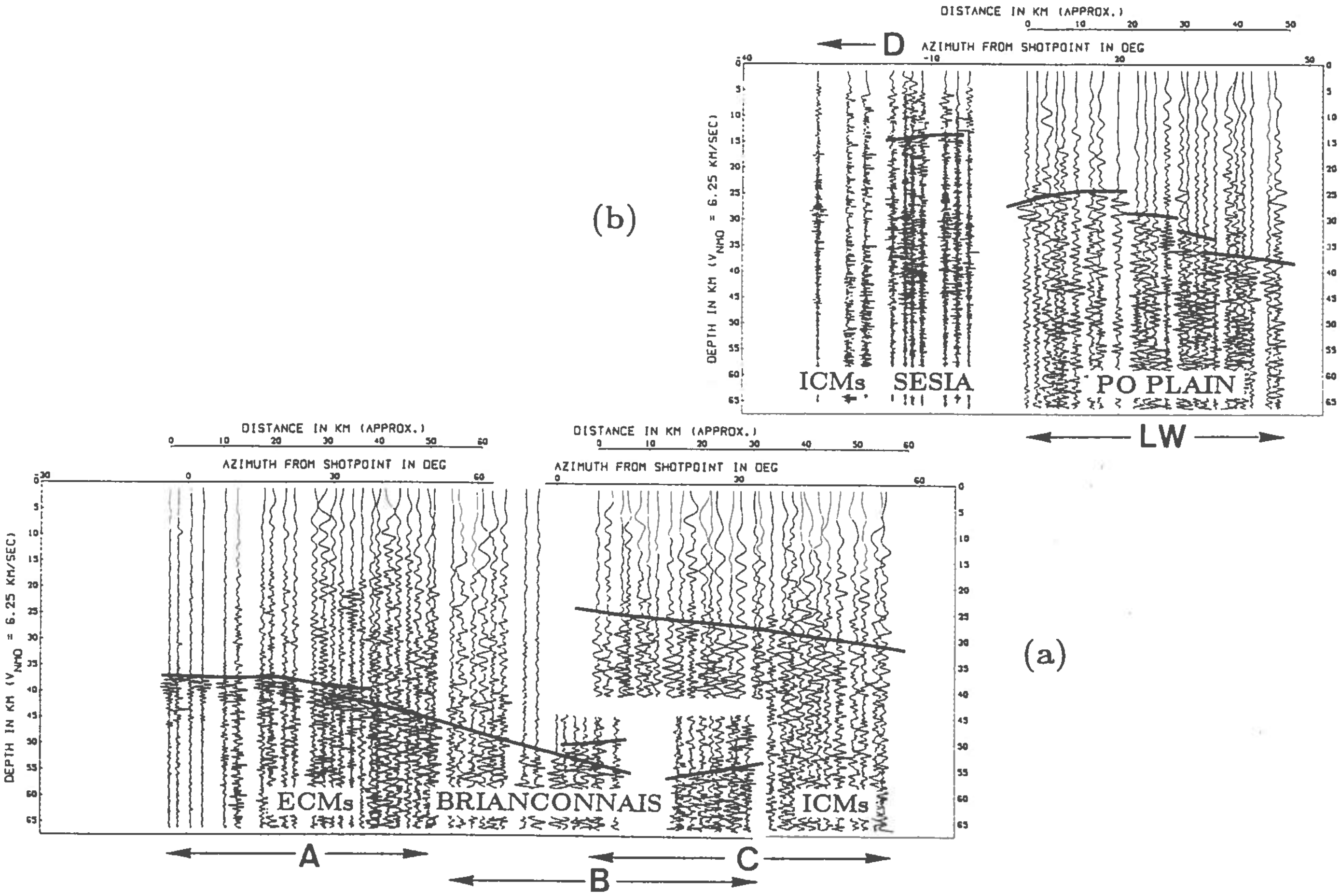

Fig. 2. Two pseudo-cross-sections of the Western Alps. (a) The three fan profiles from shotpoints A, B and C (see position on Fig. 1) are combined as a single record-section extending from the Chartreuse sub-Alpine massif (far left) to the Dora Maira Massif (far right). (b) This shorter section combines results from shotpoints D and LW and extends from the Gran Paradiso Massif (far left) to the Po Plain (far right).

topography of deep reflectors. The first section (Fig. 2a) begins 30 km west of the Belledonne External Crystalline Massif (ECM) and extends through the Briançonnais and Piedmontese zones to the east of the Dora Maira Internal Crystalline Massif (ICM); the other section (Fig. 2b), situated 40 km farther north, extends from the Gran Paradiso Massif to the Po Plain. This latter cross-section intersects the Ivrea South Alpine zone and the Insubric Line, which is believed to be the major suture boundary between the Apulian promontory of Africa and the stable Eurasia.

Large topographical variations of the Moho marker of over 20 km are evident, and dips reaching 30° and extending over distances of tens of kilometres are documented. In the ECM area, the changes in depth and dip do not occur smoothly as by a simple continuous flexure: almost horizontal at a depth of 37 km under the sub-Alpine massifs and the ECMs, the Moho dips abruptly at their eastern edge where the present-day maximum surface relief is found. Towards the innermost parts, under the Piedmontese zone and the Dora Maira ICM, it remains more or less at a deep level of 55 km.

This deep Moho is overlain by another seismic marker with high reflectivity, which may correspond to a crust–mantle boundary at shallow depths of only 25– 30 km, and extends westwards beneath the Piedmontese zone and the ICMs as far as the Briançonnais zone.

Since this shallow reflective zone is observed only for shot C, one is led to conclude that it is of limited extent: it does not reach the ECMs, and hence waves from shot B are not reflected from it, although they may propagate through it near the recording array, on their way upwards from the deep Moho. This screening effect might be also the explanation of the low-frequency content of the reflected-wave spectrum beneath the Brian-

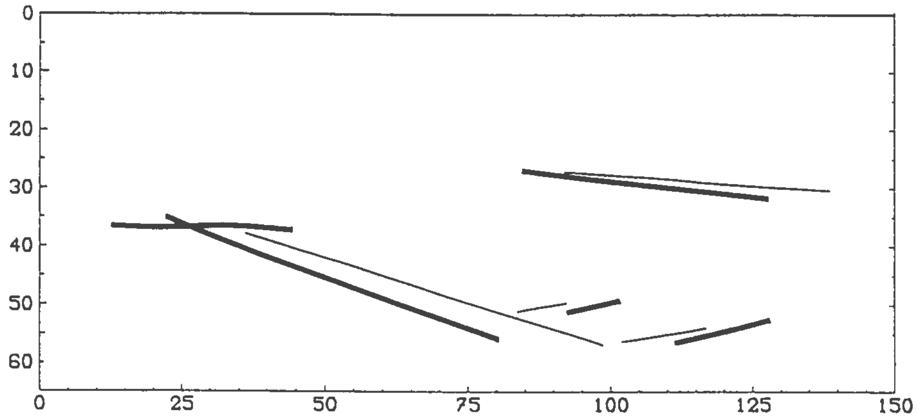

Fig. 3. Tentative migration of the section presented in Fig. 2a: light line—before migration; heavy line—after. Because the migration was performed by hand, only its qualitative effects, steepening of the Moho slope and widening of the root zone, are to be considered.

çonnais, with the shallow structure obliterating high frequencies. In a complementary way, waves from shot C are mainly screened by the shallow structure and the deep reflector is less clearly sampled as energy penetration is made more difficult. The geometry of the source–sensors layout is shown here to be of the utmost importance to enable the detection of such a feature.

Finally, the observed slight rise of the deep Moho from the root zone eastwards—about 3 km —might be insignificant. It could equally well result from a pull-up effect of the overlying mantle unit: the mean crustal velocity would then be slightly increased, which would consequently spoil our depth computations.

The hinterland Moho (Fig. 2b), more than 35 km deep under the Po Plain where thick Tertiary–Quaternary sequences occur, shallows in steps to less than 25 km approaching the Insubric Line. Across this zone, there remains a gap in the seismic data, so that one cannot rule out the existence of another high-velocity material uprising. The Sesia zone is also underlain by a strong reflector at a depth of only 13 km. It may indicate a crust–mantle boundary, but other deep reflectors in the same area make the continuation of the hinterland Moho this far west and this shallow questionable: in a zone close to the Lanzo Massif, where slices of lower crustal and upper mantle material have been brought up to the surface, reflective levels might indeed be rather discontinuous. Keeping this in mind, however, the simplest structural scheme is to link up the 13 km deep reflector discovered under the Sesia zone to the Po Plain Moho farther east.

Although a depth scale is used here, the sections presented in Fig. 2 are very similar in style to those derived from vertical reflection seismics. In the case of large dips, a migration would in fact be necessary to restore the reflectors to their true horizontal positions and depths. However, as the spatial sampling (the trace interval), is too inaccurate here to allow the use of a numerical method, a tentative migration by hand is illustrated in Fig. 3 (it assumes that reflectors can be decomposed into continuous straight segments). The main effect of this migration is to steepen the Moho slope by several degrees and to widen the root zone of the Alps.

The upper 20 kilometres

This Moho picture along the two sections of Fig. 2 is complemented, for the upper 20 km of the crust, by in-line data, decisive in this depth range since most of the fans were designed to observe much deeper reflectors. From the three western shotpoints, reflections recorded between 40 and 70 km in distance indicate interfaces situated in the 15–20 km depth range, at the base of the upper crust. However, with data sampling units as different as the ECMs, the Briançonnais zone and the ICMs, these interfaces may not have all the same significance: although in the same depth interval, it does not seem sensible to correlate them to define a horizontally layered intermediate crust across the Alpine arc. Surprisingly, the ECORS–CROP near-vertical reflection profile did not single out this depth interval as particularly reflective and continuous. As these shallow reflectors are detected close to the shotpoints, more than 50 km south of the vertical reflection line, this could be the effect of a structural variation along the strike of the Alps.

Shotpoint D, situated in the Lanzo ultramafic massif, was also recorded in-line along a profile stretching northwards through the Sesia unit (Fig. 1). The apparent velocity of first arrivals observed at short distances is significantly higher than in the western units. In a flat-layered model, this would indicate the presence of rocks of 6.3 km/s at only 5 km depth. Further velocity contrasts at approximately 15 and 25 km depth are needed to account for later reflections. (The short-range fan profile from shotpoint D has already detected a 13 km reflector, shown in Fig. 2b). This is the region near the top of the Ivrea gravimetric high, where mafic granulites and ultramafic rocks outcrop, and where former deep seismic experiments postulated the presence of lower crustal or anomalous upper mantle material only 5 to 10 km deep, with apparent velocities as high as 7.4 km/s. But, as the present profiles are non-reversed like all the previous ones, we have no better constraints on the exact velocities, depths and geometries of what definitely appears to be a high-velocity body.

Shear-wave imagery

Shear-wave observations are rare in crustal structure experiments: these experiments are very often carried out with vertical-component sensors only and, in any case, S-wave generation by explosions is generally ineffective. Here also, only stations on the fans were equipped with three-component seismometers. Fig. 4 shows an example of the western fan (shotpoint A) for S-waves recorded on horizontal components. To convert

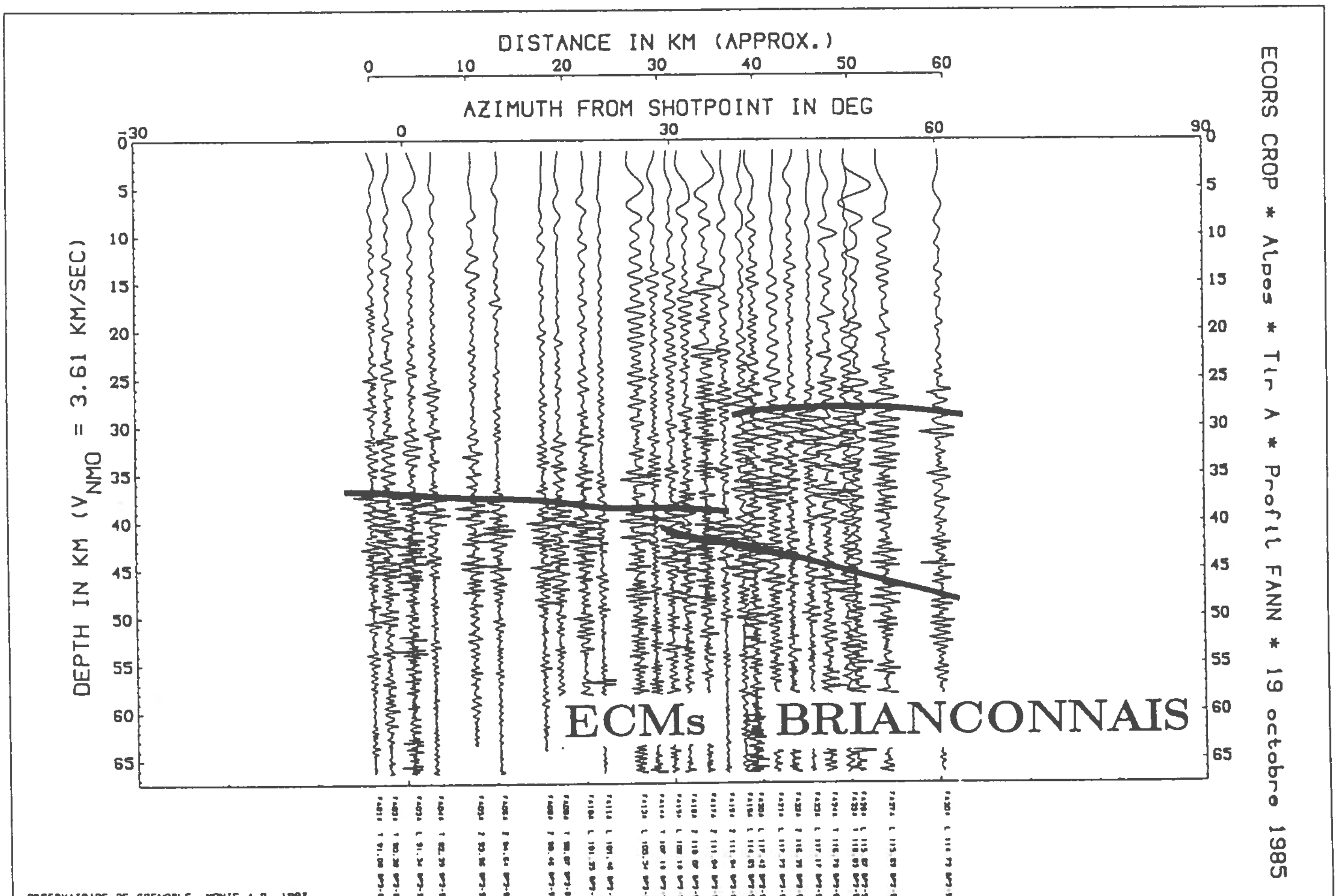

Fig. 4. The crust–mantle boundary in the external zone (far left on Fig. 2a), as seen from S-wave data. If the Moho image is almost identical to the one given by P-waves, a mid-crustal reflective zone is enhanced under the Briançonnais. This zone was more or less transparent for P-waves on Fig. 2a.

the time into the depth domain, we used a mean S-velocity of 3.6 km/s, which is in the usual $\sqrt{3}$ ratio to the 6.25 km/s P-velocity.

The Moho reflection looks very similar to the corresponding P-wave picture of Fig. 2a. But, amazingly, an intracrustal structure appears at around 30 km in depth. In the eastern part of the S-section, the amplitude of this reflection is even larger than the one referred to in the 20 km deeper Moho. This intracrustal reflector is here seen at a wide angle with S-waves and not at all with P-waves, a situation at variance with those reported in Britanny (Hirn et al, 1987) and the Black Forest (Holbrook, Gajewski and Prodehl, 1987). Strong P-reflections and the absence of S-reflections from within the crust in those regions could be accounted for by only a small increase—or even a decrease—of the S-velocity with depth in the middle crust, in contrast to a significant increase of the P-velocity with depth. This interpretation is supported by the probable increase of the Poisson ratio, σ, with depth when quartz-bearing upper crustal rocks (low σ) give way to more intermediate lower crustal materials (higher σ).

Since the situation is reversed at 25 km depth under the central part of the section through the Alps, one might then, on the other hand, think of a transition from intermediate mineralogy to upper crustal rocks with increasing depth. We would then have to appeal to a superposition of hinterland lower crust on top of foreland upper crust, which would achieve the observed crustal thickening. However, if such an interface could easily explain the absence of wide-angle P-reflections, the S-velocity would also decrease or only very slightly increase across it: in any case, the contrast would not be sufficient to generate the clear wide-angle reflections observed here.

An alternative suggestion for the situation in the Black Forest has been to imagine a cracked medium under low fluid saturation just above the interface, to increase the P- but not the S-velocity contrast (Holbrook, Gajewski and Prodehl, 1987). The enhanced S-reflectivity seen here under the Alps would, by analogy, demand a layer of low-S-velocity, fluid-saturated rock on top of the reflector. This might not be completely impossible if it can be interpreted as the base of a thick thrust zone. Clearly, basic original information is provided by the S-wave record, but the interpretation is far from being unique given the present state of general knowledge.

Azimuthal effects

In addition to the northern fans, a few stations were laid out to the south of the shotpoints along three shorter fans (Fig. 1). Although these fans do not join each other and we cannot speak here in terms of a continuous cross-section of the southern French Alps, this arrangement of stations allows qualitative comparisons with the data in the north.

Figure 5 illustrates how shot B was recorded southwards, with reflection points beneath the Digne nappe (Haute-Provence sub-Alpine chains). When comparing this section with the central part of the main northern section (Fig. 2a; shot B observed northwards), the Moho is found to be much shallower at approximately 38 km (vs. 55 km to the north). Of course, this could be expected, since here we sample the Moho in a very external position in the arc. Actually, it would be better to compare this value of 38 km with a similar depth of 37 km found for shot A northwards, with reflection points beneath the northern sub-Alpine chains (Fig. 2a, left).

However, if we again compare Fig. 6 with the central part of Fig. 2a (the same shot but with different reflection mirrors), a shift of the spectral content towards low frequencies can be observed for the northern fan. This peculiarity is clearly not related to any source effect since we are using the same shot. It evidently points to a change in the structure which can be caused by three phenomena: (1) a lateral change in the quality factor, i.e. the loss of high frequency by inelastic attenuation in the thickened crust; (2) an introduction towards the east of lamellation in the middle crust, thin layers of alternating high and low velocity which screen high frequencies from further penetration and may, for example, contribute to the enhancement of S-wave reflectivity as shown in Fig. 4; (3) a change of the Moho discontinuity to a complex transitional boundary reflecting only long wavelengths.

Discussion and conclusions

What emerges from this wide-angle reflection profiling is, first, the detailed geometry of the Moho, even in the innermost zones. Previous experiments sampled the Moho loosely, and only smooth variations could be mapped. Close-ups of the sections presented here show that this smooth picture can now be refined, as has already been suggested by a teleseismic prospecting of lithospheric contrasts beneath the Alps (Hirn et al., 1984c). This results mainly from the spatial resolution made available by the arrangement of the fans, which provided a 2 km sampling interval of the reflectors along the cross-sections.

The shallow reflective level discovered under the Briançonnais Zone has never been mapped previously, even if recent structural models of the Western Alps (Ménard and Thouvenot, 1984) have postulated such a feature. The presence of lower crustal or even upper mantle material would indicate a lithospheric thickening which occurred by tectonic superposition, with previously adjacent lithospheric segments having been thrusted onto each other. This would support the flaking of the European lithosphere under the Western Alps, and the importance of this point is worth a rapid comparison with the vertical reflection seismic data.

When we try to plot this shallow reflector onto the ECORS–CROP line drawing (ECORS–CROP Working Group, 1988), it is debatable which is the most proper way to do it. The wide-angle reflection points for shot C indeed fall at least 30 km off the vertical reflection line (Fig. 1), and each point can be projected onto the seismic line in very different ways (for instance, using a perpendicular to the line, or using the local strike of the chain), so that the reflector emplacement within the line drawing remains approximate.

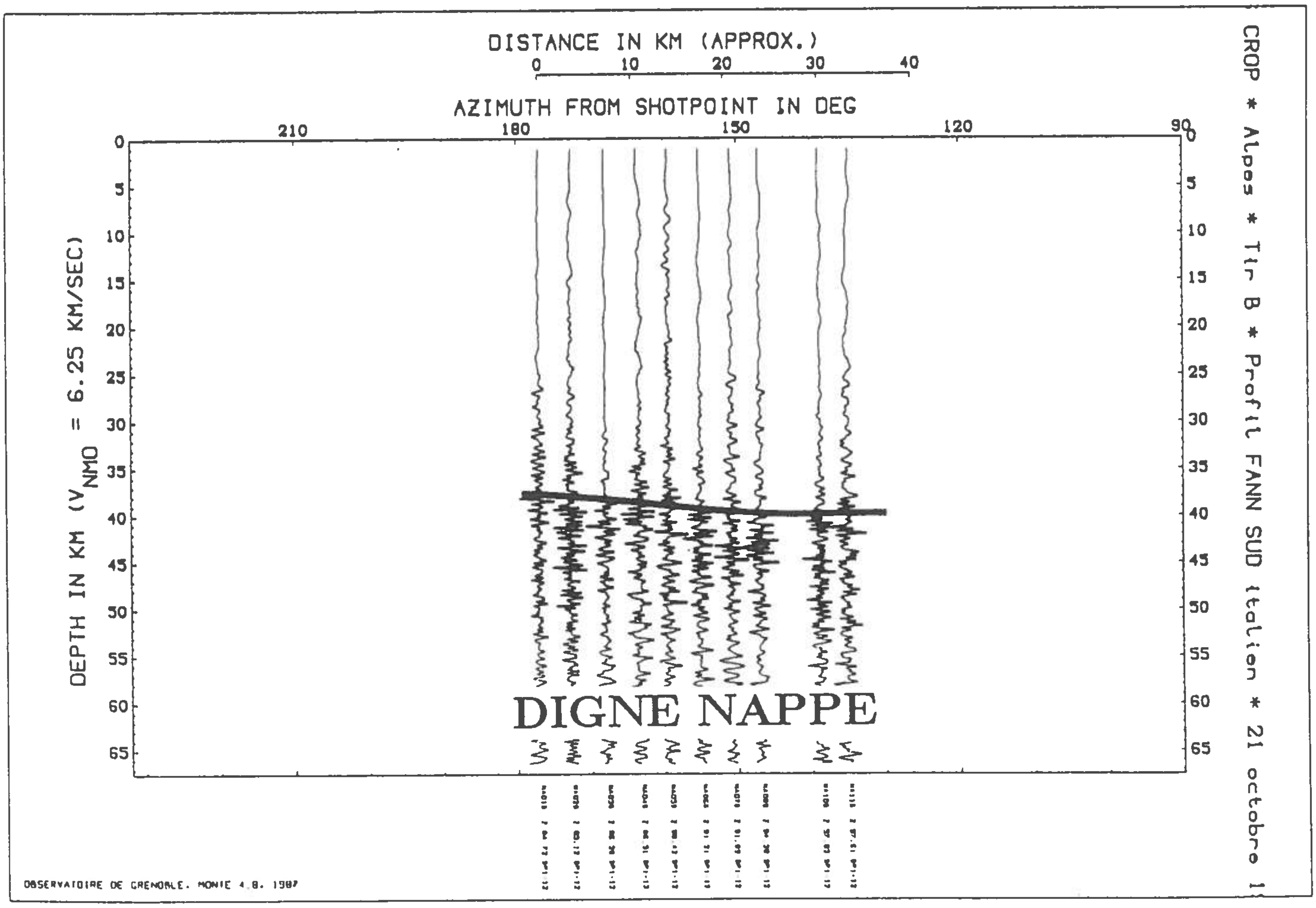

Fig. 5. Azimuthal dependence for wavelets reflected from the Moho. This W–E section across the Digne nappe (southern French Alps) records shot B southwards. Good quality reflections show a spectral content shifted towards high frequencies—compare with the central part of section (a) on Fig. 2, which shows shot B recorded northwards.

We chose here to use a curved projection which follows the Bouguer gravity isolines, because they can give a better guide to the extrapolation of deep structures. On the line drawing, we then fall into the very middle of a highly reflective zone, between 6 and 12 s two-way time, which is much thicker than is found for the layered lower crust in the sub-Alpine area (ECORS–CROP Working Group, 1988). We suggest that the upper part of this zone is related to a lower-crustal layering, while the lower part underlines a lamellation within an anomalous upper mantle. This hypothesis is supported by the non-impulsive character of the wavelets reflected from the shallow reflector (Fig. 2a, right). This upper-mantle material therefore would be very different from the sub-Alpine autochthonous upper mantle, from which highly impulsive reflected wavelets can be observed (Fig. 2a, left).

From the wide-angle data, the shallow reflector seems to be localized under the inner Briançonnais zone only, perhaps because our fan C did not extend sufficiently westwards. The vertical reflection seismics show that the associated reflective zone between 6 and 12 s two-way time extends much further to the west, beneath the Frontal Penninic Thrust. It is therefore sensible to imagine that the mantle unit discovered under the Briançonnais reaches at least this limit. In a still more external position, we saw that S-waves from shot A mapped a reflector in the 25–30 km depth range (Fig. 4), but its relation to the Briançonnais reflector is dubious.

As concerns the Ivrea body itself, the present data cannot further constrain the velocities, depths and geometries of what definitely appears to be a high-velocity body. But a reflection from its top (at a depth of 10 km) and a reflection from the deep Alpine Moho (at a depth of 50 km) have been re-identified on recent profiles transverse to the Western Alps (Thouvenot et al., 1990). For the deep Moho position these data agree with ours, in the sense that the distance and reflection time are not inconsistent with the condition of critical reflection from a 6.25–8.2 km/s boundary. In other words, if the present data agree with a velocity decrease in the crust below the high-velocity Ivrea body, there is no need to introduce materials with the extremely low-velocity values of 5 or even 4 km/s that have previously been proposed (Choudhury, Giese and de Visintini, 1971).

The fan layout was aimed, from the beginning, at the observation of very deep reflections: hence about two-thirds of the sensors were deliberately drawn off from any upper crustal imagery. As for the remaining in-line profiles, mostly used as control lines, it is clear that they were not supposed to detect any very exciting features. This was the intended role of the ECORS–CROP vertical reflection line—to gain information on upper- and mid-crustal reflectors. The wide-angle profiling allowed us to fix constraints for the layout and field parameters of the ECORS–CROP line; in this aspect, it fulfilled its purpose. The approach used here, joining together the roadroller strength of vertical reflection seismics to the more versatile wide-angle reflection method, has already proved that both kinds of profiling produce valuable and indispensable complementary results.

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