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ECORS-CROP wide-angle reflection seismics : constraints on deep interfaces beneath the Alps

by FRANÇOIS THOUVENOT*, ANNE PAUL*, GUY SENECHAL*, ALFRED HIRN** and RINALDO NICOLICH***

Key words. – Crustal structure, Wide-angle reflection seismics, Vertical reflection seismics, Synthetic seismograms, Western Alps.

Abstract. – As a preliminary experiment to the ECORS-CROP vertical reflection line, a wide-angle reflection campaign obtained a new picture of the Moho under the western Alps. This picture, besides its increased sharpness, clearly shows how the Moho deepens down to the root zone (≈ 55 km). A 23-29 km deep reflector with upper-mantle characteristics is discovered under the Briançonnais zone where it overlies the deep autochthonous Moho. This unit does not seem to connect to the so-called *Ivrea body,* situated much shallower and inner in the chain. It supports a hypothetical flaking of the lithosphere under the western Alps. A special attention is here given to the comparison between migrated wide-angle and vertical reflection results. Finally, synthetic seismograms are computed for a set of deep-crustal velocity models, at normal and wide-angle incidence. Even if the comparison with the data reveals which models should be excluded, the door is still left open for a wide range of possible deep-crustal layerings.

Réflexions profondes observées en sismique grand angle sous les Alpes (campagne préliminaire ECORS-CROP)

Mots clés. – Structure crustale, Sismique réflexion grand angle, Sismique réflexion verticale, Sismogrammes synthétiques, Alpes occidentales.

Résumé. – Une expérience de sismique réflexion grand angle a précédé de plusieurs mois la réalisation du profil de sismique réflexion verticale ECORS-CROP. Elle a permis d'obtenir une nouvelle image très nette du Moho sous les Alpes occidentales, avec une profondeur maximale d'environ 55 km dans le centre de la chaîne. Un réflecteur présentant des caractéristiques de manteau supérieur a été mis en évidence entre 23 et 29 km de profondeur sous la zone briançonnaise; il recouvre à cet endroit le Moho profond autochtone. Cette unité ne semble pas avoir de relation directe avec le *corps d'Ivrea,* beaucoup plus superficiel et situé plus à l'intérieur de la chaîne. La découverte de cette nouvelle structure abonde dans le sens d'un écaillage lithosphérique sous les Alpes occidentales, jusqu'alors hypothétique. On s'attache également ici à comparer les résultats des migrations effectuées sur les données de sismique réflexion grand angle et sur les données de sismique réflexion verticale. L'utilisation des deux types de données se poursuit par le test de différents modèles crustaux où sont calculés des sismogrammes synthétiques à incidence normale et en grand angle. Bien que cette comparaison permette d'exclure définitivement certains cas de figure, elle laisse encore une large place à de nombreux modèles de stratification crustale.

I. – INTRODUCTION

Because of their utmost heterogeneity, the Alps can be considered a real challenge when modelling the bowels of the Earth. Even if we aim – as we do in this paper – to the topography of only a few major deep interfaces, the problem can in no way be tackled as it is elsewhere in more quiet tectonic settings. The Moho discontinuity, unquestionably the major interface in the continental lithosphere, bears evidence, through its position and topography, of the regional geodynamics. As such, any reconnaissance campaign of the deep structures should bring it into focus.

As Moho data were collected in the western Alps in the last decades, successive Moho maps [Closs and Labrouste, 1963; Labrouste *et al.*, 1968; Choudhury *et al.*, 1971; Perrier, 1973; Giese and Prodehl, 1976] soon revealed the dip to the east of the Moho beneath the Alpine foreland. An anomalously shallow structure (the Ivrea body) was also detected, that covered the deep autochthonous Moho in the inner zones.

To cope with the complexity of the chain, it was first thought that the easiest layout to collect Moho data in the Alps was to design longitudinal profiles along the strike of the chain – *e.g.* ALP75 experiment from France to Hungary [Alpine Explosion Seismology Group, 1976] – : with the structures being sampled longitudinally, the interpretation hopefully keeps one-dimensional. Another way to proceed – *e.g.* profiles connected to the European Geotraverse (EGT) experiment in 1983 [Thouvenot *et al.*, 1985] – is to traverse the chain perpendicularly to the strike. Of course, one can expect the record-sections to be more complex because a two-dimensional modelling now has to be dealt with. However, this kind of profiling is suitable for observing late arrivals – reflections from a deep Moho – as well as anomalous first arrivals, for instance produced by waves travelling through the Ivrea body.

II. – THE 1985 EXPERIMENT

The Moho information provided by these layouts is obviously limited : even if transverse profiles allow a simultaneous investigation of different tectonic regions, the Moho topography made available is restricted to a zone a few tens of kilometres long at best. This is mainly due to the heterogeneity of the Alpine crust which allows reflections from the Moho to be observed only around the so-

* L.G.I.T., Observatoire de Grenoble, I.R.I.G.M., B.P. 53X, 38041 Grenoble, France.
** Institut de Physique du Globe, 4 place Jussieu, 75230 Paris, France.
*** Istituto di Miniere e Geofisica Applicata, Università, via Valerio 10, 34100 Trieste, Italy.

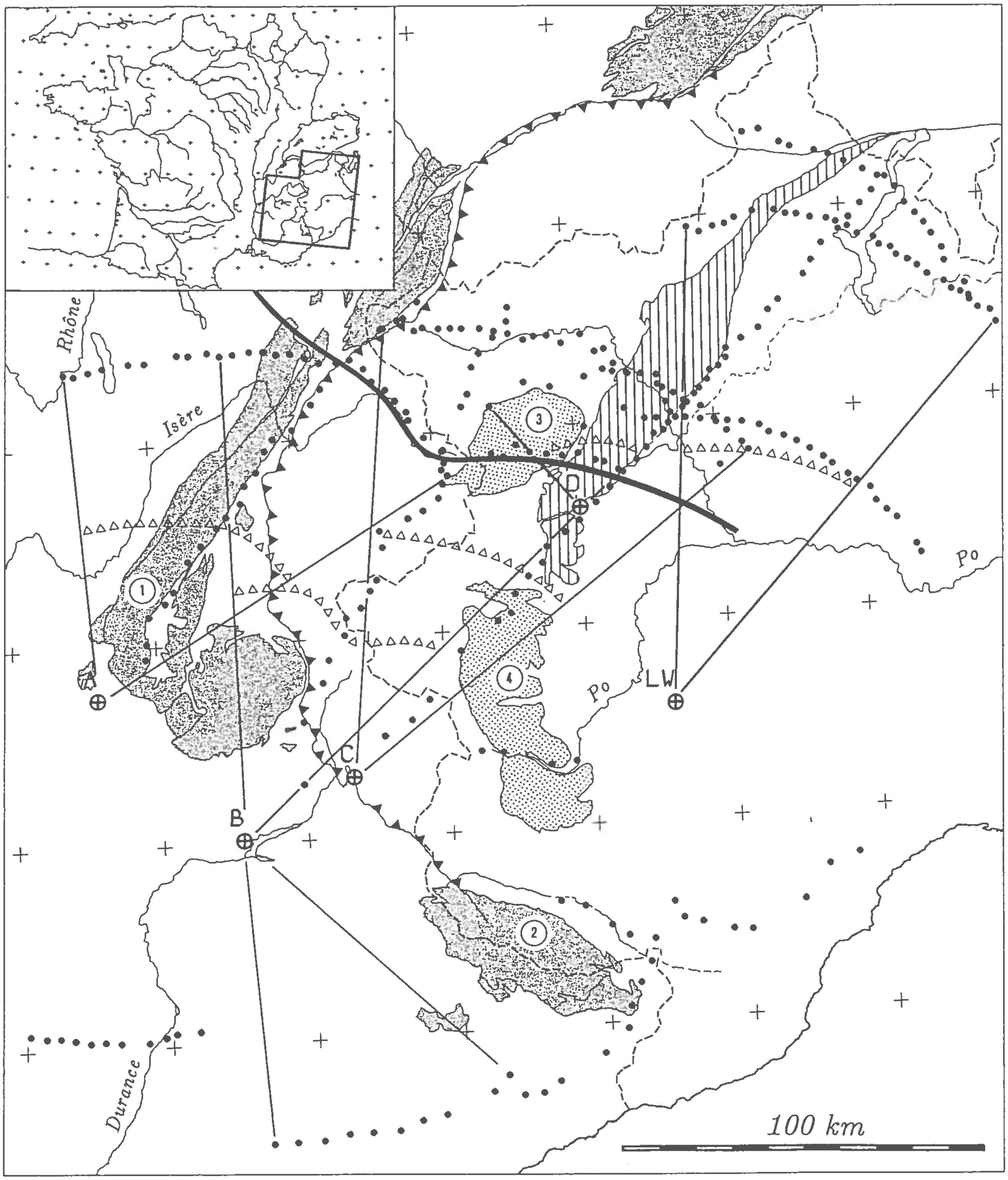


FIG. 1. – Complete position map of the layout. Shotpoints were recorded by stations (full circles) deployed along longitudinal profiles and fans. Open triangles indicate reflection points for the 5 fans used to build up figure 2. Shaded area : external crystalline massifs (1 = Belledonne; 2 = Argentera); dotted area : internal crystalline massifs (3 = Gran Paradiso; 4 = Dora Maira); hatched area : Sesia-Lanzo unit. Penninic frontal thrust identified by solid triangles. Heavy line marks ECORS-CROP vertical reflection line (VRL).

called *critical distance* (in the 90-140 km range, depending on the depth of the reflector).

When it was decided in 1985 to complement the planned ECORS-CROP vertical reflection line (VRL) with a deep seismic sounding campaign, it was considered that the best way to get a clear Moho picture across the western Alps was to use 5 shotpoints (fig. 1) and record them to the north and south along several fans, with an observation distance chosen close to the critical distance. Every station on the fan is most suitably placed to record a very energetic seismic signal which corresponds to a total reflection from the Moho. The angle of incidence of the seismic ray on the reflector is large (around 50°) – hence the qualificative of *wide-angle reflection* which will be henceforth applied to this technique.

This method had already proved successful in other orogenic belts [*e.g.* Hirn *et al.*, 1980 and 1987] and a more complete justification of the layout is presented in ECORS-CROP DSSG [1989a and 1989b]. Aimed at mapping only deep interfaces and carried out one year prior to the VRL, our reconnaissance campaign can in no way compete with the roadroller strength of the vertical seismics which provide a more complete crustal image. Using more versatile equipments, illuminating deep reflectors with different frequencies and angles of incidence, the method is however bound to bring important constraints on the physical properties of the deep crust.

III. – The northern fans

In this paper, we will basically address data obtained along the northern fans. About 30 stations were deployed every 4 km on each fan. For each shot-station couple, the reflection point is plotted half-way, so that each fan provides by itself a cross-section with the reflectors being sampled every 2 km. Because of logistics, these cross-sections have overlaps or offsets, so that it seems difficult to speak in terms of a single cross-section of the chain. The composite cross-section presented in figure 2 shows in its upper part the combination of fans A, B and C (western fans) and in its lower part the combination of fans D and LW (eastern fans).

The cross-section in figure 2(a) extends from the Subalpine chains through the Belledonne external crystalline massif (ECM) to the Dora Maira internal crystalline massif (ICM). Each seismic trace was processed so that the time scale is converted to depth using a mean crustal velocity, here chosen as 6.25 $km.s^{-1}$ [ECORS-CROP DSSG, 1989a]. The maximum energy of the signal corresponds to the Moho reflection. Almost flat at ≈ 37 km beneath the Subalpine chains, the Moho then dips to the east to reach a maximum depth of ≈ 55 km beneath the French-Italian border. This dip is observed using data from shot A and B. Results for shot C were quite unexpected : they show a relatively shallow reflective zone between 23 and 29 km which was not reached by shot B. This is a clue to the limited extent of this reflector : when shooting from B, we reach the deep Moho; when shooting from C, this reflector acts as a mask that prevents the seismic energy from penetrating deeper in the crust.

The second cross-section (fig. 2b) is much closer to the VRL and extends from the Gran Paradiso ICM through the Sesia massif to the Po plain. A reflector beneath the Sesia massif can be evidenced at 13 km, more or less in coincidence with the hitherto known Ivrea body. But what is especially clear here is how the Po plain Moho deepens from 25 to 35 km. The phase correlation presented here involves a stepwise deepening. Of course this way of seeing can be argued against, because we reach here the resolution limit of the sampling. However, fan profiles subsequently recorded in northern Italy as part of the EGT'86 experiment seem to support this idea.

For instance, one of these fan profiles recorded a shotpoint much farther to the east (fig. 3a), which provides a north-south cross-section of the Po plain (fig. 3b; this cross-section happens to complement ours at right angle; see figure 1). Results obtained by Nadir [1988] show a Moho undoubtedly deepening by steep faults between 30 and 45 km. The depth of 35 km obtained at about the third of the section is consistent with the depth reached in the eastern end of our section (fig. 2b), where the two profiles meet. To the south, the Moho topography shown by figure 3(b) is more complex due to the imbrication of the Ligurian Moho.

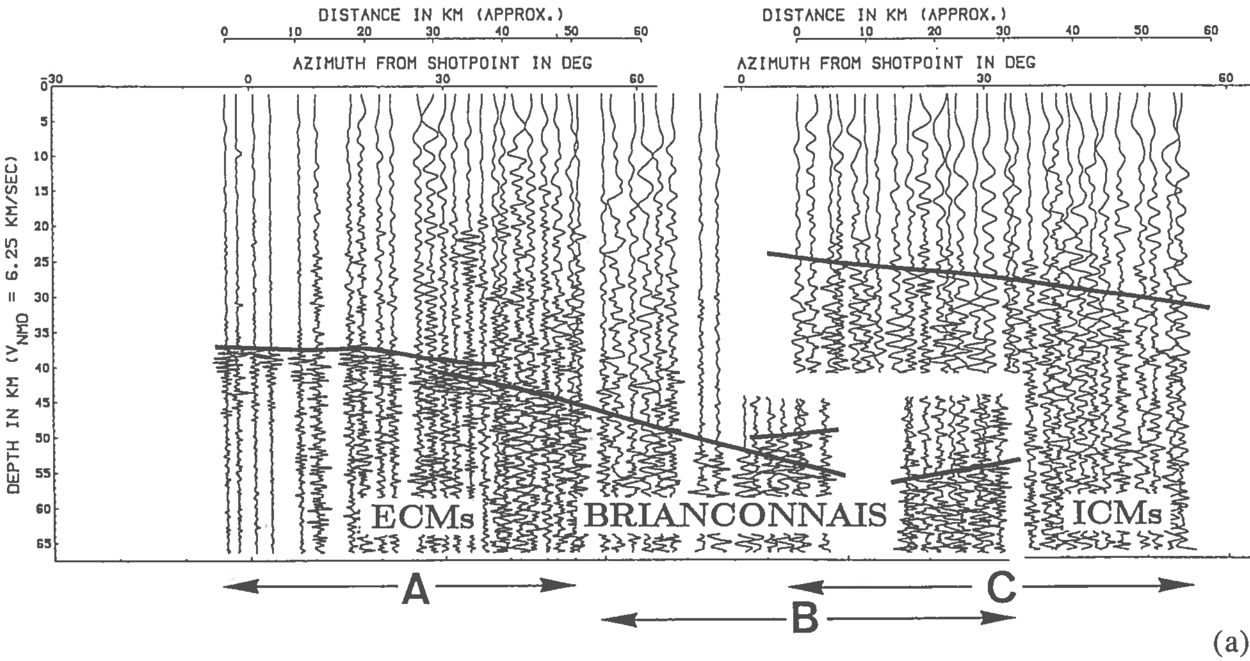
IV. – Comparison with the vertical reflection line

The shallow reflector that was shown to be overthrusting the deep Moho in the Penninic zone has never before been mapped – hence our marked interest in it. The reflection points that sample this reflector are located beneath the Ambin massif and the Upper Dora Riparia valley, more than 30 km off the VRL; for the deep Moho reached when shooting from B, the mirror points are in the Montgenèvre area, 60 km south of the VRL (figs. 1 & 4).

There is therefore an unavoidable problem of projection if one wants to take these reflectors into account when interpreting the VRL data, and there are of course different ways to proceed. For instance, projections perpendicular to the mean trend of the VRL can be used (fig. 4a) – but which trend should we consider, given the VRL is crooked ? It might be eventually more sensible to use the local Bouguer isolines as guide lines for the projection (fig. 4b), because they reflect the way deep structures continue.

Depending on the choice, the results will differ by some tens of kilometres. The westernmost part of the shallow reflector will be projected between Séez and Val d'Isère, with its easternmost end around Pont Canavese; the deep autochthonous Moho should be positioned on the VRL between Séez and Col de la Galise or between Col de la Galise and Noasca. This horizontal uncertainty is increased by a vertical uncertainty (although the latter is likely to be lessened if the projection used the local Bouguer isolines, which should prevent any dip effect of the deep structures). In conclusion, even if it is tempting to directly plot the wide-angle reflectors onto the vertical reflection line-drawing, we should keep a critical eye on it and remember that this superposition is not well constrained, neither horizontally nor vertically.

Instead of blindly merging the two types of data, we found it more advisable to separate in figure 5 the results



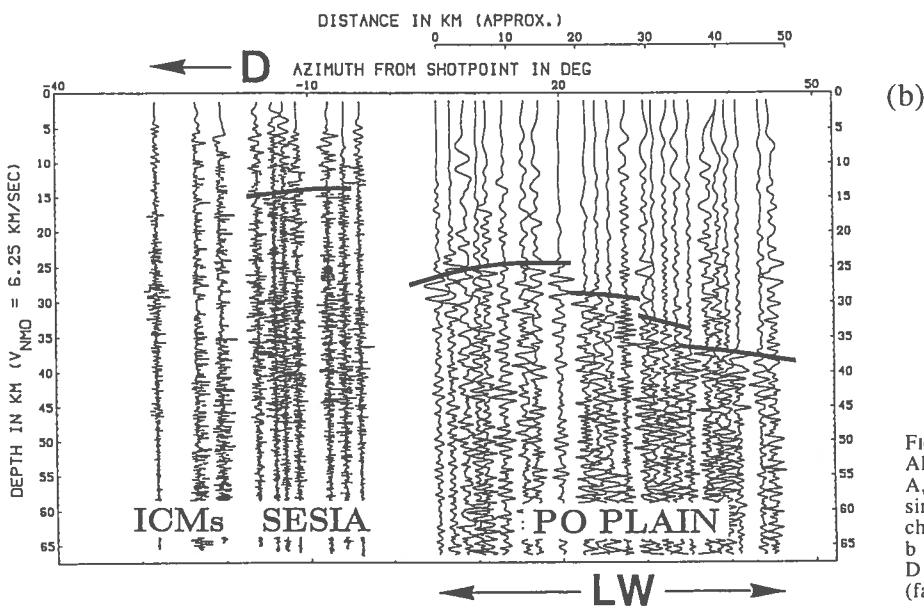


FIG. 2. – Two pseudo cross-sections of the western Alps. a : the three northern fan profiles from shotpoints A, B and C (see position on fig. 1) are combined as a single record-section extending from the Subalpine chains (far left) to the Dora Maira massif (far right). b : this shorter section combines results from shotpoints D and LW and extends from the Gran Paradiso massif (far left) to the Po plain (far right).

of the two methods (vertical reflection seismics in figure 5a; wide-angle seismics in figure 5b). The NW-SE cross-section extends from the Penninic frontal thrust to the Po plain and both data sets have been processed to migrate the reflectors into their actual positions. To this purpose, the line-drawings – either vertical reflection or wide-angle – were first digitized; allowance was made for the quality of the reflections (heavy or thin lines); strict elevation corrections were computed for the wide-angle data; velocity was eventually allowed to vary throughout the model, both vertically and horizontally. The depth scale is referred to the sea level.

The main result in figure 5(a) is the apparent transparency of the crust below 20-25 km, while the upper crust is very reflective [Bayer *et al.*, 1987; Tardy *et al.*, 1990]. This depth range where the reflectivity disappears is precisely where we find, in figure 5(b), the shallow wide-angle reflector. Figure 5(b) can however be misleading because it suggests that this shallow reflector terminates in the middle of the section. Let alone the projection problem dis-

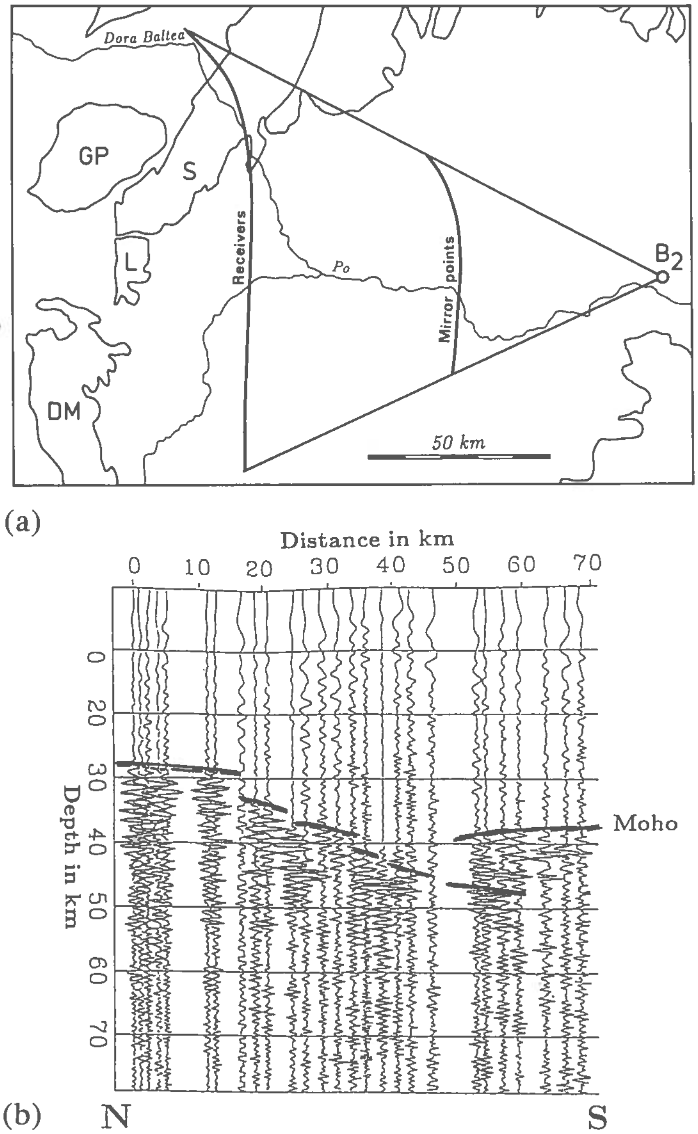


FIG. 3. – An example of fan profile in the Po plain (EGT'86 experiment). a : schematic position map with shotpoint B_2, the recording array and the corresponding mirror points. DM = Dora Maira; GP = Gran Paradiso; L = Lanzo unit; S = Sesia unit. b : north-south cross-section of the western Po plain [Nadir, 1988] showing the stepwise deepening of the Moho; compare with fig. 2b.

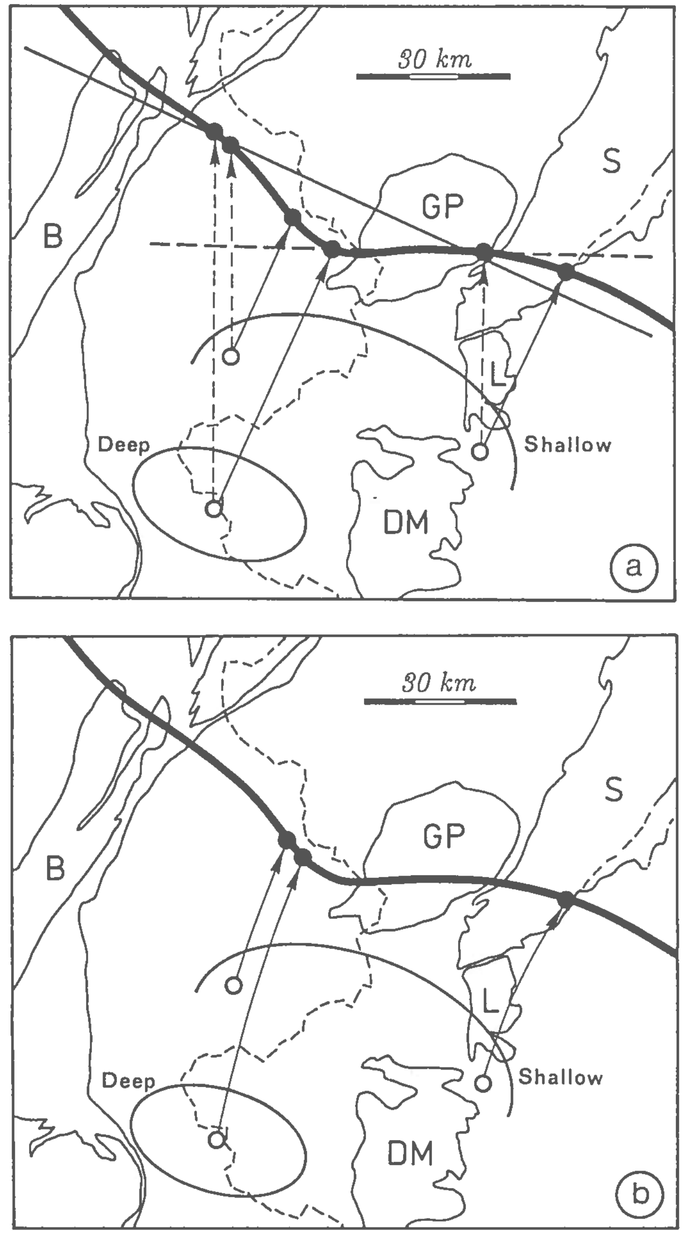


FIG. 4. – Different ways to project the wide-angle data – deep autochthonous Moho and shallow reflective unit – onto the VRL (heavy line). a : orthogonal projection on the mean trend of the VRL showing an allowance due to the crooked line. b : projection along the local Bouguer isolines. B = Belledonne; DM = Dora Maira; GP = Gran Paradiso; L = Lanzo unit; S = Sesia unit.

cussed above, we have no actual constraint on the western limit of the reflector, simply because our fan layout for shot C did not extend that far west (fig. 1). As for the deep autochthonous Moho, it could be detected by the wide-angle reflection seismics only.

V. – SYNTHETIC SEISMOGRAMS FOR DEEP-CRUSTAL LAYERINGS

Figure 2(a) also reveals a clear change in the Moho reflectivity : to go from one extreme to another, the wavelet reflected from the Moho in the external zone (westernmost traces) can be clearly identified whereas the reflectivity of the shallow reflector in the inner zone (easternmost traces) is very dull. In the first place, vertical seismics show a reflective lower crust [Bayer *et al.*, 1987; Mugnier *et al.*, 1990] which is almost transparent to wide-angle seismics; in the other place, as shown above, a very reflective zone can be seen on the VRL beneath Vanoise and Gran Paradiso (fig. 5a).

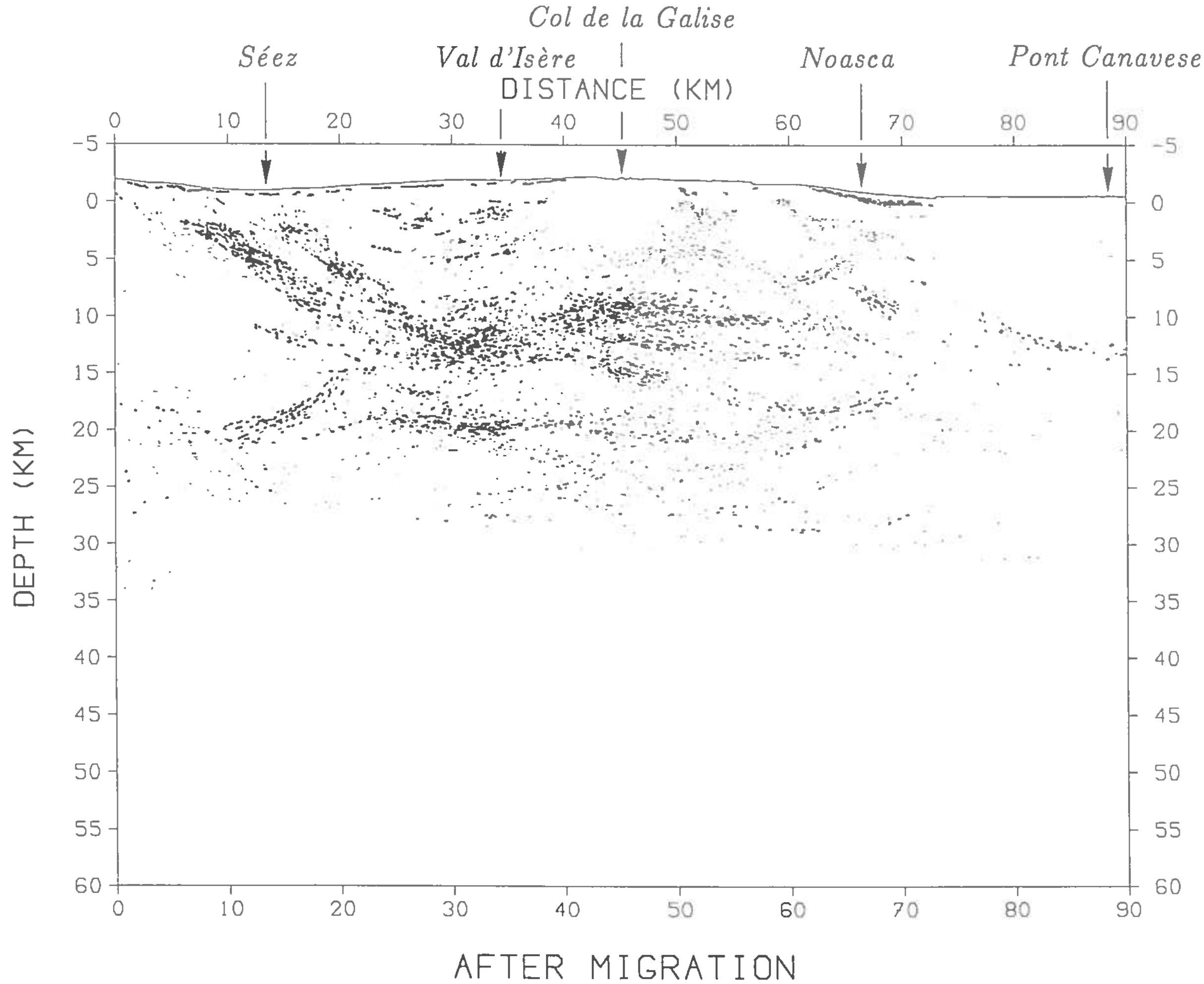


FIG. 5. – Two NW-SE cross-sections, from the Penninic frontal thrust to the Po plain, showing the seismic reflectors after migration.
a : VRL data : in the central part of the section, note the high reflectivity in the 10-15 km depth range and a deeper reflective level at a depth of ≈ 20 km; very few reflectors can be detected below it.

To investigate these variations, we used the discrete wavenumber method [Bouchon, 1981] to compute synthetic seismograms for different velocity models in the external and inner zones (figs. 6 and 7). The crust was assumed to be flat-layered, excluding any lateral heterogeneities. For simplicity and because we are here interested in deep reflections, the upper crust was modelled as a single layer with a constant 6 $km{\cdot}s^{-1}$ velocity. Introducing any further layering in this part of the model would only alter the early part of the seismograms, which is beyond the scope of this study. The computation of the direct wave was also suppressed for the same reason. Wherever lamellae were introduced in the models, their thicknesses and velocities were randomized in order to avoid any misleading constructive interference effect.

For each model, two sets of synthetic traces are presented : (1) normal incidence, with 5 receivers in the 0-8 km distance range; (2) wide-angle incidence, with 5 receivers around 90 km (external zone) or 140 km (inner zone). To account for the difference in the spectral response of the geophones used in the wide-angle experiment and vertical seismics, we used 2 source signals with different frequency bands : 9-22 Hz for normal incidence, 4-11 Hz for wide-angle.

Figure 6 addresses the autochthonous Moho in the external zone (refer to the wide-angle data, figure 2a, westernmost traces). Example a shows a lower crust modelled as a heap of lamellae with an average thickness of 250 m and velocities alternating between low values (≈ 6 $km{\cdot}s^{-1}$) and high values (≈ 7 $km{\cdot}s^{-1}$). Even if it provides a satisfactory normal incidence section with a seismic layering between 10 and 12 sec, it is not acceptable because the synthetic wide-angle section shows energetic arrivals reflected from the lamellae which mask much of the Moho reflection. Decreasing slightly the average thickness of the lamellae to 100 m (fig. 6b) makes the lower crust transparent to low-frequency wide-angle incident waves and the Moho reflection comes out more clearly. The normal inci-

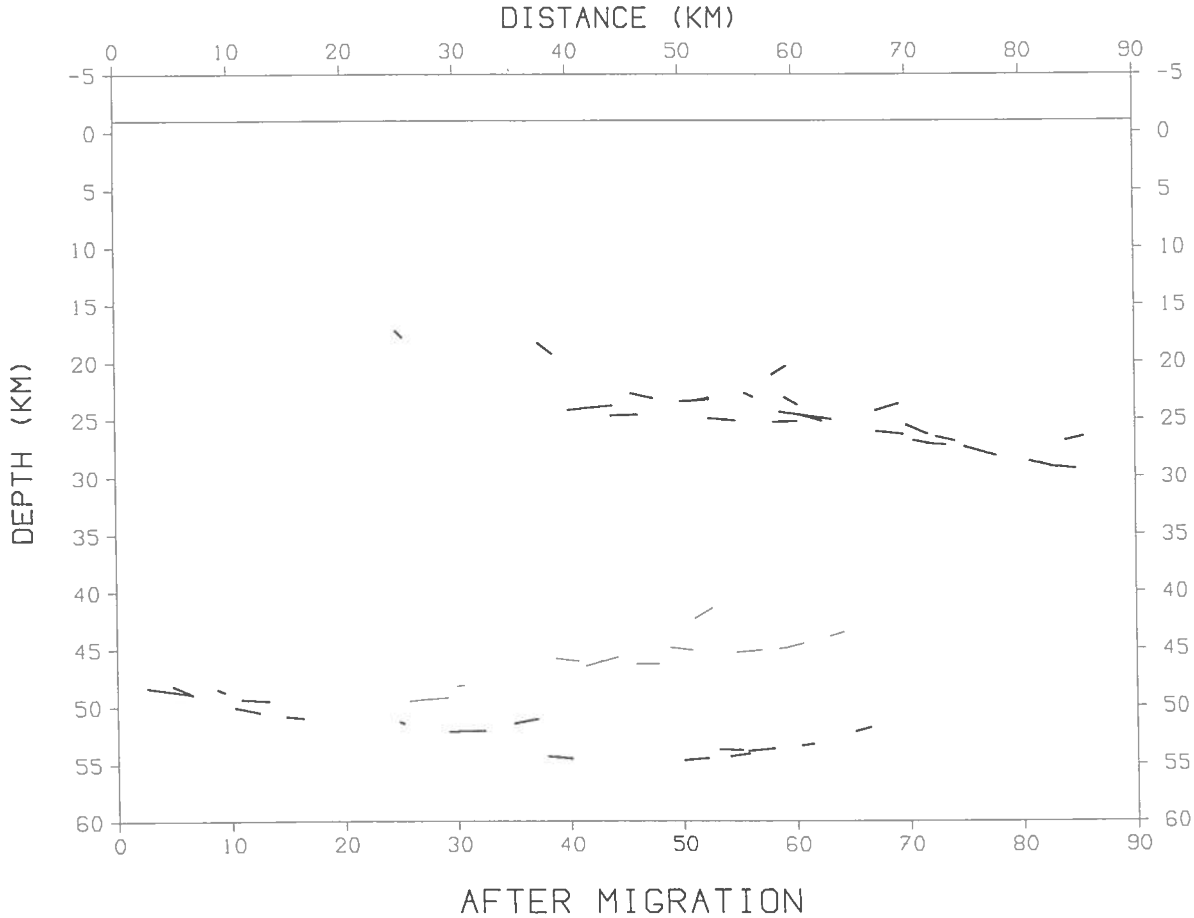


FIG. 5. – (cont.)
b : wide-angle data : the autochthonous Moho – maximum depth of ≈ 55 km – is overlain by a shallow reflective unit in the same depth range where the VRL data show that reflectivity stops.

dence section shows a reflection pattern which is not as even as in figure 6a, with a high reflectivity in the top of the lower crust and a more transparent band with the Moho reflection at its bottom. This pattern is very similar to what is observed on the VRL data in the external zone, as described for instance by Bayer *et al.* [1987].

If we do not stick to this oversimplified model of the lower crust and introduce a velocity gradient in the layering, figures 6c and d show that the average thickness of the lamellae, here taken as 500 m, is not as critical as in examples 6a and 6b : thanks to weaker velocity contrasts in the top part of the lower crust, less energy is reflected at wide-angle and the Moho reflection remains prominent. The synthetic wide-angle sections are thus not that much different from the one obtained for model b. However, the synthetic normal incidence sections in c and d show an increase in the reflectivity with depth, with the Moho reflection being the most energetic arrival. As we do not recognize this feature on the VRL data, we eventually prefer model b, even if it is rather clear that many intermediate models would also be acceptable.

The case of the allochthonous Moho in the inner zone (refer to the wide-angle data, figure 2a, easternmost traces) is only skimmed over in figure 7. It shows that a transitional shallow Moho, modelled as a gradient zone overlain by a few 500 m thick layers gives a dull reflection within a rather long wavetrain in the wide-angle synthetic section. Its normal incidence image is on the contrary quite clear, with distinct arrivals of reflected energy. It should be stressed however that we have no actual control on the velocity distribution neither within the shallow unit nor underneath.

VI. – TECTONIC IMPLICATIONS AND CONCLUSIONS

The first result of the wide-angle experiment was to demonstrate the Moho existence from the foreland to the root zone : even if the Moho reflectivity is variable, its topography is now well documented and this geometry is now to be taken into account in any structural reconstruction of the Alpine chain. No *Verschluckung*-like phenomenon can be observed.

In the external zone, we investigated different lower-crustal layerings by the computation of synthetic seismograms. A qualitative comparison with the VRL and wide-angle data shows that using both data sets brings more

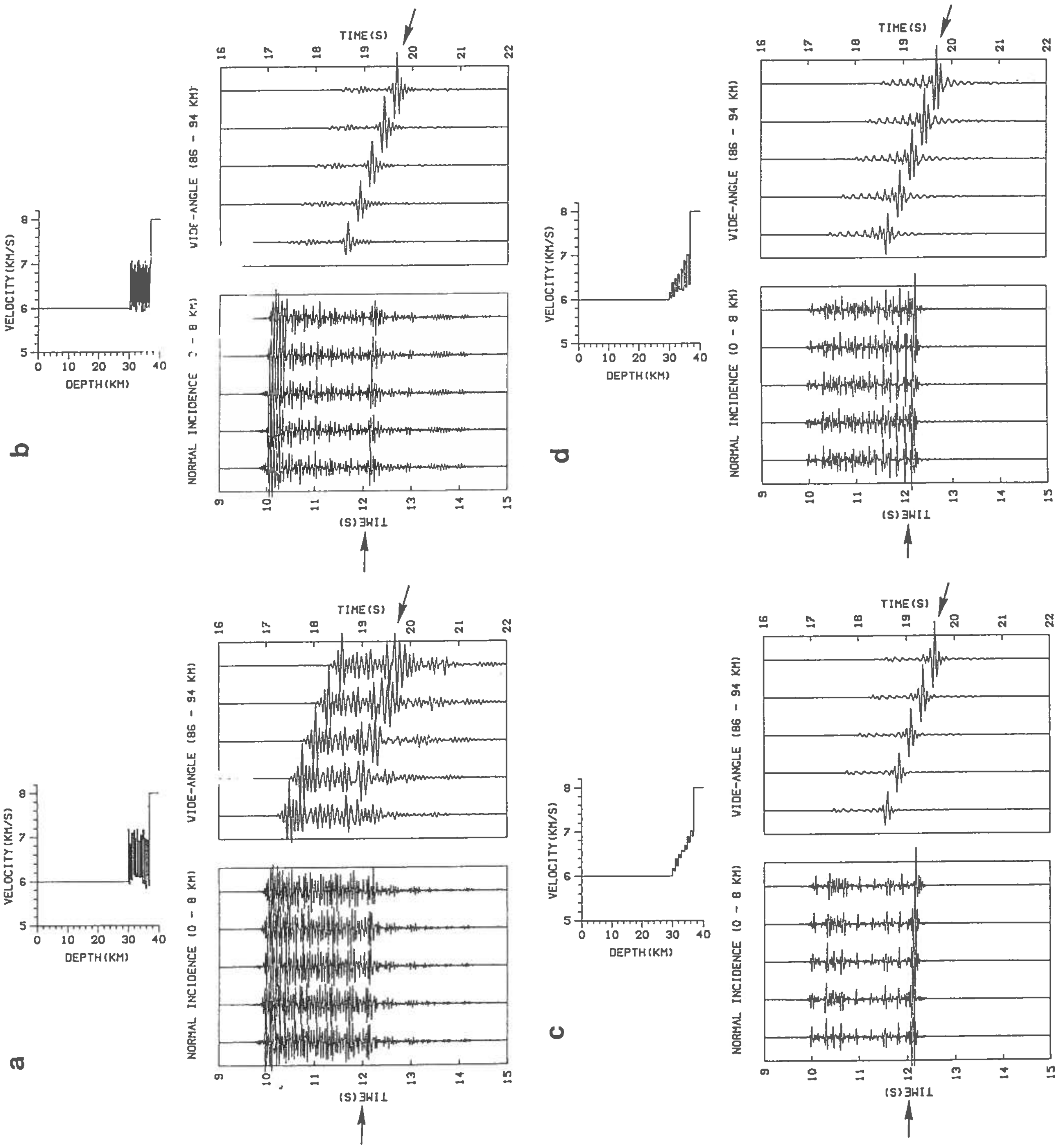


FIG. 6. – Four examples of deep-crustal velocity models for the autochthonous Moho in the external zone (fig. 2a, westernmost traces) and corresponding synthetic seismograms (left : normal incidence; right : wide-angle). Reflection from autochthonous Moho marked by arrows. Comparison with the wide-angle data show that model a – 250 m thick lamellae – can be excluded. Model b – 100 m thick lamellae – is acceptable. Models c and d – 500 m thick lamellae, but with a velocity gradient –, although fitting the wide-angle data, produce a high-amplitude Moho reflection at normal incidence which is not observed on the vertical reflection data.

constraints, as already shown by Braile and Chiang [1986]. Our preferred model for the autochthonous Alpine lower crust is a heap of 100 mthick lamellae with velocities alternating between 6 km·s^{-1} and 7 km·s^{-1}.

The relatively shallow reflector discovered beneath the Briançonnais zone has never before been mapped, although recent models of Alpine orogenesis involving a lithospheric flaking [Ménard and Thouvenot, 1984] already suggested such a feature. The seismic signature of the reflected wavelet indicates lower-crustal or upper-mantle material and, because the seismic signal is stretched and sustained, one could suspect this reflector to be actually a transition zone rather than a first-order discontinuity. When referring to VRL data, this reflector is shown to underlie a highly-reflective layer. In this aspect, it has a Moho-like behaviour : in stable areas where a layered lower crust is observed, it is now well-established that the Moho corresponds to the lower limit of the layering [Mooney and Brocher, 1987; Holbrook, 1988]. However, it should be stressed that the present data does not give us any control on the actual velocity distribution neither within the reflective unit nor underneath.

The connection of this unit to the *Ivrea body*, locally reached in our experiment under the Sesia massif, is unlikely because of the depth difference of nearly 20 km between the two reflectors. Linking it to the Po plain Moho – which would make the *Ivrea body* a detached mantle unit – would be more plausible. This idea should however be dropped if we consider the very different character of the wavelet reflected from the two reflectors – dull for the Briançonnais Moho and sharp for the hinterland Moho.

Thus, the Moho picture of the western Alps gained both in sharpness and complexity since four segments at least now have to be considered : deep autochthonous Moho, Briançonnais Moho, Ivrea body and Po plain Moho. This makes the reconstruction puzzle more constrained but also more complicated.

As a whole, the fan layout of the experiment proved successful in detecting very deep reflections. The VRL, equipped with 10-Hz geophones [Damotte, 1990], was able to provide information on upper and mid-crustal reflectors but had difficulties in finding out the deep Alpine Moho east of the ECM's. Uniting vertical reflection profiling with the more versatile wide-angle reflection method therefore provides the sort of complementary information required to determine the deep structure of such complex orogens as the Alpine chain.

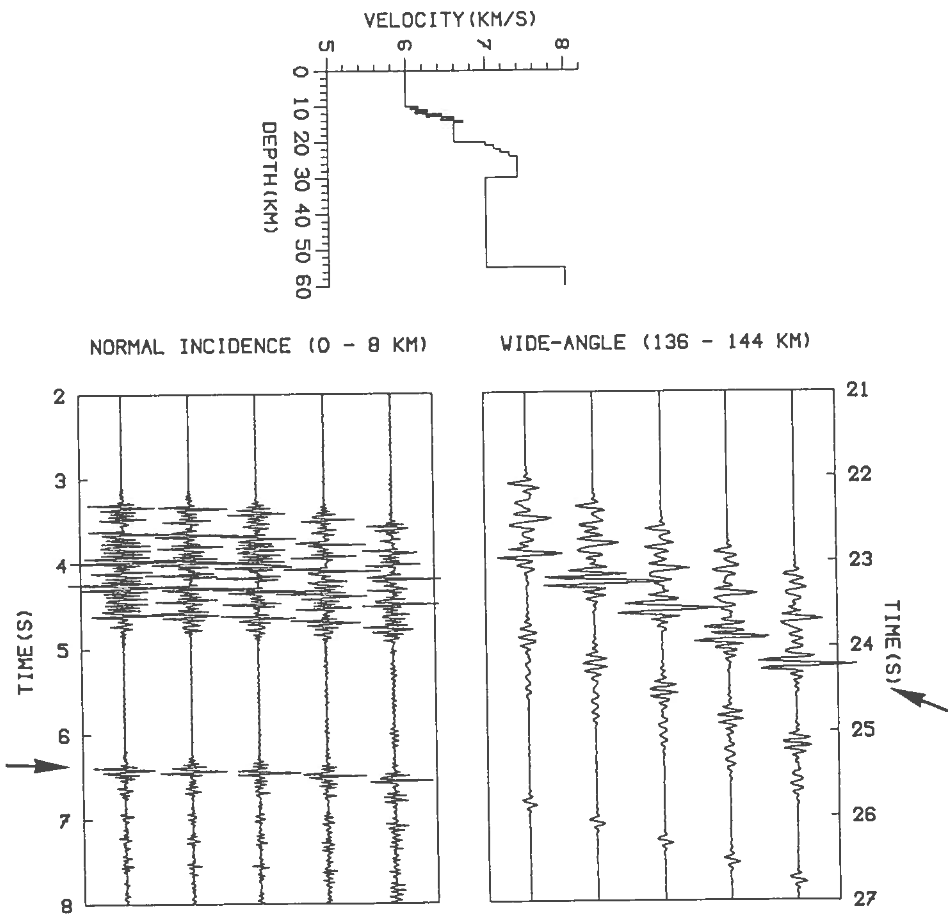


FIG. 7. – An example of deep-crustal velocity model for the inner zone (fig. 2a, easternmost traces) and corresponding synthetic seismograms (left : normal incidence; right, wide-angle). Reflection from allochthonous Moho marked by arrows.

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