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DEEP CRUSTAL STRUCTURE OF THE WESTERN ALPS: PRESENT KNOWLEDGE AND PENDING PROBLEMS

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ABSTRACT

We present, along transverse cross-sections of the Western Alps, the evolution of a deep tectonics model. The crust of the western margin of the French-Italian Alps is shown to consist of several «layers» with clear seismic reflections from their boundaries; this Subalpine crust is shown to dip eastwards at about 30° as can be seen from its basement, its intracrustal discontinuities and its Moho; further east, the Alpine crust appears to be unstructured, with no sharp seismic discontinuities, but it presents a low-velocity zone at a depth ranging from 10 to 20 km approximately.

Finally, recent seismic experiments show that a smooth Moho model may be a wrong picture: if this proves true, the deep structure of the Alps would more resemble a patchwork of lithospheric segments than it does now.

RIASSUNTO

È presentato e discusso un modello strutturale profondo delle Alpi occidentali, illustrato da alcune sezioni trasversali che si estendono dalle Alpi Meridionali all'avanpaese. Il modello pur non risolvendo tutti i problemi e proponendo soluzioni geometriche spesso ancora ipotetiche in rapporto a ricoprimenti crostali, a scagliamenti della litosfera e ad accidenti tettonici della Moho, mette in evidenza numerose caratteristiche emergenti: la crosta al margine nordoccidentale delle Alpi italo-francesi è suddivisa in numerosi «strati»; questa crosta Subalpina pende verso est di circa 30°, come indicato dal suo basamento, dalle sue discontinuità infracrostali e dalla sua Moho; verso est la crosta Alpina risulta non strutturata, priva di nette discontinuità sismiche, ma con una zona a bassa velocità situata a 10-20 km circa di profondità. Recenti prospezioni sismiche hanno mostrato che un modello a Moho indeformata potrebbe essere una ricostruzione errata della struttura profonda delle Alpi occidentali che, più verosimilmente, potrebbe corrispondere ad un mosaico di segmenti litosferici.

KEY WORDS: *Deep structure, seismics, gravity, magnetism, Western Alps, Ivrea zone.*

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INTRODUCTION

One cannot deny that the past three decades have brought an incredible amount of data concerning the deep structure of the western Alps. This was a natural test site where was designed, as soon as 1956, one of the first deep seismic experiments, introducing an international co-operation which was to be amplified year after year. Several studies constitute interesting steps (e.g. CLOSS & LABROUSTE, 1963; FUCHS *et alii*, 1963; LABROUSTE *et alii*, 1968; CHOUDHURY, GIESE & DE VISINTINI, 1971; PERRIER, 1973).

Since the International Geophysical Year many more deep seismic profiles have been covered and, for a majority of Earth scientists, the knowledge of the deep structure of the western Alps can be taken for granted. This is partially true as regards the main features, for instance the crust/mantle boundary; but this attitude is misleading if one is interested in the detailed crustal structure and its relation with surface tectonics.

This state of fact is due to several intricate reasons: the interpretation of early data could not incorporate the tectonic scheme prevailing presently for the Alpine system against a plate tectonics background; moreover it is sometimes difficult, especially when dealing with synopses of geophysical results, to decide what can be held for certain, for highly probable and for assumable; finally some special tectonic problems cannot be given an answer because of the scarcity or inadequacy of data in the concerned regions.

These points will be discussed in the light of a transverse cross-section of the western Alps. This cross-section is shown to evolve following tectonic ideas and new data which lay down further constraints. A special stress will be put: 1) on recent seismic experiments; 2) on a tectonic scheme which could be held as a guideline for further investigations.

We include a review of undisputable results such as: the stratification of the Subalpine crust vs. a lack of stratification further east; the important eastward dip of the Subalpine crust; the existence of a low-velocity zone under the external crystalline massifs; a clear mantle and/or Moho anomaly under the same massifs.

It should be stressed finally that it is not the aim of this paper to present an extensive review of available data and published results. This was achieved periodically (e.g. GIESE & PRODEHL, 1976; PERRIER, 1979; PERRIER & VIALON, 1980; MILLER, MÜLLER & PERRIER, 1982) and the reader is referred to these papers for a more comprehensive overview. Our sole ambition is to bring together geophysical studies and tectonic ideas which have been developped in Grenoble for the last ten years.

MAIN FEATURES

The mean crustal thickness has been well known in the western Alps for many years (fig. 1), even if controversies still remain for some areas. Classically, three zones are recognized:

1) *The Ivrea zone* is the internal part of the Alpine arc. It is characterized by a strong positive gravity anomaly. Deep seismic soundings along the axis of this anomaly have shown the presence of a high velocity material (7.3 km/s) at a depth of about 6 to 11 km. This very shallow structure was interpreted by NIGGLI as soon as 1946 as an upper mantle uprising under the eastern flank of the Sesia-Lanzo massif. This anomalous mantle unit can be connected to the crust-mantle transition zone and to the «autochthonous» upper mantle under the western Po plain. We reach here an interpretative aspect which we choose to disconnect completely from this factual overview.

2) *The Briançonnais zone and the external crystalline massifs* are characterized by a strong negative Bouguer anomaly. The seismic velocity in the upper mantle has a normal value of 8.1-8.2 km/s; the crust is very thick. The maximum thickness (50 km at least) is observed under the central part of the Briançonnais zone. This zone should therefore be considered as the actual root zone of the western Alps, which implies a lateral shift of the highest massifs. The depth of the Moho is 25, 35, 38 and 40 km under the Argentera, Belledonne, Mont Blanc and Pelvoux massifs respectively.

3) Under *the western and southern margins* of the western Alps, the crust grows thinner to reach a thickness of 29 km under the French Rhône valley and of 26 km near the Mediterranean coast-line. These are regions of very thick and folded sedimentary cover (e.g. 8 to 10 km under the Vercors massif). This transition zone between the Alpine arc and its foreland finds probably its most pronounced expression in the difference in structure of the deep crust (fig. 2). North of a line running from the southern French Massif Central to the Aiguilles Rouges massif, deep seismic sounding experiments show a systematical crustal stratification: two «layers» at least can be recognized. South of it, a structureless crust is the striking point revealed by seismic profiles, although few and far between. One can speculate that this NE-SW partition reflects the presence of a Provence sub-plate coupled to the European plate. The partition would thus follow great suture lines of the Alpine basement which were present at the end of the Hercynian orogenesis. These suture lines are believed to be the prolongation in the Alpine domain of the N50 Cévennes faults of the eastern margin of the French Massif Central; they would have played a very prominent part during the Alpine orogenesis (VIALON, 1974).

The three points developped here over give a good schematic idea of the variations in crustal thickness. The next section improves this overview in the light of the westernmost segment of the 1975 lithospheric experiment.

AN ALPINE CRUSTAL OVERTHRUST

This profile (shotpoint MRV in fig. 2) runs in a SW-NE direction from France to Switzerland and, beyond, to Austria and Hungary (ALPINE EXPLOSION SEISMOLOGY GROUP 1976). Its western segment clearly displays the presence of a low-velocity zone under the northern external crystalline mas-

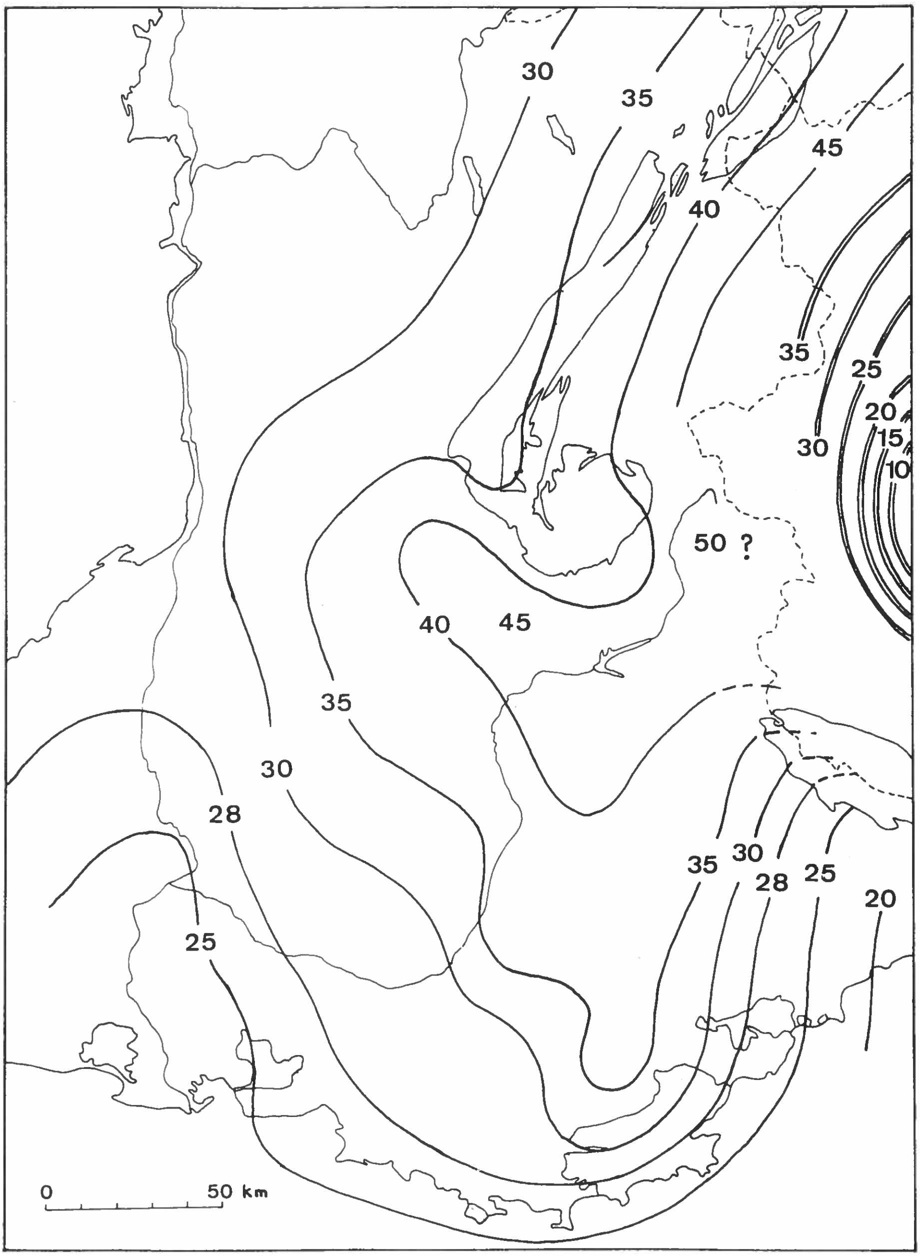

Fig. 1 - Moho contour map of the western Alps (in km). Double isolines are related to the Ivrea body. After PERRIER (1979).

sifs. The Pg wave propagating in the upper crust is strongly delayed by about 1 s from its normal position due to the Mesozoic cover of the Subalpine chains (fig. 3). Between this Pg wave and the PMP wave reflected from the Moho, energetic arrivals (P1P) can be observed on the record section. They reveal the presence of intracrustal discontinuities. The important delay between Pg and P1P can unambiguously be ascribed to a low-velocity zone in the middle crust. With a shotpoint in the Gotthard massif the reversed profile shows absolutely no energy reflected from inside the crust.

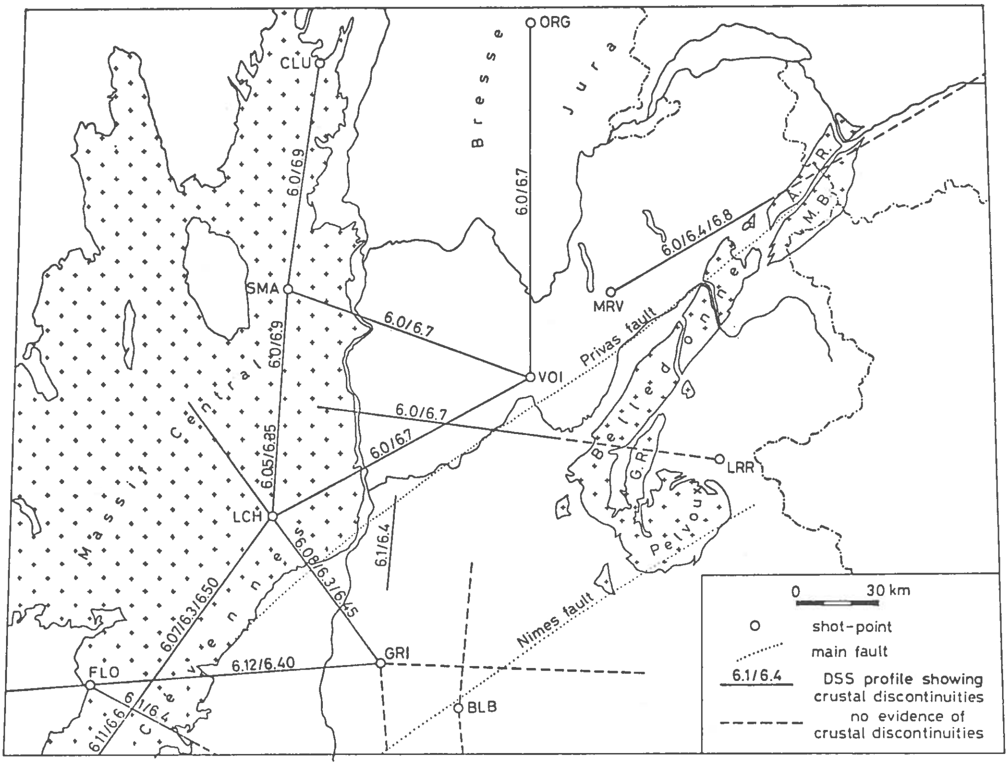

Fig. 2 - Intracrustal stratification in South-East France as revealed by deep seismic soundings. A line running from Cévennes to Aiguilles Rouges marks off a domain with intracrustal discontinuities (north) from a domain with a structureless crust (south). After THOUVENOT & PERRIER (1981).

Introducing now *a priori* conceptions it becomes possible to tackle two-dimensional models with ray-tracing techniques: seismic rays are drawn from the shotpoint through the whole structure and theoretical travel-times are computed and compared to observed arrivals. These *a priori* conceptions, which are mere prolongations at depth of ideas pertaining to surface tectonics, are essential in the construction of such two-dimensional models. Indeed a two-dimensional cross-section depends upon too many independent parameters which cannot be presently controlled by the sole seismic data. We stress therefore that such cross-sections contain a large amount of personal interpretation. If we had not been acquainted with the tectonic model by MÉNARD (1979 and 1980) for the first 10 km of the crust, we would not have grounded on it our interpretation of the frontal position of the low-velocity zone (dashed area in fig. 4). Suspecting the Alpine basement to be overthrusting the Subalpine basement, the MÉNARD's hypothesis is therefore the keystone of our model: the low-velocity zone is associated to this overthrust while a thick Mesozoic cover of some 10 km forms the Subalpine chains (THOUVENOT & PERRIER, 1981). An intracrustal discontinuity is found right under with a strong dip towards the arc. This follows the strong dip of the Subalpine basement from the Rhône valley towards the external crystalline massifs. This strong dip is indicated by seismic data. According again to seismic data, no sharp change of seismic velocities is modelled under the central part of the Alps.

A cartoon (fig. 5) is a good illustration of this concept of crustal overthrust (THOUVENOT, 1981). The bull-dozer represents the Alpine upper crust with the crystalline massifs on the trailer. Its westward motion is made easier by the low-velocity zone underneath which allows the wheels to spin. The mightful frontal blade folds the Mesozoic cover of the Subalpine chains.

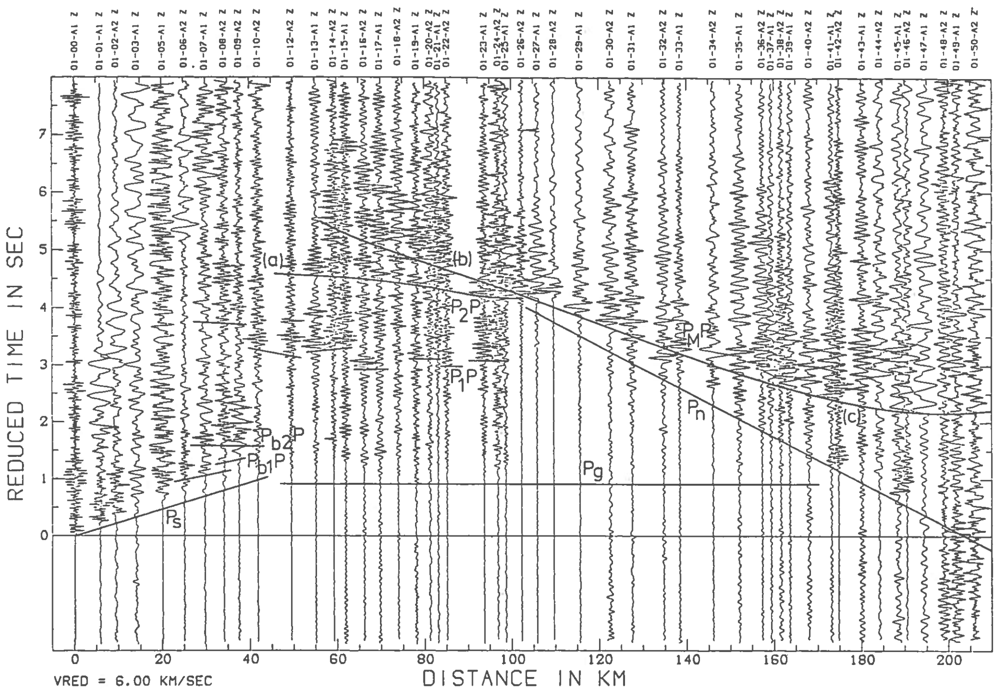

Fig. 3 - Seismic record-section for the ALP75 westernmost segment (shotpoint MRV on the map fig. 2). P1P waves, reflected from an intracrustal discontinuity, are delayed by about 2 s because of their travelling through a low-velocity zone. After THOUVENOT & PERRIER (1981).

THE FLAKING OF THE EUROPEAN LITHOSPHERE

Looking back to fig. 4, the Ivrea body is represented on the right-hand side of the cross-section in its usual position: an intrusion of anomalous mantle gets to the surface in the region of Lanzo. This interpretation was worked out gravimetrically by several authors (e.g. KAMINSKI & MENZEL, 1968). However, it is interesting to note that observed Bouguer gravity profiles across the western Alps show a systematical break in their rising part. The gravity minimum, east

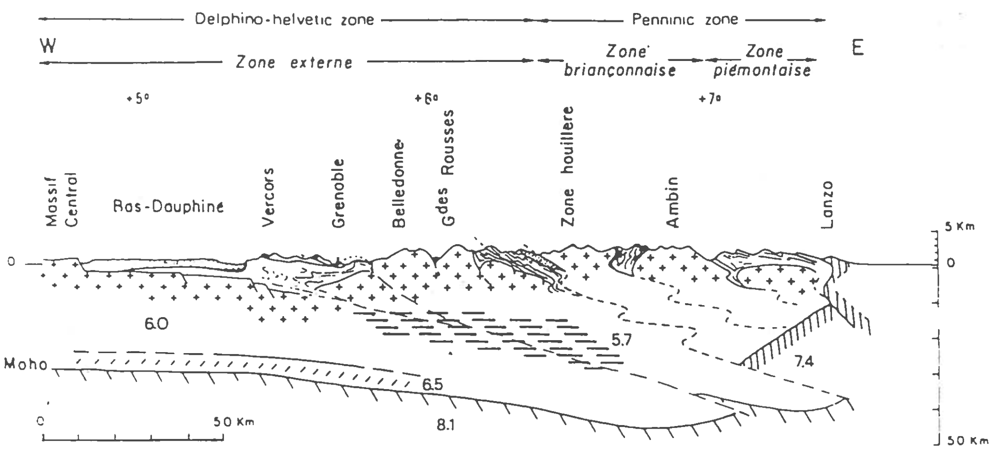

Fig. 4 - Deep structure of the western Alps: a possible cross-section (MÉNARD, 1979) in the latitude of Grenoble.

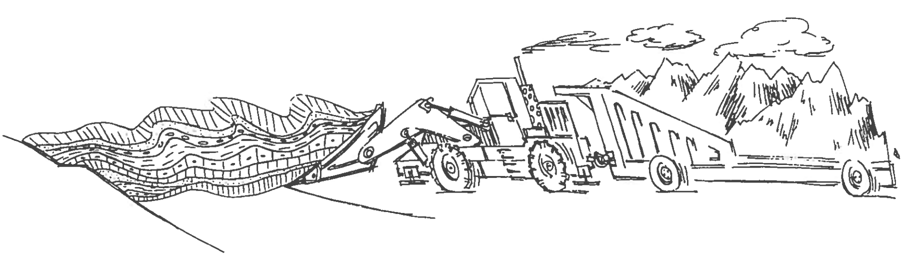

Fig. 5 - Crustal overthrust in the western Alps: an artist's vision (H. Richelet, Paris). After THOUVENOT (1981).

of the crystalline massifs, is followed first by a weak positive gradient, then by a strong positive slope; the breakpoint in question occurs some 25 km west of the Sesia-Lanzo massif. The part of the gravity curve with a weak positive gradient is usually accounted for an anomalous high density upper crust forming a kind of beak extending the Ivrea body to the west.

An alternative model would be to split up the Ivrea body in several mantle units, which implies a flaking of the European lithosphere (MÉNARD & THOUVENOT, 1984). This working hypothesis is exposed in a speculative NW-SE cross-section running through the Mont Blanc massif (fig. 6). The overthrust of the external crystalline massifs is extended a depth and joined to the bottom of a lower unit of mantle. This unit belongs to a lithospheric flake, with the Subalpine «autochthonous» lithosphere underneath. A similar process occurs for the upper unit of the Ivrea body: its bottom is on the prolongation of the frontal Pennine thrust, which forms another lithospheric flake. The top of the upper mantle unit is fixed to 6-11 km by deep seismic sounding data. It is therefore necessary to introduce an upper mantle surface unit which crops out in the Lanzo, Rivara and Baldissero massifs. In such an interpretation, two major thrusts are taking shape: the overthrust of the external crystalline massifs and the frontal Pennine thrust would be two key features for the orogenesis of the western Alps.

This schematic cross-section can be further modelled to improve the fit to observed gravity data (next Section) but, of course, any fit does not imply that we are facing the proper solution. It only shows that the arrived at model cannot be dismissed at once! Indeed the backbone of this cross-section is to integrate within a plausible tectonic scheme most geophysical results concerning the Ivrea body: seismics (LABROUSTE, CHOUDHURY & PERRIER, 1963; ANSORGE, 1968; BERCKHEMER, 1968; GIESE, 1968), gravity (KAMINSKI & MENZEL, 1968; LANZA, 1975; KISSLING, 1980) and magnetism (ALBERT, 1974; FROIDEVAUX & GUILLAUME, 1979; LANZA, 1982).

If a crustal flaking can probably be put forward wherever a chain is built by collision processes, the share of the upper mantle in such a mechanism seems to be an original feature of the western Alps. One can further

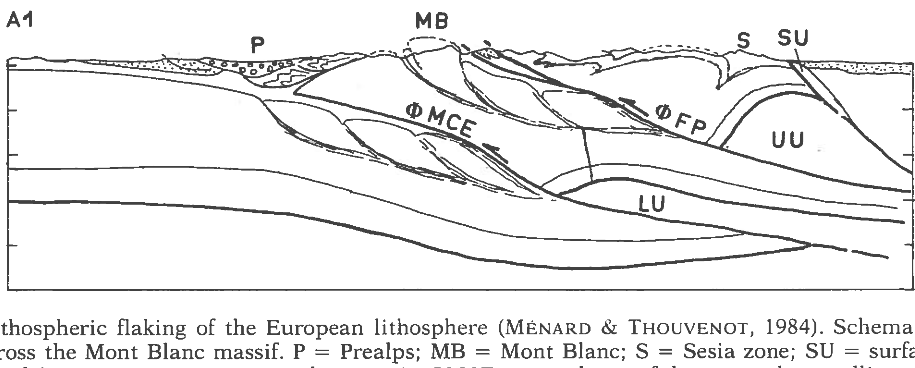

Fig. 6 - Lithospheric flaking of the European lithosphere (MÉNARD & THOUVENOT, 1984). Schematic NW-SE section across the Mont Blanc massif. P = Prealps; MB = Mont Blanc; S = Sesia zone; SU = surface unit (of the Ivrea body); UU = upper unit; LU = lower unit; ΦMCE = overthrust of the external crystalline massif; ΦFP = frontal Pennine thrust.

speculate on the origin of this lithospheric flaking (MÉNARD & THOUVENOT, 1984). An element of solution would be the formation of lenticular structures in the mantle during the Liassic rifting. The opening of the Tethys could have occured through a crustal stripping of the upper mantle and the present state, with this lithospheric flaking, would only reflect the weakness of the European crust along two zones affected by listric faulting. MATTAUER (1983) proposed a similar mechanism of crust-mantle décollement to explain Himalayan crustal overthrusts.

A LITHOSPHERIC CONTRAST BENEATH THE ALPS

As exposed in the Introduction, any model, however satisfactory it may be, cannot be considered as definitive. To tell the truth, any additional experiment lays down new constraints which very often ruin the model instead of strengthening it. This is more or less what happened with the 1982 teleseismic experiment: a temporary network of 15 triggered seismic stations was deployed along a W-E traverse of the western Alps from Grenoble to Susa, and operated during approximately two months (POUPINET *et alii*, 1984). Several teleseismic events were recorded, mainly from the NE azimuthal quadrant (North-Western Pacific). The coherence of the first arches of the signal, from one station to another, made it easy to correlate arrival times (fig. 7).

After careful corrections for differences in epicentral distances and for topographic effects, these arrival times still exhibit strong unexpected variations if referred to a «normal» arrival time. Projecting the stations on the N125 axis, which is perpendicular to the local strike of the western Alps, a systematic offset is observed across the limit between the external zone (crystalline massifs and Dauphino-Helvetic zone) and the Penninic

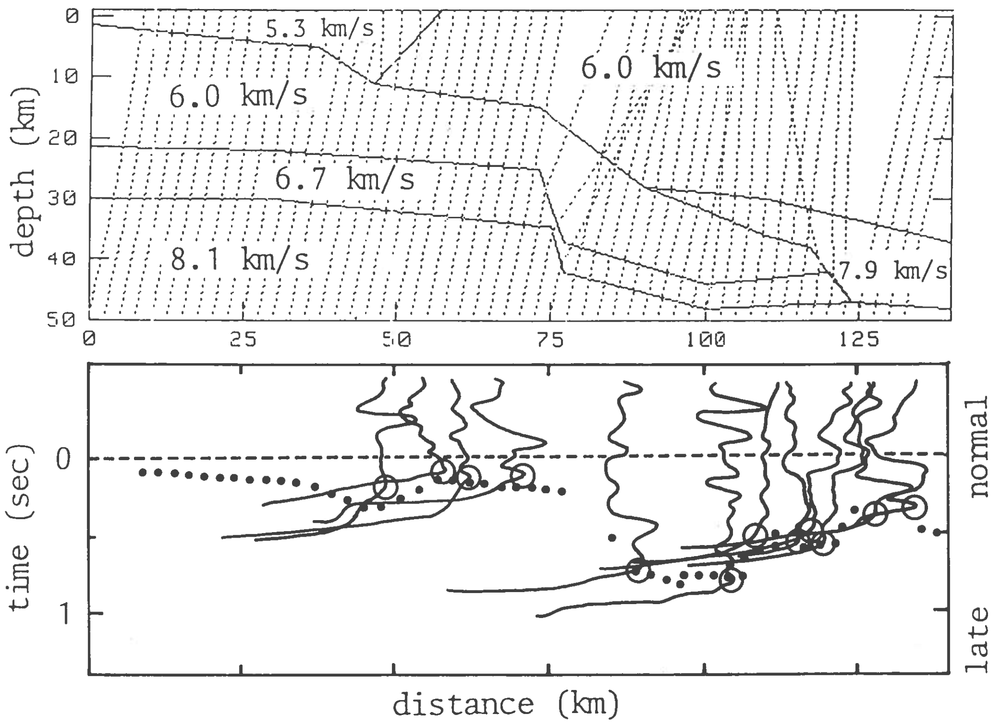

Fig. 7 - Teleseismic arrivals (Aleutian Islands event) along a N125 cross-section of the western Alps running through Belledonne. Teleseismic signals are represented with a very high amplification, which explains the apparent noise level prior to the teleseismic arrivals. Only first deviations are plotted. Open circles = observed arrival times; full circles = calculated times for the raytracing model shown above. An important Moho offset can explain a sudden jump in arrival times in the sub-Briançonnais zone. After HIRN *et alii* (1984) and POUPINET *et alii* (1984).

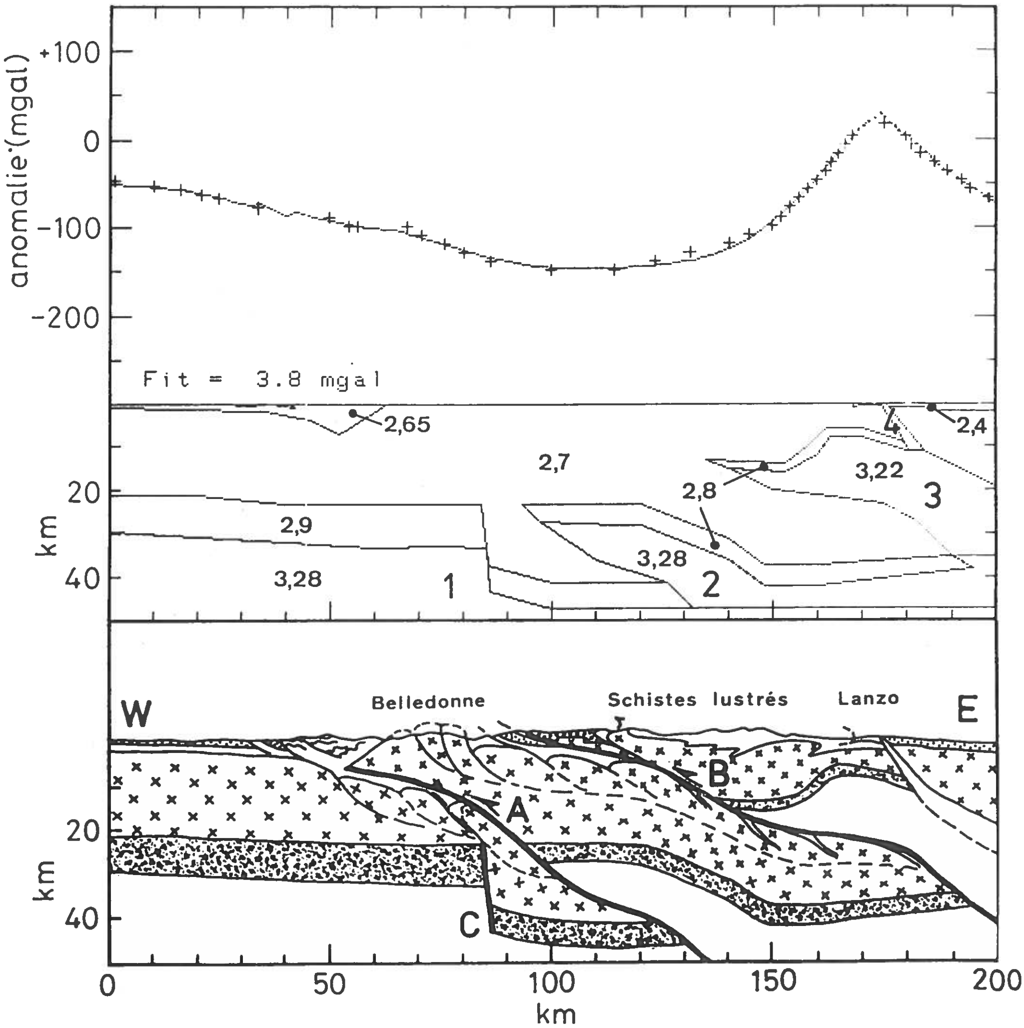

Fig. 8 - Belledonne cross-section: structural interpretative model (lower part), gravimetric model (middle) with densities in gcm^{-3} and calculated gravity profile (upper part) compared to observed gravity data (crosses). After MÉNARD & THOUVENOT (1984).

zone (Briançonnais unit). Stations in Briançonnais are about 0.5 s late when compared to stations in the Belledonne massif.

The sharpness of the variation, which occurs between two stations 15 km apart, is similar to what happens underneath the Pyrenees across the north Pyrenean fault (HIRN *et alii*, 1984). Part of this anomaly might be explained by supposing that the crust on either side differs in average velocity and composition or that mantle velocities are different. However, the sharpness of the variation makes it easier to interpret it as a Moho offset. We held this version in the ray-tracing presented in fig. 7 where travel-times computed along teleseismic rays are compared to observed arrivals. Even if this Moho step is as yet conjectural, this brings nevertheless into question the hitherto assumed smoothness of the Moho in our model, at least under Belledonne.

Fig. 8 is an ultimate modification of the model to incorporate this last constraint. The fit of calculated gravity anomalies to the observed Bouguer profile is shown to be reasonable. Note that no difference in the mantle density has been introduced: this was a deliberate choice to do so and a whole fan of gravimetric models can of course be constructed if a density variation is allowed.

PENDING TECTONIC PROBLEMS

We hope to have made it clear, all through this paper, which was the part of tectonic apriorisms in the construction of our cross-sections. As already stressed, however fascinating such models may be, nothing can replace reliable field experiments which should now be specially designed to solve peculiar problems.

This is the case for the mapping of eventual deep accidents under the Alps, of the lithospheric flaking and of the geometry of the Ivrea body (or bodies?). The Penninic zone is therefore a potential test site where we should be able to detect hitherto retained informations on the Alpine orogenesis. The extension of the Ivrea body to the north along the Swiss-Italian Alps, its vanishing to the south are so many three-dimensional moot points.

Other local tectonic problems can also be alluded to. We will restrict ourselves to two examples only. We first consider the so-called Vocotian chains which, between the Drôme River and the Durance River, form a good deal of the southern Subalpine chains. The thickness of marly calcareous sediments is due to the deep Vocotian trough which subsided during the Lower Cretaceous. A comparison between a gravity map and a Moho contour map shows something puzzling in this area: no exceptional Bouguer anomaly is detected, although the ante-Triassic basement is quite deep — 7 km according to MÉNARD (1980) — and the Moho reaches a depth of more than 40 km. This kind of enigma is a clue to a poor knowledge of the crustal structure in some parts of the western Alps.

Finally, the autochthony or allochthony of small crystalline units — as well as the one of the main massifs — is not yet well understood. It will be difficult to go deeper into crustal details if the basement is not properly mapped. For instance, not to mention the exact position of the Subalpine basement ahead of Belledonne and Aiguilles Rouges, the significance of crystalline outcrops such as Grand Chatelard should be sought. More generally speaking, the problem is linked to the determination of the dip of the basement from the external crystalline massifs towards the Briançonnais zone. What hapens to the basement between the same massifs, in areas such as Valais or Embrunais through where Penninic nappes seem to have been disgorged, is still another problem.

CONCLUSION

We presented, along transverse cross-sections of the western Alps, the evolution of a deep tectonics model which, hopefully, could be of some use to surface geologists. This model is shown not to be set at the moment by the sole geophysical data and the share of tectonic apriorisms is undeniable in it. However, even if this model does not answer any question, even if crustal overthrusts, lithospheric flaking and deep-seated Moho accidents are still conjectural, several features are emerging: the crust of the north-western margin of the French-Italian Alps consists of several «layers» with clear reflections from their boundaries; this Subalpine crust dips eastwards at about 30° as can be seen from its basement, its intracrustal discontinuity and its Moho; further east, the Alpine crust appears to be unstructured, with no sharp seismic discontinuities, but it presents a low-velocity zone at a depth ranging from 10 to 20 km approximately.

Finally, recent seismic experiments show that a smooth Moho model may be a wrong picture: if this proves true, the deep structure of the Alps would more resemble a patchwork of lithospheric segments than it does now.

ACKNOWLEDGEMENTS

This paper brings together geophysical studies and tectonic ideas which have been developped in I.R.I.G.M. Grenoble for the last ten years. The author is therefore very indebted to several contributors, mainly: Gilles Ménard, Guy Perrier, Georges Poupinet and Pierre Vialon, without whom most of these results would never have dawned.

NOTE ADDED IN PROOF

Further seismic investigations have taken place in the French-Italian Alps since this paper was submitted, which makes it slightly obsolete. Last in date, preliminary experiments to the ECORS-CROP project revealed the complexity of the inner zones and allowed a mapping of a deep-seated body. Extending westwards to the Briançonnais zone, this body corroborates the existence of the lithospheric flaking introduced in our model.

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