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EXPLOSION SEISMIC SOUNDING OF THROWS AND DIPS IN THE CONTINENTAL MOHO

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Abstract. Using critical-distance Moho reflections on fan-profiles, sections of the topography of the crust-mantle boundary across the Pyrenean mountain range are obtained. At two different places throws of more than 10km in the Moho are detected, they are situated beneath the same surface fault. Together with other features such as local dips, these results have a strong bearing on models of regional evolution. The existence of fractures through the continental lithosphere is documented by that simple technique using the Moho as a marker.

Technique

Conventional explosion seismology in the continental crust is often equated to refraction profiling and eventually regarded as having at best an output in terms of a velocity-depth function representing the averaged crustal layering beneath the profile. However in numerous places critical and wide-angle reflections from deep interfaces in the crust, or at the crust-mantle boundary have been reported. As generally profiles are recorded in-line with the shotpoint the change in arrival time and signal shape of reflected waves from one seismogram to the next are tightly related to the vertical velocity-depth variation in the crust. Only on very densely observed lines of the Soviet DSS type is there a good chance that superimposed effects of structural variation along the profile be detected. In fact indications of such deep variations, e.g. in the topography of the Moho, may be seen in interpretative cross-sections but the data crucial for their evaluation are not furnished.

A neglected use of critical-wide-angle reflections is to record them on fan-profiles, the constant epicentral distance leaving differences in arrival times of reflections to mirror the topography of the reflector. A powerful reconnaissance tool may thus be at hand particularly for deep intralithospheric markers like the Moho.

Experiment

a) Geological context. The Pyrenean mountain range resulting of the remobilization of Hercynian basement and mesozoic sediments in an orogenic cycle of early Alpine age extends almost linearly in an E-W direction for 400km from the Atlantic Ocean, Bay of Biscaye, to the Mediterranean Sea, between the Iberian peninsula and the rest of Europe. At least in its eastern half, sketched in Fig.1, three domains are classically recognized :

- the Paleozoic axial zone (P.A.Z.) characterized by i) the topographical culmination, ii) the outcrop of hercynian basement : gneisses, more or less metamorphosed Paleozoic sediments and granitic massifs of Hercynian age, iii) negative values of the Bouguer anomaly, as low as -150mgal.
- the North Pyrenean zone (N.P.Z.) separated from the former by a narrow band of low-pressure high-temperature metamorphics together with lherzolites and composed of folded Mesozoic sediments and large outcrops of Hercynian basement; the limit between P.A.Z. and N.P.Z. is an almost linear fault continuous for tens of kilometers, referred to as the North Pyrenean fault (N.P.F.).
- the sub Pyrenean zone (S.P.Z.) where younger sediments are practically not deformed ; it is overthrust by the N.P.Z. along the North Pyrenean frontal thrust (N.P.F.T.) the trace of which is complicated in its easternmost part.

b) Average crustal thickness of the different domains. From shotpoint D (Fig.1) situated some kilometers to the North of the N.P.F. numerous seismograms could be obtained at distances larger than 70km, with good P_MP Moho-reflections. In fact late phases are obvious on most of these seismograms ; their arrival times vary strongly along the two North-South fan-profiles recorded East and West of the shotpoint. Accessory short profiles have been recorded in-line with the shotpoint to control the identification of these late arrivals as Moho-reflections in different structural units. On the record-sections of these short profiles obtained to the East very different positions of the P_MP curves in the time-distance field are seen in the N.P.Z.(Fig. 2a) and the P.A.Z. (Fig.2b). At the same distan-

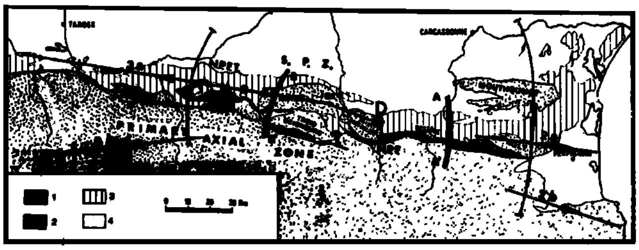

Fig.1. Eastern part of the Pyrenees : Mediterranean sea to the East, France to the North and Spain to the South. 1) massifs of Hercynian rocks forming the Primary Axial zone and some isolated outcrops in the North Pyrenean Zone ; 2) Pyrenean metamorphics ; 3) sediments folded during Pyrenean orogeny, mainly Cretaceous of the N.P.Z. 4) only slightly deformed, mainly Cenozoic cover of the S.P.Z.. Situation of profiles and crustal section.

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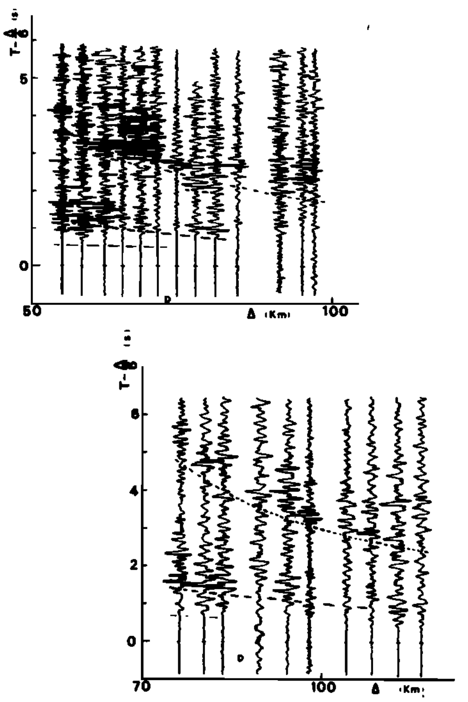

Fig. 2 Profiles to the East of shotpoint D, in the North Pyrenean Zone (upper) and Primary Axial Zone (lower). Note differences in arrival times of P_MP reflections correlated as late arrival.

ce of 90km on both profiles reduced travel-times of 1.9s and 3.5s indicate average Moho-depths of about 28 and 38km respectively. Record-sections in the other direction, West of the shotpoint are plotted in Fig.3a and 3b. In this direction the crust under the P.A.Z. appears to be so thick that P_MP arrivals are not very clear, being probably undercritical, at distances smaller than 130km. On Fig. 3a and 3b at a same distance of 150km reduced times of 1.3s and 4.1s indicate Moho-depths to be about 33km and 51km under the N.P.Z. and the P.A.Z. respectively. Further data from other shotpoints are coherent with the general feature of an important difference in crustal thickness beneath the N.P.Z. and P.A.Z. (Explosion Seismology Group Pyrenees, in press; Gallart et al., in press).

c) Topography of the Moho from fan-profiles across the Pyrenean range. Once the strong late arrivals on the two fan-profiles East and West of the shotpoint have been identified as P_MP reflections by comparison with the in-line profiles, their arrival times may be transformed into Moho-depths at the points of reflection approximately halfway between the shotpoint and the different recorder locations. After correction for a sediment cover on the northern part of the fan-profile to the West of the shotpoint, an average crustal velocity of 6.25km/s is used to plot the P_MP part of the seismograms into depth-sections of the Moho situated along the lines of reflection points.

Fig. 4 represents thus the depth-section along line A-A' (Fig.1) extending from the P.A.Z. to the S.P.Z.. The main feature of this cross-section is a change in depth of the Moho from 38km to 27km within a horizontal distance of less than 10km. The section is without vertical exaggeration so that this throw in the Moho is situated just beneath the surface trace of the N.P.F.. For the next 23km to the North of the N.P.F. the Moho is strongly down-dipping. As the seismograms have been plotted here just beneath the shotpoint to station line, the reflector depths are not exactly obtained in presence of such a relief. Migration would even increase the dip. Some further data North of the N.P.F.T. indicate that the Moho is more horizontal, or slightly shallowing towards the North in the sud Pyrenean zone.

On Fig.5 again, which represents the depth-section along B-B' the well-documented Moho reflector which is almost horizontal at a depth of about 33km beneath the N.P.Z. is brutally interrupted at the transition with the P.A.Z.. The increase in depth to the South is so important that, as recorder-shotpoint distance was kept constant for the fan-observations, the reflection become undercritical which explains their smaller amplitude. An extreme difference in depth, of at least 18km, may nevertheless be derived for the Moho ; again this step is occuring over a horizontal distance of less than 10km just beneath the surface trace of the N.P.F.

Implications

a) Mapping techniques of deep boundaries, at lower crust and upper mantle levels. Critical and wide-angle reflections from the Moho are currently reported in recent well-recorded conventional crustal surveys. We have shown in this example that off-line shooting at large offset distances provides a powerful tool to

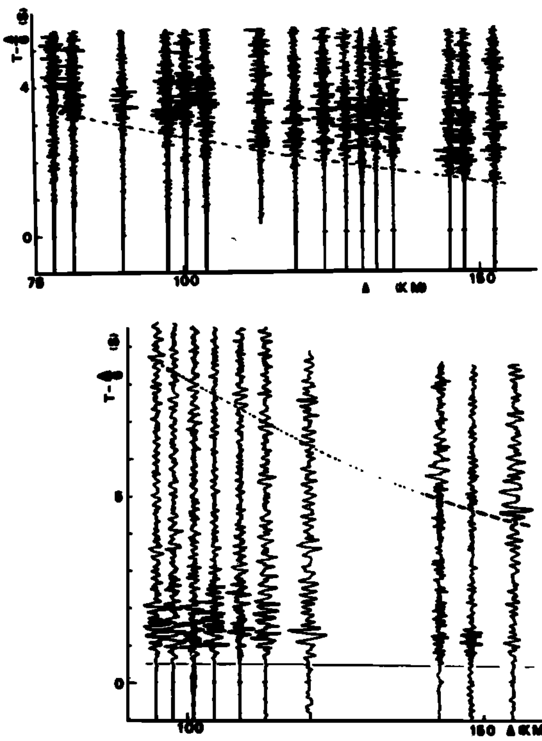

Fig. 3 Same as Fig.2 but to the West of the shotpoint.

describe the topography of the Moho. If normal profiles, crossing the N.P.F. and N.P.F.T. , with shots in line would certainly have detected the deep perturbations associated with them, the resolution obtained here is far better. For instance, to constrain the location of the Moho throw with a precision better than 5km or to detect a depth variation of 6km on a 23km long segment of a reflector about 30km deep (under the N.P.Z., fig. 4) would probably have been far from easy with in-line profiles. It is however probable that in the general case where deep structural elements are less continuous than in our example more complicated field procedures would be necessary, like the use of several shotpoints on a line at constant offset of the recording line. In the general case the longer propagation path of critical reflections evidently does not allow to achieve a resolution comparable to that obtained by recently developped continuous vertical-reflection profiling at upper and intermediate crustal levels (Oliver et al., 1976). However, although no other method than continuous vertical reflection profiling could have solved the wide range of geological-geodynamical problems reviewed by Schilt et al., (1979) no clear example has yet been reported where penetration by this technique to Moho level has allowed to sample particular topographic features of that major marker in the lithosphere. A difference in effectiveness of wide angle and vertical reflection techniques for mapping the Moho exists in the case where the velocity contrast between crust and mantle is smeared over a depth interval of the order of the signal wavelength,the wide angle amplitude being left almost unaffected but vertical reflection amplitude decreased by an order of magnitude with respect to the case of first-order velocity-depth discontinuity . From what is known of the velocity-depth function in the uppermost mantle by long-range profiling (e.g. Hirn et al., 1975) a transitional type is even more probable for the interfaces in that domain than for the Moho. Thus a fortiori, mapping of those boundaries requires an approach by critical reflection sounding, at least in addition to attempts to apply vertical reflection techniques.

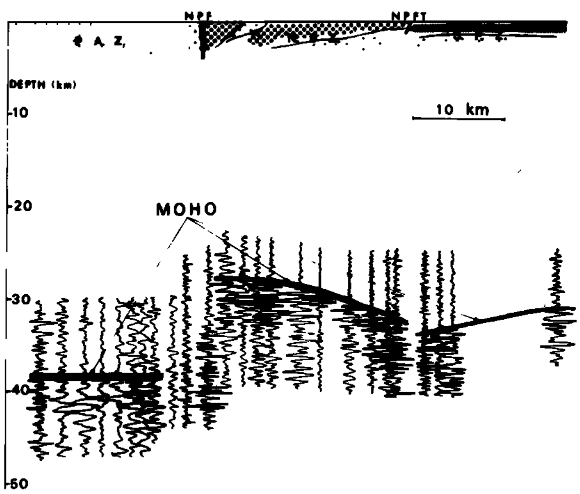

Fig. 4 Crustal section A'A, East of the shotpoint, from the P.A.Z. (left) to the S.P.Z. (right). Crosses : Hercynian basement ; dots : Mesozoic sediments of N.P.Z. ; hatches : Cenozoic cover of S.P.Z.
Depth section of the Moho without vertical exaggeration.

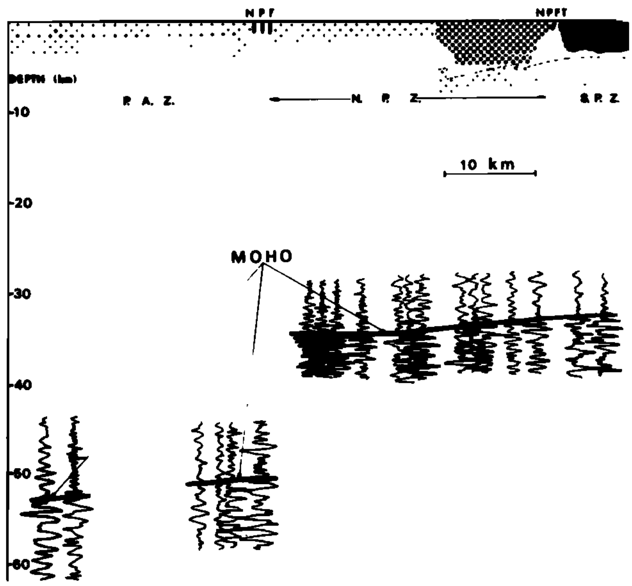

Fig. 5 Crustal section B'B, West of the shotpoint, from the P.A.Z. (left) to the S.P.Z. (right).

b) Deep fracturation of the continental lithosphere. The geographical coïncidence, at two places 90km distant, of a throw at depth of more than 10km in the Moho with the surface trace of the same major structural boundary documents the existence of a large-scale nearly vertical fracture from the surface to the mantle. Such lithospheric fractures need to be further investigated to assess if they are a general characteristic of continents. Additional to processes of ductile flow of material, which require particular thermal contexts, the rheological behaviour of the continental lithosphere might thus be, at least partly, ascribed to lithospheric fractures along which motions in reaction to imposed stress may be accomodated.

Delineation of such continental fractures in regions where seismicity is not precisely determined or the rare occurence of large earthquakes is insufficient for the determination of active zones may contribute to the definition of regions where concentrated stress may preferentially be released.

c) Geodynamical evolution of the Pyrenees. The topography of the Moho on sections (Fig.4 and 5) crossing the different structural dómains of the Pyrenees places new strong constraints on models of geodynamical evolution. Key elements have been previously considered respectively : i) the metamorphic zone, as resulting from the compression of a Cretaceous continental rift (Souquet et al., 1977) or ii) the N.P.F.T. as being the contact of two continental margins after subduction of an oceanic domain towards the South (Boillot and Capdevila, 1977) or iii) the N.P.F. as the major element in a transform region having accomodated a left lateral motion of several hundred kilometers of Iberia along Europe (e.g. Choukroune and Mattauer , 1978).

Our results have following characteristics: i) The coincidence of the Moho throw at depth with the N.P.F. at the surface designates this fault as the main tectonic element of the Pyrenees, at least in that part. ii) The clear updipping of the Moho (Fig. 4) from the N.P.F.T. towards the N.P.F. to the South could be due to an episode of thinning of the crust ; thus the N.P.Z. would resemble a continental margin, but that of the northern continent. The lack of such a feature on the other section (Fig.5) however indicates that rather than a continuous continental margin, domains of local crustal thinning should be considered, which may have originated in different contexts than continent-ocean juxtaposition. iii) The verticality of the fracture along the N.P.F. and depth of the Moho with respect to the pre-mesozoic basement on the two sides of it, lead to consider that horizontal shear has been the major type of motion.iv) The zone of maximum recent surface elevation of the Hercynian basement, resulting from the Pyrenean orogenic cycle, correlates with the P.A.Z. where the Moho depth shows a sharp increase South of the N.P.F.. The coincidence of these features may be interpreted as marking a relation between them as well for the cause as time of their formation, for which a model of differential deformation under compression of a non uniform crust is developped.

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References

Boillot G. and R. Capdevila, The Pyrenees : subduction and collision, Earth and Planetary Science Letters, 35, p.151-160, 1977.

Choukroune P. and M. Mattauer, Tectonique des plaques et Pyrénées : sur le fonctionnement de la faille transformante nord-pyrénéenne : Comparaisons avec des modèles actuels. Bull. Soc. Géol. Fr., XX, p.689-700, 1978.

Explosion Seismology Group Pyrenees, Seismic reconnaissance of the structure of the Pyrenees, Ann. Géophys., submitted.

Gallart J., Daignières M., Banda E., Surinach E. and A. Hirn, The eastern Pyrenean domain : lateral variations at crust-mantle level, Ann. Géophys., submitted.

Hirn A., Prodehl C. and L. Steinmetz, An experimental test of models of the lower lithosphere in Bretagne (France), Ann. Géophys., 31, p. 517-530, 1975.

Oliver J., Dobrin M., Kaufman S., Meyer R. and Phinney, Continuous seismic reflection profiling of the deep basement, Hardeman County, Texas, Geol. Soc. Amer. Bull., 87, p.1537-1546, 1976.

Schilt S., Oliver J. Brown L., Kaufman S., Albaugh D., Brewer J. Cook F., Jensen L. , Krumhansl P., Long G. and D. Steiner, The heterogeneity of the continental crust. Results from deep crustal seismic reflection profiling using the vibroseis technique, Rev. Geophys. and Space Phys., 17, p.354-367, 1979.

Souquet P., Peybernes B., Bilotte M. and E.J. Debroas, La Chaîne Alpine des Pyrénées, Géologie Alpine, 53, p.193-216, 1977.

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