PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Features of the Crust--Mantle Structure of Himalayas--Tibet: A Comparison with Seismic Traverses of Alpine, Pyrenean and Variscan Orogenic Belts

A. Hirn

Phil. Trans. R. Soc. Lond. A 1988 **326**, 17-32
doi: 10.1098/rsta.1988.0079

Phil. Trans. R. Soc. Lond. A **326**, 17–32 (1988)

Printed in Great Britain

Features of the crust–mantle structure of Himalayas–Tibet: a comparison with seismic traverses of Alpine, Pyrenean and Variscan orogenic belts

BY A. HIRN

Laboratoire de Sismologie and Project ECORS, Institut de Physique du Globe, 4 pl. Jussieu, 75252 Paris, France

Seismic data able to resolve the crustal structure are limited in quantity and quality with respect to the size and complexity of Tibet–Himalayas. They may be interpreted as indicating a strong heterogeneity: lack of continuity of even major interfaces across strike, defining different crustal blocks, but also lack of continuity of surface tectonic features down through the whole lithosphere. A thickening by imbrication of both the upper crustal and the lower crust–upper mantle levels is suggested. Indications from recent high-resolution surveys in other domains of thickened crust are also of a less smooth geometry of structures and depth than intuitively considered.

1. INTRODUCTION

Evidence on the seismic structure of Tibet–Himalayas has traditionally only been obtained with sensors outside the region. In 1977 explosion seismology, deep seismic sounding by so-called refraction profiles, was initiated by the Institute of Geophysics, Chinese Academy of Sciences (1981). The use of this technique was developed in 1981–1982 by a Sino-French cooperative programme that also deployed temporarily long-period seismographs for surface-wave dispersion studies (Jobert *et al.* 1985), did gravity (Van de Meulebrouck *et al.* 1983) and heat-flow (Francheteau *et al.* 1984) measurements and other geophysical and geological studies (Allègre *et al.* 1984). In other regions like the Alps, similar studies initiated over 30 years ago are still currently supplemented almost every year without the picture of the deep structure having reached a sharpness and precision such that a consensus about its nature and the evolutionary models it supports being reached. For Tibet–Himalayas, that single experimental effort has unfortunately remained quite isolated and further sampling of the medium to control the significance of data and suggested interpretations is not forthcoming.

We review here particular aspects of the presentation of the seismic data acquired and of suggested interpretations, which still remain of a speculative nature as there has been no chance to test them by new experiments. Recently we gained a new insight into the deep structure of other regions of abnormally thickened crust in the Alps and the Pyrenees that shall be used to shed nevertheless some light on interpretations or speculations we suggested of the deep structure of Tibet–Himalayas. First, in the frame of our ECORS programme the particular type of gross explosion-seismology single-trace oblique-incidence profiling as used in Tibet could be tested against the much more resolving multiple-coverage vertical-reflection profiling derived from expensive industrial prospecting, now currently used (Matthews & Smith 1987). Second, the particular structures we detected (ECORS Pyrenees Team 1988; Daignières *et al.* 1988; Bayer *et al.* 1987; ECORS–CROP Deep Seismic Sounding Group 1988) provide interesting examples of structural styles unsuspected from other data or at odds with currently admitted interpretations, a situation that might bear some resemblance to that in Tibet where the simplest explanation of some seismic observations would yield pictures unexpected by commonly considered models.

2. Seismic sounding for the lithospheric structure

Seismic waves artificially generated at the surface of the Earth penetrate the lithosphere and can be sensed and studied if turned back to the surface either by refraction in a medium of strong positive velocity gradient with depth or by reflection on interfaces of strong local velocity contrast or by propagation as head-waves along such interfaces. The main, unavoidable limitation of the seismic-prospecting method comes from both the sources and the sensors being at the surface, which causes non-unicity of the interpretations of data in terms of the underlying structure. Nevertheless, variations in experimental designs are possible, mainly in the relative geometry of the sources and sensors that control the incidence of waves detected, the spectral content and amplitude level of the signal, and in the number of data, which is controlled by financial aspects. The sensitivity of an experiment may be adapted, for instance, rather to the study of the velocity–depth function of a presumably horizontally stratified structure by following the wave field as a function of range from the source and hence as a function of penetration into the structure. Commonly called a refraction profile, this arrangement where source and sensors are indeed on a straight profile line provides, in fact, a seismic sounding and the clearest waves detected are most often the wide-angle reflections of the sharpest changes in the velocity–depth function. In contrast to this reconnaissance method for the average layering of the structure, the vertical reflection method used by the prospection industry and now also in lithospheric studies (see, for example, Brown & Barazangi 1986) profiles the topography of subsurface interfaces with an extremely fine resolution, because of the density of source and sensor arrays. This succeeds if signals can be made strong enough by adding many individual observations in the multiple coverage, and provided the interface responds to this particular vertical incidence and its response and the attenuation in the medium of propagation are fitted to the high-frequency character of sources and sensors tuned for fine resolution.

For the investigation of the lithospheric structure of Tibet, deep seismic sounding along two 400 km long bases with shots at both ends and in the middle was performed along the strike, just north of the High Himalayas and 400 km further north. To gain furthermore an impression on the variation of the deep crust across the strike, we used a wide-angle reflection method that we designed and used some years earlier through the Pyrenees (Hirn *et al.* 1980) and more recently through the Variscan Belt of northern and western France (Hirn *et al.* 1987; Matte & Hirn 1988) and the Alps (ECORS–CROP Deep Seismic Sounding Group 1988) as will be shown later for comparison. Sensors placed on fan profiles with respect to the source, i.e. at constant offset of it, record waves for which this range corresponds to a critical or wide-angle reflection of maximum amplitude. Differences of arrival times of a given wave on neighbouring traces mirror differences in reflector depth or average velocity above it at the different turning points of waves. From one single source, wide-angle reflection profiling provides as many data points as there are sensors and with a separation adjustable by that of the sensors, e.g. with 30 sensors spaced at 5 km intervals along the fan a 75 km segment of reflector can be followed with a 2.5 km sampling, mid-way between the shotpoint and the profile of receivers. The usual vertical reflection method of industrial prospection may be viewed as an extreme case of this scheme in which the constant offset is set to zero. In this layout each shot is recorded by a multichannel array of nearby geophones but data are summed to form about only one single zero-offset trace for each shot, hence the sampling of the medium along the profile line depends on source separation. However, the energy of each source may then be reduced as only the vertical distance to the reflector has to be penetrated and stacking and signal-processing techniques can be used on a pattern of close-by sensors. In the first approximation interesting for the Tibetan expedition, the use of wide-angle reflection profiling is a cheap reconnaissance ersatz to vertical reflection resolution having thus to be subordinated to the length of cross section to be obtained; this section is, however, only for the depth range to which the offset is tuned. Another important reason for using it was that adequate response at wide angle to a low-frequency signal is much more probable than at steep angle to a high-frequency one in the case possible in Tibet of a transition zone at crust–mantle boundary and of long paths of propagation through a possibly attenuating crust.

3. Average lithospheric layering

3.1. *Average layering of the crust between High Himalayas and Yarlung Zangbo, depth to Moho and a comparison with the western Alps*

Seismic nature and depth of the crust–mantle boundary

Probably the most firmly established result of explosion seismology in Himalaya–Tibet is the unequivocal identification of the crust–mantle boundary and determination of its depth just north of the High Himalayas (Hirn *et al.* 1984*a*, *c*). It is probably one of the most clear and precise examples of such determination worldwide as both the upper mantle is well identified by Pn head waves propagating just beneath this limit with a 8.7 km s^{-1} reversed apparent velocity, and the lower crust and transition zone are well expressed in, and can be modelled by, amplitudes and waveforms of wide-angle reflections (figure 1).

The uppermost mantle has a high velocity: even correcting the measured value for Earth curvature and pressure due to abnormal depth leaves us with a very high value for the material that might call for reduced temperatures and anisotropy or only anisotropy with an east–west orientation of the fast direction. There is no straightforward interpretation for this were it not that it is the direction of tectonic escape of the lithosphere or certain levels of it in the general shortening between points respectively in undeformed Asia and India and that high velocities in the uppermost mantle have been proposed elsewhere to be related to anisotropy induced by stress or differential motion (see, for example, Hirn 1977; Fuchs 1983).

The mantle is identified as lying about 80 km beneath the surface, or 75 km beneath sea level; crustal material reaches 65 km thickness, i.e. extends over 60 km below sea level, and a 10–15 km transition layer in between allows us to model the low-frequency seismograms. This passage from crust to mantle may look differently if it could be resolved with shorter wavelengths signals.

The region where this large crustal thickness is measured is situated only 30–50 km north of the highest Himalayan peaks, nearer to them than to their border with Tibetan terranes at the Yarlung Zangbo Suture. We are here still on the slope of the Bouguer anomaly, with values of the order of −300 to −350 mGal,† far from the minimum of the order of −500 mGal. This constraint from seismic sounding, the maximum thickness of the crust extending far south

---

† 1 mGal = 10^{-3} cm s^{-2}.

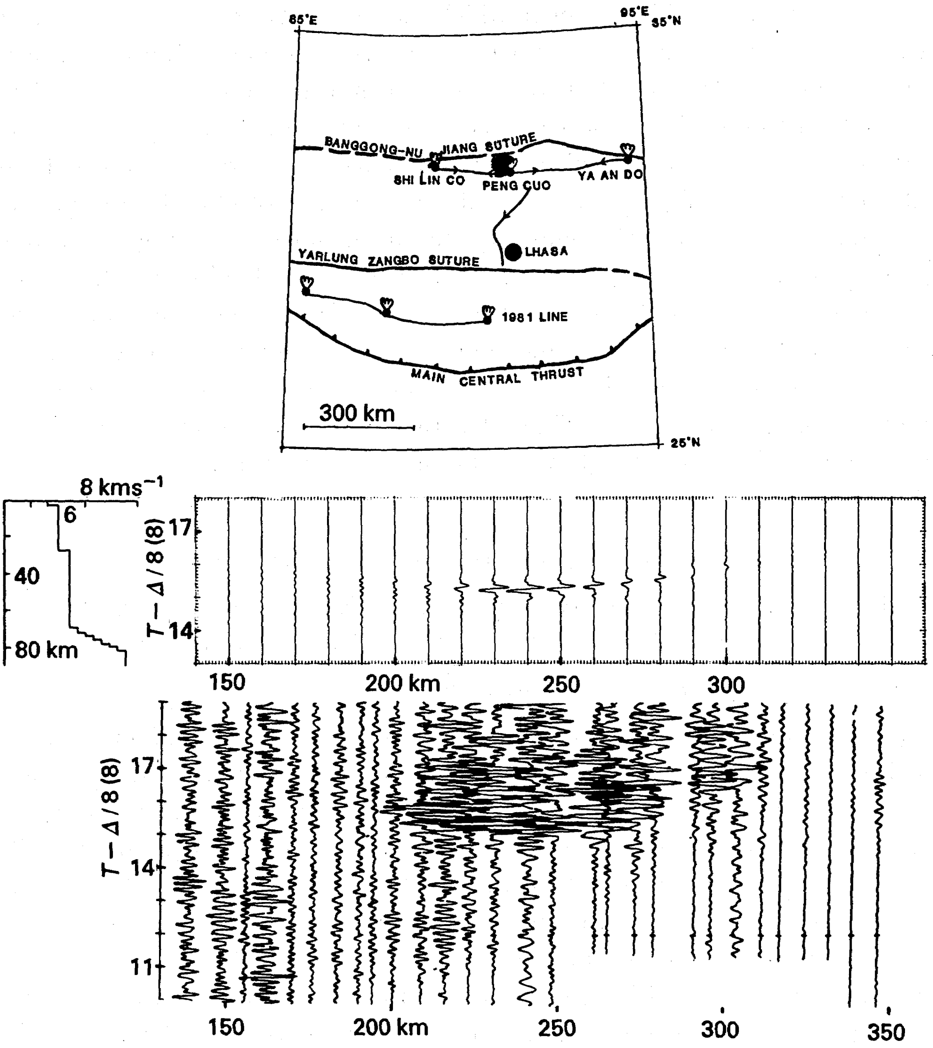


FIGURE 1. Part of seismic sounding along the reversed line recorded along strike around 40 km north of the High Himalayas. Constant gain on all traces reveals strong energy at offsets around 200 km, modelled as a reflection on the Moho, a transition zone about 10 km thick centred around 70 km beneath the surface. Mantle refractions with 8.7 km s^{-1} high apparent velocity are identifiable on amplified section only (figure 7 in Hirn *et al.* 1984*c*). Insert shows position of main seismic lines in Tibet.

towards the High Himalayas, is difficult to reconcile with the considerations developed by Karner & Watts (1983) and Lyon-Caen & Molnar (1983, 1985) when trying to account for the support of the topography of the Himalayas and Ganga Basin and for the gravity anomaly by the sole flexure of the Indian Plate without introduction of an anomalous repartition of masses. A smooth slope of the Moho of an Indian Plate continuous to the Yarlung Zangbo would have this Moho situated still shallower just north of the Himalayas than we find. Furthermore, we establish that as the crust is already very thick at this latitude it does not have a marked further increase towards the Yarlung Zangbo, whereas this is the region where Lyon-Caen & Molnar (1983) would need the strongest flexure, i.e. gradient in Moho depth (from 50 to 115 km), after having already been obliged to allow a strong variation in elastic parameters of the Indian crust, which in fact does weaken the simplicity of the model of its continuity towards north.

Comparison with the response of the Alpine thickened crust

Although the topography of the Moho across the Himalayas that we propose later as the simplest interpretation of seismic data may be debatable in its complexity, it would appear that maximum crustal thickness is reached earlier across the mountain range than if its topography were only supported by a flexed plate. A possibly similar feature was revealed by our wide-angle reflection profiling of the Moho across the western Alps (ECORS–CROP Deep Seismic Sounding Group 1988), the time section of which is shown in figure 2, converted to depth after correcting for normal moveout. A strong change in the rate of increase of crustal thickness is seen to occur at the edge of a relatively horizontal Moho that reaches to the east of the External Crystalline Massif of Belledonne. If the Moho reflection was strictly continuous and straight to the east of it, the reflector should be obtained by migrating the reflection from its position in

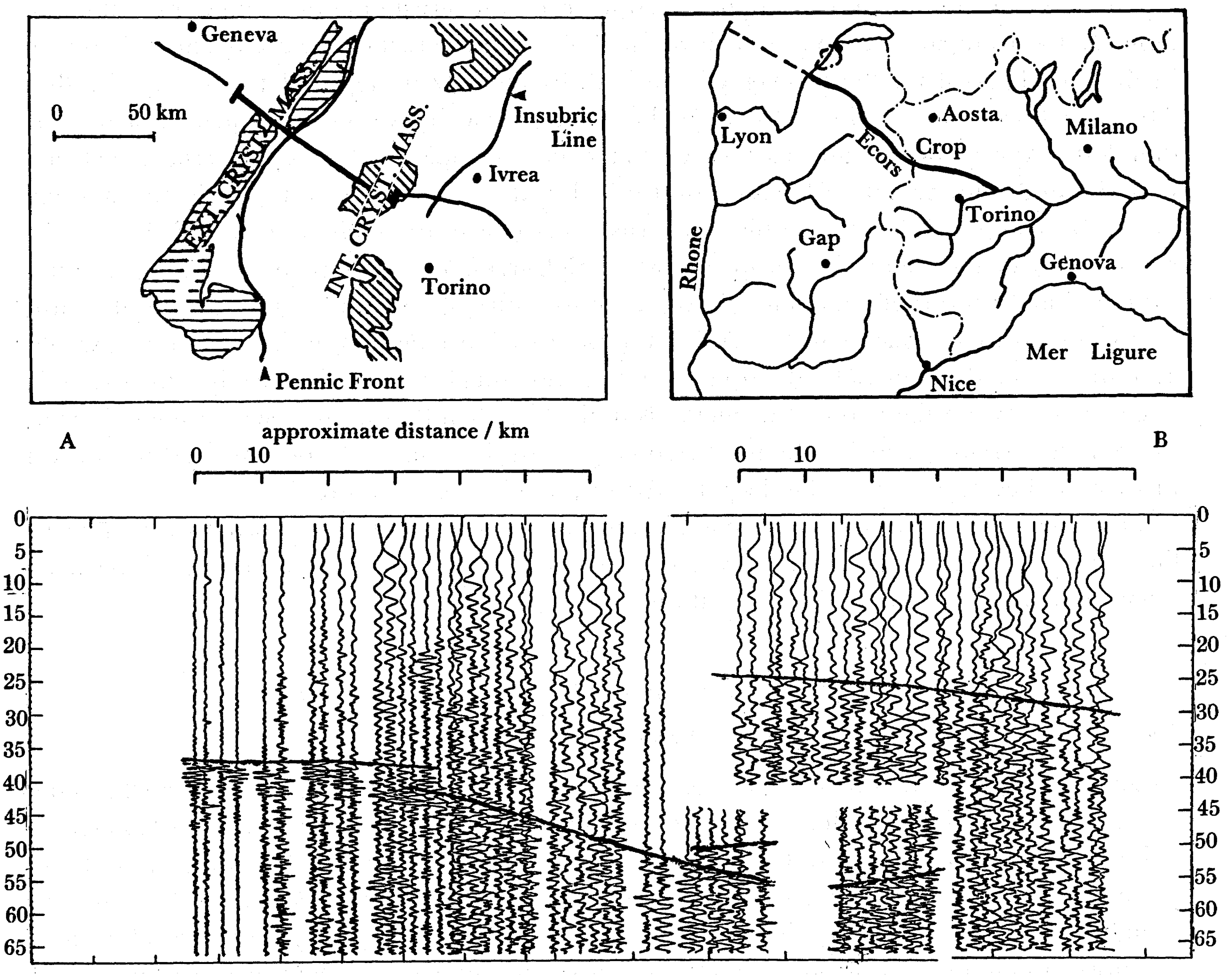


FIGURE 2. Western Alps, wide-angle reflection composite cross section of Moho topography, after ECORS–CROP Deep Seismic Sounding Group (1988). Data corrected for normal moveout with an average crustal velocity of 6.25 km s^{-1} from their offset between 100 and 150 km (insert map shows position of section, mid-way between shotpoints and recorders). Note change in rate of variation in crustal thickness east of Belledonne, Moho would be even steeper there if migrated in the assumption that its reflection is a piecewise continuous and straight segment. Note also the change in signal character and frequency content, the reflection signal losing higher frequency when Mono gets deeper (recording of the same shots outside the region of thick crust allows to exclude a source effect).

figure 2 and would be even steeper than it appears. The change in rate of increase of crustal thickness to the east would then be even more important with respect to that considered for simple support of topography by flexure, which model has hence to be complicated by introduction of abnormal repartition of mass (Karner & Watts 1983).

The Alpine example illustrates another feature for which hints exist in Tibet: propagation of seismic waves to the Moho is not just like twice the propagation through a normal crust, but indicates that a change of internal or Moho structure occurred upon thickening. In the Alpine wide-angle Moho cross section (figure 2) the reflection signal loses its high frequencies from the foreland to the zone of thick crust. Also the coincident vertical reflection section, for which the prospection method derived from industry was used, so that signals cannot contain frequencies lower than 10 Hz and incidence is restricted to near vertical, completely loses track of the Moho in this internal part (Bayer *et al.* 1987). In Himalaya–Tibet, we modelled the contrasting broad-spectrum intracrustal and low-frequency Moho wide-angle reflections obtained and derived in addition to a transitional character of the crust–mantle boundary either an abnormally strong attenuation in the lower half of the thick crust or the occurrence of a screen in the middle crust for the propagation of high frequencies to depth (Hirn & Sapin 1984). Although there is no evidence for it in the average velocity structure, which indicates the double-thickness Himalayan crust to be made of an upper half of upper-crustal velocity material and a lower half of lower-crustal velocity material, slivers of high-velocity material might be contained locally within the crust and constitute such a screen if that is the explanation of the ineffective propagation of high-frequency signals to the Moho. Similar explanations in terms of a modified lithospheric structure, by inclusions into the middle crust, change of nature of crust–mantle transition or increased attenuation in the lower crust, would account for the differences between vertical and wide-angle seismics in the Alps, the example of coincident use of the two seismic methods indicating then that it may be extremely difficult to apply a current version of the most resolving vertical seismic reflection method to unravel further the heterogeneity of the deeper parts of the Tibetan structure.

This relative effectiveness of wide-angle reflection hence has to be resorted to, despite its limitations, for what remains a very gross reconnaissance of lateral variations of the deep structure across the Himalayas and within Tibet.

3.2. *Hints at crust and mantle layering in the Lhasa Block*

The Shi Lin Lake to Ya An Do sounding (*Sapin et al.* 1985)

Logistical constraints restricted the possibility of achieving a 400 km base reversed seismic sounding to the vicinity of what turned out to be the northern limit of the Lhasa Block, between Shi Lin Lake, Peng Lake and the town of Ya An Do. The lack of continuity and the perturbation of the wave pattern with distance is probably caused by its interference with the strong north–south variability discussed later. Nevertheless at very large distances of each of the three shotpoints used, strong arrivals are consistently noted for a few traces. Distances and times of arrivals are almost comparable to the Moho reflection beneath the line south of the Yarlung Zangbo and may hence be attributed to a Moho around 65 km deep; it seems difficult to imagine an alternative way of bringing such seismic energy to these offsets and times of propagation.

The lack of the complete wavefield prevents us from estimating precisely both the depth to Moho and the average crustal velocity, between which there is a trade-off. If the average velocity was smaller than that south of the Yarlung Zangbo, Moho depth would be smaller than proposed above, and conversely.

The upper 30 km of the crust, as their sampling occurs by shorter sounding lines, are better defined and exhibit fine structural layering. The particular situation of the profile probably prevents us, however, from generalizing to the whole-block details of this layering, although a line from the central shotpoint of the line, Peng Lake, recorded to the south all through the block is strikingly similar as far as the reflectivity around 20 km depth is concerned.

The upper mantle from surface-wave dispersion (*Jobert et al.* 1985)

No penetration below the crust could be achieved by explosion seismology. To cope with this, the acquisition of a complementary data set by a different method had been prepared. Four long-period seismic stations could hence be positioned and maintained for several weeks by taking advantage of personnel and logistical support of the explosion seismology experiment. The geometry of the array, 400 km distance between stations, and the occurrence of a few distant earthquakes of adequate magnitude and azimuth allow us to constrain the shear velocity–depth function by the inversion of Rayleigh wave phase-velocity dispersion curves between pairs of stations. The two southern stations are between the Himalayas and Yarlung Zangbo, the two northern ones at the northern limit of the Lhasa Block, which is thus the region principally sampled by this study, in the region of the explosion seismology surveys. The velocity–depth function (for shear waves) below 65 km depth shows a similarity with that for the Western Europe platform or mobile region rather than with the Eastern Europe shield region. Besides the need for an increase of velocity between the upper half and the lower half of the crust, the inversion of dispersion data mainly tends to show a reduced thickness of a mantle high-velocity lid for these different starting models. Above a region of velocity decrease in the mantle that may correspond to the base of the lithosphere and is situated at similar depths of 100–150 km in the models for Tibet and Westen Europe, the crustal part of the lithosphere in Tibet is thicker by a factor of two whereas its mantle part is not, or is even thinner. If originating from a lithosphere originally having a thicker mantle than crustal part, this would mean that while the crust thickened the mantle lithosphere returned partly to the asthenosphere, by delamination or thermal modification.

This relatively low average velocity in the mantle under Tibet (Molnar & Chen 1984; Romanowicz 1982) has also been more recently confirmed by Lyon-Caen (1986) with the independent study of direct and surface-reflected shear waves to be confined to the uppermost mantle, i.e. to a reduced thickness of the mantle lithosphere.

3.3. *Evidence for internal structure of the lithosphere south of the High Himalayas*

The seismic determination of the crustal structure of the Lesser Himalayas would well deserve a reversed sounding along the strike; unfortunately such data of a quality similar to southern Tibet are still missing. This leaves much room for speculation as to the evolution of this structure across the Himalayas as it is not even known where the Indian Plate approaches this complex domain. Having only shotpoints north of the Himalayas we could do no better than at least place recording stations in Nepal, unfortunately across strike and without shot in the south to reverse the profile. Several relatively clear waves are recorded showing a heterogeneous crust but obviously there is a trade-off between velocities and dips of interfaces. A later section will present the composite picture derived across the Himalayas (Lépine *et al.* 1984; Hirn & Sapin 1984).

4. MAJOR LATERAL VARIATIONS: THE SUTURES OR WRENCH FAULTS LIMITING THE LHASA BLOCK

The Mohorovičić discontinuity between crust and upper mantle is the major seismic marker in the lithosphere. Most recently results of vertical reflection profiles of COCORP in the Western United States and BIRPS around Britain would suggest the Moho be less immutable than previously thought, perhaps able to change its identity and migrate in depth in the lithosphere in geodynamical contexts where extension and high temperatures prevail (see, for example, Barton 1986). Nevertheless in compressive contexts its depth situation and its shape may be remnants of the major deformational history.

In the north–south cross section of the Tibetan Moho based on wide-angle reflection fan-shooting we proposed (Hirn *et al.* 1984*b*), the two limits of the Lhasa Block inferred from surface geology appear to be associated with clear perturbation to the topography of the Moho. This whole section was obtained as a composite from several shotpoints but the part of data across each of these limits comes each time from only one shot situated near its surface trace. Also the stations either side of the limit are really at the same offset from shotpoints so that the uncertainty that may be introduced elsewhere in normal moveout correction by the lack of precise knowledge of the velocity–depth function does not disturb the picture of the Moho topography obtained here. The coincidence of changes of structure at Moho depth with the vertical of limits between terranes at the surface would in general favour the idea of a strike-slip enhanced limit of the sutured blocks. However, as the structure between surface and the Moho marker is unknown there may be an unknown amount of imbrication (see figure 3).

4.1. *The southern limit of the Lhasa Block: the Yarlung Zangbo Fault Zone*

The Angren drillhole shotpoint on the Yarlung Zangbo provides a picture of deep reflections across this feature. With respect to a situation at around the maximum depth of 70 km on either side at 40 km distance, the Moho stays at about this position in the south, possibly sloping very slightly northward, whereas a clear reflection gets shallower from 70 to 50 km depth when approaching the suture from the north. These figures suppose the same average crustal velocities on either side, which seems to hold regionally but is not precisely established at this particular location. There is no clear observation of a prolongation of the southern Moho towards the north under the shallower one. It might, however, exist; rays that might sample it could be screened off deeper propagation by the shallow Moho. It is also clear that, at this scale, we are detecting lateral heterogeneities of spatial extent along the section that are on the order of, or smaller than, their depth and that the very precise way seismic wavefronts have travelled would need more data to be effectively modelled in detail. Fortunately, Van de Meulebrouck *et al.* (1983) were able to carry out a dense gravity profile across the suture zone, some tens of kilometres east of the zone sampled by seismology. After the general steep slope through the Himalayas that brings the Bouguer values to −470 mGal some 50 km south of the suture, a local maximum of −430 mGal is reached just on the suture before the anomaly decreases again to reach the minimum value of −530 mGal at the northernmost observation point, 70 km further north. The wavelength of this relative Bouguer maximum confirms that early reflection times on the Moho just north of the suture are caused by the shallow position of that reflector rather than by the influence on propagation of a local high average velocity in the crust above, as the mass heterogeneity of this would be situated higher and cause a

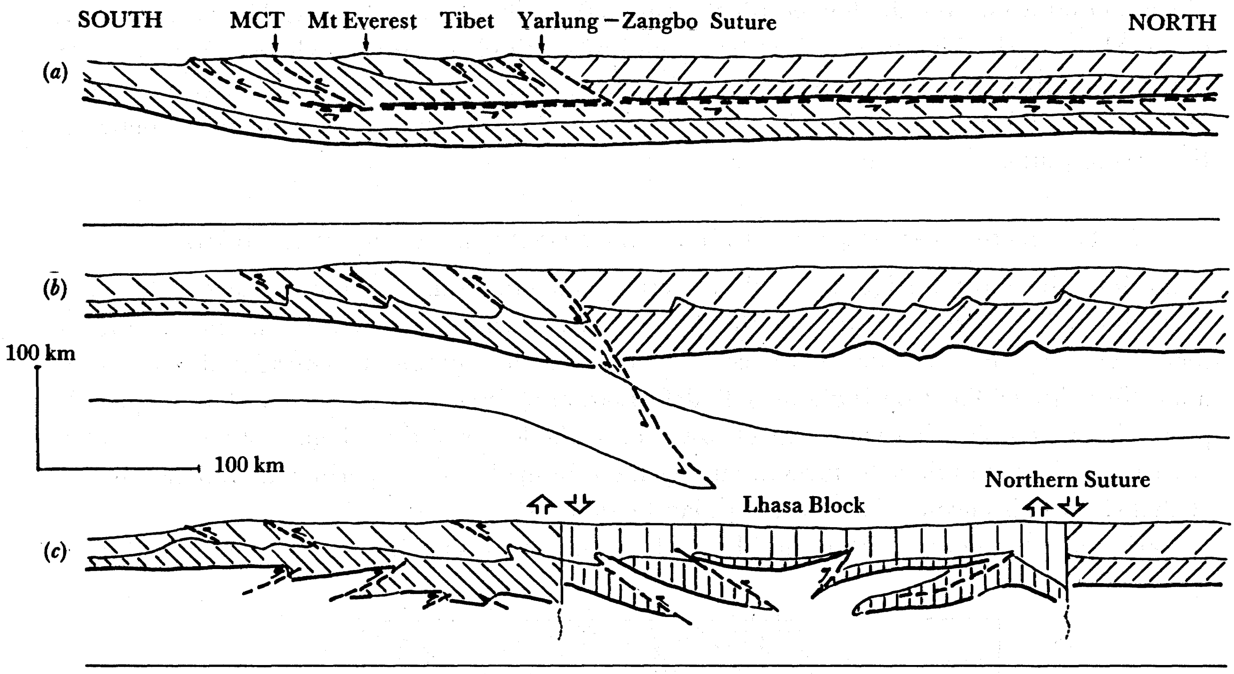


FIGURE 3. Schematic cross sections through Tibet–Himalayas, after Hirn (1984). Indian and Asian crusts are indicated by shading in opposite directions, heavier for the lower than upper crustal material, and vertical for the Lhasa Block introduced in (*c*). The lower section (*c*) illustrates what explosion seismic data would suggest for the heterogeneity within the lithosphere. Difference in depths to the Moho are documented under two ophiolite belts and fault zones, which define a Lhasa Block between these sutures with India to the south and terranes accreted to the north to Eurasia. Wrench motions along these verticalized sutures and within the block allow shortening by escape of parts of the lithosphere out of the plane of the figure. In this block, if the crust has been thickened, it does not appear to have been homogeneously as the Moho and lower crustal marker are neither horizontal nor continuous. Tectonic deformation near the crust–mantle boundary and a zone of decoupling within the crust would allow the lower and upper parts of the crust to thicken separately. A similar behaviour would be indicated south of the Yarlung Zangbo Suture if the thickening of the crust had not occurred progressively from south to north through the Himalayas but rather stepwise as there would be an indication for it in the seismic data.

The upper section (*a*) is inspired from the Argand model of the crustal part of the Asian lithosphere being completely through the section underlain by the Indian lithosphere to provide the abnormal crustal thickness and north–south shortening (Powell & Conaghan 1973; Ni & Barazangi 1983). The middle section (*b*) inspired from Dewey & Burke (1973) limits the extent of Indian lithosphere to the north and deforms the Asian lithosphere.

narrower anomaly. The gross test of the gravity response of the seismic model containing the local topography of the Moho across the Yarlung Zangbo in Hirn & Sapin (1984) is consistent with observations.

What cannot be decided from seismic data is whether the signature on the deep structure has been left by the converging tectonics at the suture or by a later strike-slip motion along this limit during the tectonic escape of Tibet. The apparent limitation of the northern Moho just under the Yarlung Zangbo Fault might favour the second interpretation.

4.2. *The northern limit of the Lhasa Block: the Bang Gong–Nu Jiang line*

Across the Bang Gong–Nu Jiang ophiolite marking the northern suture of the Lhasa Block about 300 km further to the north, a similar picture emerges from seismic data, this time without the gravity control. Data could not be extended more than 30 km into the northern block, so that we see the shallow position around 50 km depth only that far. The deep position of the Moho of the Lhasa Block is clearly seen just south of the suture, whereas further south the crust–mantle region becomes less simple or clear. Again the limit between the two domains at Moho depth occurs at the vertical of the ophiolite belt and fault traces at surface between the two terranes.

5. Heterogeneities within the lithosphere of the main domains

Possibly the most intriguing result of seismic reconnaissance is the existence of strong variations of the structure around the Moho marker within the main lithospheric blocks themselves. These were not predicted by either of the commonly considered models of underthrusting of Tibet by India or bulk deformation of separate segments, and are depicted, probably overemphasized with respect to them, in the lower of the schemes of figure 4 (after Hirn 1984). In detail these features are not well established as the experiments were not aimed at them; the existence of some of them may be debated.

Variations of structure within the Lhasa Block and across the Himalayas are obtained from

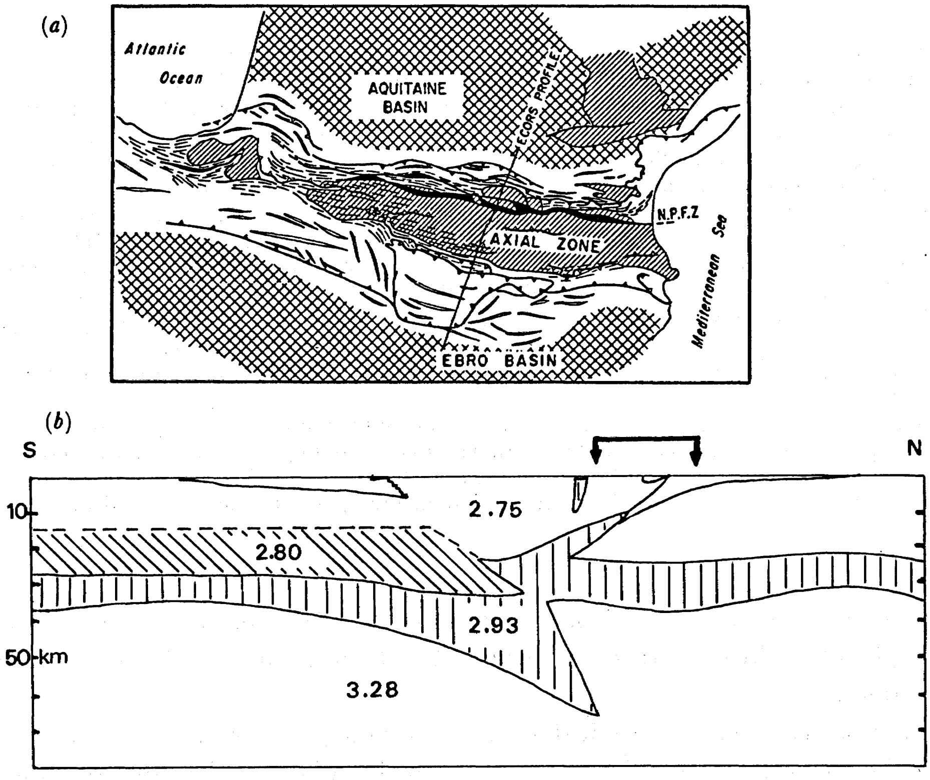


Figure 4. ECORS seismic profile through the Pyrenees (after ECORS Pyrenees Team 1988) and Daignieres *et al.* (1988). Along the line in (*a*), the cross section (*b*) derived from seismic reflection is compatible with gravity control. It shows an example of strong variation of Moho depth, lower limit of the black lower crust discovered by wide-angle and confirmed by vertical reflection seismics. South-verging tectonics in the upper part of the section are well documented north of the NPF which limits the Axial Zone to the north and even crossing its surface trace, whereas at lower crustal depth the vergence is towards north, resulting in an imbrication of the crusts. Vertical reflection seismic data displayed as (*c*) correspond to the part just north of the NPF between the arrows. South-dipping reflections are obvious around 3–6 s, TWT; the shallower, northern Moho is seen around 12 s. The significantly later very conspicuous straight reflection, strongly north-dipping from 15 to 21 s TWT, migrates to the south to give the (tectonic) limit of the wedge of southern thickened crust under the northern mantle.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

wide-angle reflection fan-shooting. General limitations of this have been commented on earlier but here in addition, as the geometry was not exactly aimed at them, some additional problems and uncertainties arise from the necessity of resorting to composite sections with only limited knowledge of how different shotpoints should be tied in and also from the fact that the offset distances may vary. This, however, only limits the value of a precise correlation of absolute Moho depths between distant parts of the general, 500 km long traverse of Moho topography (figure 2 in Hirn *et al.* 1984*b*) but the existence of local lateral changes in the features of the seismograms is obvious and cannot be reconciled with a horizontally stratified lithosphere.

5.1. *Lateral variations across the Lhasa Block of Tibet*

What is established beyond doubt is that the Moho is not flat, horizontal and continuous across the Lhasa Block. There are places where branches of strong reflections, which at these very large offsets must be attributed to interfaces of strong, about crust–mantle, velocity

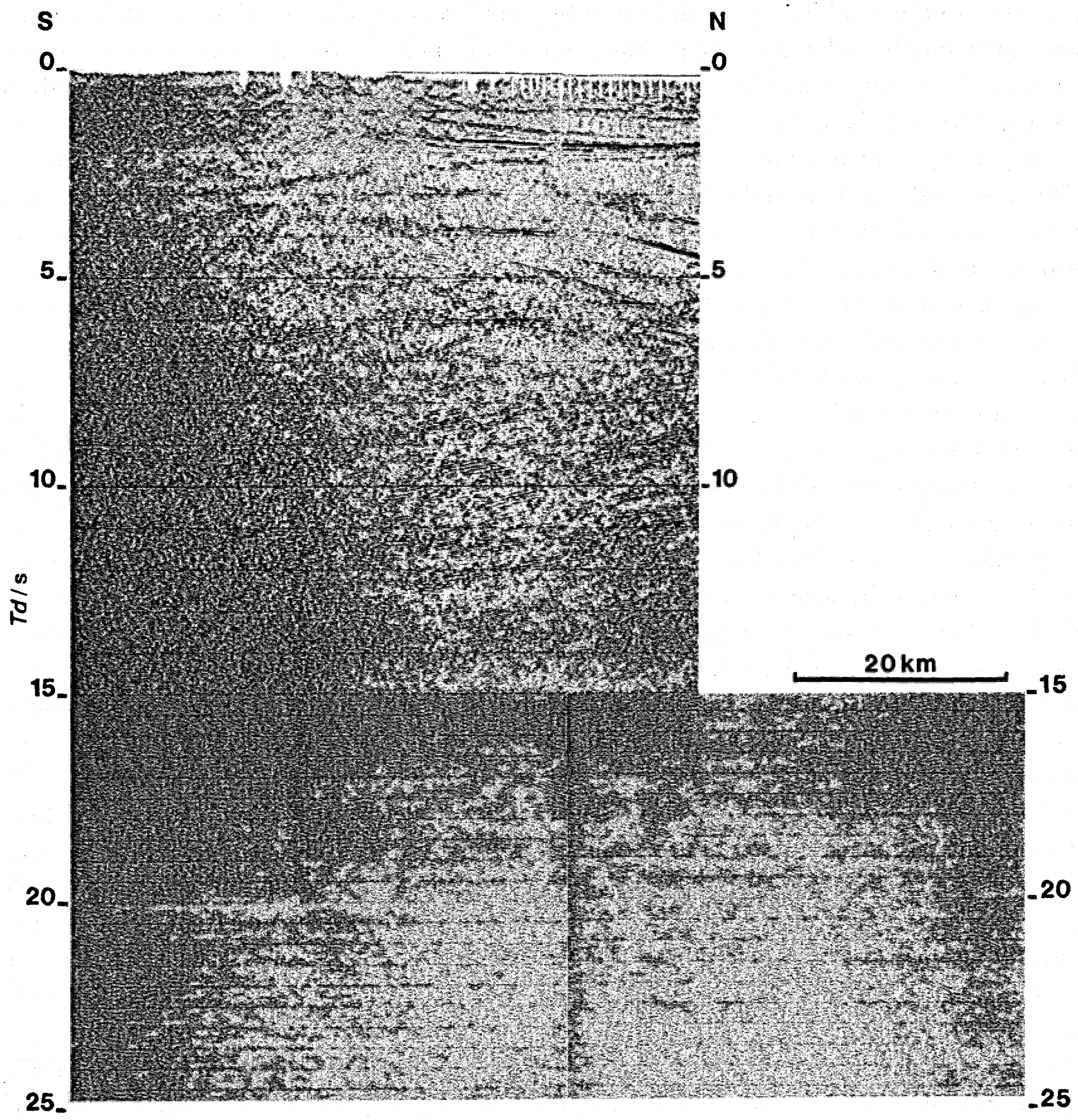


Figure 4*c*. For description see opposite.

contrasts, seem to relay each other at different times, i.e. corresponding to different distances of the reflector from the source–receiver line. There is no control with these data alone on the possible importance of echoes out of the vertical plane from source to receiver. Such a possibility is not taken into account by the way seismic time-sections are plotted, that is attributing all energy to reflection at half source–receiver distance, vertically. In the most similar case available, that of the Pyrenees (discussed later), the hypothesis attributing strong variation in aspect of wide-angle seismograms only to the abrupt change in structure at the vertical without any noticeable side echoes (Hirn *et al.* 1980) could be verified by coincident high resolution vertical seismic reflection (ECORS Pyrenees Team 1988). Hence it is reasonable to consider that strongly heterogeneous structure exists around the Moho marker in the Lhasa lithosphere.

We proposed that the imbrication of crust and mantle suggested by Moho profiling may mark an average thickening of the lower crust. Correlative, but possibly separated by an intracrustal ductile layer (Meissner 1974), thickening of the upper crust could have contributed to the total Tibetan thickening by heterogeneous deformation, a combination of brittle and ductile behaviour, depending on local thermal régime and rock properties. Significant deformation at the surface was implied by this inferred deformation with the lithosphere around the crust–mantle boundary. This was then poorly known but seems to be recently gaining evidence and support (Tertiary deformations, J. F. Dewey, unpublished).

The case needs further study, but the possibility of the existence of the most provocative features suggested in the simplest interpretation of gross seismic data at that time, non-continuity and imbrication of Moho and separation of deep crustal from upper-crustal tectonics, has been now shown elsewhere. Although not a common occurrence this shows *a posteriori* that the odd features once suggested from scarce deep seismic data may exit in Nature. Eighty kilometres north of the Pyrenees, high-resolution multichannel vertical reflection seismics shows unequivocally a loss of continuity accompanied by brutal change in depth of the Moho (ECORS Pyrenees Team 1988). Also on this line, the middle crustal domain clearly separates an upper-crustal domain of north-verging reflections from a lower one where all dips, intracrustal or at Moho depth are south verging. The presently favoured interpretation, on the considerations of regional geology, of different ages for the two levels of dipping reflectors, may somewhat weaken the argument, if correct. That opposite vergences are found on the same vertical is, however, the strongest case in favour of an intracrustal decoupling, which we proposed for Tibet and Himalayas having allowed upper and lower crusts to thicken separately. Indications of this decoupling may also be seen, as in the case of the Caledonides (Matthews & Hirn 1984), already in the lack of continuity through the middle or lower crust of structural reflectors even if these have the same general vergence on either side. The occurrence of a second brittle layer in addition to the upper crustal layer is attributed to the compositional change at the top of the upper mantle. Brittle tectonics at the Moho decoupled, as proposed here, from the surface by an intracrustal ductile layer should also be decoupled from deeper layers by a weak zone in the uppermost mantle. In Europe clear evidence for a sub-Moho low-velocity layer in the lithosphere was firmly documented by several very-long-range refraction profiles first in the Variscan part (Hirn *et al.* 1973), and this layer seemed to possess adequate rheology to allow accommodation of differential motions of small segments of crust in the continental part of the larger-scale lithospheric plate (Bottinga *et al.* 1973). In Tibet the reduced thickness of the mantle part of the lithosphere, which seems to underlie parts of the plateau itself, would allow the accommodation of the tectonics at Moho level to reach the asthenosphere. At the southern margin, near the Himalayas, the east–west seismic sounding gives indication of coherent energy after the Moho head-wave that bears some similarity to the situations encountered in Europe indicating seismic boundaries within the mantle.

5.2. *Variations across the Himalayas*

The variation of the structure of the lithosphere across the Himalayas has been proposed by fitting together three types of observation (Hirn *et al.* 1984*a*; Lépine *et al.* 1984; Hirn & Sapin 1984): that of a fan, but with increasing offset to the south of the High Himalayas; that of an unreversed profile across the range, from North to South; and isolated observations on short profiles at very large offsets. Other interpretations may be possible, but the question of the deep structure beneath the Himalayas and of the different evolutionary models suggested cannot be definitely settled without new data. We originally decided to publish the seismic data with the indication of what kind of structure and model they would suggest to us if we were not prejudiced by other knowledge (see figure 5 of Hirn *et al.* (1984*a*) or the southern extremity of the lower scheme of the present figure 3). Basically the seismic data suggested that the Moho may not be continuous, crustal thickening may occur by steps and deep tectonics may exist with a different vergence from that at the surface, which led to an image of imbrication of the lithosphere or a kind of indentation in the vertical section. Recently documented examples of lateral variations in the lithosphere elsewhere were given in the previous section. Admittedly further tests were needed to favour this picture or that of a postulated and more commonly admitted smooth and continuous dipping Moho suggestive of flexuration of the Indian Plate underriding Tibet. In the absence of new data to discuss the points where these approaches most diverge, it seems, however, possible to consider that there is not formal contradiction between that part of the seismic model that is best constrained, that is a thick crust extending to the south, and those features of the flexural model for Moho topography that are consistent with its initial aim at a simple explanation.

The extensive tests of the flexural model by Karner & Watts (1983) and Lyon-Caen & Molnar (1983, 1985) have not established that, in its simplest form, this type of model can account for the topography and gravity across the Himalayas, which limits the attractiveness of this approach. To achieve the fit by flexural models alone, the flexural rigidity of the Indian lithosphere had to be decreased by two to three orders of magnitude, i.e. its equivalent elastic thickness divided by seven north of the High Himalayas and the Moho postulated to increase continuously in depth from 50 to 115 km from the High Himalayas to the Yarlung Zangbo. The first of these complications introduces such a change along the plate that one might as well choose to consider that it is the negation of the continuity of the same plate north of the High Himalayas; the second, position and dip of the Moho, is contradicted by unequivocal high-quality seismic data on the reversed east–west sounding line situated 30–50 km north of the High Himalayas (§3.1).

The simplest, hence attractive, model considered by Lyon-Caen & Molnar (1983, 1985) that accounts for the shape of the Ganga Basin and the shape of the Bouguer anomaly is that where the Indian Plate is continuous, supports the topographic load and is flexed by it only as far north as the high peaks of the Himalayas. This limitation of its continuity does not allow it to support the topography north of the high peaks. There the observed Bouguer anomaly then demands that the crust be already of great thickness and uniform to the Yarlung Zangbo, which is just what was not foreseen but established by explosion seismology. This combination over the Himalayas of a flexural model where it works simply, and of a mass heterogeneity where it is well documented by seismic methods might be envisioned independently and before a further step where the much more debatable suggestions by wide-angle profiles of mass heterogeneity further south, would then be considered. It seems unavoidable that high-precision, adequate-penetration seismic data would be required on a traverse from the Ganga to the High Himalayas to proceed further with this discussion.

6. Case history of a limit between lithospheric domains suggested by wide-angle reflection fan profiling: the Pyrenees

In 1978–1980 we designed a wide-angle fan-profiling experiment to follow the Moho topography across the Eastern Pyrenean mountain range as an addition to the reversed seismic sounding lines recorded along strike that indicated that the crustal thickness differed by over 10 km between the axial Palaeozoic zone and the north Pyrenean zone (Daignières *et al.* 1982). Our simplest interpretation of that fan was that the change in Moho depth occurred in less than 10 km north–south horizontal distance (Hirn *et al.* 1980). In the western part of the Pyrenees, as the Moho did not respond adequately to reflection, we had to resort to a transmission method with waves from distant earthquakes, which in spite of its nominal low resolution yielded the same result (Hirn *et al.* 1984*d*).

One fashionable model for the structure and evolution of the Pyrenees advocated by Boillot & Capdevilla (1977) was then that of a southward-directed subduction of the northern, European Plate under the southern, Iberian Plate along the North Pyrenean Frontal Thrust. Such an underriding before collision and blocking would call for a smoothly dipping Moho. Our wide-angle seismic data could not completely disprove such a smoothness but we resisted pressure to erase a strong and sharp step in crustal thickness. We resisted also the temptation to consider that we had only measured artefacts even when the possibility of this structure resulting from our simplest seismic interpretation was completely negated by a later, all the more fashionable but completely different model of Williams & Fisher (1984). Since then, high-resolution vertical reflection seismic data confirmed that the picture suggested by some limited seismic data was not wrong but that the proposed models, although attractive could be rejected.

More interestingly, vertical reflection seismics, if it does not contradict that previous seismic evidence, shows that its simplest interpretation (if it was less wrong than the models cited) must be completed by taking into account structure between the surface and the Moho. The imbricated internal structure of the Pyrenean crust, which only vertical reflection seismics could reveal, is of particular importance in our present resistance to give up the complicated, imbricated image of the Himalayan crust with its opposite vergences at upper-crustal and upper-mantle levels. We do not pretend that the Pyrenees and Himalayas are similar, but only that some speculative features proposed for the Himalayas cannot be excluded from existing in Nature as we see them in the Pyrenees: the upper part of the southern, Iberian crust is thrust onto the European crust, whereas its lower part is overridden by it. We have here a thickening of crust related to an imbrication of lithospheres. We could only see the brutal change in Moho depth with wide-angle data, but vertical reflection sees also the south-verging contact of the upper-crustal part of the imbrication. It also sees the change of this vergence with depth when approaching the deeper, southern Moho and we contend that the upper, very long, continuous, straight and steeply north-dipping reflection, which appears very prominently at two-way times between 18 and 26 s on a 40 km long segment of the line further north, migrates into a position that allows it to be interpreted as the north-verging limit along which the northern lithosphere is imbricated into the southern crust (figure 4) (Daignières *et al.* 1988). That this feature cannot be seen by wide-angle seismics in the Pyrenees nor in the Himalayas if the crust is really thickened there by a succession of imbrications as we suggested from the unsmooth Moho topography, may be because of its seismic nature of a decrease in velocity with depth, from the European mantle wedge to the overridden Iberian lower crustal wedge, a situation that cannot generate critical, hence strong-amplitude reflections at large offset, whereas the impedance contrast is adequate for strong vertical reflection.

I acknowledge the action of Claude Allègre and Guy Aubert who imposed on us the challenge to gather significant seismic data in a single experimental effort in an obviously particular geographical, technical and geodynamical context. Georges Jobert shared enthusiasm and anxiety in the field and was instrumental in tying together the Sino–French crews. Logistical and technical expertise of my Chinese, French and Nepalese colleagues allowed us to secure fine data. More of the same are obviously needed for further progress. Main support in personnel came from Laboratoire de Sismologie, IPG Paris, the Changchun Institute of Geophysics and Geophysical Team 562, Beijing, of the Chinese Ministry of Geology, the Geophysical Institute of Academia Sinica and the Nepalese Department of Mines and Geology. Funding was under an agreement of the Chinese Ministry of Geology and the French CNRS-INSU.

Peter Molnar, while writing his review on geophysics in the Himalayas–Tibet for this symposium, kindly communicated his critical comments and reinterpretations of explosion seismology data. New interpretations cannot be rejected, but what is badly needed is new experimental evidence. Brian Windley forced me *in extremis* to the present discussion of both the points I consider well established and those I admit are very loosely constrained or controversial. For most of the latter, in the absence of additional data, I consider that the simplest interpretation from the strictly seismological point of view should still not be rejected in favour of others more generally or intuitively coherent with usually accepted models. After all, examples may be presented here of higher quality, more reliable seismic data in Europe that document structures that also turn out to be often at odds with reasonable or fashionable models based on a much better geological knowledge.

I thank my academic colleagues who have helped maintain active crustal research by explosion seismology within Institut National des Sciences de l'Univers and my colleagues in the different ECORS profile teams for having made reflection seismics available for crustal research. ECORS is a joint project of INSU, IFP, SNEA(P) and IFREMER.

REFERENCES

Allègre, C. J. *et al.* 1984 *Nature, Lond.* **307**, 17–22.
Barton, P. 1986 *Nature, Lond.* **323**, 392–393.
Bayer, R. *et al.* 1987 *C. r. Acad. Sci., Paris* (II) **305**, 1461–1470.
Boillot, G. & Capdevilla, R. 1977 *Earth planet. Sci. Lett.* **35**, 151–160.
Bottinga, Y., Hirn, A. S. & Steinmetz, L. 1973 *Bull. Soc. géol. Fr.* **7**, 500–505.
Brown, L. & Barazangi, M. (eds) 1986 *Reflection seismology*, vols 13 and 14, Geodynamics Series, American Geophysical Union. Washington, D.C.: American Geophysical Union.
Daignières, M., Gallart, J., Banda, E. & Hirn, A. 1982 *Earth planet. Sci. Lett.* **57**, 88–100.
Daignières, M., de Cabissole, B., Gallart, J., Hirn, A. & Surinach, E. 1988 *Tectonics.* (Submitted.)
Dewey, J. F. & Burke, K. C. A. 1973 *J. Geol.* **81**, 683–692.

ECORS Pyrenees Team 1988 *Nature, Lond.* **331**, 508–511.

ECORS–CROP Deep Seismic Sounding Group 1988 (Submitted.)

Francheteau, J., Jaupart, C., Shen, X. J., Kang, W. H., Lee, D. L., Bai, J. C., Wei, H. P. & Deng, H. Y. 1984 *Nature, Lond.* **307**, 32–36.

Fuchs, K. 1983 *Phys. Earth planet. Inter.* **31**, 93–118.

Hirn, A. 1977 *Geophys. Jl R. astr. Soc.* **49**, 49–58.

Hirn, A. 1984 *La Recherche* **156**, 878–881.

Hirn, A. & Sapin, M. 1984 *Ann. Geophys.* **2**, 123–130.

Hirn, A., Daignières, M., Gallart, J. & Vadell, M. 1980 *Geophys. Res. Lett.* **7**, 263–266.

Hirn, A., Steinmetz, L., Kind, R. & Fuchs, K. 1973 *Z. Geophys.* **39**, 363–384.

Hirn, A., Lépine, J. C., Jobert, G., Sapin, M., Wittlinger, G., Xu, Z. X., Gao, E. Y., Wang, X. J., Temg, J. W., Xiong, S. B., Pandey, M. R. & Tater, J. M. 1984*a* *Nature, Lond.* **307**, 23–25.

Hirn, A., Nercessian, A., Sapin, M., Jobert, G., Xu, Z. X., Gao, E. Y., Lu, D. Y. & Teng, J. W. 1984*b* *Nature, Lond.* **307**, 25–28.

Hirn, A., Jobert, G., Wittlinger, G., Xu, Z. X. & Gao, E. Y. 1984*c* *Ann. Geophys.* **2**, 113–118.

Hirn, A., Poupinet, G., Wittlinger, G., Gallart, J. & Thouvenot, F. 1984*d* *Nature, Lond.* **308**, 531–533.

Hirn, A., Damotte, B., Torreilles, G. & ECORS Scientific Party 1987 *Geophys. Jl R. astr. Soc.* **89**, 287–296.

Institute of Geophysics, Chinese Academy of Sciences 1981 *Acta geophys. sinica* **24**, 155–170.

Jobert, N., Journet, B., Jobert, G., Hirn, A. & Sun, K. Z. 1985 *Nature, Lond.* **313**, 386–388.

Karner, G. D. & Watts, A. B. 1983 *J. geophys. Res.* **88**, 10449–10477.

Lépine, J. C., Hirn, A., Pandey, M. R. & Tater, J. M. 1984 *Ann. Geophys.* **2**, 119–121.

Lyon-Caen, H. & Molnar, P. 1983 *J. geophys. Res.* **88**, 8171–8191.

Lyon-Caen, H. & Molnar, P. 1985 *Tectonics* **4**, 513–538.

Lyon-Caen, H. 1986 *Geophys. Jl R. astr. Soc.* **86**, 727–749.

Matte, Ph. & Hirn, A. 1988 *Tectonics.* (In the press.)

Matthews, D. & Hirn, A. 1984 *Nature, Lond.* **308**, 497–498.

Matthews, D. & Smith, C. 1987 *Geophys Jl R. astr. Soc.* **89**, 1–447.

Meissner, R. 1974 *J. Geophys.* **40**, 57–73.

Molnar, P. & Chen, W. P. 1984 *J. geophys. Res.* **89**, 6911–6917.

Ni, J. & Barazangi, M. 1983 *Geophys. Jl R. astr. Soc.* **72**, 665–689.

Powell, C. M. & Conaghan, P. J. 1973 *Earth planet. Sci. Lett.* **20**, 1–12.

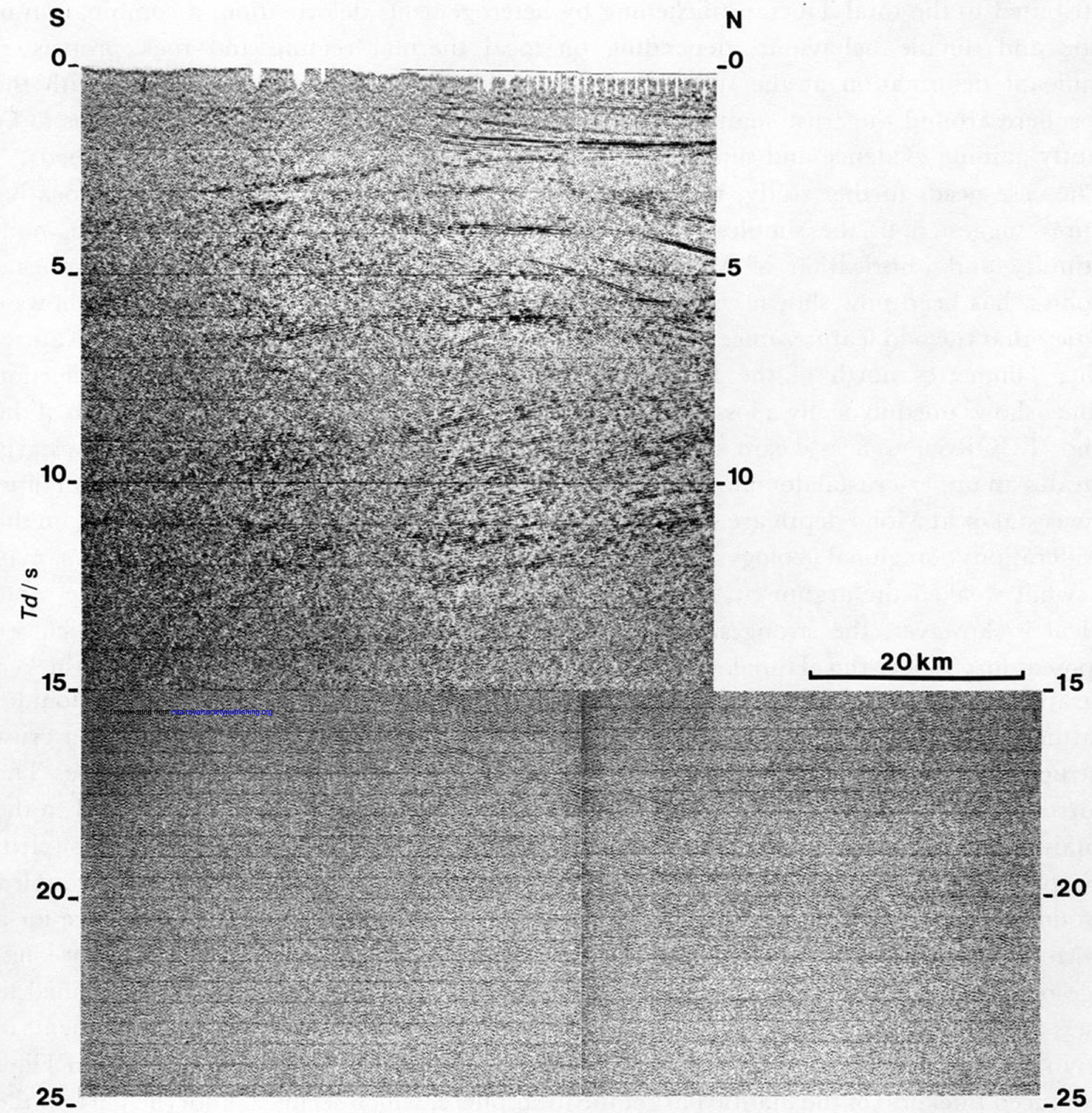
Romanowicz, B. 1982 *J. geophys. Res.* **87**, 6865–6883.

Sapin, M., Wang, X. J., Hirn, A. & Xu, Z. X. 1985 *Ann. Geophys.* **3**, 637–646.

Tang, B. X., Liu, Y. L., Zhang, L. M., Zhou, W. H. & Wang, Q. S. 1981 In *Geological and ecological studies of Qinghai-Xizang Plateau*, pp. 683–689. Beijing: Science Press.

Van de Meulebrouck, J., Tarits, P., Le Mouel, J. L. & Men, L. S. 1983 *Terra cogn.* **3**, 272.

Williams, G. D. & Fischer, M. W. 1984 *Tectonics* **3**, 773–780.



IGURE 4. ECORS seismic profile through the Pyrenees (after ECORS Pyrenees Team 1988) and Daignieres *et al.* (1988). Along the line in (*a*), the cross section (*b*) derived from seismic reflection is compatible with gravity control. It shows an example of strong variation of Moho depth, lower limit of the black lower crust discovered by wide-angle and confirmed by vertical reflection seismics. South-verging tectonics in the upper part of the section are well documented north of the NPF which limits the Axial Zone to the north and even crossing its surface trace, whereas at lower crustal depth the vergence is towards north, resulting in an imbrication of the crusts. Vertical reflection seismic data displayed as (*c*) correspond to the part just north of the NPF between the arrows. South-dipping reflections are obvious around 3–6 s, TWT; the shallower, northern Moho is seen around 12 s. The significantly later very conspicuous straight reflection, strongly north-dipping from 15 to 21 s TWT, migrates to the south to give the (tectonic) limit of the wedge of southern thickened crust under the northern mantle.