Crustal laminations in deep seismic profiles in France and neighbouring areas

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Summary. Remarkable crustal features appear on the ECORS profiles carried out in northern France and the Bay of Biscay as well as on the SWAT profiles shot in the western Channel and the Celtic Sea. The most striking one is the occurrence of flat laminations in the lower crust. Dipping events and laminations are also present in the upper and lower crust, especially in the SWAT profiles. They can readily be related to tectonic events, Variscan in age, some of them identified in the field. The flat laminations in the lower crust are at first interpreted as resulting from delamination, shearing, magmatism and metamorphism at the crust-mantle transition during the Variscan orogeny. This interpretation raises some difficulty concerning the space and time correlation of the laminations with the Variscan orogeny. They seem to have been emplaced after the Permian-Triassic infilling of the Plymouth Bay basin and before the early Cretaceous opening of the Bay of Biscay. An early to middle Jurassic age is suggested, a period when large cratonic basins were formed without noticeable extension. Heat flow increase and magmatism are proposed as a second hypothesis for the formation of the lower crust laminations. Choosing between orogenic and non-orogenic causes of these laminations will require further deep seismic profiles together with good velocity determination.

1. Introduction

In France and neighbouring areas, the crust was essentially formed during the Variscan orogeny between 380 and 300 Ma ago. Since the Mesozoic, it has been subjected to subsidence in large cratonic basins such as the Paris and Aquitaine basins (Fig. 1). This subsidence was coeval with the opening of two new oceans, the Alpine Tethys at the beginning of the late Jurassic and the Bay of Biscay in the early Cretaceous. Then from the late Cretaceous, new orogenic ranges, the Pyrenees and the Alps, were formed as a result of the collision between fragments of the European and African plates. However, major rifts were also formed in the Oligocene in the Rhine and Rhone valleys while the margin of the western Mediterranean Sea was rifted. We shall study the crust in this area on the basis of
the ECORS deep seismic profiles carried out in northern France and the Bay of Biscay as well as the SWAT profiles shot in the western Channel and Celtic Sea in cooperation with the BIRPS group (Fig. 1).

2. The laminated lower crust

The crust shows remarkable common features in the whole area in spite of its complicated geodynamic history. The most striking one is the occurrence of conspicuous flat laminations in the lower part of the crust below a comparatively transparent upper crust. This laminated zone, about 4 s thick, is present in the southern two-thirds of the northern France profile shot across the Variscan front (Fig. 2) (Bois et al. 1986; Cazes et al. 1986). This zone seems to have been offset by the Bray fault, active several times in geological history: strike-slipping in the Carboniferous, normal faulting during the Mesozoic, and strike-slipping again in the Eocene. The laminations fade out towards the north in the area where the Brabant foreland was overlain by the outermost Variscan nappes. In the central portion of the northern France profile they form several bands of very high-energy, straight, flat and parallel reflections (Bois et al. 1986). The individual reflections may reach 10 km. The Moho corresponds to the deepest band according to wide-angle experiments. Velocity averages 6 km/s in the upper crust and 6.7 km/s in the lower crust.

A laminated lower crust is present in the Bay of Biscay profile which runs from the southern Armorican Shear Zone down to the Pyrenean front and crosses the Parentis basin formed during the Bay of Biscay's opening in the early Cretaceous (Fig. 2) (Pinet et al., this issue). This zone, 2.5 to 3 s thick in the north, was attenuated and the Moho uplifted below the Parentis basin. To the south, it is again 2 to 2.5 s thick then undergoes a local
attenuation below the Landes high and a strong thickening towards the Pyrenean front in relation to the Eocene compression. ESP experiments have given the same average velocities as in northern France. On the northern portion of the Bay of Biscay section, laminations also occur in the upper crust. They have been interpreted as lower crust material thrust and uplifted during the Variscan orogeny (Fig. 2).

A laminated lower crust is also observed on the SWAT profiles over an average thickness of 3.5 to 4 s (Fig. 2) (BIRPS and ECORS 1986). It is present below the Variscan frontal nappe and extends into its foreland. It also lies below major sedimentary basins such as Plymouth Bay (Fig. 3). This basin, at least 10 km thick, was mostly infilled by Permian and Triassic sediments, the parallel layering of which suggests a gradual sagging of the crust. There is no evidence that the subsidence was controlled by any extensional rifting below the sedimentary infilling. The present laminated zone is however flat below the basin and without any change in thickness. According to the available velocities, any Moho uplift compensated for by basin infilling would be small.

A laminated zone in the lower crust was found in a large area covering at least half of France, southern England (Chadwick et al. 1983) and westernmost Germany (DEKORP 1985), changing however in depth, thickness and energy.

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**Figure 2.** Geological interpretation of portions of SWAT 4, SWAT 9, northern France and Bay of Biscay profiles (see location in Fig. 1) showing the main structural features and the distribution of the laminated lower crust. BF: Bray fault, LA: Landes High, M: Moho, MM: Moho from wide-angle experiment, PA: Parentis basin, PY: Pyrenean front, PL: Plymouth Bay basin, SASZ: Southern Armorican Shear Zone, VA: Variscan front.
Figure 3. Line-drawing of SWAT 8 and 9 profiles (see location in Fig. 1). LC: top lower crust, M: Moho reflection, PL: Plymouth Bay basin.
3. Dipping events and laminations in the crust

Dipping events are frequent in the upper crust of the northern France and SWAT profiles (Fig. 2). Only a few of them can be traced from the upper crust to the lower crust in the northern France profile. In the SWAT profiles, they cut across the whole lower crust and even seem to extend into the upper mantle (Fig. 3). Some of these events have been related to Variscan thrusts observed in the field (Leveridge et al. 1984). They do not offset the laminated lower crust and the Moho (Fig. 3).

Dipping laminations have been observed in the Appalachians (Ando et al. 1984). They have been described as sinous and anastomosing reflections. They seem to be comparatively shorter and less energetic than the flat reflections of the European lower crust. They are found at various depths in the crust and are not necessarily associated with the lower crust and the Moho. Like the SWAT dipping events, they form major sets of reflections cutting across the crust within limited areas.

Similar features have also been observed in the upper crust of northern France (Fig. 2) (Cazes et al. 1986). These events have been interpreted as a zone of imbricated thrusts which may involve metasediment packets and connect the main Variscan detachment with inner zones. A similar interpretation has been postulated for the Appalachian profiles.

4. Possible causes of the lower crust laminations

While dipping reflections in the crust can readily be related to tectonic events, the cause of the flat laminations deserves further discussion. However, we shall assume that the seismic laminations correspond to actual lithological changes in the crust (Fuchs 1969).

Fig. 4 summarizes possible causes of such changes. We have first classified them according to the latest major orogeny which formed the present crust. Laminations
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contemporary with or later than this orogeny may be assigned to three main geodynamic causes: compressional, thermal or extensional. Thermal events go along with compression which thickens the crust and increases the temperature of the down-going slabs. Extension is related to uplifting of asthenospheric hot material and the temperature increase of the overlying crust. However, we should also consider that a thermal event may have occurred by itself without previous mechanical stress in the crust.

We shall review arguments for orogenic and non-orogenic causes of the lower crust laminations in the light of the regional geological history of France and neighbouring areas.

5. Orogenic cause of the lower crust laminations

The quite schematic model in Fig. 5 is one way to picture the crustal evolution and to explain the actual seismic data. Stacking of the crust resulted from the Variscan orogeny. The thickened crust was transformed by heat and pressure. The surface was strongly eroded and late orogenic basins infilled. In the meantime, the roots of the old mountain range were gradually uplifted and their material equilibrated in new temperature and pressure conditions. However, cratonic basins like Plymouth Bay may have been formed when the crust was still thickened. The related thinning of the crust may have disappeared in the final stage of crustal equilibration. Thus, lithological differentiation in the present lower crust would result from (1) crust-mantle delamination and shearing during the compressional stage, (2) subsequent melting, intrusion and metamorphism in the thickened crust and (3) further melting,

Original crust

![Diagram of crustal evolution](https://academic.oup.com/gji/article/89/1/297/673123)

Figure 5. Very schematic model of the crust evolution until the late Triassic in France and neighbouring areas. Not to scale. See explanation in text.
intrusion and metamorphism during root uplift. Migration of solutions during the latter process increased the lithological differentiation initiated by the tectonic process. In this hypothesis, there should be no genetic differences between flat and dipping laminations that were formed together in the crust.

In northern France, the lower crust laminations were offset by the ductile strike-slippping of the Bray fault in the Carboniferous (320 Ma) (Matte et al. 1986). This places the lamination formation before this event.

6. Nonorogenic lower crust laminations

The above model raises a few objections corresponding to the seismic facies, the areal distribution and the relation of the flat laminations to geological events.

Dipping and flat laminations frequently show different seismic facies. Flat laminations consist of reflections which often are more energetic, longer and straighter than the dipping ones, suggesting that they were formed by different processes.

Flat laminations extend beyond the Variscan front, especially in the Celtic Sea (Fig. 2). On the contrary they fade out in the inner Variscan zones of southeastern Germany (DEKORP, this issue). There is no definite correlation between the Variscan orogeny and the occurrence of the flat laminations in the lower crust.

The lower crust laminations and the Moho are not offset by dipping events related to the Variscan orogeny, suggesting that the flat laminations might have postdated this orogeny. Moreover, they seem to have been emplaced after the Permian-Triassic infilling of the Plymouth Bay basin below which they are flat and undisturbed by the basin formation. Each objection should deserve a full discussion which is beyond the scope of this paper. Sustaining them would lead to the conclusion that the flat laminations in the lower crust were not formed before the late Triassic. On the other hand, the laminated lower crust was readily deformed by the Eocene compression in the Pyrenees and across the re-activated Bray fault (Fig. 2). It was strongly attenuated below the early Cretaceous Parentis basin and seems to have been cut by late Jurassic normal faults in the North Sea. Assuming that the lower crust laminations were formed by the same cause all over these areas, we find an early to middle Jurassic age for this cause.

This is the period of formation of major sedimentary basins such as the Paris basin and the rifting of the margin of the Alpine Tethys Ocean. Extension occurred during this period along many normal faults. However, extension rates are very small in the upper crust with a maximum of 25% in the Alpine margin (Rudkiewicz, in press). It is the same in the lower crust where previous Variscan events have been preserved (Fig. 3), suggesting that extension was a subordinate factor in the formation of the lower crust lamination. The only remaining cause to be put forward is a regional increase in the heat flow probably associated with magmatism that almost obliterated the previous events and re-equilibrated the crust-mantle transition. Such a process might imply some transformation of crustal material into upper mantle material.

Available data are not sufficient to definitely prove an orogenic or non-orogenic cause of the lower crust laminations. Moreover, both processes might have played a part in their formation. Further deep seismic profiles, especially across Jurassic basins, should be carried out together with good velocity determination to check these hypotheses.
References


