Reasons for the high reflectivity of the lower continental crust in ultra deep reflection seismic sections

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Abstract

Ultra-deep reflection seismic lines (American COCORP, diverse European projects such as ECORS, some industrial surveys such as those from ION-GXT) have conspicuously shown that the lower part of the continental crust is highly reflective. Strong, short, discontinuous, sub-horizontal, wavy reflections are characteristic, imparting an undulating highly reflective pattern to the lower continental crust. Most of the times, the Moho is interpreted at the base of such reflections, at the boundary with the seismically transparent upper mantle. The other important crustal discontinuity, the Conrad, is usually interpreted at the top of such reflectors, at the boundary with the seismically transparent upper crust. In this manner, ultra deep seismic sections usually display the lower continental crust as a strongly reflective wavy layer of varying thickness sandwiched between the transparent upper crust and the transparent sub-continental upper mantle. The reasons for such high reflectivity include the development of abundant sub-horizontal ductile shear zones and the dominant sub-horizontal foliation so characteristic of exposed high-grade metamorphic rocks of the lower crust.

Introduction and Discussion

Since the start of the recording of ultra-deep reflection seismic lines, first in Europe, later in the USA, it has been recognized that the lower crust is characterized by an anomalous high reflectivity when compared to the seismically transparent upper continental crust and mantle. Strong, short, discontinuous and undulating reflections form a wavy band of variable thickness at the base of the continental crust in most ultra-deep seismic sections that imaged several locations around the globe (Figure 1). Interestingly, this is exceptionally visible at places where the crust has undergone stretching and thinning due to extensional stresses in a breaking continent. Examples of this are known from the Rhine Graben in Europe (Figure 2), in the Basin and Range Province of Western USA and in the passive margins of the South Atlantic Ocean (Figure 1).

In most cases, the Moho does not appear as a single, strong reflector. Usually its position is inferred at the base of the lower crust short and strong reflections. Below them the mantle is practically devoid of seismic reflections (Figures 1 and 2). The Conrad discontinuity, that marks a significant increase in the velocity of the compressional seismic waves, broadly coincides with the top of the reflective lower crust (Figure 2); but, interestingly enough, it appears much more frequently as a well marked seismic reflection than the Moho (Zalán et al., 2009).

On the other hand, the thinner oceanic crust does not show such reflectivity layering throughout its 7 to 11 kilometers of thickness. Well exposed outcrops of obducted oceanic crust, such as those in the Oman Mountains, and high resolution seismic sections, point to a tripartite division of this type of crust consisting of a thin, weakly reflective, lower layer of banded gabbros, a thick middle layer composed of criss-crossing sheeted dykes and an upper seismically transparent layer of pillow lavas (Zalán et al., 2011). The sub-oceanic Moho, contrary to the sub-continental Moho, is almost invariably displayed as a discrete strong continuous to discontinuous seismic reflection.

These distinct seismic behaviors between the continental and oceanic crusts point to differences in composition and depths of occurrence; thus, differences in confining pressure and temperature. All these converge to suggest that strong differences in the rheology of both types of crust may be responsible for their characteristic seismic response.

The reason for such strong, sub-horizontal reflectivity of the lower continental crust has been historically attributed to ductile sub-horizontal shear zones, developed in response to the change in the rheology of quartz and feldspar, the two most abundant minerals in the continental crust, from brittle to ductile behavior. Their brittle friction and plastic flow laws indicate a change in rheology below the depths of 10-12 km for quartz and 20-30 km for feldspars (Figure 3). So, above such depths the continental rocks tend to behave in an elastic manner, displaying mostly brittle deformation. Below these depths, the behavior is predominantly plastic, dominated by ductile deformation.

The concept of sub-horizontal shear zones dominating the lower continental crust was derived from the exposures of stretched lower crustal rocks exhumed in the metamorphic core complexes of the Basin and Range Province of the Western USA (Figure 4) (Wernicke and Burchfiel, 1982).

Recent AFTA studies of uplifted passive continental margins have shown tremendous amounts of rising and erosion. Presently outcropping basement lithologies around continental margin basins display rocks formed at the base of the crust under extremely high pressures and temperatures. These exposed lower continental crust rocks are not always sub-horizontal mylonites; on the contrary, they are usually gneisses, migmatites and granulites (lato sensu) formed under granulite metamorphic facies displaying strongly developed sub-horizontal foliation given by very tight recumbent folding The mountains surrounding the southeastern coast of Brazil, at the margins of the Campos and Santos Basins (Figure 5), and the isostatically rebounding western shore of Greenland (Figures 6 and 7) display beautiful examples of the structure of rocks formed under lower crust conditions, presently at the surface. Sub-horizontal mylonites and ultra-mylonites are commonly found either, but they are surely not the sole lithologies of the lower crust.

At depths below 20-25 km the rocks tend to be crushed into a sub-horizontal attitude whatever the acting tectonic stresses. In a compressional environment rocks are piled up (via thrusting or under thrusting) along sub-horizontal ductile shear zones in order to allow the crust to be shortened and thickened. Folds will be predominantly recumbent in nature leading to the formation of sub-horizontal axial plane foliation. In an extensional environment, when a continent is rupturing and breaking apart, lower crustal rocks are stretched and thinned via ductile sub-horizontal shear zones in order to allow the crust to be hyper-extended and then finally parted. In the internal part of the passive margin the ductile shear zones are less numerous, but, towards the external part of the hyper-extended crust the ductile shear zones prevail.

The conjunction of sub-horizontal ductile shear zones formed during the amalgamation of continental masses, reactivated during the separation of a mega-continent, together with the dominant sub-horizontal foliation of high grade metamorphic rocks, act as discontinuities that reflect the compressional waves towards the surface of the Earth (Figure 8). The tight packing of the grains is probably responsible for the significant increase in the seismic velocity observed at the Conrad Discontinuity, roughly coinciding with the start of the high reflectivity zone.

Conclusions

The high reflectivity of the lower continental crust when compared with the absence of reflections in the upper continental crust above and in the mantle below is due to the ductile rheology of the dominant quartz-feldspar rocks at such great depths and pressures, that gave rise to a predominantly plastic style of deformation. A conjunction of sub-horizontal ductile shear zones composed of mylonites/ultra-mylonites and sub-horizontal axial plane foliation developed via recumbent folding are responsible for the great amount of short, strong, tightly packed, discontinuous and undulating reflectors that characterize the lower continental crust in ultra-deep seismic sections.

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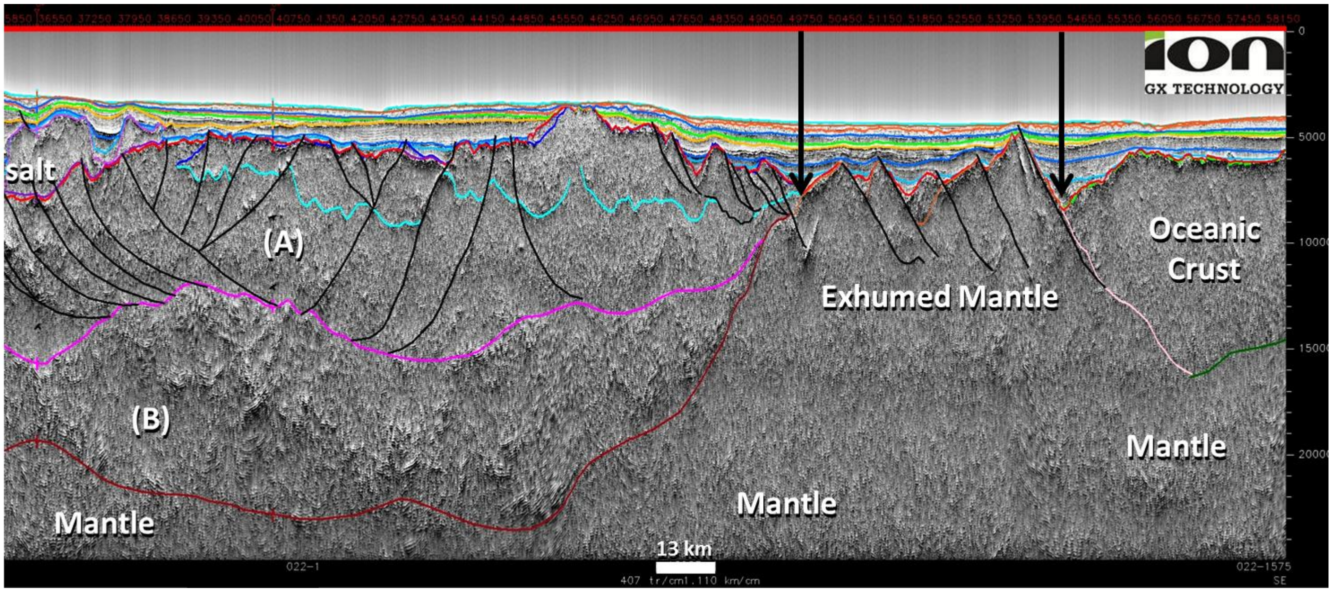

Figure 1 - Dip seismic section (depth) in the Santos Basin displaying the dual rheological nature of the continental crust (upper brittle in A and lower ductile in B), the exhumation of the mantle (between arrows) and the passage to oceanic crust. Also shown are the Conrad (magenta reflector) and Moho (dark red reflector) discontinuities. Notice that exhumed mantle underwent extension by planar rotational faults at shallow levels, indicating that rifting was still taking place during exhumation. Visualization of seismic section in tecVA_RFASE (Petrobras patented in-house technique) (figure taken from Zalán et al., 2011).

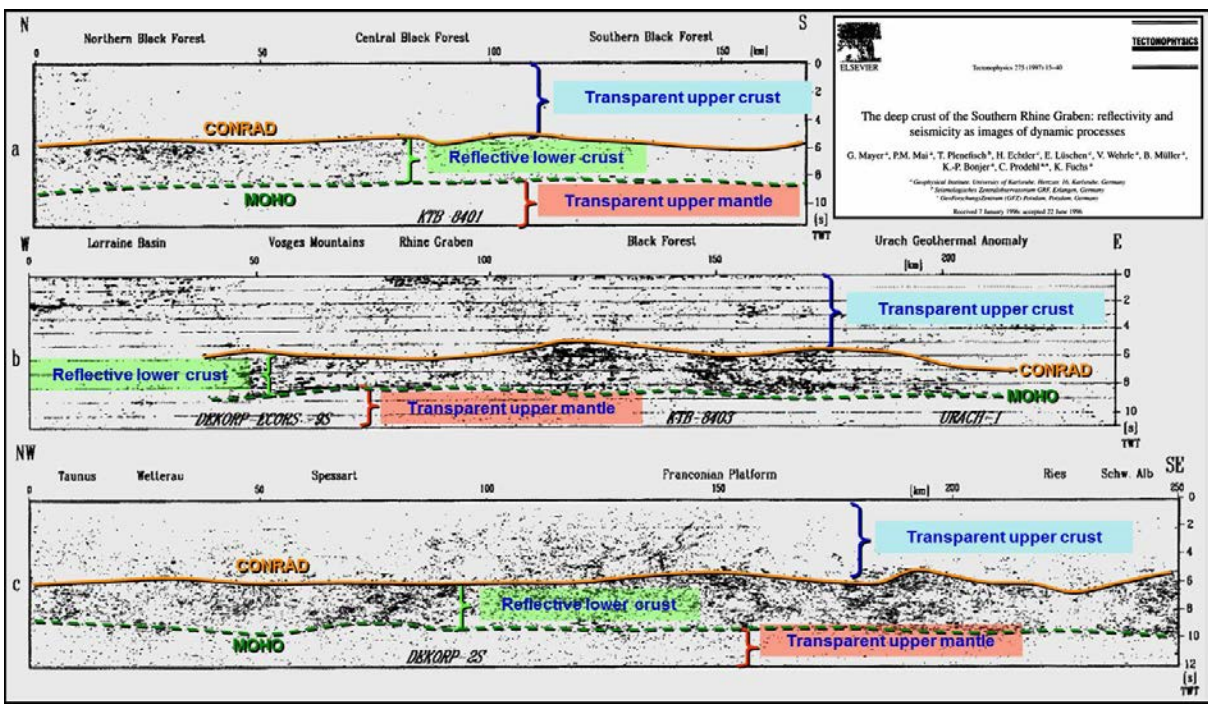

Figure 2 – Sketches of deep seismic sounding in the southern Rhine Graben revealed a crystalline upper crust of comparatively low P-wave velocities (5.9-6.0 km/s) with little and discrete reflectivity and a strongly reflective lower crust with higher P-wave velocities (about 6.4-6.8 km/s). Both are separated by the Conrad discontinuity. Modified (colored interpretation) from Mayer et al. (1997).

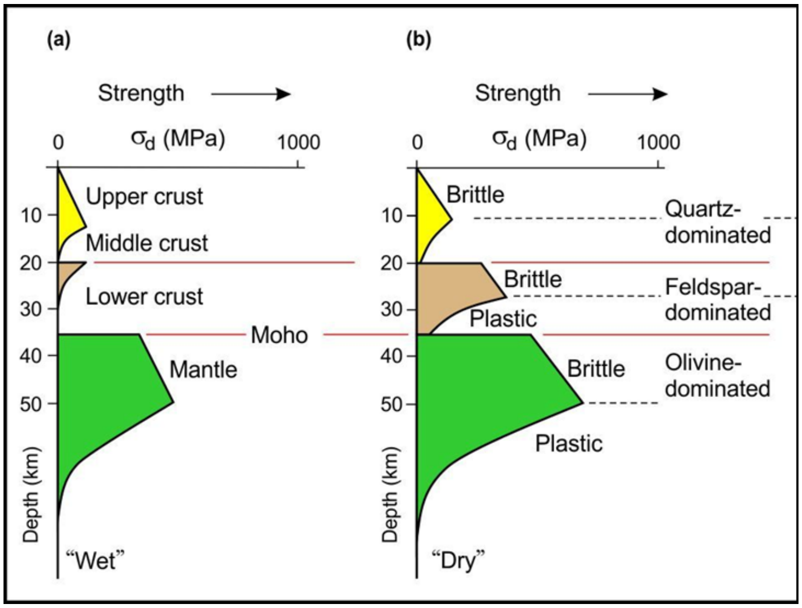

Figure 3 – Strength profiles for the upper continental lithosphere. (a) and (b) for individualized layers of quartz-dominated and feldspar-dominated rocks of the crust (from Fossen, 2010). (a) for wet rocks and (b) for dry rocks. Two brittle-plastic transitions would occur within the crust.

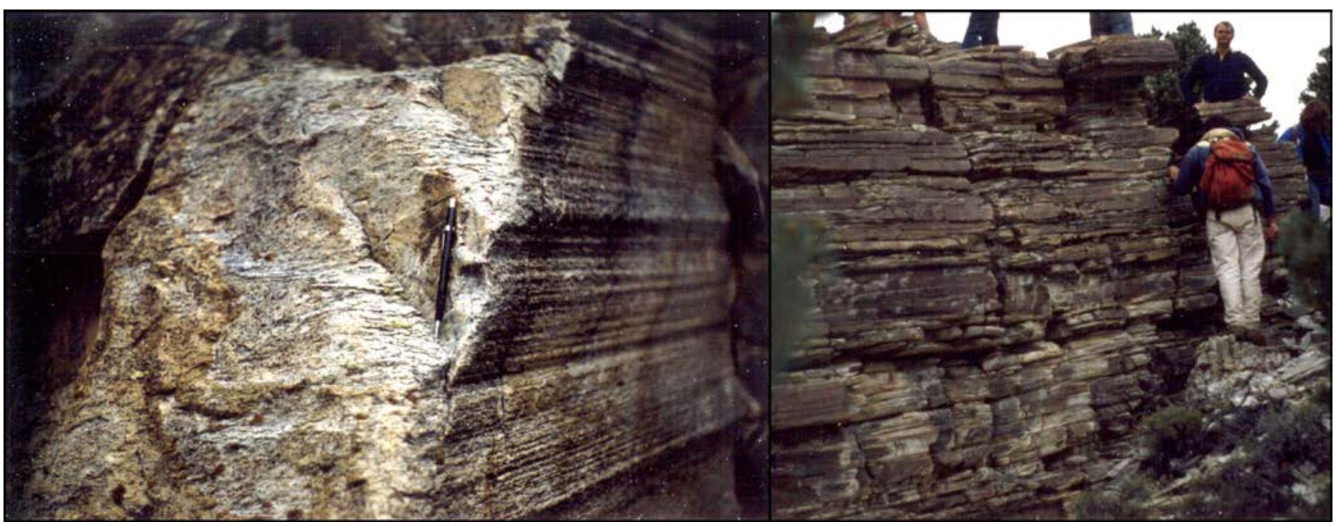

Figure 4 – Ultramylonites in sub-horizontal ductile shear zones (LS-mylonites) in a metamorphic core complex in Nevada, USA. The rock to the left is a granite mylonite. In the right, the bedding (S_0) of the mylonitic quartzites is vertical; the visible sub-horizontal foliation is the mylonitic texture. These rocks represent exhumed continental lower crust formed by normal ductile simple shear processes at great depths. They were brought up to the surface by the sliding and thinning of the upper plate on top of the lower plate (Wernicke model), unroofing the lower plate and allowing the exhumation of the lower crust.

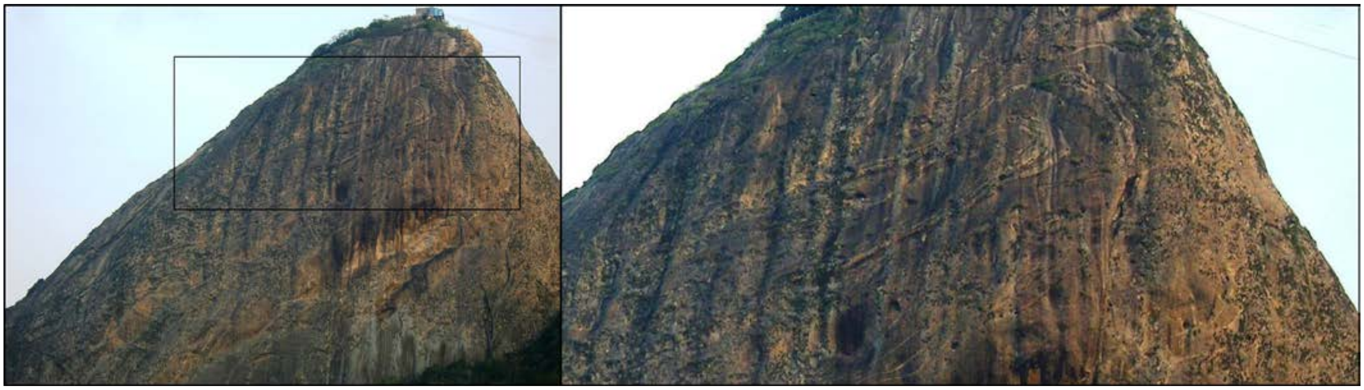

Figure 5 – View of the famous Sugar Loaf hill in Rio de Janeiro, Brazil. Notice that the gneiss that makes up this monolith consists of recumbent folded beds with sub-horizontal axial plane foliation., These rocks formed under lower crust P-T-conditions, during the Brasiliano/Pan African Orogenic Cycle, and are nowadays exposed at the surface. AFTA data indicates that these rocks underwent significant uplift and erosion during the Late Cretaceous, in the order of several kilometers.

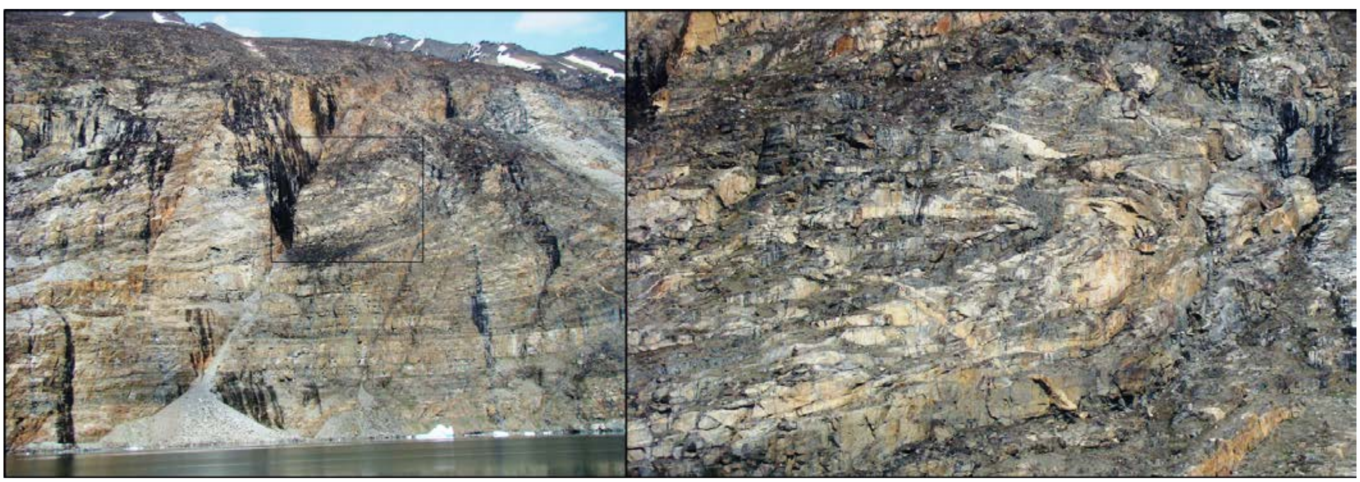

Figure 6 – View of granulite-facies gneisses/migmatites in Kangerdlugssuaq Fjord, Western Greenland. The rocks display strong recumbent folding resulting in a well-developed sub-horizontal axial plane foliation.

Figure 7 – View of granulite-facies gneisses/migmatites in Western Greenland, to the east of Upernivik Island. The rocks display strong recumbent folding (arrows point to the axis of folds) resulting in a well-developed sub-horizontal axial plane foliation.

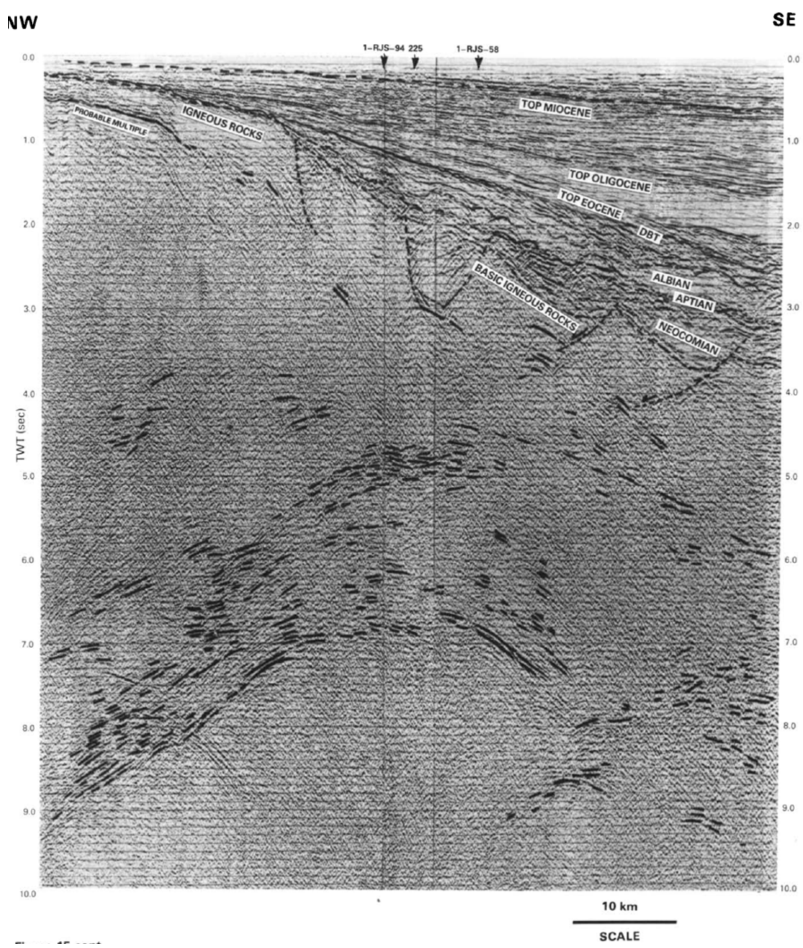

Figure 8 – Interpreted 2D time seismic section from the Campos Basin displaying a mantle uplift below a strongly reflective lower crust, composed of short, strong, discontinuous wavy reflectors (Mohriak et al., 1990). This structure was attributed by the authors, among other hypothesis, to shear zones and gneissic banding. We concur with this interpretation.