

An Entirely New 3D-View of the Crustal and Mantle Structure of a South Atlantic Passive Margin – Santos, Campos and Espírito Santo Basins, Brazil*

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Abstract

The interpretation of 12,000 km of ultra-deep (PSTM to 16 sec., PSDM to 25 km) 2D seismic sections acquired by ION-GXT, coupled with gravimetric and magnetometric modeling line-by-line, and the integration of the results with the regional data bank of Petrobras, all together viewed in terms of the recent tectonic models developed for the rupturing and separation of mega-plates, led to a regional (500,000 km²), first-time ever 3D-view of the deep structure underlying the prolific sedimentary basins of Santos, Campos and Espírito Santo in southeastern Brazil ([Figure 1](#)).

The interpretation of such special seismic sections required the application of very specific geological and geophysical criteria as well. The abundance of seismic reflections within the deep continental crust, significantly below the stratified sedimentary section, prompted the recognition of a basal lower crust, whose seismic facies is highly reflective, typically composed of numerous short reflections with strong amplitude, invariably crossing the lower part of the sections in a sub-horizontal, sub-parallel, wavy pattern ([Figure 2](#)). Throughout most of the area, such layer did not show evidence of faulting, except in a few very specific locations. These characteristics led to the interpretation of a ductile lower crust, topped by a more continuous strong reflector; locally a remarkably strong event, here considered to represent the Conrad discontinuity. We do not favor the interpretation of magmatic bodies underplated at the base of the crust for this seismic facies because of its continuous distribution throughout an area of around 500,000 km² and a consistent pattern of thinning from onshore to offshore. This oceanward thinning is frequently punctuated by single necking

or multiple neckings (boudinage). Densities between 2.92 and 2.96 g/cm³ point to dense lithologies formed in the granulite and eclogite metamorphic facies.

The upper brittle continental crust tends to be a seismically poorly reflective layer, practically a blind zone (Figure 2). The top of the crystalline basement is rarely a significant reflection. Most of the times, it was tentatively interpreted at the basal termination of the reflective and stratified sedimentary section. Important exceptions are a few, but distinct, thin sub-horizontal short reflections clustered in a continuous and wavy pattern, cutting the crust in a diagonal direction. Their terminations downward usually merge with the ductile lower crust. These were interpreted as intra-crustal simple shear zones, probably composed of mylonites and ultra-mylonites. Large, planar rotational normal faults that form and control the rift sections at the base of the sedimentary basins usually detach on such mid-crustal shear zones. They are more abundant where the continental crust is thicker, merging with the lower crust and disappearing oceanwards, where the continental crust is more stretched and thinned. In these distal hyper-extended crustal zones, the rift faults merge directly into the Conrad discontinuity; sometimes cutting it and displacing it when the detachment zone lies within the ductile crust. The brittle crust displays densities between 2.72 and 2.76 g/cm³ suggesting less dense lithologies developed in the amphibolite and upper granulite metamorphic facies, intruded mostly by granites and a few other magmatic rocks.

The termination of the reflective seismic facies of the lower crust downwards represents the Moho discontinuity and the transparent seismic facies below the continental mantle (Figure 2). It is interesting to note that very rarely did the Moho show up as a continuous reflector under the continental crust, as one would expect in a more classical approach to the interpretation of deep crustal structure. This characteristic and the failure to recognize the ductile lower crust has misguided early interpretations of a thinner continental crust here in the Brazilian Atlantic margin and elsewhere. Gravity modeling and/or seismic refraction data should always be used to correctly ascertain the identity of the strong continuous reflector(s) that may appear deep within the continental crust: the Conrad or the Moho discontinuity, or both. A structural contour map of the Moho is presented in Figure 3.

Oceanic crust is a thin slab of circa 7 to 9 km thick (Figure 4) and gradually thins to the east. It always displays a characteristic box-shaped geometry, where one can easily recognize the tripartite division of the oceanic crust: lower stratified cumulate gabbros (mildly reflective, thin, sub-horizontal seismic facies), mid-crust sheeted dykes (thickest seismic facies presenting criss crossing high-angle reflections) and upper pillow basalts (thick transparent seismic facies).

The dual nature of the continental crust (Figure 2) is also reflected in the stretching and thinning modes. The upper brittle crust is only stretched to a lesser degree in the proximal areas (shallow and deep waters, between 300 and 2000 m of water depths). In the distal areas (ultra-deep waters, > 2000 m of water depths) the brittle crust is highly stretched and thinned. On the other hand, the ductile lower crust is much more strained than its shallower counterpart throughout the entire area (Figure 5 and Figure 8), indicating that most of the stretching and thinning of the continental crust was accomplished via ductile deformation of the lower crust. Rifts situated

above simply extended continental crust that acted as resistant terrains during extension are relatively less developed. On the other hand, rifts are better developed in areas where the brittle crust consisted of more plastic terrains, and is stretched and thinned, or hyper-extended by simple shear (similar to H-Blocks that had been broken and separated as described by Péron-Pinvidic and Manatschal, 2010; see [Figure 8](#)). That is also the case where the ductile crust is perforated by mantle uplifts and the brittle crust is necked by pure shear (similar to H-Blocks in aborted rifts, Péron-Pinvidic and Manatschal, 2010; see [Figure 6](#)).

Exhumation of the mantle ([Figure 2, 5, 6, 7, 8](#)), as proposed by Péron-Pinvidic and Manatschal (2009) for the Iberia and Newfoundland conjugate margins, marks the continental-oceanic crustal transition and can be mapped continuously from Santos to Espírito Santo; sometimes attaining significant widths ([Figure 3](#)). Serpentinization of the exhumed mantle can be deduced from the gravimetric modeling (mantle densities gradually decreasing to as low as 2.60 g/cm^3) to occur down to several kilometers (6-8) deep ([Figure 5](#) and [Figure 8](#)). This is in sharp contrast to the widely held assumption that such phenomena would occur down to only 2 or 3 kilometers. The surface geometry of the mantle subcrop is influenced by major continental and oceanic structures ([Figure 3](#)).

The three basins are situated onto a continental margin that narrows gradually, from south to north, from a very wide (Santos, [Figure 1](#), [Figure 5](#) and [Figure 6](#)), through an intermediate (Campos, [Figure 1](#) and [Figure 7](#)), and then to a narrow (Espírito Santo, [Figure 1](#) and [Figure 8](#)) passive margin. The crustal structure of the Santos Basin shows a zonation from west to east of alternating bands of NE-SW-trending thin (plastic basement terrains) and thick (resistant basement terrains) stretched continental crust. In vertical section this zonation is displayed as a series of necking zones, leading to a highly irregular, low to moderate crustal taper ([Figure 5](#) and [Figure 6](#)). Such zonation is less developed in Campos Basin, where the crustal taper is moderate and regular ([Figure 7](#)), and practically non-existent in the Espírito Santo Basin, where the crustal taper is high ([Figure 8](#)). The gradual narrowing of the alternating bands towards the north in the Santos Basin creates sub-basins similar to V-shaped basins described in the North Atlantic margins of Ireland and Canada. Continental crust perforated by mantle can be seen at the tips of such sub-basins (as in [Figure 6](#)).

The continental margin of southeastern Brazil, constituted by the Santos, Campos and Espírito Santo basins, is a typical example of a magma-poor passive margin. It presents a well marked continuous belt of exhumed mantle at the transition between continental and oceanic crusts that flanks all three basins. The sedimentary sections deposited during the rifting of the margin are relatively poor in magmatic rocks. Seismic facies representative of seaward-dipping reflectors are practically non-existent, with some possible localized exceptions in each basin. In sharp contrast, the Pelotas Basin situated to the south of the Florianópolis Oceanic Fracture Zone ([Figure 1](#)), is the classical example of a volcanic margin, with huge rifts filled mostly by volcanic material and a continental-oceanic transition zone marked by superb seaward-dipping reflectors that prevented exhumation of the mantle.

References

- Péron-Pinvidic, G., and G. Manatschal, 2010, From microcontinents to extensional allochthons: witnesses of how continents rift and break apart?: *Petroleum Geoscience*, v. 16, p. 189-197.
- Péron-Pinvidic, G., and G. Manatschal, 2009, The final rifting evolution at deep magma-poor passive margins from Iberia–Newfoundland: a new point of view: *International Journal of Earth Sciences*, v. 98/7, p. 1581-1597, doi:10.1007/s00531-008-0337-9.

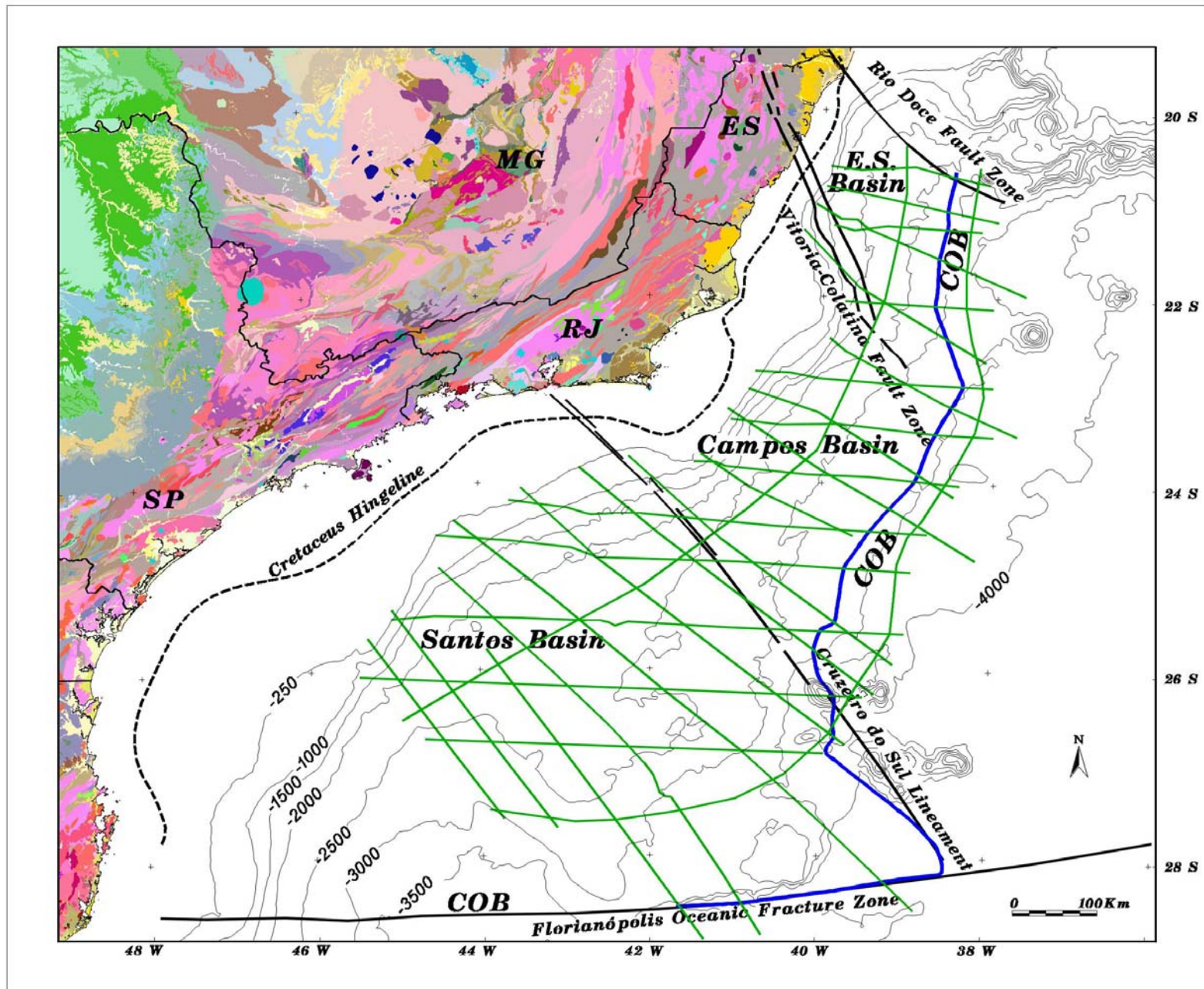


Figure 1. Location map of the study area displaying the onshore geology, the shoreline, the bathymetry (meters), the Cretaceous hingeline, the grid of ultra-deep seismic lines (in green) available for this study, the continental-oceanic crustal boundary (COB, blue line) and the major tectonic features that are here considered to be the boundaries of the Santos, Campos and Espírito Santo (ES) basins.

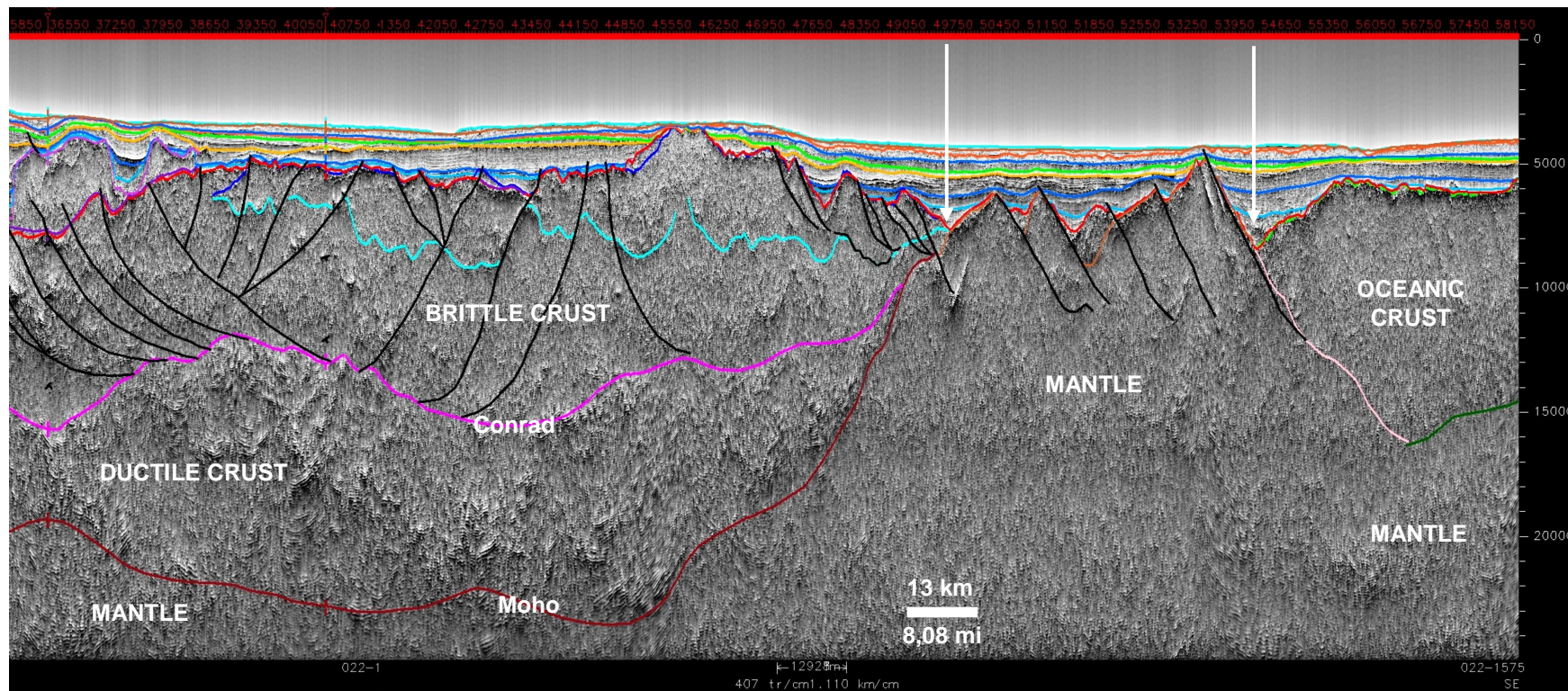


Figure 2: Dip seismic section (depth) in the Santos Basin displaying the dual nature of the continental crust (upper brittle and lower ductile crusts), the exhumation of the mantle (between arrows) and the passage to oceanic crust. Also shown are the Conrad and Moho discontinuities. Notice that exhumed 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)

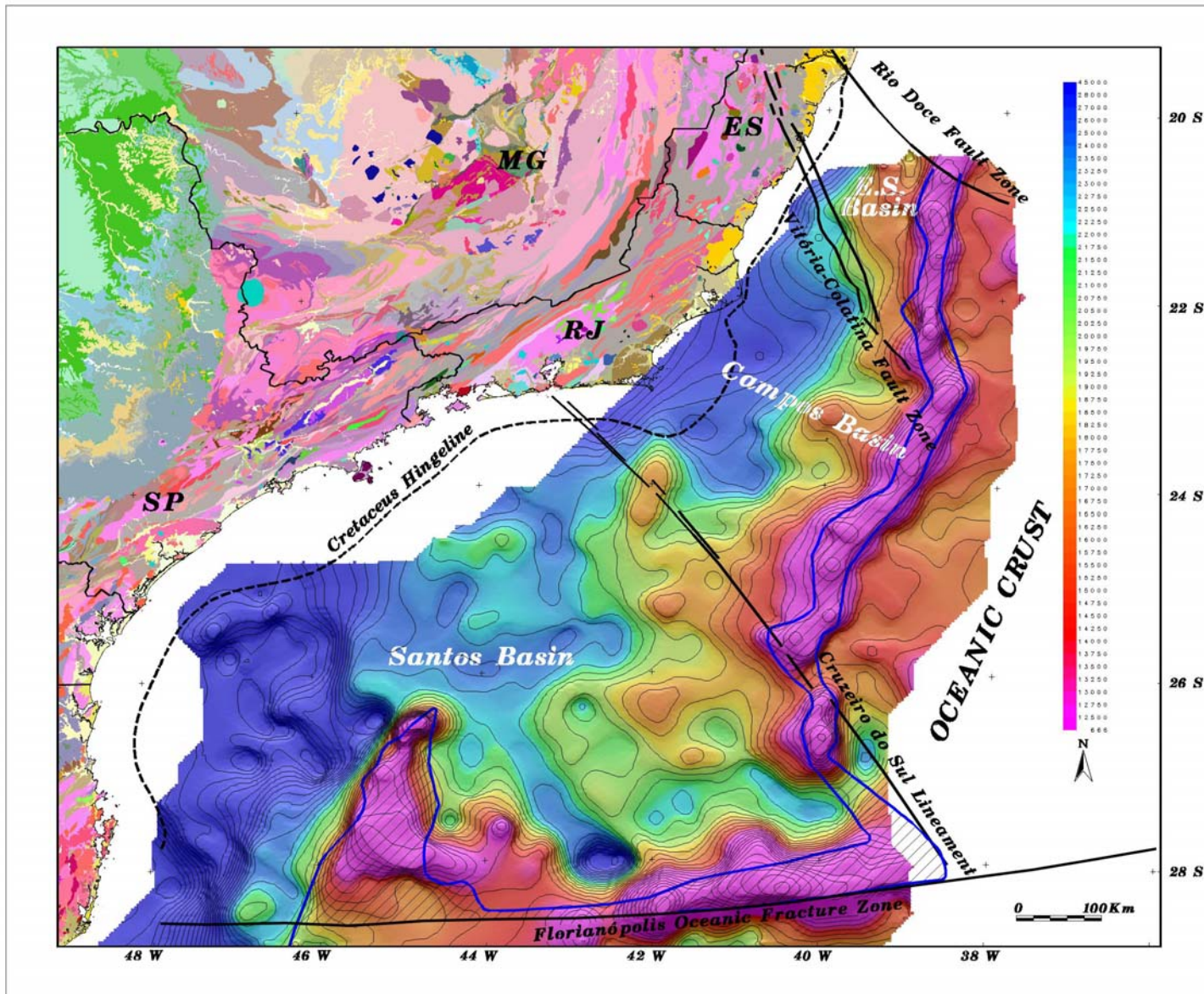


Figure 3. Structural contour map of the Moho discontinuity (depth to mantle). The dashed area encompassed by the two blue lines in the eastern part outline the exhumed mantle (at the time of rifting and breakup). To the west, continental crust extends below the sedimentary packages of the Atlantic passive margin until outcropping in the adjacent onshore area. The realm of the oceanic crust extends to the east and south of the blue lines.

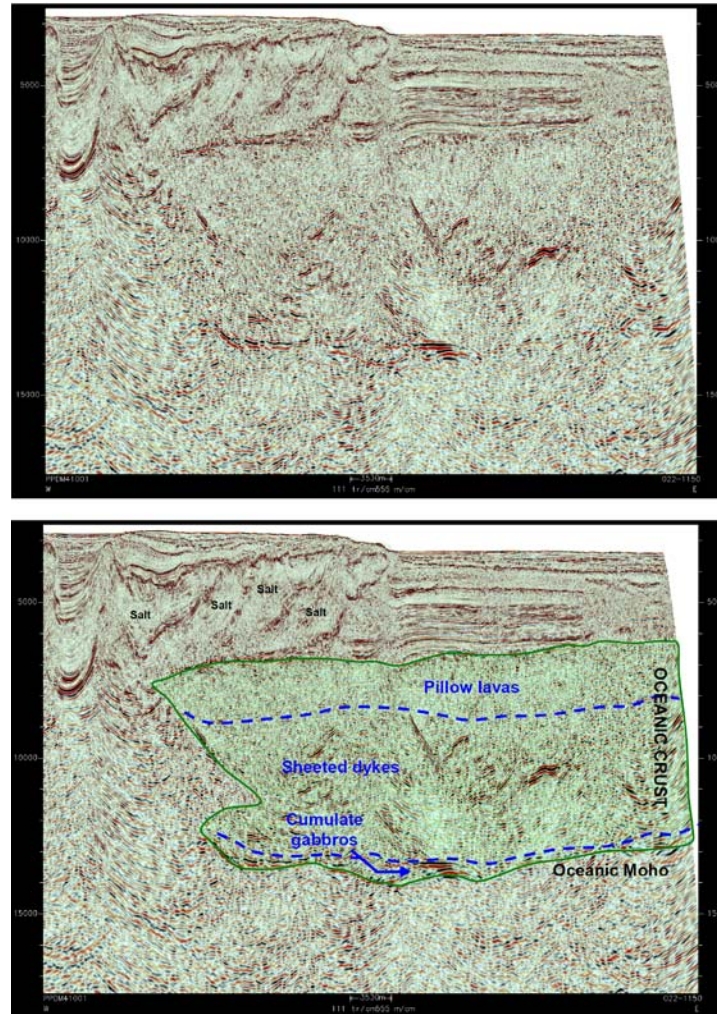


Figure 4. Non-interpreted and interpreted dip seismic section (depth) in the Espírito Santo Basin displaying the typical box-shaped geometry of the oceanic crust, the salt nappe thrust upon it, and the tripartite division of the oceanic slab; from bottom up: cumulate gabbros, sheeted dykes and pillow lavas.

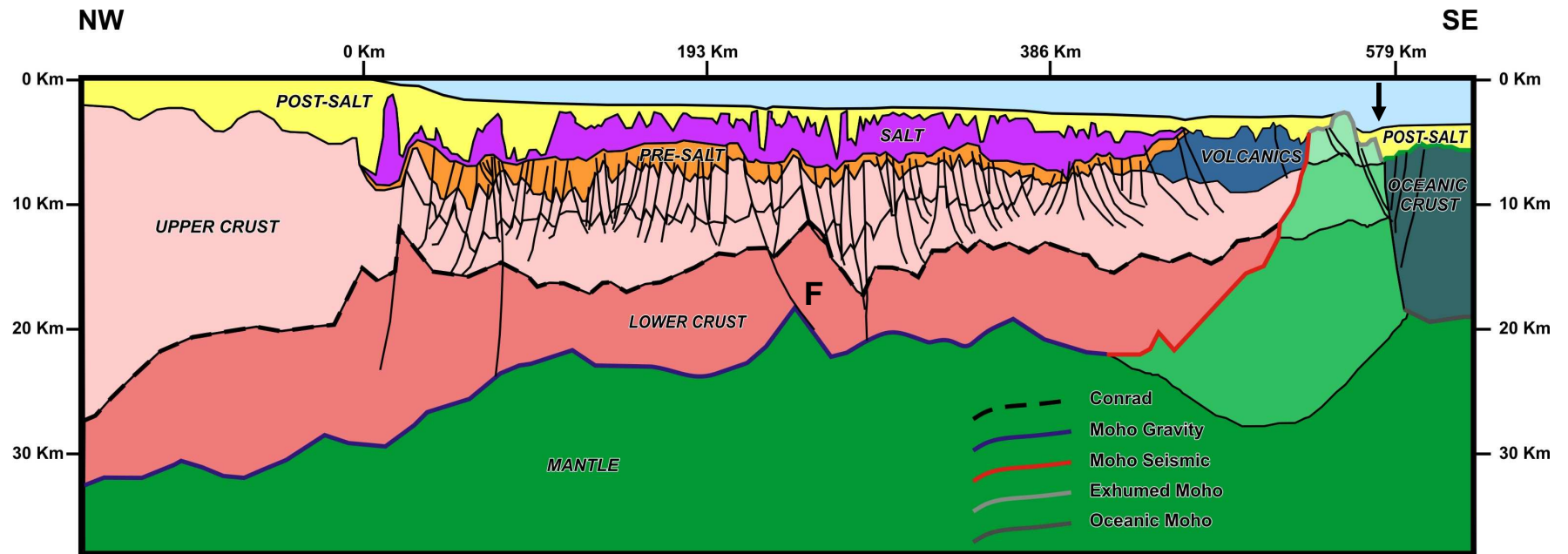


Figure 5 – Geological section interpreted (seismic and gravity) for the southern part of the Santos Basin. Horizontal and vertical scales in km. Notice the wide margin profile, with low crustal taper and one major necking zone due to a large scale crustal fault (F). Exhumed mantle crops out at sea bottom because of the Florianópolis Oceanic Fracture Zone (FOFZ, at arrow). In this location, the Continental-Oceanic Boundary (COB) is marked by a fault (FOFZ). Exhumed mantle needed to be divided into three zones of decreasing densities (different shades of green) in order to promote the fit between measured and modeled gravity data.

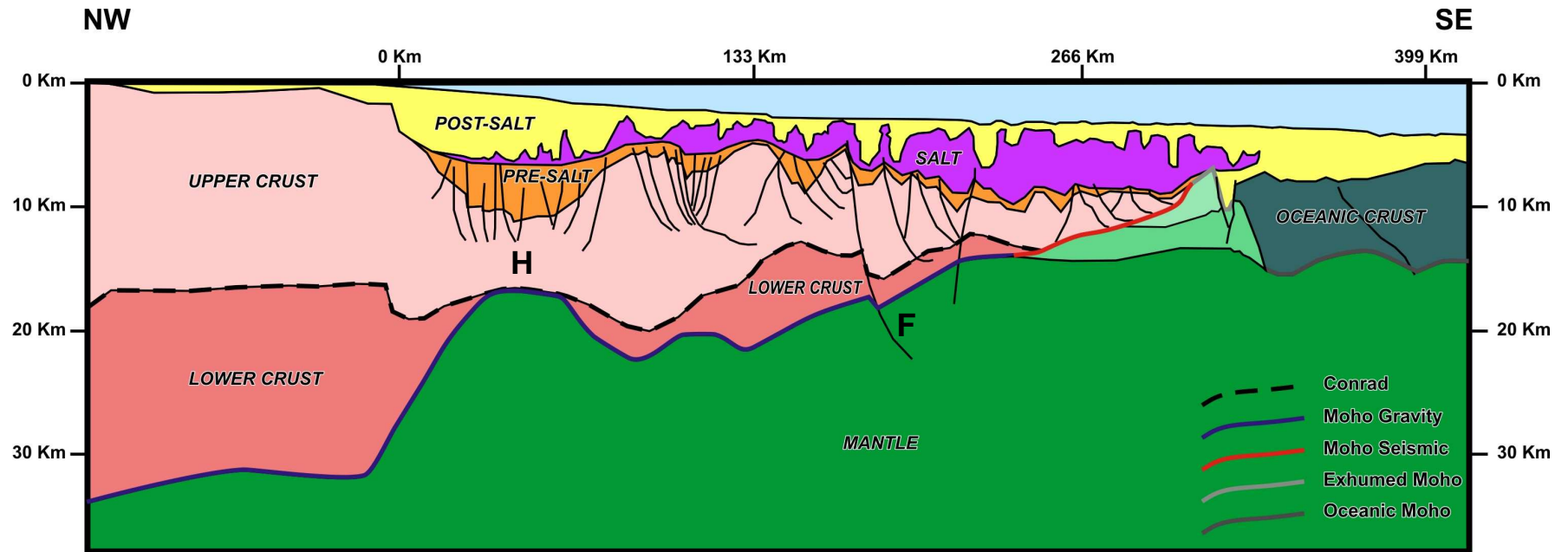


Figure 6 – Geological section interpreted (seismic and gravity) for the northern part of the Santos Basin. Horizontal and vertical scales in km. Notice the relatively wide margin profile, with moderate crustal taper, strongly necked at the western portion by a protrusion of the mantle that cut the ductile crust and promoted the formation of an aborted H-Block (H). A large scale crustal fault (F) separates hyper-extended crust to the right from stretched and thinned crust to the left. Exhumed mantle needed to be divided into two zones of decreasing densities (different shades of green) in order to promote the fit between measured and modeled gravity data.

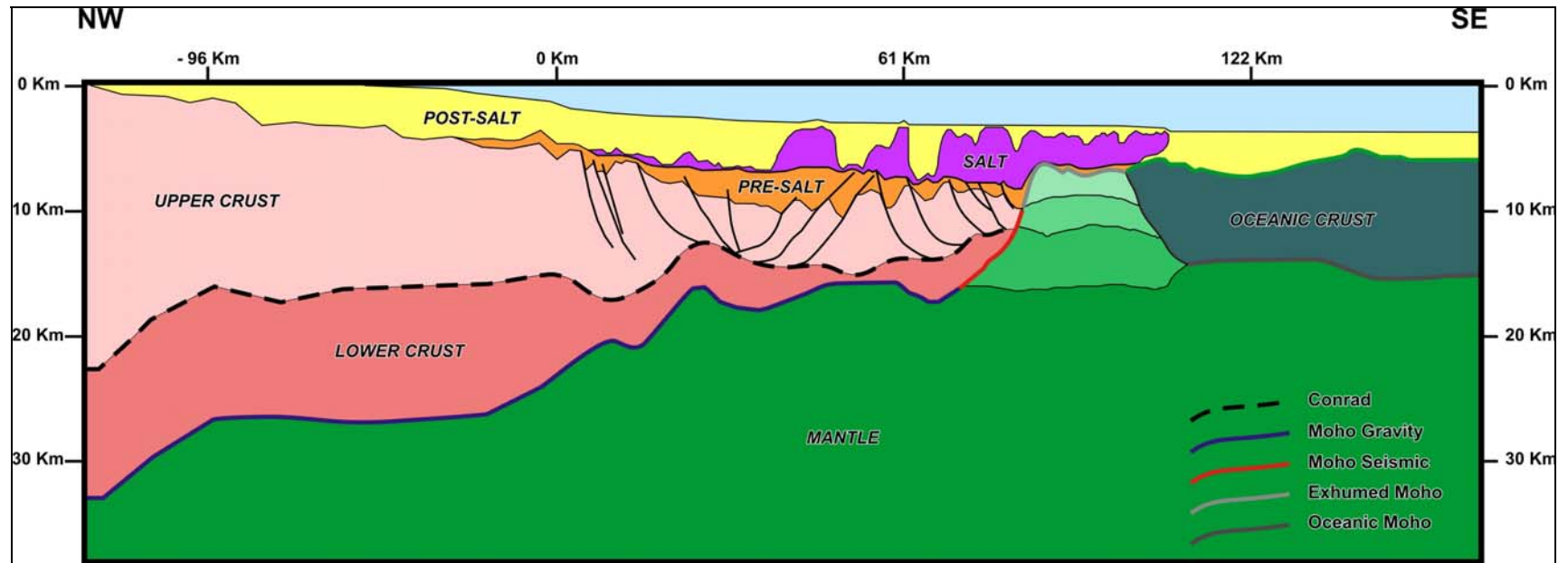


Figure 7. Geological section interpreted (seismic and gravity) for the Campos Basin. Horizontal and vertical scales in km. Notice the intermediate margin profile, with moderate crustal taper, without major neckings. Exhumed mantle needed to be divided into three zones of decreasing densities (different shades of green) in order to promote the fit between measured and modeled gravity data.

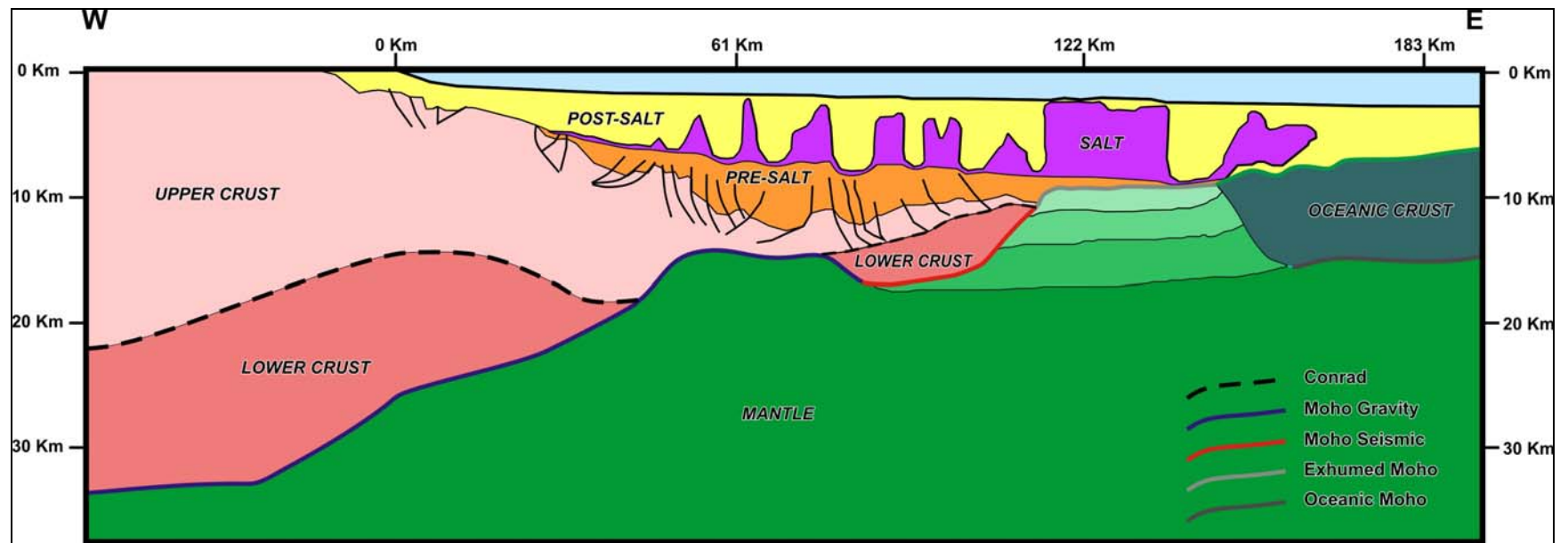


Figure 8. Geological section interpreted (seismic and gravity) for the Espírito Santo Basin. Horizontal and vertical scales in km. Notice the narrow margin profile, with strong crustal taper, strongly necked in the central portion by a protrusion of the mantle that cut the ductile crust. Exhumed mantle needed to be divided into three zones of decreasing densities (different shades of green) in order to promote the fit between measured and modeled gravity data.