[EA]Crustal Framework Control of the Pre-salt, Santos and Campos Basins, Brazil*

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Abstract

The Pre-Salt of the Santos and Campos Basins is a remarkable world class petroleum province. Twenty-five Pre-Salt accumulations hold proved reserves and contingent resources in the order of 40 Gboe. Discovered in 2006, its first production started in 2009. Ten years in a row and cumulative production surpassed 3.0 Gboe in October 2019. By then, production was in the order of 2.6 MMboepd. All this production came from 114 wells, of which 42 produced over 20,000 bopd. The producing 19 fields are systematically located on top of a major crustal structural feature; whose surficial expression is the External High.

The Santos and Campos Basins were developed on top of continental crust. Their structural framework has been studied in detail in the last 10 years, mostly via the interpretation of ultra-deep seismic sections and geophysical modelling. These studies determined that the underlying crust is roughly divided into three major domains that run roughly parallel to the shoreline (Figure 1), which, in turn, mimics the structural grain of the outcropping Precambrian basement in the coastal areas. From proximal to distal offshore, right seaward of the Cretaceous Hingeline, a first domain of stretched/hyper-extended crust controls the location of deep and thick grabens where an Internal Hydrocarbon Kitchen, consisting of mature saline lacustrine source rocks, developed. This thin crust domain is followed by a continental resistate, which is a thick crust domain relative to its surroundings, with much thinner grabens. The outer domain consists of very thin and highly faulted hyper-extended crust that controls the location of deep and thick grabens, that constitute an External Hydrocarbon Kitchen (Figure 1). A continuous belt of Exhumed Mantle marks the boundary of the continental and oceanic crusts, and its external limit is considered the beginning of the Oceanic Realm (Figure 1).

The continental resistate is thicker than the bordering bands of stretched/thinned and hyper-extended crusts, thus, isostatic compensation determines this domain to be a structural high, termed the External High (Figure 2). Its vertical relief, the long continuity and its optimal position in relation to the Internal and External Kitchens constitute a major focusing region. Most hydrocarbons produced in these kitchens preferentially flowed towards this mega-high. All the producing Pre-Salts fields and discovered accumulations are situated upon the External High (Figure 1). Recently acquired 2D seismic lines, shot in the ultra-frontier area of the southernmost Santos Basin, beyond the Pre-Salt

Polygon and the 200 NM limit of the EEZ, extended the External High to the south of known accumulations and identified a plethora of very large undrilled prospects.

The Internal Kitchen

The presently known prolific Pre-Salt petroleum system is sourced from syn-rift organic-rich shales of Late Barremian to Early Aptian age (Brazilian local Jiquiá age) that occur in both the Campos and Santos Basins. They occur in the inner portions of the basins, in the upper parts of grabens that are situated between the External High and the Cretaceous Hingeline (Figure 1 and Figure 3). These shales had been drilled, sampled and analyzed by several Petrobras exploratory wells, mostly in the Campos Basin, a few in the Santos Basin. They are usually interlayered with coquina levels and their thicknesses are in the order of several tens of meters. Their geochemical markers yielded oils that characterize saline to brackish water lacustrine depositional environments. Practically all the known accumulations of oil in the Pre-Salt of the Santos and Campos Basins are derived from such shales. As a matter of fact, all Post-Salt accumulations in the Campos Basin situated upon and to the west of the External High are also derived from these shales. Thus, the term Internal Kitchen is used to designate these inner grabens and their syn-rift saline to brackish water organic-rich shales, matured into the oil- and gas-windows of hydrocarbon generation.

The External Kitchen

New 2D ultra-deep seismic surveys were shot by Spectrum (nowadays TGS) over the southern extension of the External High and over the largely unchartered terrain to the east of it. The seismic data revealed a potential External Kitchen. The continental crustal terrains situated to the east of the External High are predominantly situated over hyper-extended crust. Several grabens, some with significant thicknesses (up to 3000 m), can be clearly seen far out to the east of the External High (Figure 4). Seismic facies are sometimes very similar to the ones known in the Internal Kitchen, pointing to a similar sedimentary fill. In a general way, such grabens are less abundant and thinner than in the Internal Kitchen. In the more external reaches of the hyper-extended crust the seismic facies within the grabens may differ significantly, raising the possibility of volcanic filling (Figure 3 and Figure 4). The abundance of syn-rift volcanic edifices throughout this area seems to point to an environment of sparser shallow lakes of high alkalinity, surrounded by active volcanos.

The Importance of the External High for the Pre-Salt Petroleum System

The External High is a long and wide, continuous trend of structural highs that runs along the Campos and Santos Basins in the N-S-direction (Campos) and in the NE-SW-direction (Santos), cutting these basins “in the middle” (Figure 1). The External High is the surface expression of a continental crust resistate that presents a deep Moho underneath it and a significant larger crustal thickness than the surrounding stretched/thinned and hyper-extended areas of continental crust (Figure 2). It divides the Campos and Santos Basins into an inner narrow corridor and an external wider depressed area, where grabens were developed upon much thinner stretched/thinned and hyper-extended crust. This crustal geometry developed during the rift phase (extension/thinning/rupturing) that affected this area of the Gondwana supercontinent. The different crustal thicknesses possibly reflect variable rheologies of different Precambrian terrains, whose trends are similar to Precambrian terrains exposed in the coastal zone of Southeastern Brazil (Araçuaí, Ribeira and Tijucas orogenic belts of the Mantiqueira Province). These old terrains had significantly different compositions, and probably acted/reacted in different ways to extension during the rifting process. Some

were more plastic and stretched and thinned (for instance, metasedimentary fold-and-thrust belts), and even broke up, more easily, constituting at the end the stretched/thinned and hyper-extended terrains. Others were stiffer (for, instance, magmatic arcs) and resisted extension maintaining their crustal thicknesses close to original, forming at the end the continental resistate. The External High floats isostatically amidst the adjacent thinner terrains (Figure 2 and Figure 3).

This geometry of a central high flanked by deeper areas is highly favorable for focusing of migration. Hydrocarbons generated in the depressed areas would migrate towards this central high (Figure 3). Figuratively speaking, the External High acts like the backbone of the Campos and Santos Basins, displaying on both sides the flattened downwards ribs. The inner, proximal rib cage represents the Internal Kitchen. The outer, distal rib cage represents the External Kitchen (Figure 2).

Conclusions

The complete understanding of the functioning of a world class petroleum system, in this case the Pre-Salt of the Santos and Campos Basin, can only be achieved when a complete analysis of the basins and their basements, that is, the continental crust underneath, is performed. When the crustal domains underlying the basins are mapped and related to the hydrocarbon kitchens, to the focusing structural highs and to the different prevailing thermal regimes during the rifting stages, it becomes possible to understand the distribution of discovered accumulations and to predict the occurrence of new ones. It also becomes clear the fundamental role that structural inheritance of different older terrains within the basement had upon the development of the different components of the petroleum system.

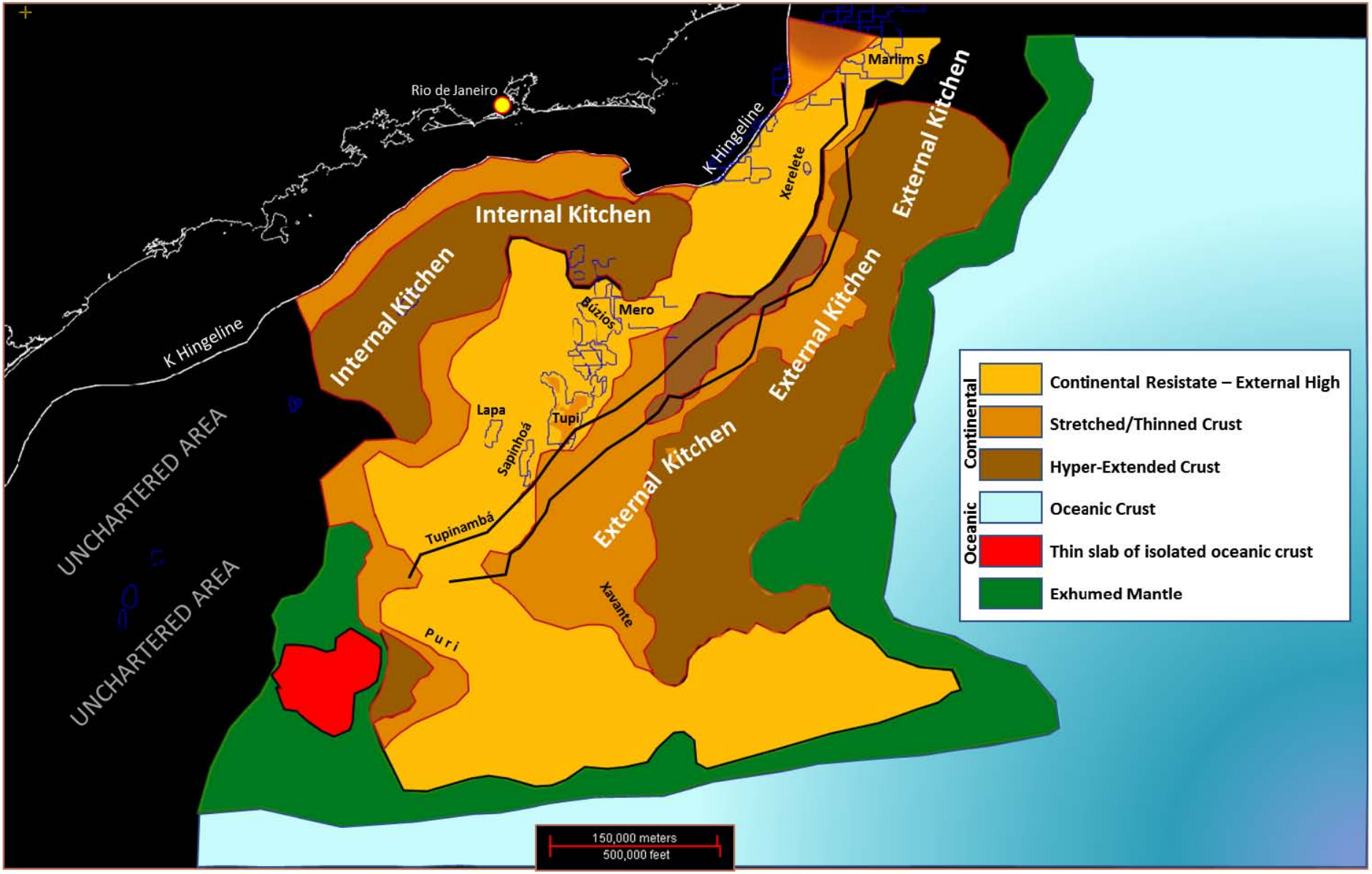

Figure 1. Map of the crustal domains for the Santos and Southern Campos Basin. Three major domains are recognized. The Stretched/Thinned and Hyper-Extended domains contain the most extensive and deepest grabens where source rocks are abundant and mature. The External High is the surficial expression of a Continental Resistate, upon which most of the Pre-Salt hydrocarbon accumulations are found. Selected names of Pre-Salt fields are shown for geographical reference. Puri, Xavante and Tupinambá are huge undrilled Pre-Salt prospects that may turn into super-giant fields in the future.

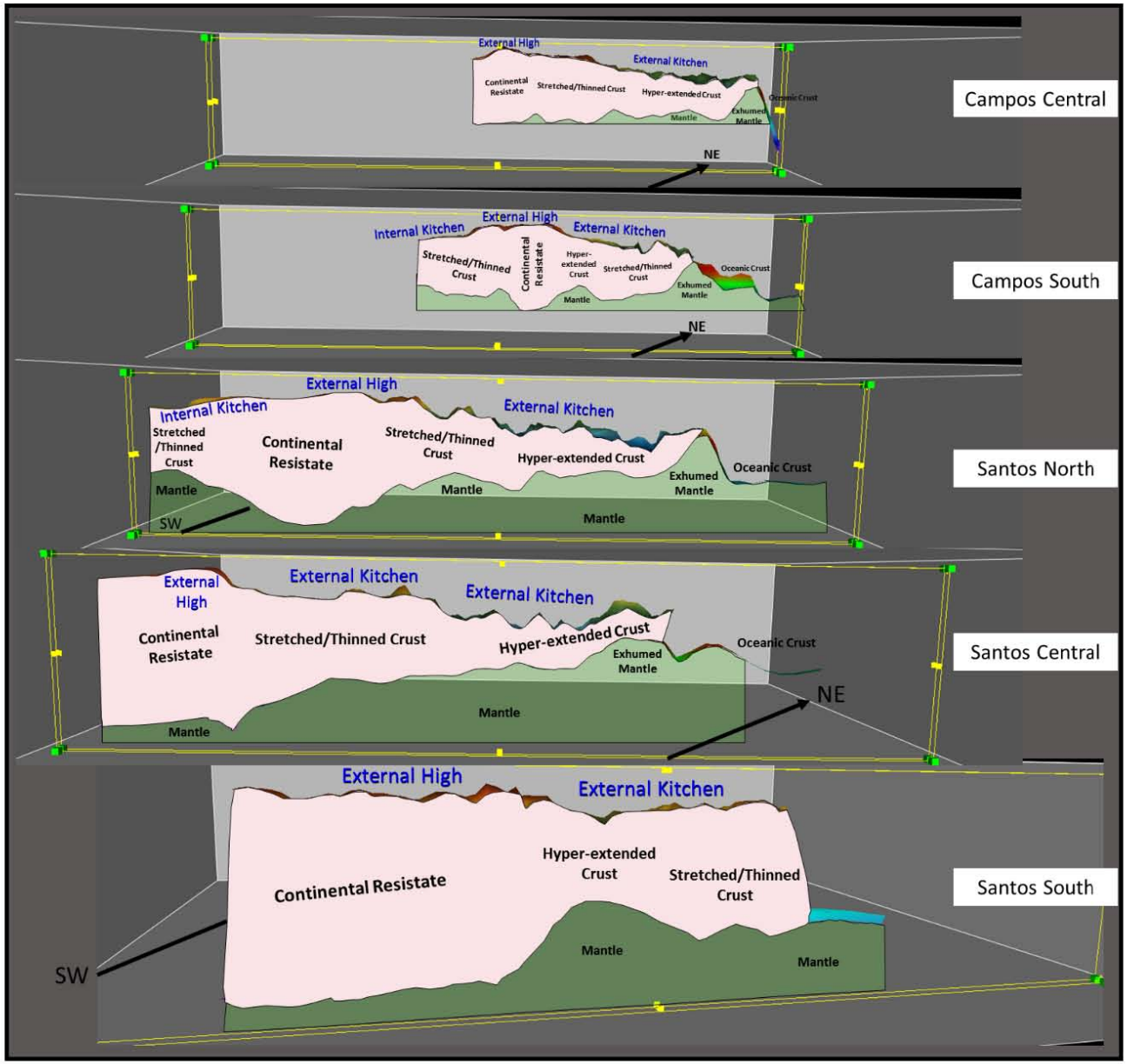

Figure 2. Perspective view (from SW to NE) of several crustal profiles along the Santos and Campos Basins illustrating crustal inheritance control upon elements of the Pre-Salt petroleum system. All profiles are dip-oriented along NW-SE-running ultra-deep seismic lines shot by Spectrum. The continental crustal profiles are bound by the Base of the Salt horizon and the Moho. Several different modes of thinning reflect the rheology of basement lithologies. An internal domain of Stretched/Thinned crust controls the location of the Internal Kitchen. A Continental Resistate controls the External High. The External Kitchen developed over a wide outer domain consisting of mostly Hyper-Extended Crust.

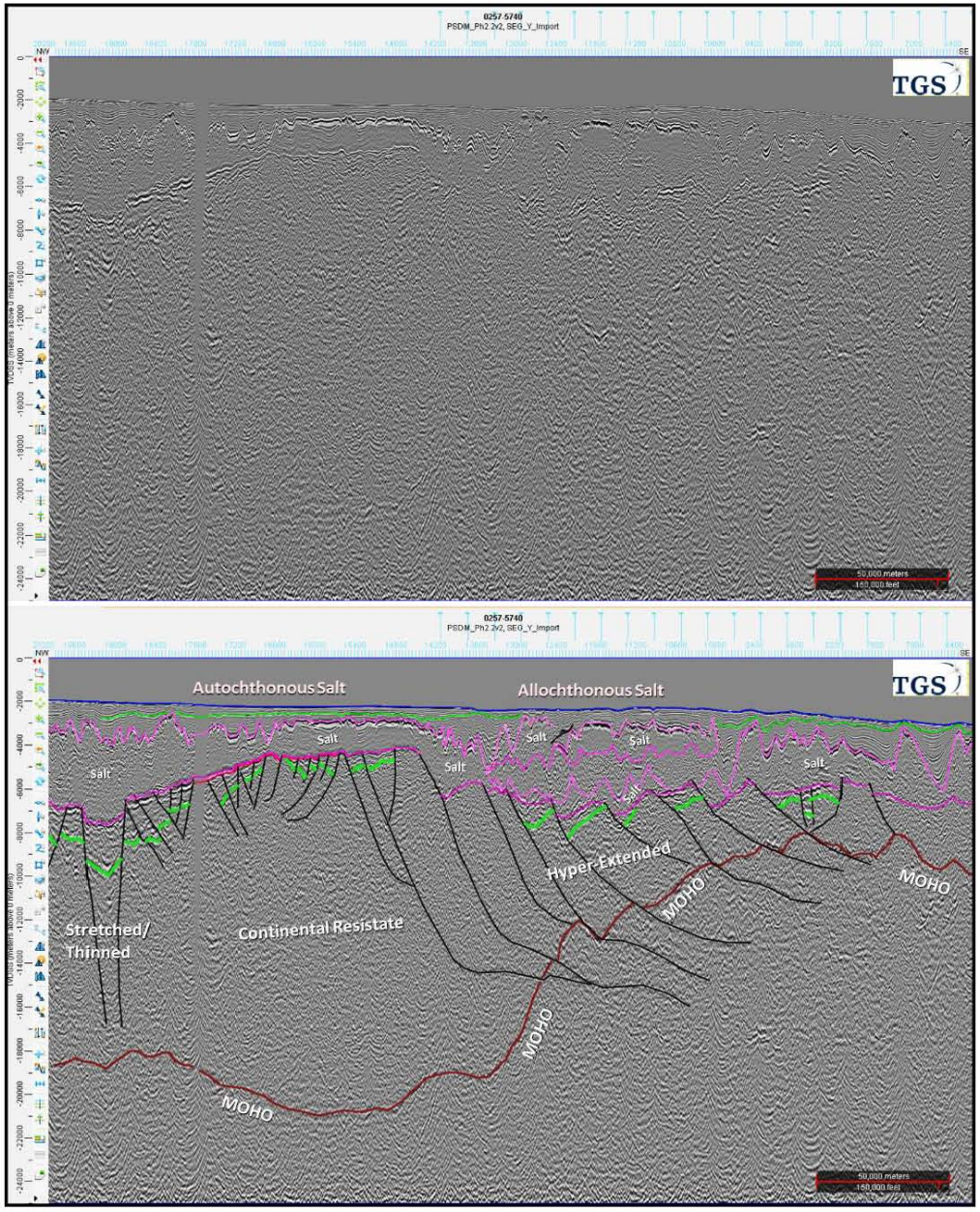

Figure 3. Depth dip-oriented ultra-deep seismic section in the southern part of the Santos Basin. Three structural domains can be observed. From left to right, the Stretched/Thinned domain displays grabens (between Base of Salt and green horizon) attributed to the Internal Kitchen. The Continental Resistate forms a huge structural high at the Base of Salt level (External High). The Hyper-Extended domain shows dramatic thinning of the crust and rheological coupling between the upper brittle and lower ductile crusts. The focusing character of the External High is obvious.

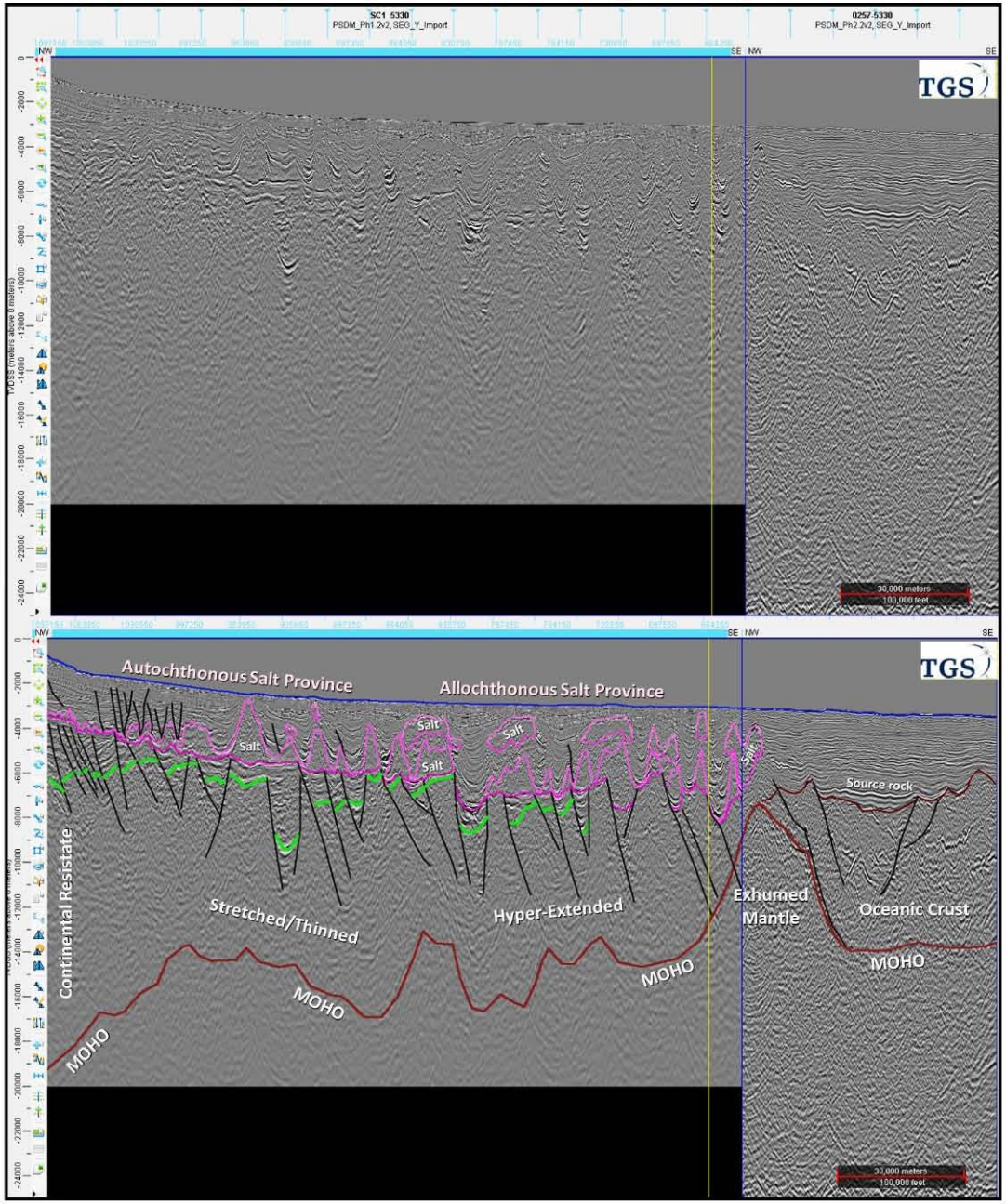

Figure 4. Depth dip-oriented ultra-deep seismic section in the southern part of the Campos Basin. The External Kitchen is well displayed in several grabens (between Base of Salt and green horizon). Its development took place upon Stretched/Thinned and Hyper-Extended domains. Exhumed Mantle and Oceanic Crust are also observed.