Five Kilometers of Paleozoic Sediments Beneath the Pre-Salt of Santos Basin*

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Abstract

The Early Cretaceous syn- to post-rift pre-salt petroleum system of the Santos and Campos basins in southeastern Brazil is already one of the most prolific petroleum systems of the world. In only ten years after the first discovery of light oil in the uncommon microbialite reservoirs, ten fields are already producing over 875,000 bopd and 34.3 MMm3/d of gas, for a total of 1,090,700 boepd from only 52 wells. Some wells produce slightly over 36,000 bopd (ANP Oil and Natural Gas Production Bulletin, December 2015). About 40-50 Gboeip have been discovered by Petrobras and statistical extrapolations point to yet-to-find-oil resources between 120-217 Gbor. Three super-giant fields are known in the Santos Basin: Lula/Tupi, Buzios/Franco, and Libra. Several other giant fields such as Guará/Sapinhoá, Carioca/Lapa, Iara, Iracema/Cernambi, Carcará, Sagitário, Pão de Açúcar and the pre-salt accumulation under the Cretaceous/Paloeogene sandstone reservoirs of the Whales Park; these last two in the Campos Basin complete the scenario of this prolific petroleum province.

What if, beneath this rich and prolific petroleum system in the Santos Basin, a whole new exploratory play(s) existed? What if a large chunk of a previously continuous and enormous Paleozoic Basin remained trapped below the Early Cretaceous rifts as an underlying Pre-Rift Supersequence? What if this Pre-Rift basin contained the entire stratigraphic section known in the nearby Paleozoic onshore Paraná Basin with thicknesses of up to 5 km? What if in this Paleozoic section an extremely rich source rock is known to exist? What if most of the structural traps of the rift section are mirrored in the underlying Pre-Rift section?

Introduction

The Santos Basin is a huge (circa 400,000 km^2) offshore Brazilian basin situated in a magma-poor passive margin rimmed by a continuous belt of exhumed mantle (Zalán et al., 2011a). The sedimentary filling consists basically of a widespread and thick (up to 5 km) mixed carbonate-clastic rift system, with some volcanic layers, of Hauterivian to Aptian age, covered by a thick section of Late Aptian (113-112 Ma) evaporites (layered evaporites may reach up to 4 km), topped by a relatively thin drift sequence composed of Albian to Recent post-salt carbonates, shales and sandstones of diverse origin (Moreira et al., 2007). The post-rift unconformity is a time-crossing surface that may be situated well below

the base of the salt in the internal and central parts of the basin, or may top the salt in the most distal parts where the lattermost rifting encompassed the deposition of the salt sequence (Zalán et al., 2011b).

The Pre-Salt petroleum system consists of organic-rich shales (source rocks up to 110 m thick) of Late Barremian/Early Aptian age, deposited during the rifting stage, and carbonate reservoirs of Barremian to Late Aptian age. The carbonate reservoirs consist mainly of Aptian microbialites and, secondarily of Barremian coquinas interlayered with the source rocks. The overall extension and huge thicknesses of the evaporites provides one of the best sealing systems known in the world (Figure 1). The microbialite reservoirs may consist of two distinct layers, one positioned in the late rift stage and the other in an early thermal subsidence stage. Such is the case in the Lula/Tupi Field where the net pay in both reservoirs may reach 100 m (Figure 1). Sometimes, this distinction is not possible and one huge column of continuous microbialites is developed (Guará/Sapinhoá Field, 186 m net pay). In other instances, coquinas may merge upward into microbialites forming net pays up to 326 m (Libra Field).

Ultra-deep seismic sections from the Santos Basin show a thick section of layered reflectors beneath the economic basement of the Pre-Salt petroleum system (Camboriú Formation basalts). These reflectors show parallel-layered, tabular internal geometries similar to stratigraphic sequences typical of intracratonic basins. Comparisons between these reflection patterns with the seismic-stratigraphic pattern displayed in seismic sections from the adjacent onshore Paleozoic Paraná Basin, suggest that the same layers that fill the nearby Paleozoic basin are present underneath the Pre-Salt in the Santos Basin, with thicknesses of up to 5 km. The Camboriú basalts are correlated to the Serra Geral lava flows (134-132 Ma) that top the Paraná Basin (Mizusaki et al., 1992; Mizusaki and Thomaz Filho, 2004; Stica et al., 2014). It is plausible to assume that the thick tabular layered sequence below the top of these basalts would correspond to the Paleozoic section of the nearby Paraná Basin.

If this hypothesis is confirmed, a whole new exploratory play would open in the ultra-deep realms of the Santos Basin. Excellent reservoirs such as the Triassic Pirambóia, Jurassic Botucatu and Permian Rio Bonito sandstones could be filled with oil and gas sourced from the organic-rich shales of the Permian Irati Formation. The best areas to test this new play are the culminations of footwall blocks associated with large rotational planar normal faults, such as the Lula/Tupi High. There, the Paraná Basin reservoirs could be reached by wells in the order of 6000-7000 m deep, after crossing about 500-1000 m of the Camboriú lavas.

Layered Sequence Beneath the Pre-Salt in Santos Basin

Several lines that cross the oil fields discovered in the Pre-Salt petroleum system of the Santos Basin display a characteristic, reflective layered sequence beneath the Rift Sequence. In particular, a 3D seismic section shot and processed by CGG (2008), using Reverse Time Migration, across the super-giant Lula/Tupi Field, illustrates very well this ultra-deep layered sequence (Figure 1).

Although faint when compared to the bright Rift and Layered Evaporite Sequences, the parallel nature of the reflective package, cut and rotated along numerous planar normal faults, stands out clearly. In terms of tectono-stratigraphy, such sequence can be classified as a Pre-Rift Sequence. The tabular nature of the reflectors points to a pre-tectonic sequence. The mapping of such sequence, where possible (naturally, not all seismic sections are of high definition as the one displayed in Figure 1) showed a wide distribution (around 80,000 km^2) in the central part

of the Santos Basin, right below the core of the Pre-Salt Play. Its thicknesses vary from 2000 m to over 4000 m, reaching close to 5000 m to the southwest of the Lula/Tupi Field.

These deep reflections have already been recognized by other authors. Henry et al. (2009a, 2009b) interpreted these tabular sequences as an older Valanginian Syn-Rift Sequence; interpretation with which we strongly disagree. The only tabular sedimentary sequences beneath the Serra Geral/Camboriú lavas known in southern/southeastern Brazil are the Paleozoic sequences of the nearby Paraná Basin.

Paraná Basin Seismic-Stratigraphy

The Mesozoic and Paleozoic sections of the Paraná Basin have long been studied and its stratigraphy is well established (Figure 2). The basin is filled by 4000-6000 m of sedimentary and volcanic rocks. The oldest sedimentary record is of Ordovician age. The Paleozoic section presents three sequences: Ordovician-Silurian, Devonian, Late Carboniferous-Permian-Early Triassic. The Mesozoic section presents three sequences: Triassic, Jurassic-Early Cretaceous, and Late Cretaceous. The Early Cretaceous Serra Geral basalt flows cover almost 1,000,000 km^2 of the basin and their correlatives can be found on the other side of the Atlantic Ocean in the Etendeka lavas of Namibia. The Santos Basin is situated exactly between these two originally attached continental margins.

In order to determine the possible Paleozoic stratigraphy underneath the Mesozoic Santos Basin, typical seismic sections from the Paraná Basin were analyzed and interpreted. Figure 3 and Figure 4 show typical seismic sections displaying the key markers of the seismic stratigraphy of the basin. The uppermost reflective layered horizontal sequence corresponds to the Serra Geral basalt flows. The deeper reflective and stratified, but faulted, section corresponds to the Devonian Ponta Grossa Formation strongly intruded by sub-horizontal dolerite sills. In an intermediate level, another reflective stratified subhorizontal section can be observed and it can be tied to the Irati Fm. Here again, this formation only stands out in the seismic section because of the numerous intrusions of dolerite sills. As a general rule, the Paraná Basin would appear as an almost transparent package in seismic sections because of a chronical lack of contrasts in the acoustic impedance of its sedimentary filling. Only the uppermost lava flows and the diabase intrusions stand out as strong reflectors. They show a preferred positioning in the shale-rich Irati and Ponta Grossa formations, thus revealing their locations in seismic sections.

Interpretation of the Ultra-Deep Reflective Section

The interpretation of the seismic section displayed in Figure 1 is easily achieved by the recognition of the strongly layered and folded section of evaporites, resting upon a sub-horizontal tabular sag section, which in turns unconformably overlies a faulted and rotated syn-rift section clearly displaying growth strata controlled by the faults (Figure 5). These form the Passive Margin Supersequence of the Santos Basin. A faint, but clear, reflective section, consisting of tabular reflectors, underlies what is usually considered the economic basement of the Santos Basin (top of Camboriú basalts). Immediately below this level, a package of relatively strong, tabular reflections stand out. According to the criteria outlined for the seismic stratigraphy of the Paraná Basin, this package was interpreted as representing the Serra Geral/Camboriú lava flows, with a thickness of around 500-600 m.

Another deeper reflective section, also consisting of tabular reflectors lie well below the supposed Serra Geral lavas, from which it is separated by a more or less transparent section. These ultra-deep reflections were interpreted as indicative of the Ponta Grossa Formation intruded by diabase sills. In the middle of the intermediate transparent section, one isolated subtle reflector was assigned to the Irati Formation (Figure 5).

In summary, by using the criteria of three reflective sections usually displayed in the seismic sections of the Paraná Basin, a complete stratigraphic section of this adjacent Mesozoic/Paleozoic intracratonic basin was tentatively recognized underneath the Santos Basin.

Conclusions

The economic implications of this hypothesis are outstanding. If proved true, another potentially rich petroleum system would exist underneath the mighty Pre-Salt petroleum system.

This petroleum system would be sourced by the organic-rich shales of the Irati Formation. Light oil, condensate and gas should be expected to occur in the Botucatu and Pirambóia eolian sandstones, right underneath the Serra Geral/Camboriú basalts. The traps would be the same structures already known in the Pre-Salt system. Faulted blocks, rotated or not, hold the majority of the reserves of the Pre-Salt petroleum system. These same structures could hold additional reserves in the deeper Irati-Botucatu/Pirambóia petroleum system; provided that mapping indicates the existence of this deep reflective tabular section.

The best way to prove this hypothesis would the drilling of an exploratory well, or the deepening of an appraisal well, in the highest structural position of the Lula/Tupi structure (see Figure 5). There, the Pirambóia and Botucatu sandstones could be reached by a well less than 6000 m deep, after crossing about 500-600 m of the Camboriú lavas.

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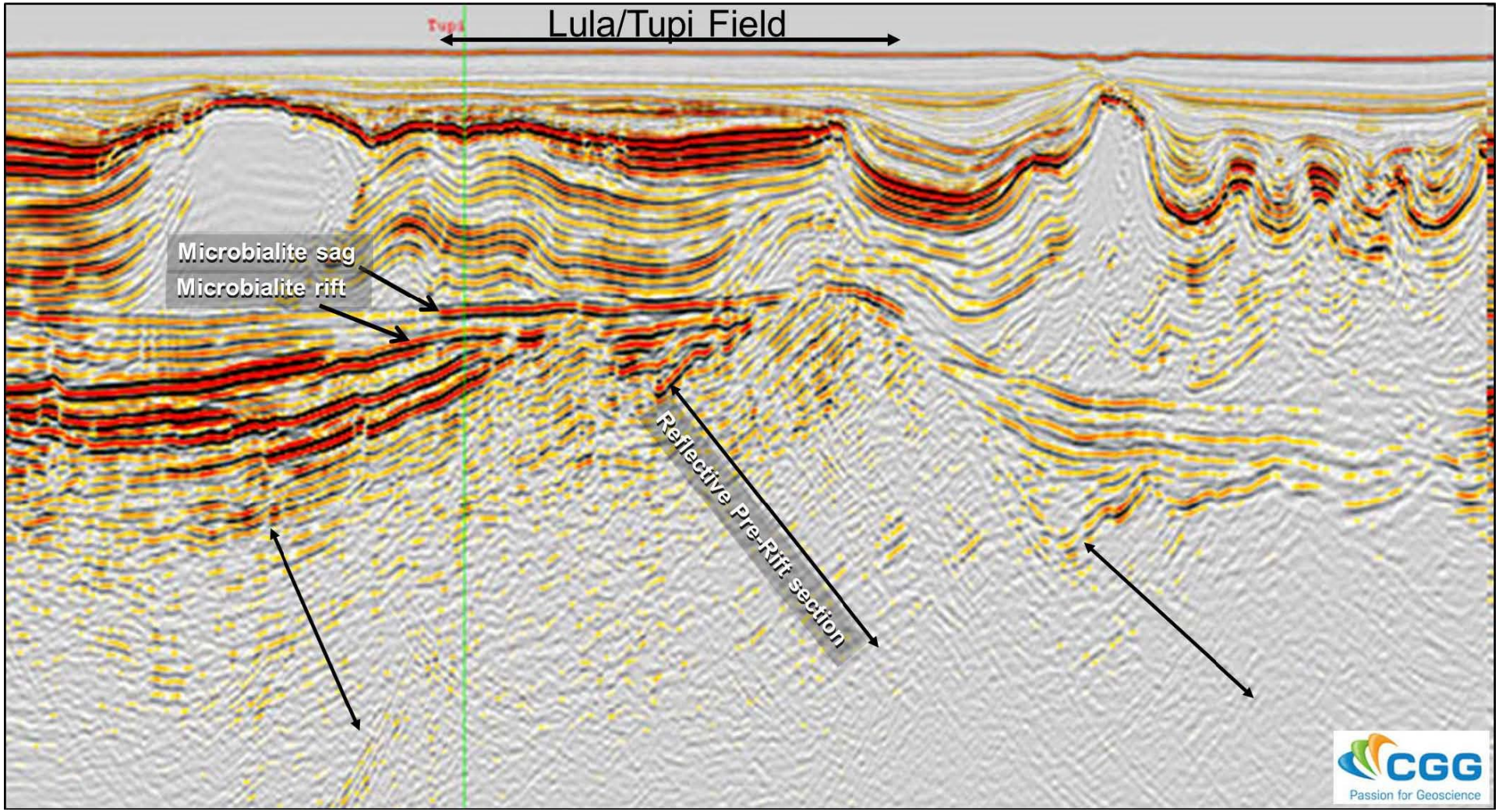

Figure 1. Non-interpreted depth seismic section, acquired and processed by CGG (PSDM using Reverse Time Migration) (CGG, 2008). The section displays extremely well the stratified and strongly folded evaporite section, below which microbialite reservoirs that constitute the super-giant Lula/Tupi Field can be observed and are pointed out. Below the strong red reflectors of the Pre-Salt section, a faint but clearly stratified section can be observed (black double arrows) indicating the presence of either lava flows or sedimentary rocks, or both. The regular tabular nature of such section suggests a pre-rift section deposited in a non-tectonic environment. The great thickness and extent of this section points to an older intracratonic basin lying underneath the marginal Santos Basin. Vertical and horizontal scales were not available. Sea bottom at Lula Field is about 2100 m deep, top of salt around 2900-3000 m, thickness of the salt varies between 2000-2200 m and the base of the salt (top of the sag microbialite) is around 5000 m.

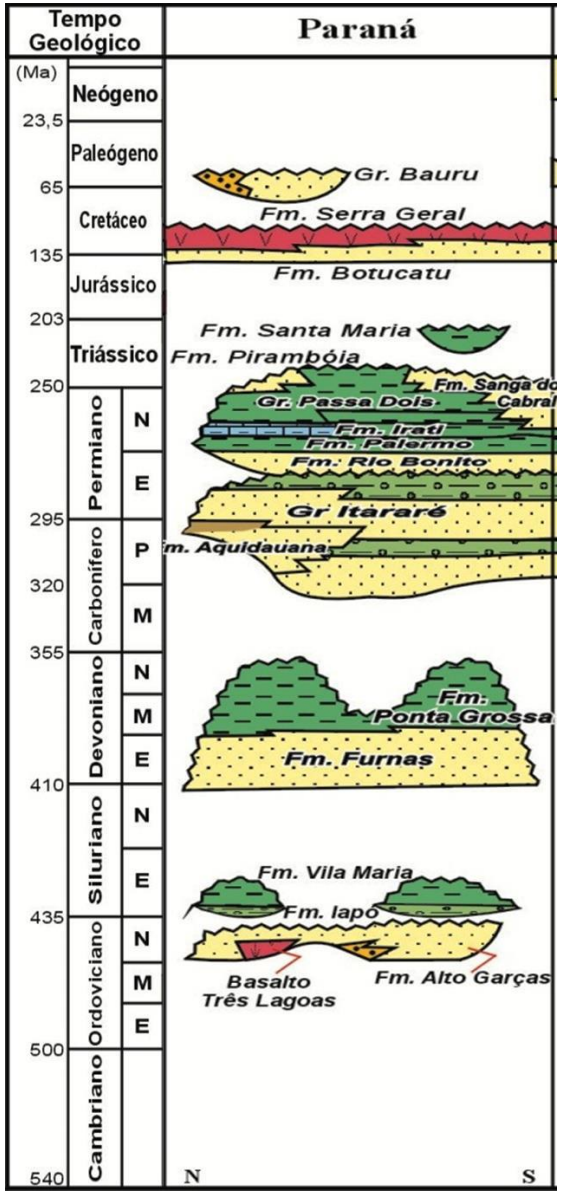

Figure 2. Stratigraphic column of the Mesozoic/Paleozoic Paraná Basin (Zalán, 2004). The best source rock would be the organic-rich shales of the Mid-Permian Irati Formation. In the Paraná Basin this formation is rarely buried enough to achieve thermal maturation. A leaner source rock is the Devonian Ponta Grossa Formation that achieves thermal maturation by either burial or by the thermal effect of diabase intrusions. The best reservoirs known are the Jurassic Botucatu and Triassic Pirambóia eolian sandstones. As secondary objectives, the deltaic sandstones of the Early Permian Rio Bonito Formation and the glacial-derived sandstones of the Carboniferous Itaraté Group are indicated.

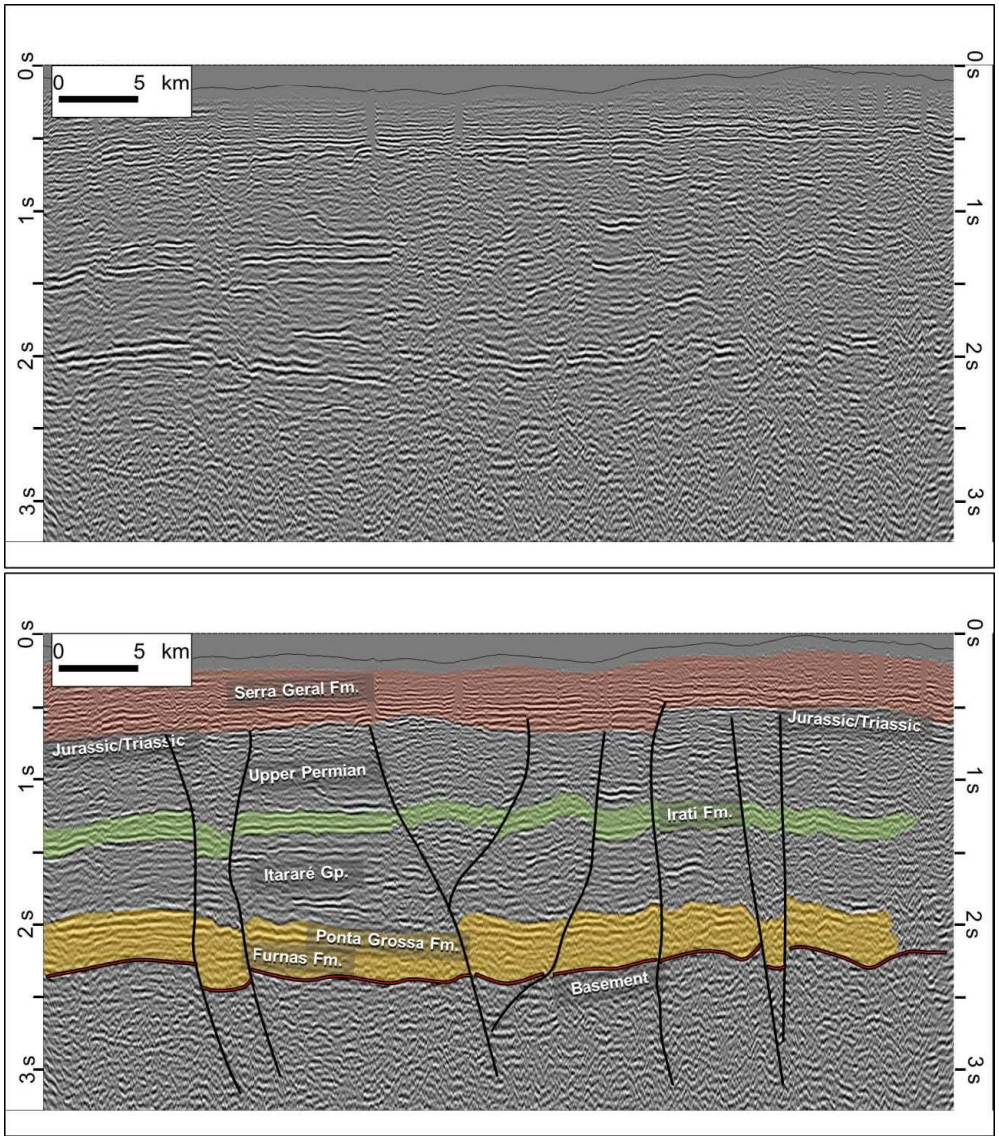

Figure 3. Typical seismic section from the Paraná Basin (TWT display). Three marked reflective sections can be observed. The uppermost section corresponds to the Serra Geral basalt flows. It is usually unfaulted. The middle reflective section indicates the presence of the organic-rich shales of the Irati Formation strongly intruded by diabase sills. The lowermost reflective section highlights the organic-rich shales of the Ponta Grossa Formation, also strongly intruded by diabase sills. If it were not for the volcanic and intrusive igneous rocks, the Paraná Basin would be practically devoid of seismic reflections. Flower structures are conspicuous in the basin.

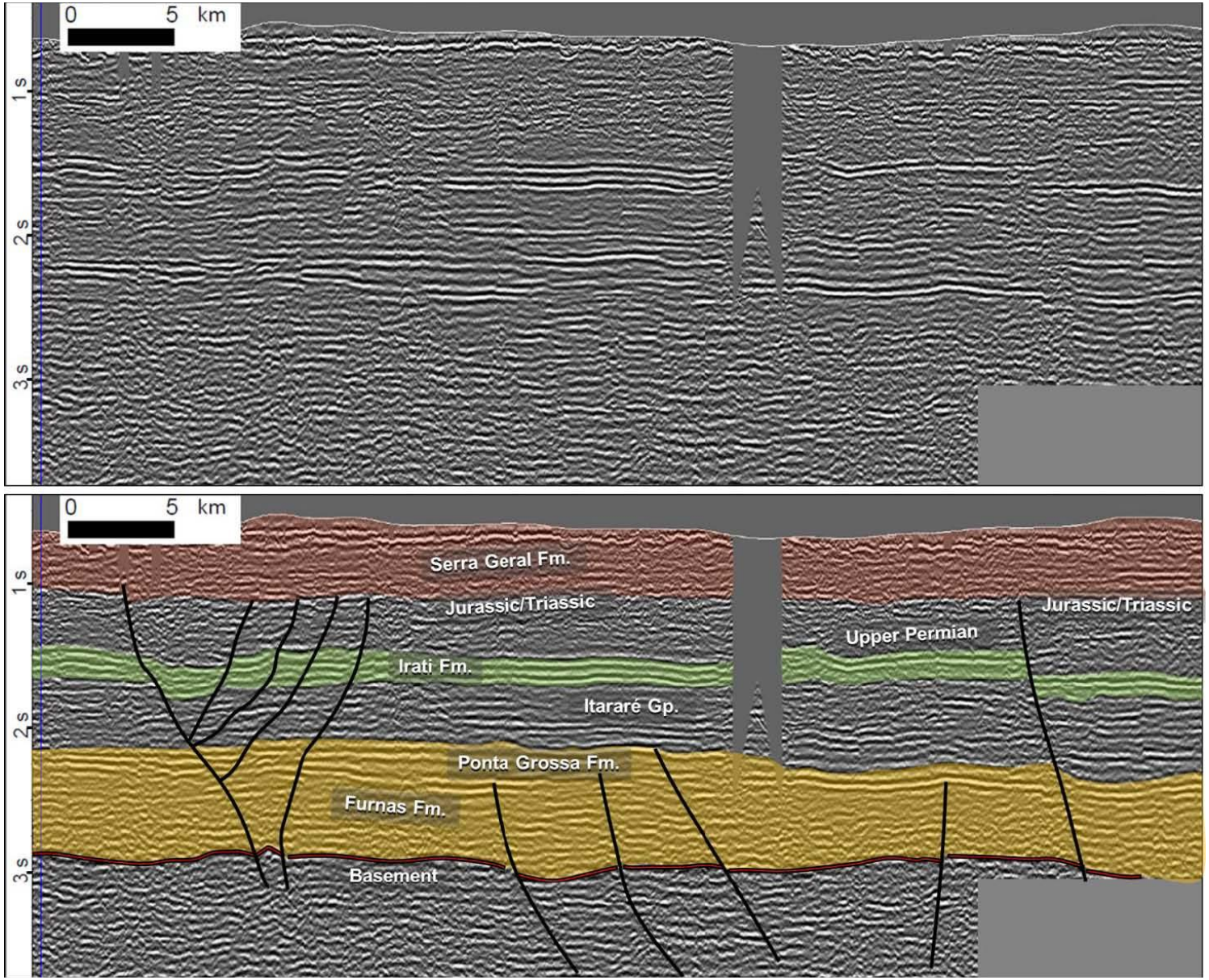

Figure 4. Typical seismic section from the Paraná Basin (TWT display). Three marked reflective sections can be observed. The uppermost section corresponds to the Serra Geral basalt flows. It is usually unfaulted. The middle reflective section indicates the presence of the organic-rich shales of the Irati Formation strongly intruded by diabase sills. The lowermost reflective section highlights the organic-rich shales of the Ponta Grossa Formation, also strongly intruded by diabase sills.

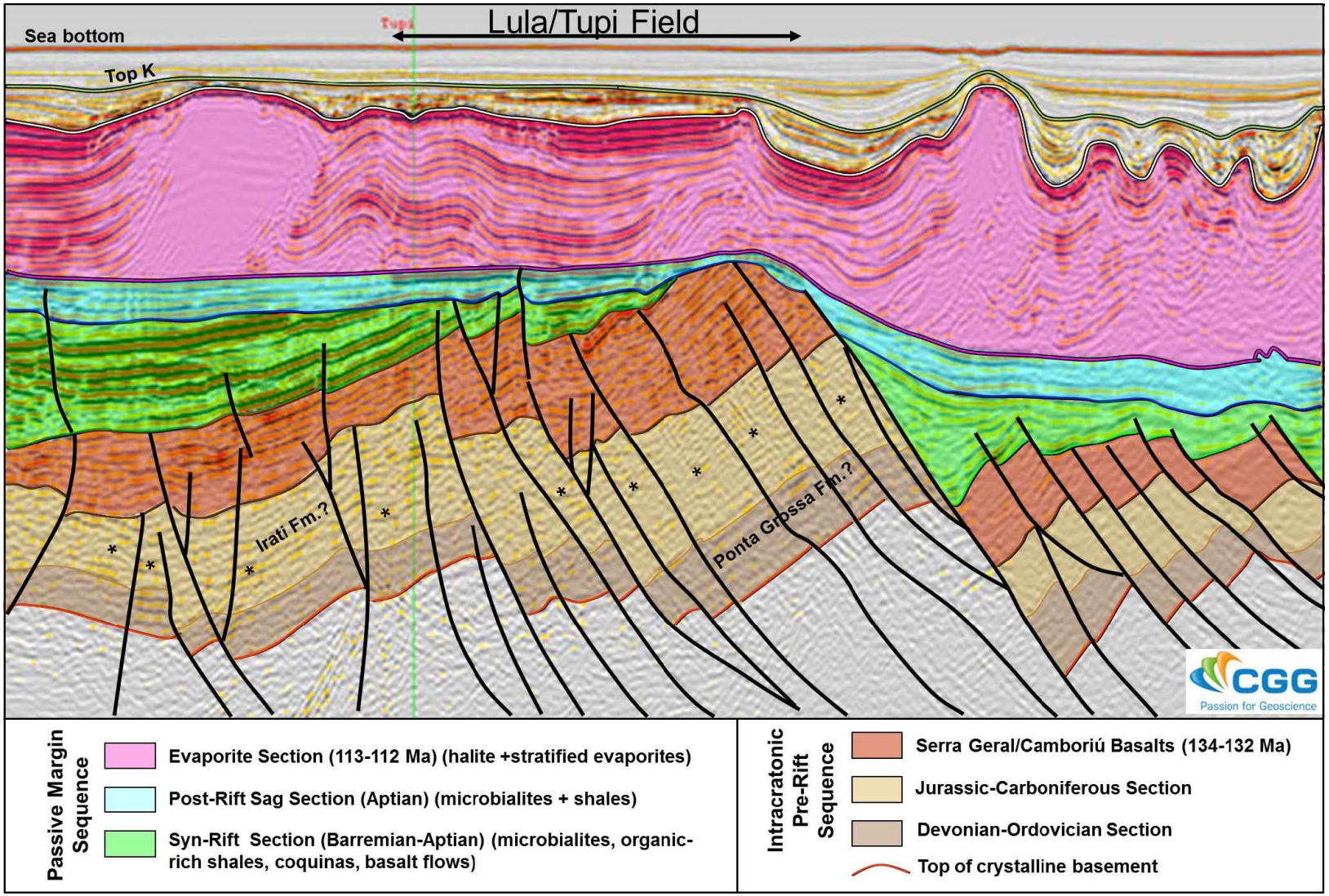

Figure 5. Full interpretation of the seismic section shown in Figure 1. The Passive Margin Sequence of the Santos Basin is clearly formed by a Syn-Rift section, followed by a tabular sag section, capped by a thick section of evaporites. The overlying Drift section is very thin at this location. The thick reflective section underlying the so-called Pre-Salt section of the Santos Basin is here tentatively interpreted as the Mesozoic/Paleozoic section of the Paraná Basin using the criteria described in Figure 3 and Figure 4. The tentative location of the Irati Formation (best source rock) is highlighted by asterisks; as well as of the Ponta Grossa Formation (secondary source rock). A perfect spot to test this hypothesis would be an exploratory well located at the highest point of the base of the salt, at the highest structural level of the Lula/Tupi Field. The primary objectives (Botucatu and Pirambóia sandstones) would be right underneath the Serra Geral/Camboriú basalts.