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Oil Discovery in Ordovician Prerift Sequences Las Breñas Formation, Lomas de Olmedo Sub-Basin, Northwestern Argentina*

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Abstract

Historical production in Cretaceous sub-basin of Lomas de Olmedo, northwestern Argentina, comes from Cretaceous and tertiary sandstone, carbonate and volcanic rocks. No hydrocarbon production was ever documented in the Ordovician Prerift sequences. Recent exploration wildcat in Los Blancos High, southern flank of the basin, discovered good quality oil (32-36° API) in highly fractured Las Breñas Ordovician quartzite's. This new petroleum system Yacoraite-Las Breñas (!) belongs to a structural high creating entrapment in buried erosional relief (buried hills). The source rock is Yacoraite Formation (Maastrichtian/Danian) and the pod of active source is located approximately 30 km to the north. The carrier from the active pod to the trap is the post rift Balbuena Group (Lecho and Yacoraite formations). The present study addresses available geological and geophysical data, subsurface structural maps, 2D and 3D seismic and well data. This information has been integrated allowing understand the process of petroleum generation, migration and accumulation, also the structural setting and reservoir characteristic in a frontier exploration region in the southern flank of the Lomas de Olmedo sub-basin.

Paleozoic Stratigraphic Setting

The tectonostratigraphic Paleozoic column is a representation of the subsurface in the region of Los Blancos High, based on available well data and seismic stratigraphic interpretation. Correlation with tectonics events was achieved by structural-stratigraphic analysis of these data.

Ordovician

Ordovician sedimentary deposits in the Northwest Basin are associated to a clastic platform, whose coastline was to the east, limiting the Pampean Terrane (Ramos, 2008). On the southern flank of the sub-basin of Lomas de Olmedo (Figure 1; Figure 2), have been partially drilled by the wells Rivadavia es-1, La Unión x-1, Tordillo x-1, La Horqueta x-1, Los Blancos-1, x-1001, x-1002 and x-2001. This lithological unit was defined in the subsurface as Las Breñas Fm. (Russo et al., 1979). Las Breñas Fm. is composed of quartzite sandstones, whitish and pinkish gray, with irregular intercalations of amorphous silica and schist grayish black.

Silurian to Devonian

Subsequent to the terrane accretion generating an orogenic belt to the west, a flexural subsidence associated with a foreland basin was established (Starck, 1995, Comínguez and Ramos, 1995). This depocenter was covered by a shallow marine transgression from the north, depositing a considerable thickness of sediments, in three cycles, with a coarsening-upward arrangement (Starck et al., 1993). Tordillo x-1 well, documented above the Ordovician Las Breñas Fm., black, laminar and micaceous shales, with the presence of pyrite, interbedded with siltstones and quartzite sandstones belonging to Copo Fm. (Wenlockian), deposited in a distal marine environment (Vistalli, 1989). Overlying Copo Fm., in a regressive arrangement, the shallow marine quartzite sandstones of Emsian Caburé Fm. were deposited. These whitish to pinkish gray, very fine and abrasive quartzite, interbedded with thin levels dark gray micaceous shales. This transgressive-regressive sequence was drilled by the Rivadavia es-1 well too (Figure 2). A new transgressive cycle of dark gray micaceous shale occurred during the Emsian-Givetian time (Rincón Fm.).

Upper Devonian to Jurassic

Upper Devonian to Jurassic sequences are present only in the northern flank of the basin. In the study area (Figure 2) this sequence has been eroded or not deposited.

Tectonic Framework

In the study area, several important tectonic events have been identified (Figures 2, Figure 3a), where each stage of reactivation has used preexisting structures or zones of weakness. The tectonic architecture is response of the following events:

1) Ocloyic Orogeny (Late Ordovician)
2) Chanic Orogeny (Middle Devonian to Early Carboniferous)
3) Uplift and Rifting (Late Jurassic to Early Cretaceous)
4) Andean Tectonics (Tertiary)
5) Present day tectonism

The Ocloyic orogeny affected the peri-Gondwanan back arc basin in response to the accretion of Arequipa-Antofalla terrane. Collision created shortening episodes and distinct features across and along the margin, some of which persisted into the present Andean structure (Ramos, 1988).

Chanic orogeny is an episode of folding and basin inversion during the Late Devonian to Early Carboniferous, along the eastern margin of Chilean terrane, Starck 1995, Heredia et al., 2015. These two compressive events (Ocloyic and Chanic Orogenies) related with NW-SE stress orientation (Figure 3a, Figure 4a,c), were caused by accretion along the western margin of South America. These structures (folds and faults) have a SW-NE orientation, and are associated to previous reactivated lineaments.

Subsequently, a pre-Cretaceous stage of large-scale uplift followed by collapse and rifting was produced, developing a radial system of graben assigned to the Cretaceous basin. One of these branches, Lomas de Olmedo sub-basin, Figure 1, presents an elongated shape, with normal parallel faults of general orientation NE-SW (Bianucci and Homovc, 1982).

During the Andean orogeny, the basin has been influenced by compressive stress from west-northwest, Figure 3, forming tectonic inversion in several points of the basin (Bianucci, 1999). In the study area the pre-rift Lower Paleozoic have been deformed and developed a large number of strike-slip faults and dextral run reactivating pre-existing structures (Agüera et.al, 2017, 2018). Los Blancos structure (Figure 4a,b), is a NE-SW-trending left-lateral transpressional strike-slip fault system with an anastomosing array of sub-vertical, individual fault planes or fault zones causing a fractured reservoir behavior. Borehole breakout and DIFs (drilling-induced fractures) indicate that the present-day maximum horizontal stress in Los Blancos field is oriented approximately NE-SW (Figure 3a, Figure 4d,e).

Petroleum System

The source rock of the hydrocarbon discovery in Los Blancos High is from Yacoraite Fm. (Maastrichtian/Danian) and the active pod is about 30 km to the north, Figure 1. Three major sequences totalizing 80 meters of black shale and mudstone in the Upper Member Las Avispas with type II-III of lacustrine origin kerogen were recognized, with low content in organic matter (0.5% to 3%), Gómez Omil and Boll, 1999 and 2005. Hydrocarbon generation, 'peak oil' and subsequent migration occurred in the Upper Oligocene with a subsidence of about 3200 m. The fluid samples obtained from the LB.x-1002 well test show an intermediate to light, thermally mature and well-preserved oil. Chromatographic, isotopic and biomarker data correlate with an origin in the Yacoraite Fm., with a level of average maturity close to the generation peak. A second analysis shows a 32° API graduation under STD conditions and a sulfur content of 0.1%/Weight (ASTM Standard). Likewise, the PVT laboratory analysis on a sample in the reservoir, determined a gas-oil ratio order of 7.9 m^3/m^3.

Migration

Migration was through the permeable levels of the Yacoraite and Lecho formations (Balbuena Subgroup), belonging to the lower post-rift. In the basin' border where Los Blancos High is located, these both formations are onlapping without covering the high (Figure 2, Figure 4a). The oil is connected laterally through the fractured quartzite of the Ordovician Las Breñas Fm. or by incised valleys filled with clastic, interpreted in seismic 3D (Figure 4a, Figure 5a). Oil fields located in the Southern flank of Lomas de Olmedo sub-basin are in marginally mature positions and reduced source rock thickness (Gómez Omil and Boll, 1999). The evolution of the key petroleum system elements, the generation, expulsion, migration and accumulation of hydrocarbons in Ordovician fractured quartzites has been controlled by the regional structural high in Los Blancos Area (Figure 1, Figure 5a).

Trap and Seal

Detailed local study and regional maps were required to interpret the regional seal. The primary regional top seal on and around the Los Blancos High are the Paleocene Maiz Gordo and Mealla formations respectively, full covering Ordovician sequences (Figure 5a,b). The effectiveness of the seal was corroborated with 150 meters' oil column tested in Los Blancos oil field. Los Blancos regional high located in the southern flank of the Lomas de Olmedo sub-basin (Figure 1), may have both focused migration and trapped hydrocarbons. Los Blancos structure was formed by several compressive stages, from the Paleozoic to the Tertiary. The reactivations took place during the Ocloyic, Chanic and Andean Orogenies, generating the present-day structural framework (Figure 3a). It is important to highlight that the trapping configuration is enhanced by the erosion of the Paleozoic relief (pre-Cretaceous unconformity) (Figure 3b, Figure 4a, Figure 5a). The geometry of this trap is a 4-way closure, northeast-southwest elongated and dipping 7° northwest (Figure 5 b,c). A new oil system is proposed in Lomas de Olmedo sub-basin: Fm. Yacoraite – Fm. Las Breñas, Ordovician (!).

Reservoir Characterization

Based on the sidewall cores and drill cuttings (Figure 6a) from Ordovician Las Breñas Fm. in Los Blancos oil field, quartzite to sublitharenite, very fine to fine, yellowish gray, composed mainly by quartz with inclusions of micas and feldspars were defined. Thin levels of dark gray clay, with abundant sandy inclusions, micaceous and pyrite are interbedded. Palynological studies on drill cuttings samples were sterile. The petrographic study of these samples showed more than 90% of quartz with generation of secondary quartz that acts as cement, with presence of quartz ductile deformation, dynamic recrystallization, development of pressure shadows, migration of grain boundaries and generation of new grains (Figure 6 b,c,d,e). Very little presence of potassium feldspar, plagioclase and lithic fragments with very low degree of metamorphism was described.

Irregular, randomly orientated microfractures planes were observed. Microfractures extended along the thin section, approximately subparallel to each other. Porosity is frequently related or interconnected to microfractures (Figure 6 f,g). These sandstones exhibit very poor reservoir quality, with abundant siliceous cement (secondary growth of quartz), high degree of consolidation (drilling rate order <0.5 m/h), and poor porosity. Only 2% of total porosity is related to intragranular pores due to partial dissolution of feldspars (micro-pores of 0.01-0.02 mm), and 98% due to a microfractured system (Mf: aperture <0.01 mm). Mud losses during drilling and borehole imagines indicated that the quartzite of Las Breñas Fm. is a natural fractured reservoir.

Evidences of Naturally Fractured Reservoir

All the wells in Los Blancos were drilled in Ordovician sequences with water-based drilling fluids. Loss of circulating fluids and an increase in penetration rate during drilling are positive indications that a fractured formation has been penetrated. During drilling in Los Blancos field, significant mud loss was observed. Qualitative fragility or fracturing rocks index, such as the relation of the ROP/WOB drilling parameters (Figure 7, track 4), as well as the detection of torque peaks are indirect evidences of the existence of natural fractures. The wireline log data were interpreted using the Aguilera Method (Aguilera, 1995), where the porosity was calculated with the acoustic log, distinguishing a matrix porosity (φm) and a fracture porosity (φf). In addition, using this methodology, a water saturation (Sw) was calculated. It was concluded that in the reservoir, matrix porosity is very low, but fracture porosity is important, therefore, storage productivity is almost mainly in the fractures. The result of the interpretation of Sw, indicated no oil water fluid contact is observed, but in the lower zone the Sw calculated is slightly higher (Figure 7).

Fracture porosity cutoff (φf)> 0.01 v/v was used to calculate net pay thickness. The result showed a reservoir thickness of 41 m over a total of 116 m, which corresponds to a NTG of 0.35, for the partial drilled section of Las Breñas Fm. According to the petrophysical interpretation two zones were interpreted: Upper Zone with major deflection of the SP curve, the GR indicates minor frequency of shale interbedded, ratio of deep and shallow resistivity: Rt> Rxo and lower density of fractures per meter. In the Lower Zone with minor deflection of SP curve, higher frequency of shale interbedded, Rt <Rxo and higher fracture density per meter. The water saturation Sw and NTG higher than the Upper section. All these parameters summarized in Figure 7 and Table 1.

The fractured reservoir in Los Blancos field is related to a transpressional zone generating a fractured network with a macrofracture patterns observed in high resolution borehole acoustic image (Figure 8 a,b) and a microfracture set observed in fragments of drill cutting quartzite sandstones (Figure 6 b,c,f,g). The matrix porosity may be provided by a microfracture connected network system. According to the classification of Nelson's fractured reservoir types, (Nelson, 1985) we interpreted that Las Breñas fractured reservoir is Type 2, where macrofractures provide the essential permeability, and the matrix (microfractures) provides the essential porosity. Microfractures (<0.1 mm), which can only be characterized by using optical and electron microscopy of drilling cuttings are commonly observed in the quartzite sandstone reservoir. These microfractures, which are associated with the macrofractures observed in borehole image, are also the major pathways of fluid flow and have an important impact on the development high quality reservoirs in these low porosity sandstones.

Ultrasonic Borehole Imager (UBI) shows acoustic amplitude contrast which is a response to changes in acoustic impedance at the borehole wall. Macrofractures are defined as those that can be detected from individual borehole-scale images. Well LB x-1002 shows an intensely fractured system in fine to medium grained quartzite sandstones of Las Breñas Fm., where 115 NE-SW opened fractures and 39 NE-SW and NW-SE closed fractures were interpreted (Figure 8 b). The open fractures are dominantly steeply dipping (74-78°), with a density per meter of 1 fracture/m increasing by sectors to 5 fractures/m. The apparent apertures fractures values obtained by analyzing the resistive image data present a frequency distribution between 0.1 and 0.9 mm, being the most frequent between 0.3 and 0.7 mm.

Conclusion

A new petroleum system was discovered in the sub-basin Lomas de Olmedo: Yacoraite - Las Breñas (!), consisting of the lacustrine shale Maastrichtian to Danian Yacoraite Fm. as the source rock and the quartzite sandstone Ordovician Las Breñas Fm. as the natural fractured reservoir rock. The pod of active source rock is located approximately 30 km to the north of Los Blancos field, in the depocenter of the basin. Migration occurred in the Upper Oligocene. Trap formation is defined as the tectonic events related to the Ocloyic, Chanic, Late Jurassic to Early Cretaceous and Andean. This last compressive phase in Late Eocene time, formed a NE-SW trending left-lateral transpressional strike-slip fault system. The macro and microfracture quartzite sandstones observed in Las Breñas Fm. are related to this last compressive phase. Los Blancos regional high located in the southern flank of the Lomas de Olmedo sub-basin, may have both focused migration and trapped hydrocarbons. The effectiveness of the seal was proved with 150 meters' oil column tested in the field. Los Blancos field produce intermediate to light, thermally mature and well-preserved oil. Chromatographic, isotopic and biomarker data correlate with Yacoraite Fm.

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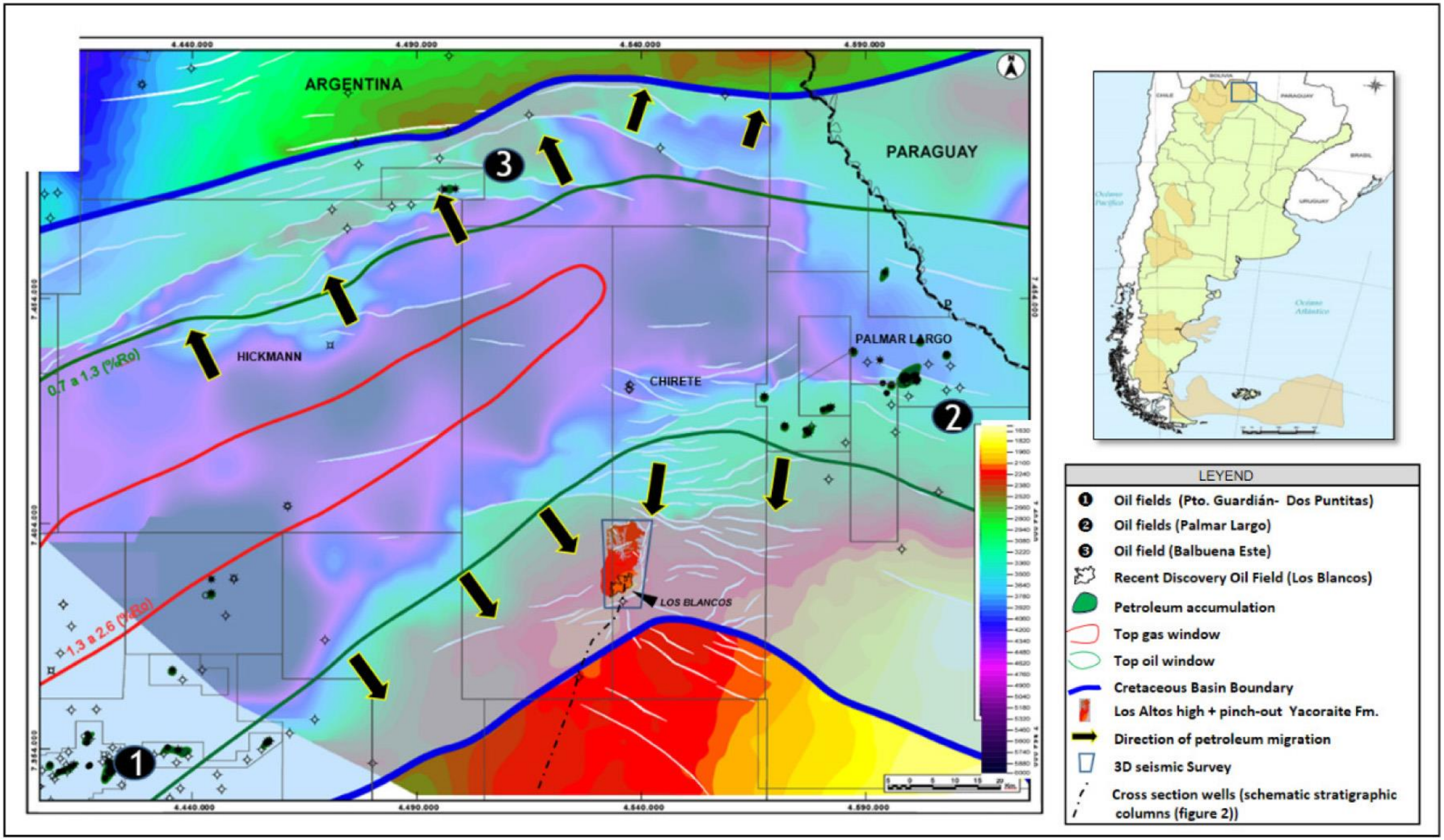

Figure 1. Time structural map at the top of Ordovician sequence in eastern Lomas de Olmedo sub-basin showing the essential elements of the petroleum system Yacoraite-Las Breñas (!). Based on interpretation of 2D and 3D seismic data. Top of oil and gas window adapted from Dow and Villar, 2002.

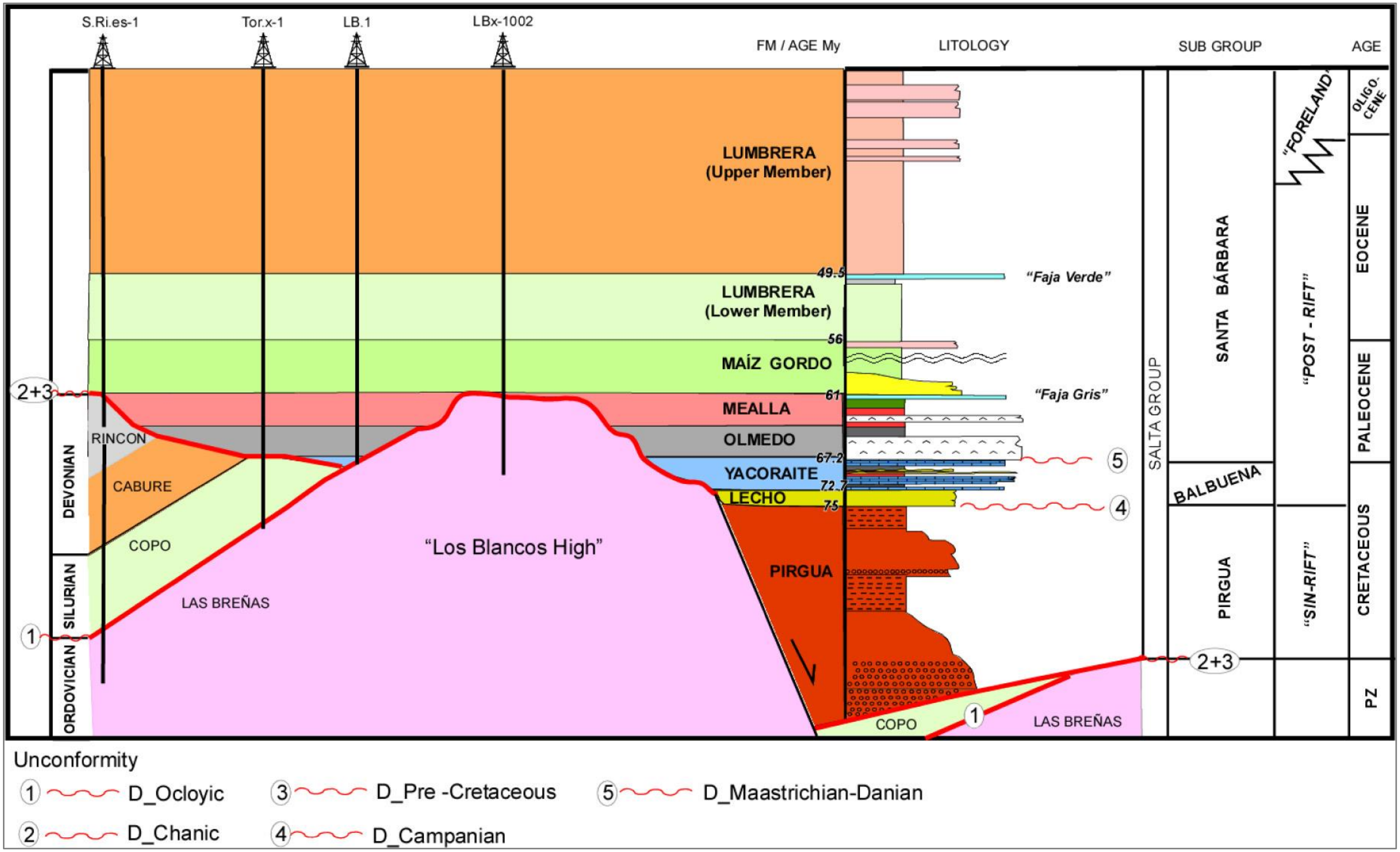

Figure 2. Generalized tectonostratigraphic chart of Los Blancos High, southern flank of Lomas de Olmedo sub-basin, adapted from Chiarenza and Ponzoni, 1989; Disalvo et al., 2002; Starck, 2011; Agüera et al., 2018).

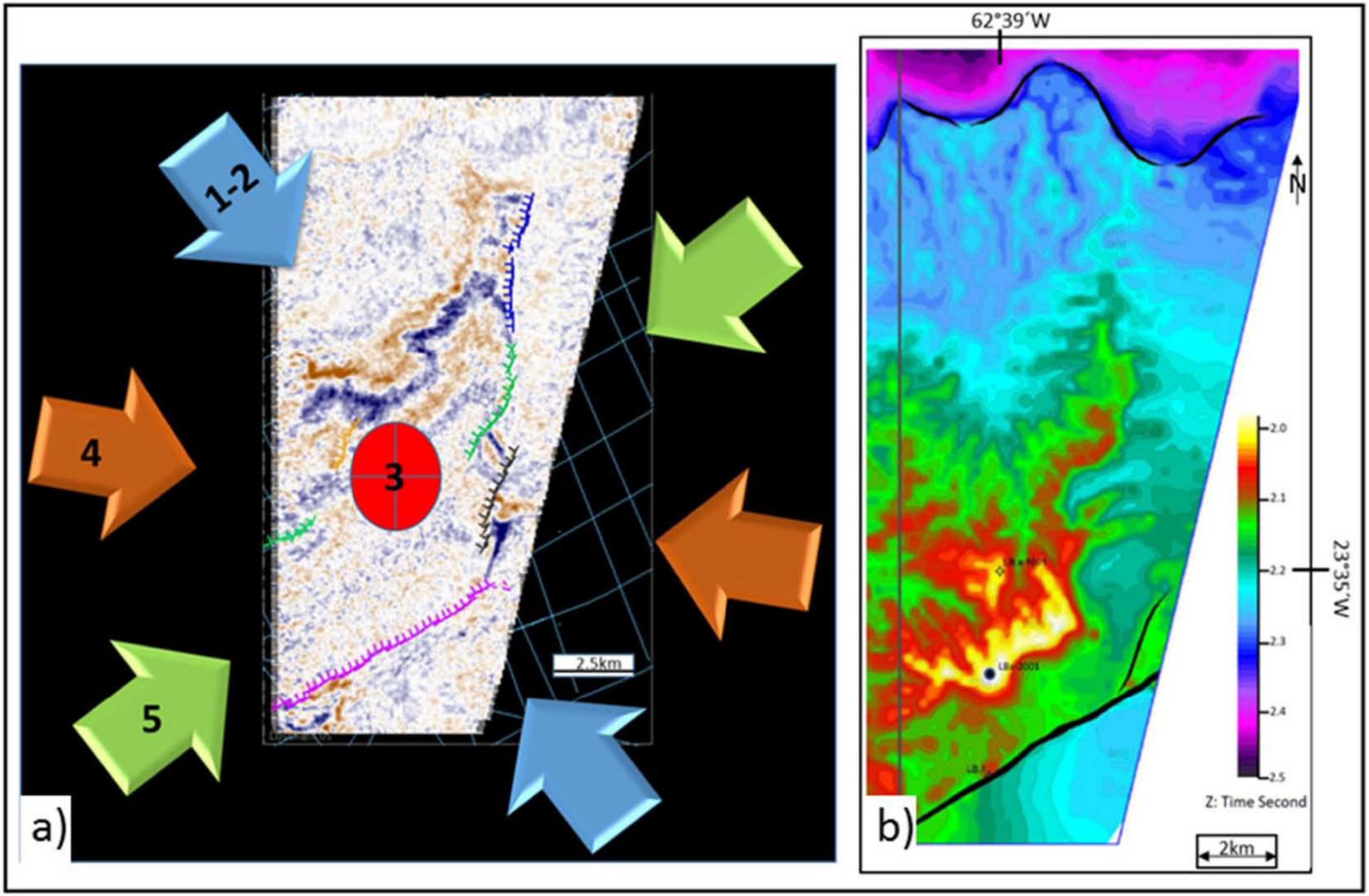

Figure 3. a) Time slice to 2629 milliseconds showing the structural framework in the "Los Blancos High" area. Arrows indicate the orientation of the stress in different tectonic stages (blue arrow: Ocloyic and Chanic Orogenies, red arrow: Uplift and rifting, brown arrow: tertiary Andean tectonics, green arrow: Present day stress). b) Time structural map top Ordovician, where the expression of the pre-cretaceous unconformity is observed.

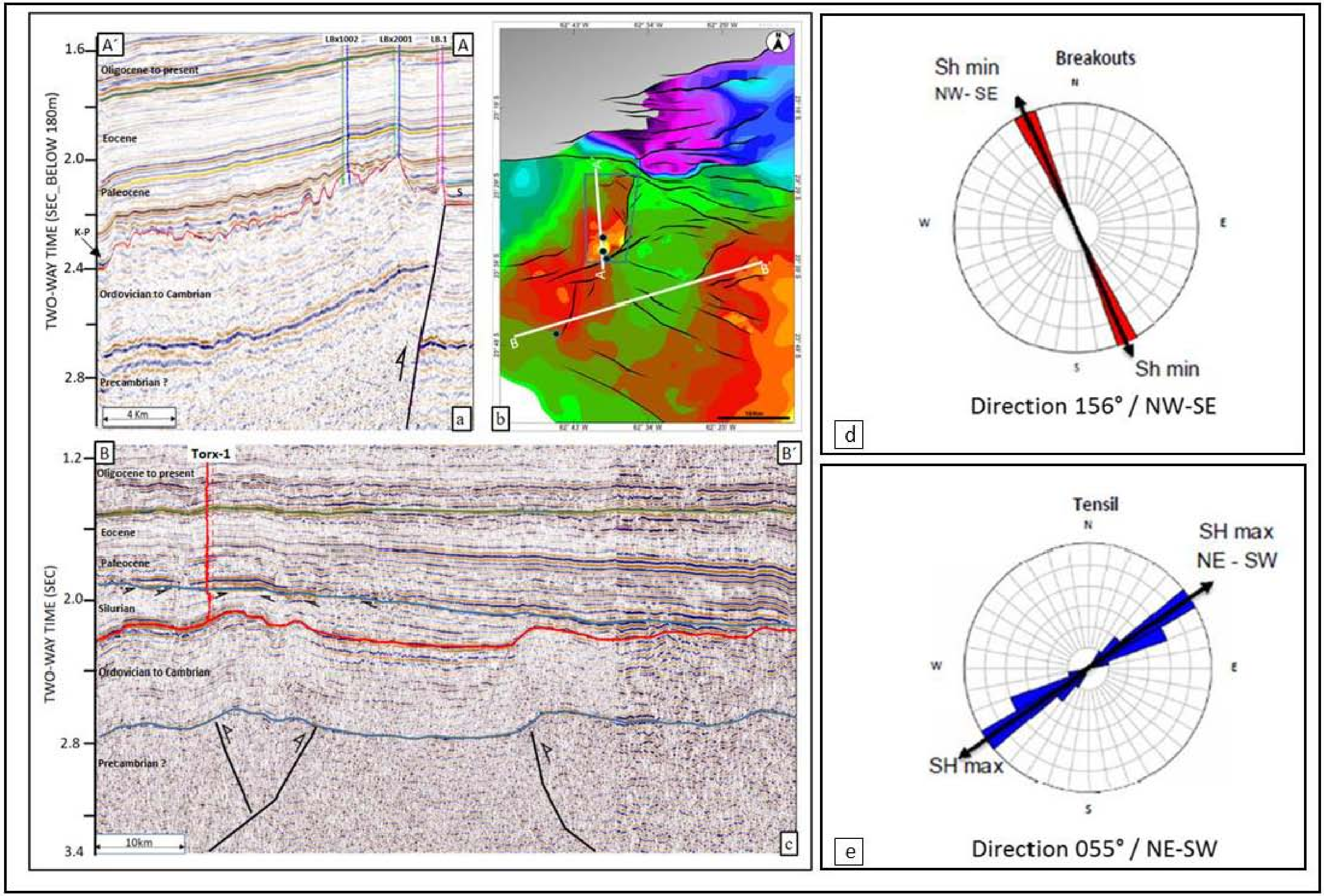

Figure 4. a) North-south oriented 3D seismic over Los Blancos High. b) Time structural map at the base of the Cambrian to Ordovician sequences, modified after Fernandez et.al, 2011. c) ENE-OSO oriented 2D seismic line showing Ocloyic and Chanic structures. Note the top of Silurian sequence is erosional truncated (black arrow) by the pre- cretaceous unconformity. d) The borehole breakouts are oriented parallel to the minimum horizontal stress NW-SE (in red). e) DIFs (drilling-induced fractures) are created when the stresses concentrated around a borehole exceed that required to cause tensile failure of the wellbore wall and is oriented NE-SW (in blue) parallel to present-day maximum horizontal stress.

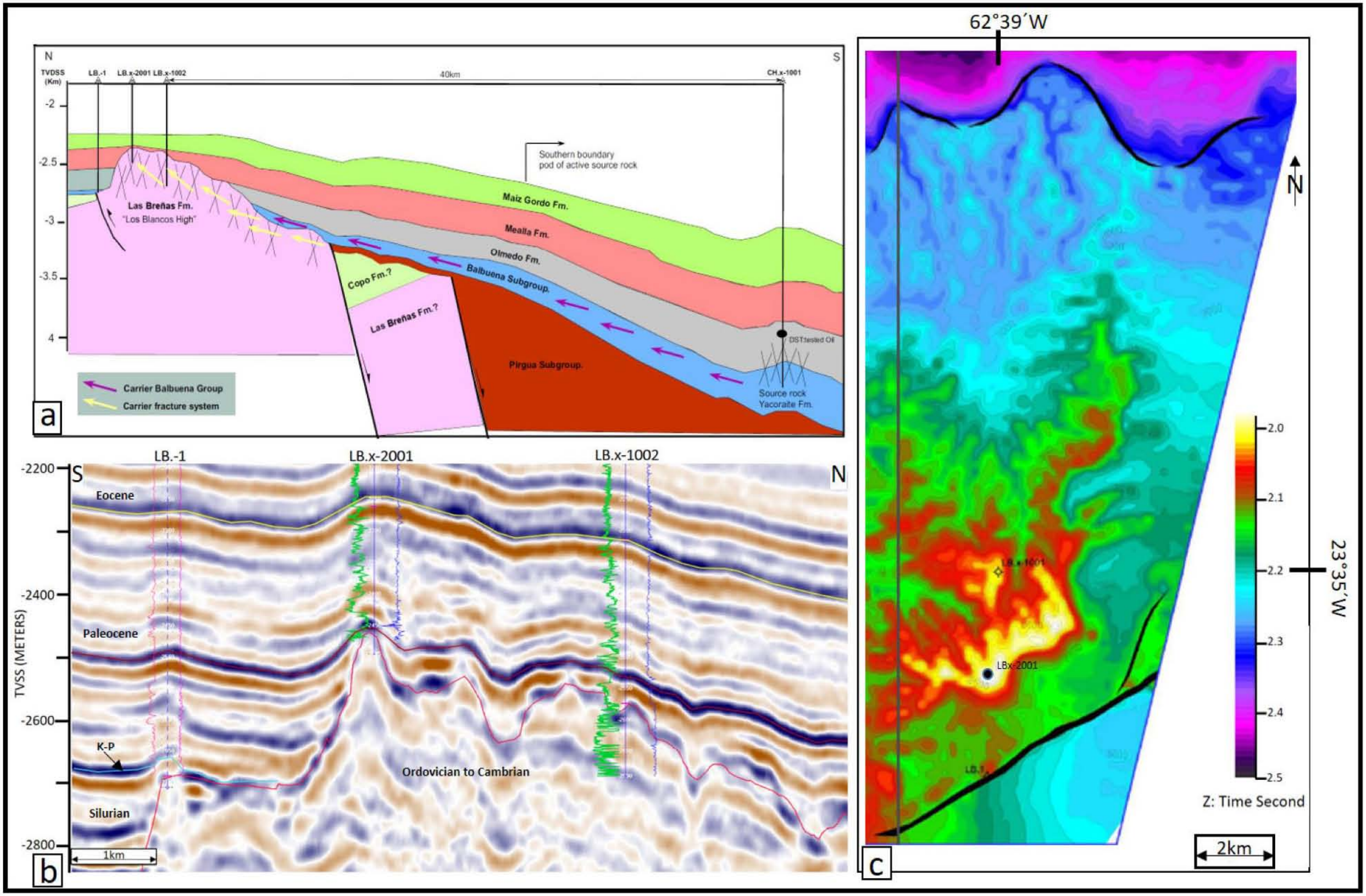

Figure 5. a) Schematic model of migration from source to the trap in Los Blancos High. b) 3D seismic showing the configuration of the trap. c) 3D time structural map at the top Ordovician Las Breñas Fm. showing the dendritic pattern of the pre-cretaceous discordance.

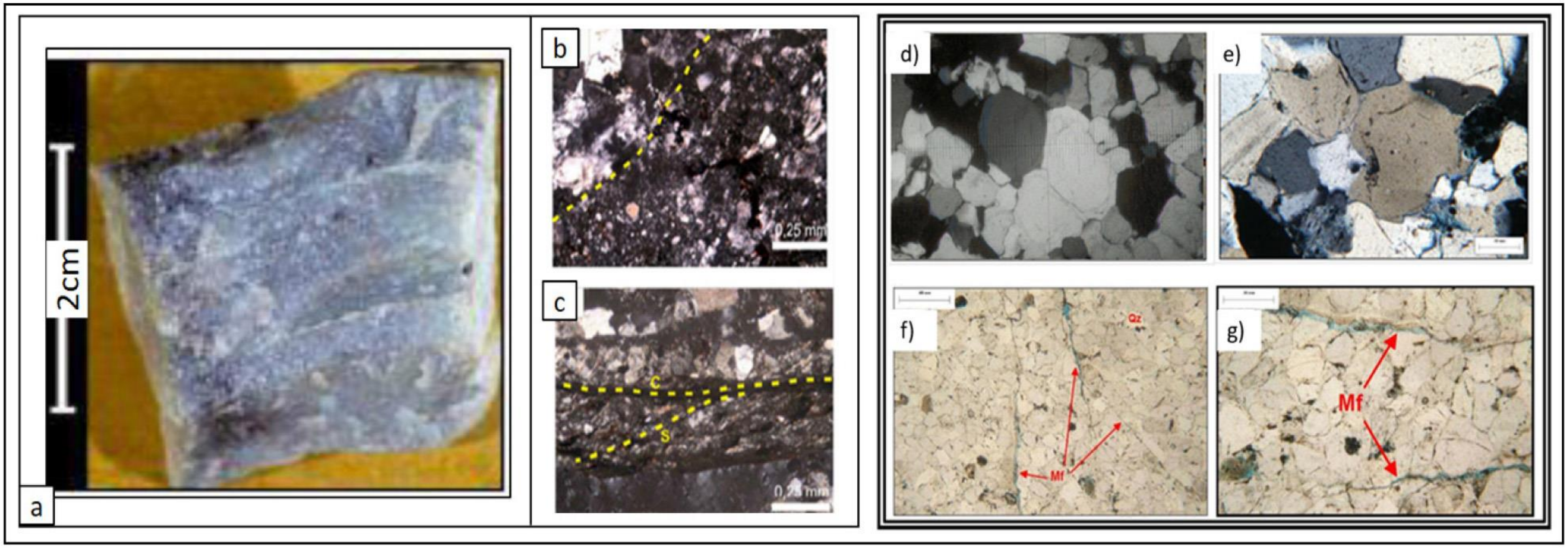

Figure 6. a) Fragments of drill cutting quartzite sandstones of Las Breñas Fm. b and c) Subparallel microfractures in thin section quartzite of Las Breñas Fm. in Los Blancos field. In yellow dotted lines, contact surface between coarse aggregates and fractured rock finely breached. c) Early development of S-C fabric (S-foliation plans, C- Shear bands). d and e) Petrographic studies of the Las Breñas quartzite sandstone in thin section of Los Blancos field, exhibiting secondary growth of quartz. f and g) Quartzite sandstone showing subparallel micro-fractures (Mf).

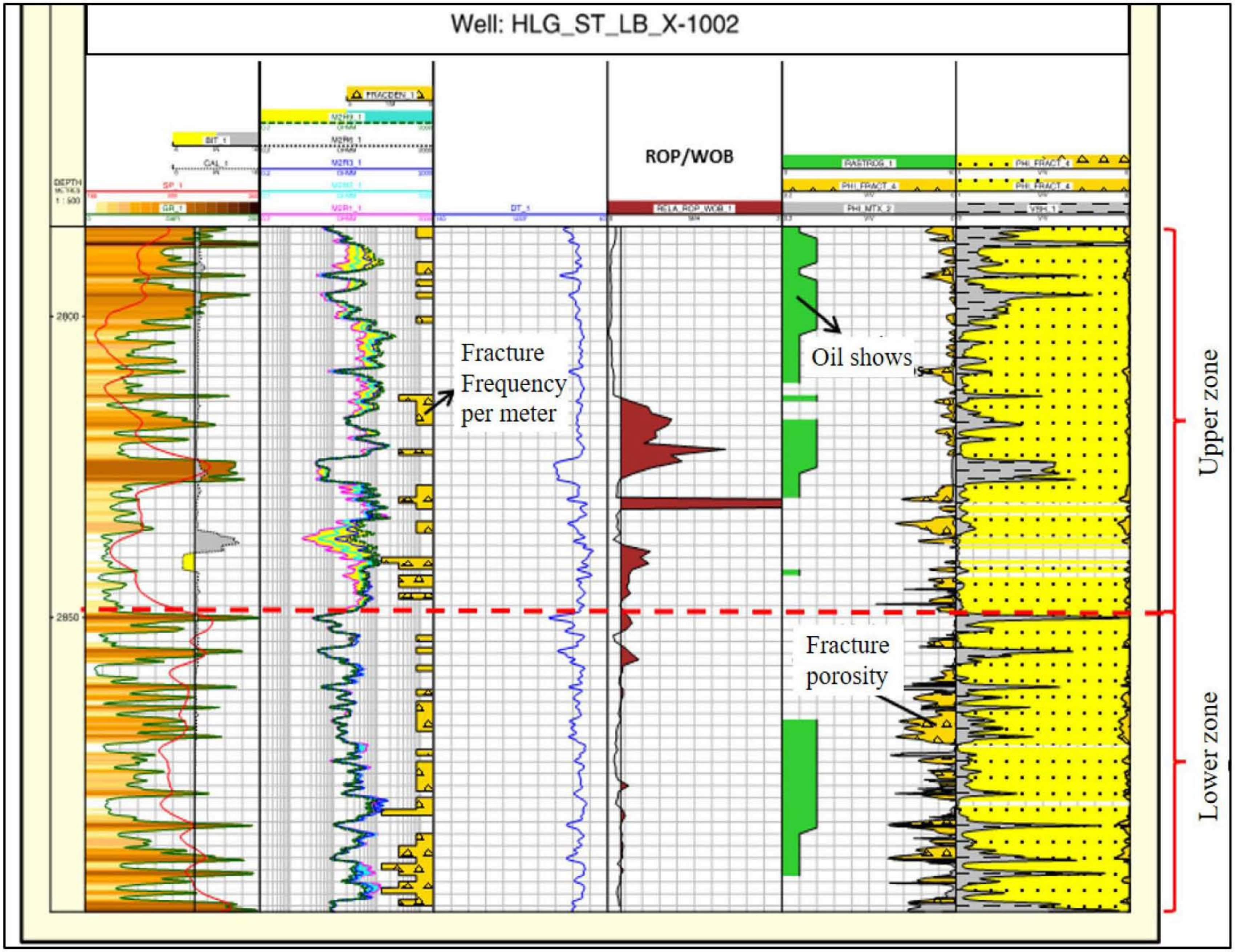

Figure 7. Petrophysical logs in Las Breñas Fm. in well LB x-1002 with 2 zones: Upper (2784-2848 meters) and Lower (2848-2900 m) with different percentage of quartzite sandstone and fracture frequency calculated from electrical and ultrasonic borehole image (UBI) logs.

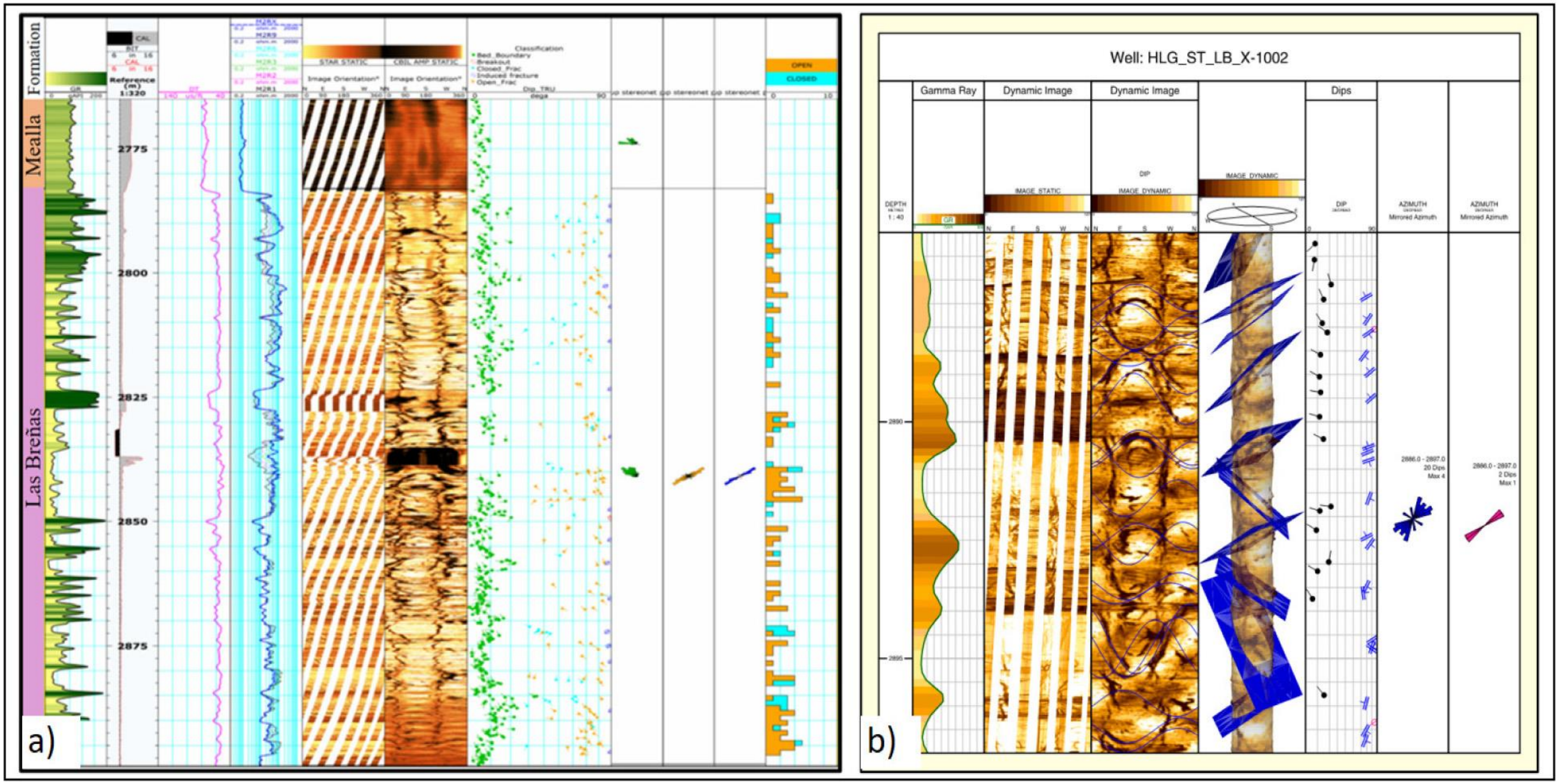

Figure 8. a) Resistivity and acoustic image log interpreted. Electrical and ultrasonic borehole image (UBI) logs in Well LB x-1002 (Los Blancos) with sinusoidal traces indicating natural fractures. b) Integrated interpretation of ultrasonic borehole image (UBI) and petrophysical logs in the well LB x-1002.

Zone	GR	DT	Resistivity Difference (M2R1-M2R9)	Φ Matrix %	Φ Fracture %	Sw %	Fracture Density (per meter)	NTG
Upper (2784/2848 m)	90	57.9	-35.7	0.25	1.25	1.8	0.4	0.28
Lower (2848/2900 m)	77	57.4	10.1	0.6	1.5	6.3	0.8	0.43

Table 1. Petrophysical parameters of Las Breñas Fm. at Well LB.x-1002.