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THE LA HOCHA HIGH AND ASSOCIATED OIL FIELDS (UPPER MAGDALENA VALLEY, COLOMBIA): A NEW 3D STRUCTURAL MODEL BASED ON SUBSURFACE DATA

O ALTO LA HOCHA E CAMPOS PETROLÍFEROS ASSOCIADOS (VALE ALTO MAGDALENA, COLÔMBIA): UM NOVO MODELO ESTRUTURAL 3D COM BASE EM DADOS DE SUBSUPERFÍCIE

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RESUMO - O Alto La Hocha High (LHH), na Bacia do Alto Magdalena da Colômbia, consiste em um embasamento cristalino recoberto por uma sequência sedimentar do Triássico ao Neogeno de até 9 km de espessura. A Falha de San Jacinto (SJF) é uma estrutura de flor positiva dextral NE-SW com cisalhamento de Riedel subordinado que atinge N-S com mergulho subvertical a alto para o oeste. Ela separa dois domínios estruturais principais: (i) o LHH e o sinclinal Tesalia no bloco de parede suspensa ocidental; e (ii) um bloco de parede de pé oriental com um sinclinório com três anticlinais en echelon de tendência norte-sul (mostra um anticlinal reclinado, apertado, em forma de Z mergulhando entre 45 e 90° para o oeste), definindo os campos de petróleo La Cañada e La Cañada Norte. O LHH passou por pelo menos cinco pulsos de transpressão entre o Maastrichtiano e o presente. Variações da orientação da direção resultaram em segmentos flexurais locais que são mais transtensivos para a direita e transpressivos para a esquerda. Interpretações estruturais anteriores baseadas em seções balanceadas 2D sugeriram empilhamento de escamas de empurrão destacadas na base como resultado da convergência de placas ortogonais. No entanto, esta nova interpretação 3D, baseada em geologia de superfície, dados de poços e uma recente pesquisa sísmica 3D, mostra evidências claras de componentes andinos destrais de empurrão em falhas normais preexistentes que controlaram o rifteamento do Triássico-Jurássico.

Palavras-chave: Alto La Hocha. Campos petrolíferos. Transcorrência. Modelo estrutural 3D. Bacia do Vale Alto Magdalena. Colômbia.

ABSTRACT - The La Hocha High (LHH), in the Upper Magdalena Basin of Colombia, consists of a crystalline basement overlain by a Triassic to Neogene sedimentary sequence up to 9 km thick. The San Jacinto Fault (SJF), is a dextral NE-SW striking positive-flower structure with subordinate Riedel shears which strikes N-S with subvertical to high dip to the west. It separates two main structural domains: (i) the La LHH and the Tesalia syncline in the western hanging wall block; and (ii) an eastern footwall block with a synclinorium with three north-south trending *en echelon* anticlines (shows a recumbent, tight, Z-shaped anticline dipping between 45 and 90° to the west), La Cañada and La Cañada Norte oil fields. The LHH has undergone at least five pulses of transpression between the Maastrichtian and present. Variations of the strike orientation have resulted in local flexural segments that are more transtensive to the right and transpressive to the left. Previous structural interpretations based on 2D balanced sections suggested stacking of thrust sheets detached in the basement as a result of orthogonal plate convergence. However, this new 3D interpretation, based on surface geology, well data and a recent 3D seismic survey, shows clear evidence of dextral Andean thrust components on pre-existing normal faults that controlled Triassic-Jurassic rifting.

Keywords: La Hocha High. Oil fields. Wrenching. 3D structural model. Upper Magdalena Valley Basin. Colombia.

INTRODUCTION

The La Hocha High (LHH) is located in the southern part of the Upper Magdalena Valley Basin (UMV) in central southern Colombia (Figure 1). Surface, 3D seismic and well data indicate that the structural evolution of this high is controlled by the San Jacinto Fault (SJF). Its western uplifted side shows two basement highs, named from north to south the Upar and La Hocha highs (Figure 1).

The LHH forms the hanging wall block to the west of the fault and is composed of basement rocks that form the core of the anticline of the same name (Mojica & Franco, 2000). In the eastern footwall block, hydrocarbons are produced in the La Hocha, La Cañada and La Cañada Norte fields bounded by the Garzón and Algeciras faults (locations in Figure 1B) (Butler & Schamel, 1988; Buitrago, 1994; Sarmiento & Rangel, 2004; Velandia et al., 2005; Veloza et al., 2008; Mantilla, 2019).

The western uplifted hanging wall block of the SJF, termed the 'Dominio Occidental Neiva', constitutes of the LHH and the Tesalia syncline, and the eastern footwall block, the 'Dominio Oriental Neiva', consists of the Neiva synclinorium (Jiménez et al., 2012). From seismic surveys, this syncline is asymmetrical, with a gentle western flank and a short steep eastern flank, and contains the main hydrocarbon accumulations in the area, including the La Hocha, La Cañada and La Cañada Norte fields (Figure 1).

The Yaguará field is located in the hanging wall block and the Gigante field is located near the axis of the Neiva synclinorium, close to the Algeciras fault system (Figure 1). ECOPETROL ICP (2001), Veloza et al. (2006), among others, consider the Altos de Patá and Natagaima highs as elements of the geographic division of the UMV into the Girardot sub-basin to the north and Neiva to the south.

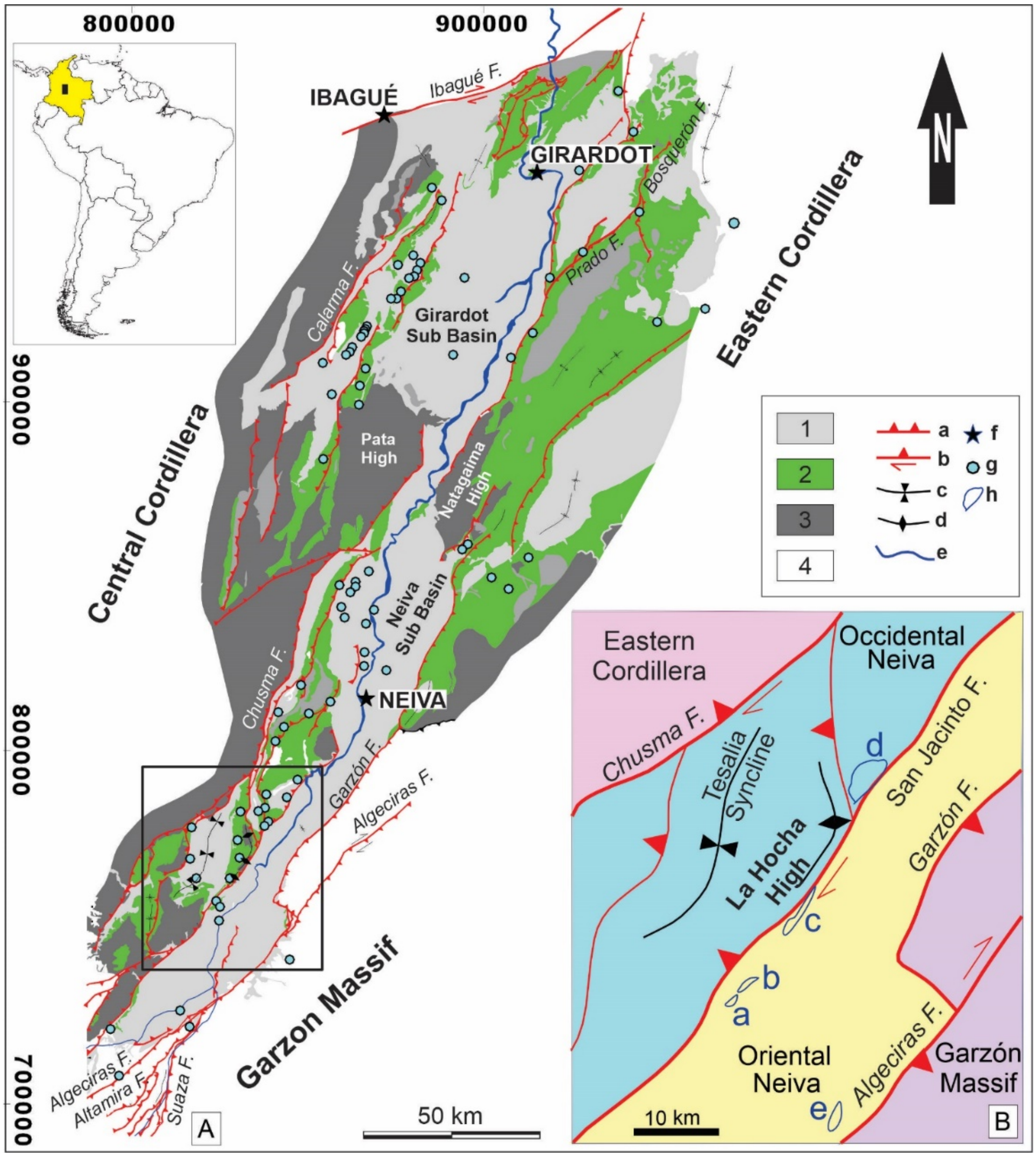

Figure 1 - A: Generalized geological map of the Upper Magdalena Valley Basin showing its structural provinces and the hydrocarbon accumulations found in the study area (modified from Veloza et al. (2006). 1: Tertiary and Quaternary, 2: Cretaceous, 3: Jurassic and Triassic, 4: Precambrian and Paleozoic. a: thrust, b: transpression, c: synclines, d: anticlines, e: rivers, f: towns, g: wells, h: oil fields. B: Schematic tectonic map of the study area. a: La Cañada field; b: La Cañada Norte field; c: La Hocha field; d: Yaguará field; e: Gigante field.

The history of oil exploration in this area began with the discovery of the La Cañada field in the 1970s, followed by La Hocha (2002) and La Cañada Norte (2007). The structural understanding of the area was originally based on balanced 2D sections showing the superposition of a series of thrust sheets in duplexes with little overall displacement. In the La Hocha field, the tectonic vergence was to the southeast with the development of an antiformal stack associated with a triangular zone, whereas at La Cañada Norte the vergence is to the northwest (Colleta, 2001; Jiménez et al., 2012).

Colleta (2001) carries out a transect with thrusts associated with basement decollements, which include the Tesalia syncline, the La Hocha anticline, the Neiva syncline and the Garzón massif, and he also explains the trap formed for the La Hocha field as a product of structural stacking formed in a triangle zone. Mantilla (2019) describes structural sections of the La Hocha Anticline based on 2D balanced sections, introducing different thickness and rheological behaviour in the units previously considered similar.

The objective of the study is to propose a new 3D structural model that better explains the nature of the structures observed around the SJH and the structural characteristics of the nearby oil fields. This model is proposed on the basis of a recently acquired 3D seismic volume together with subsurface data from exploration and development wells and control data from surface exposures.

The different interpretation perspective that we propose could create the opportunity to re-evaluate existing fields and generate new development and exploration strategies locally and in other equivalent sectors of the Magdalena Valley basins. We believe that this new 3D tectonic model understanding of the structural style of this sector of the Sub-Neiva Basin will be useful in the current exploration and production of its oil and gas potential.

GEOLOGICAL SETTING

The study area is located in the Neiva sub-basin in the southern part of the NNE-SSW trending Upper Magdalena Valley Basin, Colombia (Beltrán & Gallo, 1979; Caicedo, 2000). The Neiva and adjacent Girardot sub-basins are structural depocenters between the Central and Eastern Cordilleras, bounded by regional NE-SW striking faults (Figure 2).

Structural setting

According to the World Stress Map South America is currently undergoing thrust faulting due to horizontal compression produced by the Nazca Plate. Overall, the horizontal maximal stress is approximately oriented in Azimuth 84° (Heidbach et al., 2016). From the reconstruction of the seven structural sections, Jiménez et al. (2012) observed variations in thickness of the entire Cretaceous and Cenozoic sequence based on well information. The greatest thickness obtained from cartography was on the hanging block of the San Jacinto Fault (SFJ) and the least on the footwall block (Mantilla et al., 2014, 2016).

However, the use of two methods to determine the thickness of the Bambuca Formation may have led him to obtain apparent thickness variations on either side of the SJF. Ramón and Rosero (2006) also found variations in the thickness of the Villeta Group in the Girardot sub-basin and related them to the control exerted by the geometry of the basin, with the thinner levels indicating proximity to the basin margin and the thicker levels to the basin interior.

Schamel (1991), although he did not identify the thickness variations, interpreted the shales of the Bambuca Formation as detachment horizons between a competent Tertiary unit and a delaminated and rigid basement. Gil (2008) also identified these thickness variations within the Villeta Group in two stratigraphic sections studied to the west of the La Cañada Norte field, on the uplifted block of the SJF, due to an angular unconformity associated with a Late Albian-Cenomanian (Figure 4).

The western margin of the Upper Magdalena Valley Basin is bounded by the Chusma and Calarma reverse faults to the east and the Algeciras-Garzón fault system to the SE. Both regional faults have thrust basement rocks over the thick Meso-Cenozoic sedimentary sequence (Figure 1). The dextral Ibagué Fault marks the boundary with the Middle Magdalena Valley Basin to the north (Campbell & Burgl, 1965; Barrero et al., 2007).

Jiménez et al. (2012) indicates the presence of a paraconformity between the top of the Monserrate Formation and the base of the Guaduala Group, following the interpretation of Veloza et al. (2006).

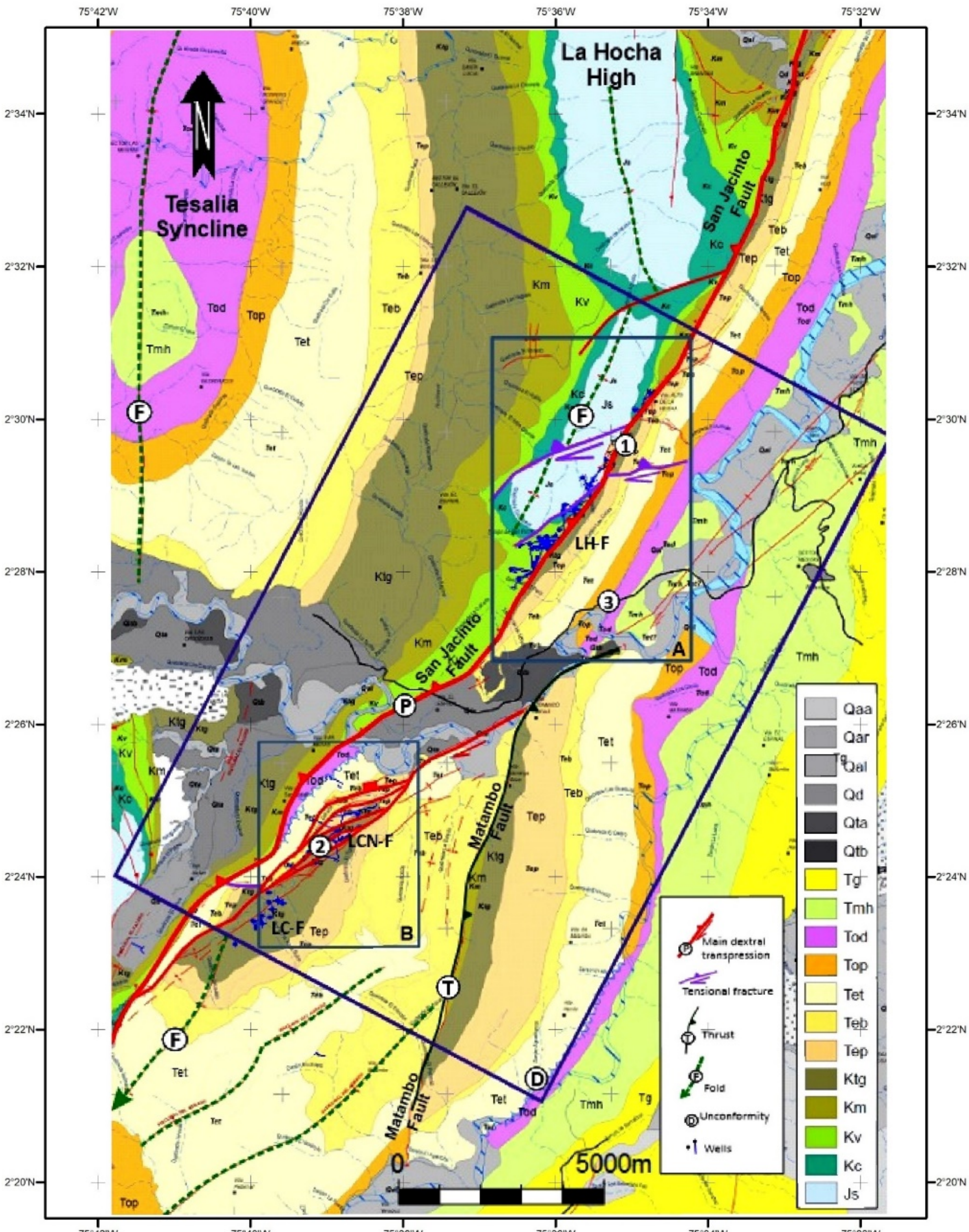

Figure 2 - Geological surface map. Letters indicate geological elements recognised on the surface Qaa, Qar, Qal, Qd, Qta, Qtb: Quaternary units: Tg: Gigante Fm.; Imh: Honda Fm.; Tod: Doima Fm.; Top: Potrerillo Fm.; Tet: Tesalia Fm.; Teb: Bache Fm.; Iep: Palermo Fm.; Ktg: Guaduala group; Km: Monserrate Fm.; Kv: Villeta group; Kc: Caballos Fm.; Js: Saldaña Fm. The purple polygon indicates the area of the 3D seismic volume studied. Blue dots and lines indicate the location and trajectory of the wells in the La Cañada Field (LC-F), La Cañada Norte Field (LCN-F) and La Hocha Field (LH-F). Numbers 1, 2 and 3 locations of the outcrops shown in Figure 5.

In this sense, Mantilla (2019), based on field observations, interprets: a) the contact of the Guaduala Group with the overlying Palermo Formation as clear and not conforming, b) the Baché Formation as being in transitional contact with the Tesalia Formation, c) the base of the Doima Formation as being in net contact with the Potrerillo Formation, and d) does not describe the nature of the contact between the latter unit and the Honda Formation.

Schamel (1991) suggests that in the Upper and Middle Magdalena Valley the Cretaceous record is overlain by three molasse sequences, each of which is related to tectonic events associated with the tectonics of the Central and Eastern Cordillera (Horton et al., 2000; Mora et al., 2006, 2016): a) the first is angular to the north of the Upper Magdalena Valley, formed by the Gualanday Group, whose basal contact is the Guaduala, while south of Neiva it appears to be paraconformal, b) the second by the Honda Group, and c) the third is related to the Plio-Pleistocene deposition of the Mesa Group, which in the study area would be represented by the Gigante Formation. Ramón & Rosero (2006) identify two angular unconformities in the Girardot sub-basin: a) Eocene, the first, which separates a Cretaceous-Paleocene sequence that has been subjected to uplift, folding, faulting and erosion, from the Eocene deposits of the Chicoral Formation; b) Miocene, the second, formed by the overthrusting of the Barzalosa and Honda Formations, which are in angular contact with the sedimentary sequence of the basin and the basement.

For the kinematic analysis, we assumed that the maximum principal stress σ1 and the fault surfaces always maintain angles of less than 45°, often of the order of 30-40°, known as Anderson's law (Ramsay & Huber, 1983; Price & Cosgrove, 1990; Davis & Reynolds, 1996; Célérier, 2008; Rossello, 2001, 2018). Therefore, the maximum principal stress (σ1), regardless of whether it is a normal, inverse or transcurrent fault, must always be located at an angle of less than 45° (closer to 30-40°) with respect to the fault plane on which it acts (Anderson, 1905; Célérier, 2008). Subordinate faults associated with the main SJF are considered to be Riedel or anti-Riedel faults, depending on their angular relationship, showing their respective syn- and anti-slip displacements (Ramsay & Huber 1983; Biddle & Christie-Blick, 1985; Price & Cosgrove 1990; Davis & Reynolds 1996; Katz et al., 2004).

Stratigraphy

The stratigraphy of the Neiva sub-basin (Figure 3) has been adapted from the Upper Magdalena Valley Basin (Mora 2003; Jaimes and De Freitas 2006; Veloza et al., 2006; Mora et al., 2010; Mantilla et al., 2016). The base of the sedimentary infill is the Triassic rhyolitic volcaniclastic of the Saldaña, Payandé and Luisa Formations (Payandé Group), which overlie a Paleozoic crystalline basement (Cediel et al., 1981; Duarte et al., 2018).

The Triassic-Neogene sedimentary sequence in the Neiva sub-basin is up to 9,000 m thick and can be divided into the following three main depositional sequences:

a) *Triassic to Jurassic non-marine volcano-clastics, siliciclastics and underlying carbonates*, whose deposition was at least partly controlled by pre-existing Paleozoic extensional faults (De Freitas, 2001; Mantilla et al., 2014; 2016).

b) *Cretaceous to Paleogene marine to non-marine clastics and carbonates*, was affected by successive phases of the Andean orogeny beginning with the mid-Cretaceous Peruvian phase (Cobbold et al., 2007). Thermochronological evidence has identified this 'Early Andean event' as an intense deformation phase in the Balcón area, which shows a slight inversion of half-graben geometries in the Late Albian-Cenomanian (Etayo-Serna, et al., 1976; Van der Wiel; 1991; Etayo-Serna, 1994; Jaimes & De Freitas; 2006; De Freitas et al., 2006). The Bambuca Formation occurs at the base of the Doima Formation and completely erodes the underlying Potrerillo Formation (Figure 3). The Incaic phase of the Andean orogeny began in the early Eocene, caused by an increase in the rate of convergence between the Nazca and South American plates (Cobbold et al., 2007). This phase is widely recognised in the Upper Magdalena Valley Basin, but its effects have been partially obscured by more recent tectonic phases.

c) *Neogene non-marine molasse succession* as a result of the Quechua phase of the Andean orogeny between the late Miocene and the present (Cobbold et al., 2007; Rossello & Gallardo, 2022) resulted in the compression and uplift of the Eastern Cordillera with the development of the basement-involved Boquerón thrust system. From the Miocene onwards, the Upper Magdalena Valley Basin became a marginal foreland basin with deposition of continental siliciclastics of the Gualanday Group and the Barzalosa Formation, which evolved into a modern intermontane basin with the Honda Formation (Barrero et al., 2007). Folds with NNE-SSW oriented axes suggest WSW-ENE compression during the Middle Miocene Honda Formation. During the Pliocene, NW-SE strike-slip faulting involving the basement displaced fold axes and pre-existing faults (Schamel, 1991; Montes et al., 2019).

This orogenic phase produced, in the study area, the subsequent onlap deposition to the west of the continental Honda Formation on the Patá and Natagaima high, formed by uplifted blocks of exposed or exhumed Jurassic-Triassic units (Figure 3).

Its depositional history is probably linked to normal Triassic-Jurassic faults, which were later reactivated at the end of the Cretaceous or the beginning of the Palaeogene.

This last deformation event coincided with the deposition of the Doima-Honda Formation, associated with the transcurrent horsetail displacement of the Algeciras fault system (Velandia et al., 2005; Mantilla et al., 2016).

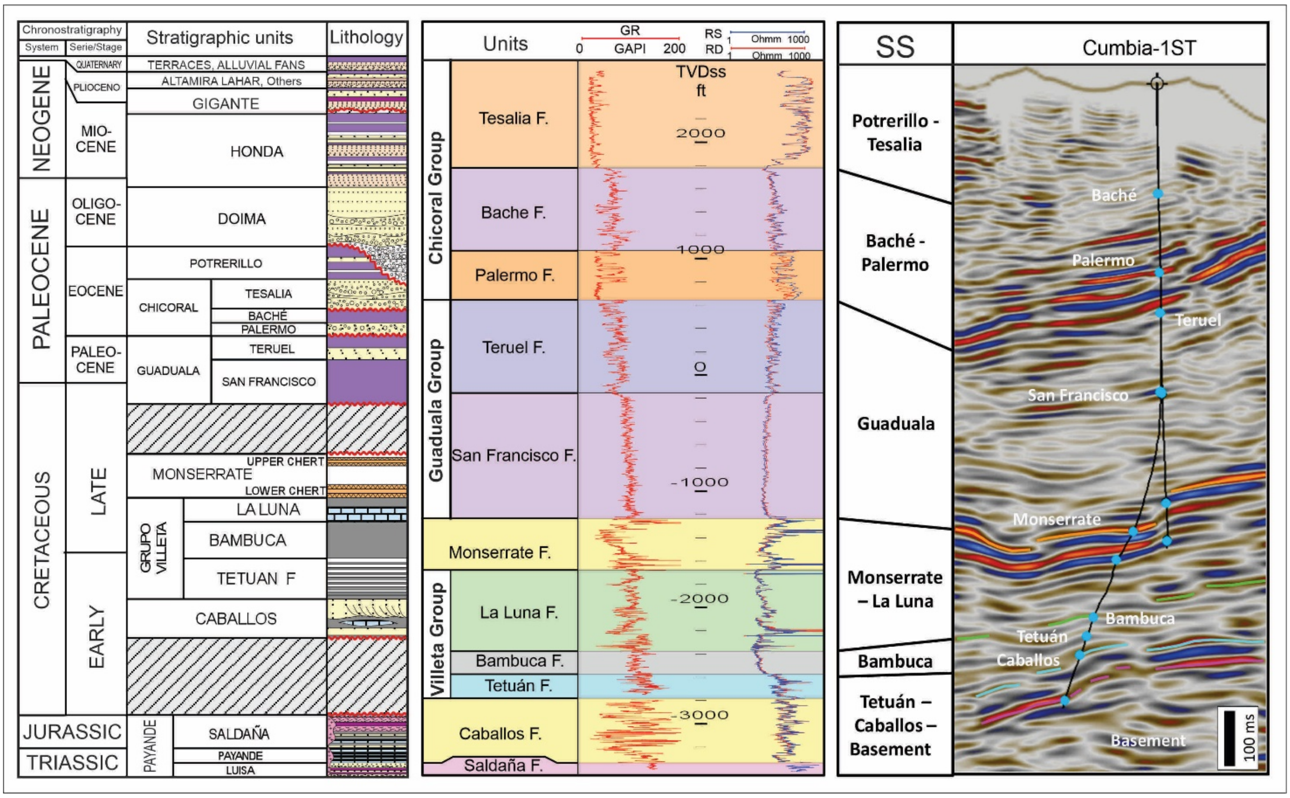

Figure 3 - Stratigraphic column of the Neiva Subbasin (left), electrical logs and their response in the stratigraphic units (centre), defined seismic-stratigraphic units (SS) integrated with the well data and the chronostratigraphic units (right) (taken from Mantilla, 2019).

MATERIALS AND METHODS

The present work is mainly based on the interpretation of a 3D seismic volume merged from the La Hocha 3D programme (2005, 168 km²) and the La Cañada Norte 3D programme (2010, 35.9 km²). The resolution in the analysed volume (174 km²) was improved by varying the velocity functions with which the pre-stack time migration (PSTM) volume was processed, while preserving the amplitude and lateral continuity of a seismic event.

Seismic stratigraphic sequences were defined by transgressive and regressive cycles bounded by unconformity surfaces or maximum flooding surfaces (Mitchum et al., 1977), and six such units were defined (Figure 3). Thickness ano-malies and the partial or total absence of the Tetuán, Bambuca, La Luna and Monserrate Formations (Albanian to Campanian) and differences in the dip direction of the Caballos Formation were also taken into account.

A geological surface map of the Neiva sub-basin, characterized by a discreet relief covered by abundant vegetation (Figure 4), was constructed from available geological maps (Marquínez et al., 1999; Caicedo et al., 2000; Dunia, 2005; Bayona et al., 2007; Gil, 2008) together with photogeological and satellite imagery analysis of an area of 352 km² covering the La Cañada, La Cañada Norte and La Hocha fields.

The field data were used for geological control (Servigecol, 2014). This map was integrated with subsurface information obtained from seismic interpretation. The combination of the geological maps, the photogeological analysis, the field survey and its integration with the interpretation of the 3D seismic information and the geological data of the fields kinematic analysis was made.

The morphology of the La Hocha field was only constructed from boreholes and surface geology, as the high dip of the bedding (greater than 45°) did not allow a reliable seismic image. The rest of the area was interpreted using surface geology and wells integrated into the 3D seismic information.

Figure 4 - Field photographs. A and B: Panoramic views to the north showing the SJF traces corresponding to the La Hocha field area with evidence of bending associated with transpression (1 in Figure 2). Js: Saldaña Formation; Kv: Villeta Group; Kg: Guadala Formation; Tep: Palermo Formation; Teb: Bache Formation; Tet: Tesalia Formation; SJF: San Jacinto Fault. C: Teruel Formation affected by normal faulting. D: The Chicoral Formation with evidence of normal faulting in the vicinity of the La Cañada Norte Field (2 in Figure 2). E: internal access cut showing sandstone beds affected by faults. F: road cut view of the stepping bedding outcrops of the Chicoral Formation (3 in Figure 2).

A total of 65 wells were drilled in the study area: 12 in the La Cañada field, 14 in the La Cañada Norte field and 32 in the La Hocha field; the remainder (seven) were previous exploration wells. Information from these wells included GR, resistivity, density, neutron, sonic, borehole image (electrical), check shot and VSP logs. The La Cañada Norte 4 hole was used to tie in the structural evaluation due to its favorable location in a low deformed, relatively stable area with a gentle structural dip to the SE.

A well correlation was constructed based on easily identifiable seismic reflectors. The well logs and images using the SCAT methodology (Statistical Curvature Analysis Techniques, from Bengtson, 1981) allow the structural stratigraphic analysis to construct oriented sections of each well. The dip direction of the structures (cut angle) and perpendicular to it and the corresponding apparent dip values were used to: a) include them in the correlation software and thus work in true stratigraphic thickness (TST), b) make chronostratigraphic correlations, c) follow with greater precision the flooding maximum and accommodation minimum of the different stratigraphic cycles, and d) identify repetitions or absences of sedimentary records due to the effects of faults interpreted with SCAT.

The identification of faults, unconformities, fold axes, bedding inflection points and pitch of structures was integrated into a kinematic model using information from detailed surface geology, 3D seismic interpretation and well logs. In order to understand the mechanical response of the seismic-stratigraphic units and the spatial relationship between the stress field and the fractures, it was necessary to distinguish between (i) faults as discontinuity surfaces bounding blocks with independent movements along the surface and (ii) joints as smaller discontinuity surfaces whose movements are perpendicular to the block extension.

RESULTS

Regional kinematic model and structural styles

The compilation of all the data makes it possible to identify a sub-latitudinal orientation of the main compressional stress. The approximately sub-meridional orientation of the Tesalia syncline axis with the central Doima-Honda outcrops (Figure 5) confirms a regional sub-latitudinal tectonic convergence supported by the World Stress Map data (Heidbach et al., 2016) and plate tectonic analysis (Cobbold et al., 2007; Montes et al., 2019).

The structural interpretation of the basement is based on 3D seismic data, drilling and surface geology. Based on these, new structural faults, not previously proposed, have been identified, generally dipping high to vertical. The main fault (P), which includes the SJF, has a high angle inversion.

Since the spatial relationship between the location of the maximum principal stress (σ_1) and the surfaces of the SJF is at an angle of less than 45°, we consider that strike-slip movement affects the entire sedimentary sequence (Figure 5). As a consequence, based on Anderson's law, a dextral strike-slip component has resulted along this trace.

If the regional N-S trace of the SJF is decomposed into subordinate segments according to the local bending and stepping, different tectonic scenarios can be recognized: a) when the segments turn to the left (towards more NW-SE orientation), they express a more transpressional behaviour, and b) in the opposite sense, when the segments turn to the right (towards more NE-SW direction), a more transtensional behaviour is generated (Figure 5).

In the La Hocha field, two uplifted sectors consisting of the Palermo and Tesalia formations are associated with the area of influence of the left-dipping transpressional segment of the SJF. As a result, the Saldaña Formation is thrusting eastward onto the San Francisco Formation. (Figure 4A). Consequently, these positive reliefs contain rocks that are older than the surrounding rocks, indicating their uplift by transpression. Vertical and inverted bedding of the Palermo Formation is parallel to the line of the SJF, providing additional evidence for right-lateral transpression (Figure 5).

The analysis of the breakouts and orientation of the induced fractures in the well logs of the La Hocha and La Cañada Norte fields shows evidence of the current action of the stresses, which is consistent with the orientations obtained at the regional scale. In the field, along the flexural SJF trace, the inverted Palermo formation can also be seen to the north of the La Hocha field (near the LH-3 and LH-4 wells).

In contrast, in the La Cañada Norte field area, outcrops of the Teruel and Palermo formations are located along a different segment of the SJF, which is displaced to the right. For this reason, this area shows the predominance of subordinate extensional faults associated with blocks outcropping younger rocks (Figure 6).

The map at the top of the Basement shows three sets of faults that influence the Basement-Caballos-Tetuán seismic-stratigraphic sequence (Figure 6). The main set (P), belonging to the SJF arrangements, has the same regional character,

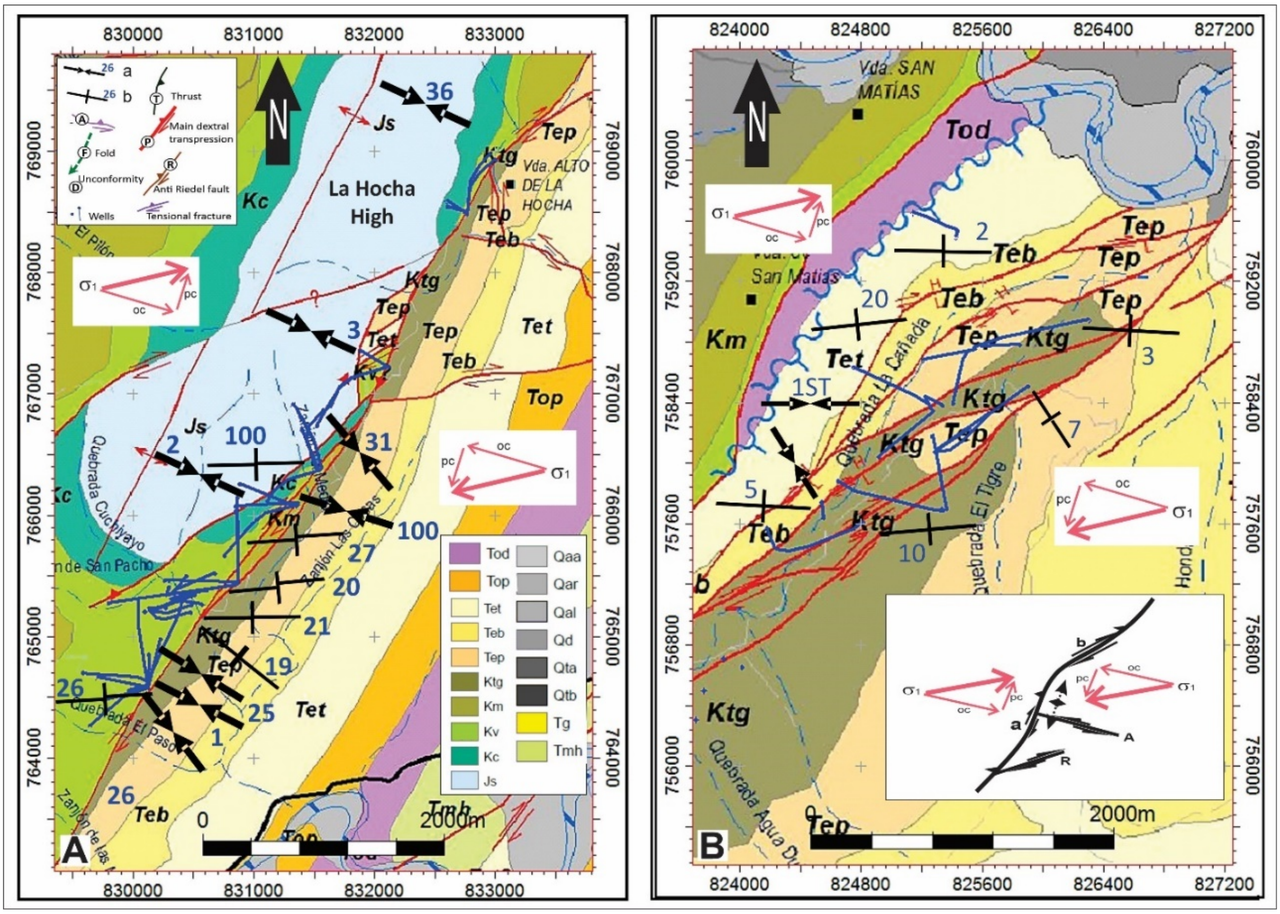

Figure 5 - Acquired data and kinematic evaluation of the SJF and its relationship to the direction of the regional stress field from the surface survey (location in Figure 2). The stress field is indicated by the principal maximal horizontal stress (σ1) and its orthogonal compound (oc) and parallel to fault compound (pc). A: La Hocha field detail (local average for maximum stress direction Az. 84°. B: La Cañada Norte field detail (local average for maximum stress direction Az 87°). Conventions: a; fractures from well number, b: induced fractures from well number.

with a northeast-southwest orientation, and is associated with high-angle reverse faults with a dextral strike-slip component. This fault displacement affects the entire sedimentary column and separates the La Cañada and La Cañada Norte fields.

Two other families of faults are interpreted as subordinate Riedel's faults genetically related to the trace of the main SJF: a) dextral synthetic Riedel (R) with preferential NE-SW orientations (showing a more acute angle with the main fault plane) and lengths greater than five kilometres, and b) antithetical sinistral Anti-Riedel (A) with preferential NW-SE orientations (showing a more obtuse angle with the main fault plane) and developments not greater than five kilometres (Figure 5A).

It is noteworthy that these subordinate faults only affect the Basement-Caballos-Tetuán seismic-stratigraphic sequence associated with the basement, with no evidence of their displacement within the Bambuca Formation (Figure 3).

The map of the top of the Monserrate Formation represents the upper limit of the La Luna-Monserrate stratigraphic seismic sequence overlying the Bambuca Formation (Figure 6B). In this map it is possible to confirm the total disappearance of the secondary faults (A and R) identified in the basement (Figure 6A), but the main faults present in the basement (P) are preserved.

On the uplifted western block of the SJF, the structural contours show smooth evidence of deformation or folding, probably produced by the fault movements on the basement blocks, with little evidence of displacement to the top of the Monserrate Formation (Figure 6B).

The map shows three associated anticlines (F) on the eastern footwall block of the SJF: the southern anticline of the La Cañada field with surface expression has a SW dipping axis (Figs 4 and 6B). The northern extreme, associated with the La Cañada Norte field, has the same orientation but dips NE (Figure 6B).

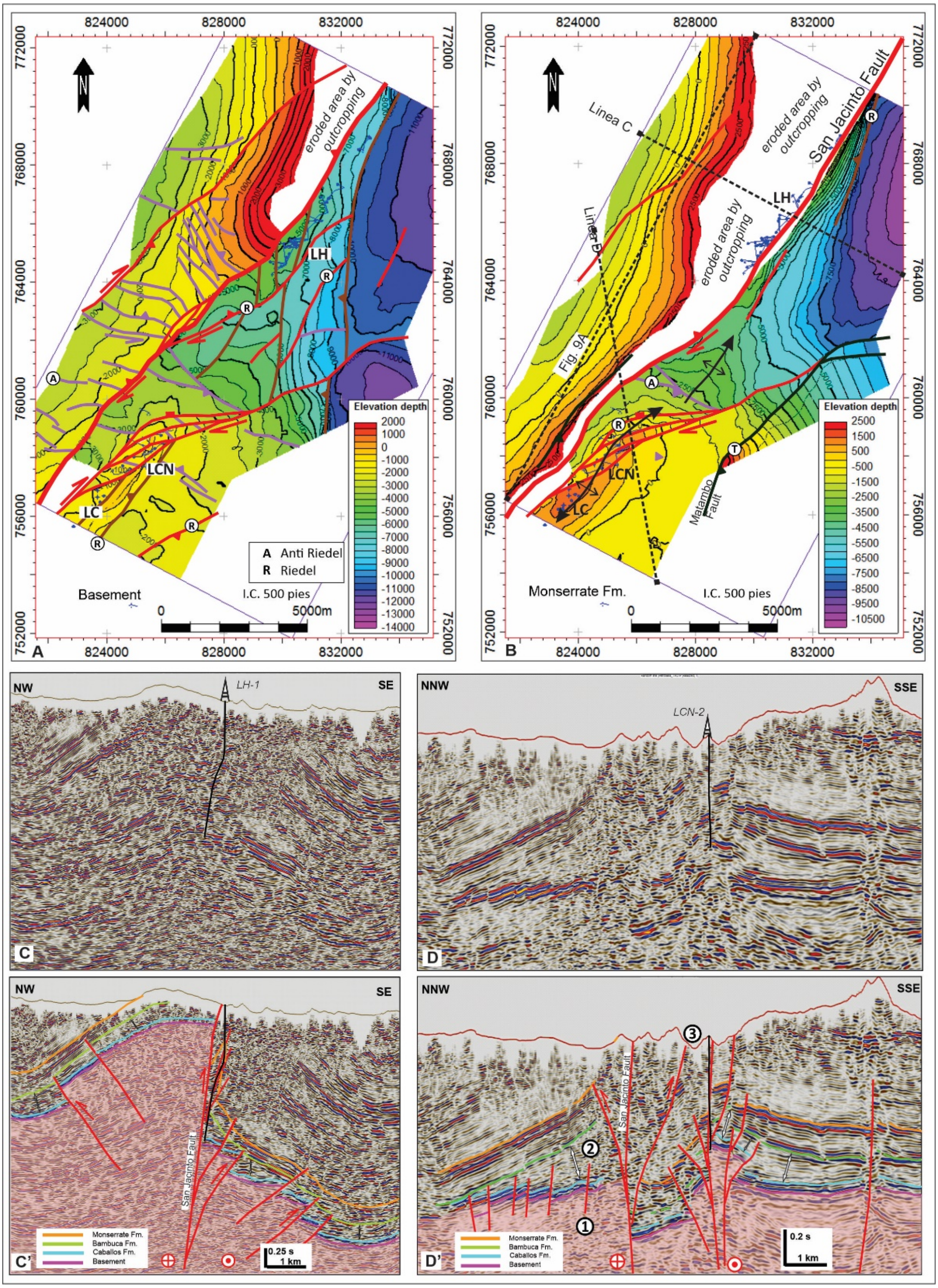

Figure 6 - Subsurface maps of the studied area with the location of the three sets of faults: R: Riedel and A: AntiRiedel. A: Map at the top of the Basement. B: Map at the top of Monserrate Formation. lines show localization of Lines C and D (R: Riedel, A: Anti-Riedel, T: thrust and P: main plain fault). C: Dip seismic line showing the seismic expression of the La Hocha field area. C': interpreted. D: Dip seismic line showing the structural behavior of the La Cañada Norte field. D´(interpreted) across the LCN-2 well.

From the seismic information, we interpret that the Matambo Fault has western vergence and is related to a more recent tectonic pulse compared to the faulting associated with the Basement and La Luna - Monserrate sequences (Figure 6B). The seismic interpretation of this fault (P) shows more than one reactivation. The Matambo Fault is an equivalent fault related to the hydrocarbon traps observed in the western foothills of the Eastern Cordillera, such as Boquerón, Bituima, Honda, etc. in the Espinal and Guando fields (ECOPETROL ICP 2001).

The three anticlines are also cut by a secondary fault (type A) associated with a north-dipping basement, and the northernmost fold corresponds to a tight structure that leads to the formation of the La Hocha field structure and is cut to the north by the SJF (Figure 6B). It is noteworthy that the northern culmination of the third anticline and the southern culmination of the northernmost anticline are almost in the same location.

The surface and subsurface structural data associated with the Basement and Monserrate formations and the disconformities between the Monserrate and Guadala formations determine the tectonic reactivations of the main fault families (P) from the end of the Cretaceous and during part of the Cenozoic. The oblique orientation of the maximum horizontal stress field with the strike of the fault planes gives a dextral transpressive displacement in the area of the La Hocha field and a transtensive displacement in the area of the La Cañada and La Cañada Norte fields. (Figure 6A).

Morphology of the La Hocha field

The La Hocha field (LHF) is associated with a segment of the SJF that is more NE trending in plain view. It is associated with a series of subordinate dextral transtensional faults arranged in duplex, creating an extensional environment. Comparison of the outcrop strike of the SJF with that obtained at depth from seismic and borehole interpretation shows a change in orientation at the top of the Monserrate Formation. Here the SJF truncates the dorsal limb and anticline axis of the field. This change in the strike of the fault also coincides with the change in the dip of the strata (Figure 7). In this way it is sub-parallel to the orientation of some other faults identified in the field, which affect the Palaeogene sequence up to the base of the Doima Formation.

The morphology of the LHF has only been constructed from wells and surface geology. Several producing wells of the LHF are drilled from locations on the western uplifted block of the SJF, but they produce oil from the eastern footwall block. Regarding the complexity of the La Hocha field structure, in many cases the well crosses and/or repeats the same unit in a normal sequence, and in others it is inverted due to folding or faulting, both related to the SJF (Mantilla et al., 2014).

The La Hocha-21 well allows the reconstruction of the spatial characteristics of the repetition of the production levels of the Monserrate formation in the lower block of the SJF. Based on the electrical logs, the quality of the reservoir has been divided into four lithostratigraphic units, defined from top to bottom as Km1, Km2, Km3 and Km4 (Figure 7C).

In the LHF, 32 wells have intersected the sedimentary sequence containing the producing Monserrate Formation at this location, but only wells LH-1 and LHD-1 have successfully penetrated the underlying Saldaña Formation. The intervals drilled in the San Francisco, Monserrate, and partially in the La Luna formations have bedding dips of nearly 60° in the LHD-1 well and 80° in the LH-1 well (Mantilla, 2019). Below the shales of the Bambuca formation, in the Tetuán and Caballos formations, the bedding dips are between 15° and 30°, similar to the seismic sections. The anterior limb near the fold hinge is inverted and becomes vertical at depth, later flattening to dips of nearly 60° to the northwest, as in the LHD-1 well.

We have interpreted a recumbent Z-type anticline, the posterior limb of which is shorter than the anterior because it is truncated by the SJF towards the southwest end of the field (Figure 7B). The incompetent mechanical behavior of the Bambuca Formation contributes the detachment and exhumation of the basement and Saldaña-Caballos-Tetuán seismic sequences in the La Hocha High, which also contributes to detachment surfaces and disharmonic folds and thrusts in the overlying La Luna - Monserrate seismic-sequence with more competent mechanical behavior.

Morphology of the La Cañada (LC) and La Cañada Norte (LCN) fields

The La Cañada Norte (LCN) field is a gentle anticline cut by normal faults with a dextral component that determines a right horsetail structure with more than 230 m of vertical displacement. This displacement creates independent traps with different oil-water contacts and API gravity oil reservoirs in the Monserrate Formation. The greatest changes in thickness are associated with the flanks of the synclines, which are partially outcropping due to ductile extrusion and detachment associated with the influence of the SJF.

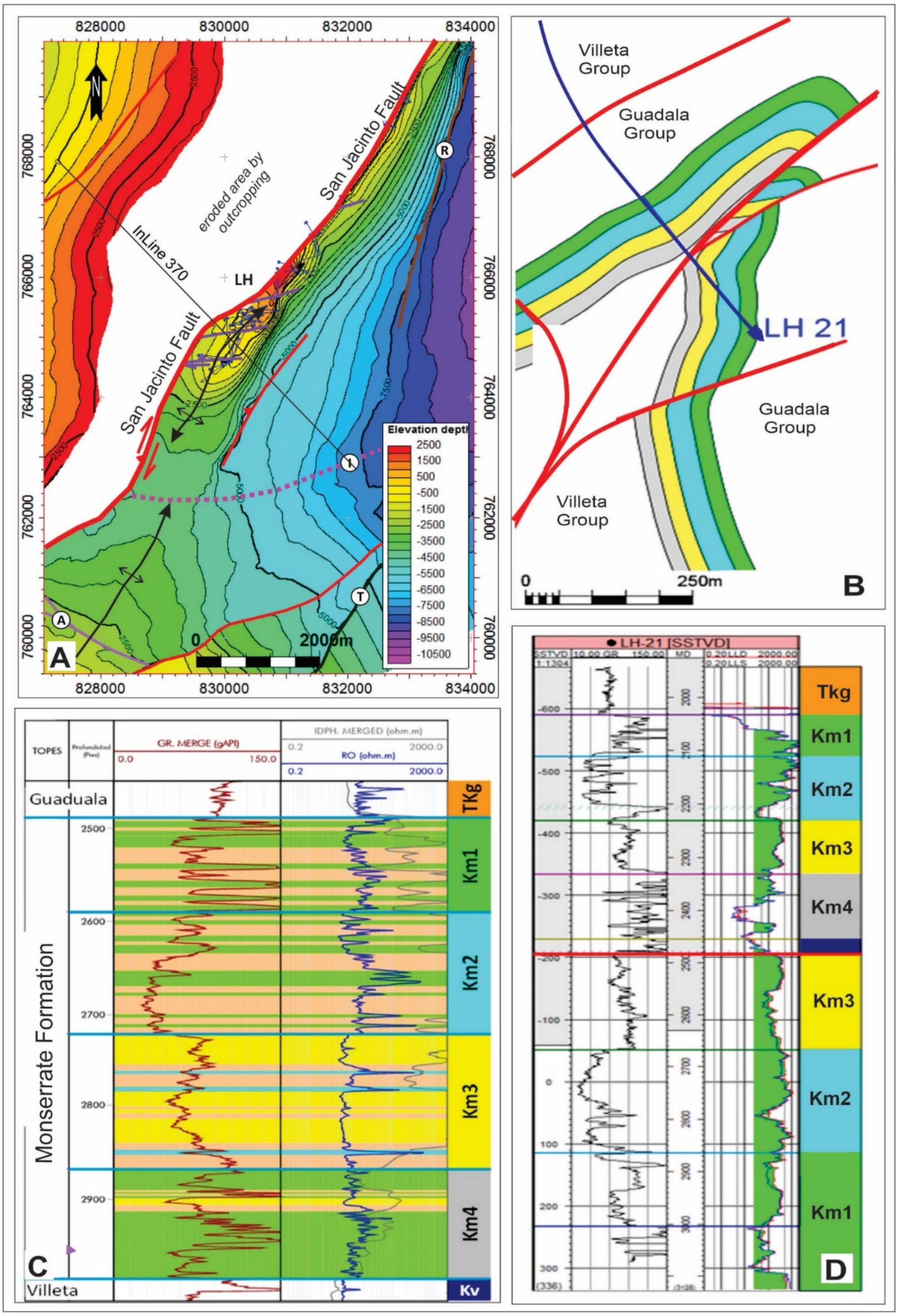

Figure 7 - A: Upper structural map of the Monserrate Fm from a seismic acquisition. The black line indicates the trace of the seismic dip section shown in Figure 6. B: An interpretative section of the structure traversed by the La Hocha-21 well, showing the four lithostratigraphic units of the Monserrate Fm (from Mantilla et al., 2014). C: Stratigraphic diagram of the La Hocha field showing the different reservoir levels of the Monserrate Formation in the footwall block of the SJF. These units have been defined by electrical logs. D: Identification of lithostratigraphic units in the LH-21 well logs, showing inverted repetition units due to the SJF

The temporal structural map of the LC and LCN fields shows the main fault system (P) striking northeast-southwest with variable intensity of transpressional dextral displacements (Mantilla et al., 2016). The secondary normal Riedel faults (R) strike northeast-southwest and the reverse anti-Riedel (A) with left-lateral movement strike northwest (Figure 8). Both structures form a common anticline cut and displaced by dextral transtensional faults about 2.5 km from its axis (Figure 9).

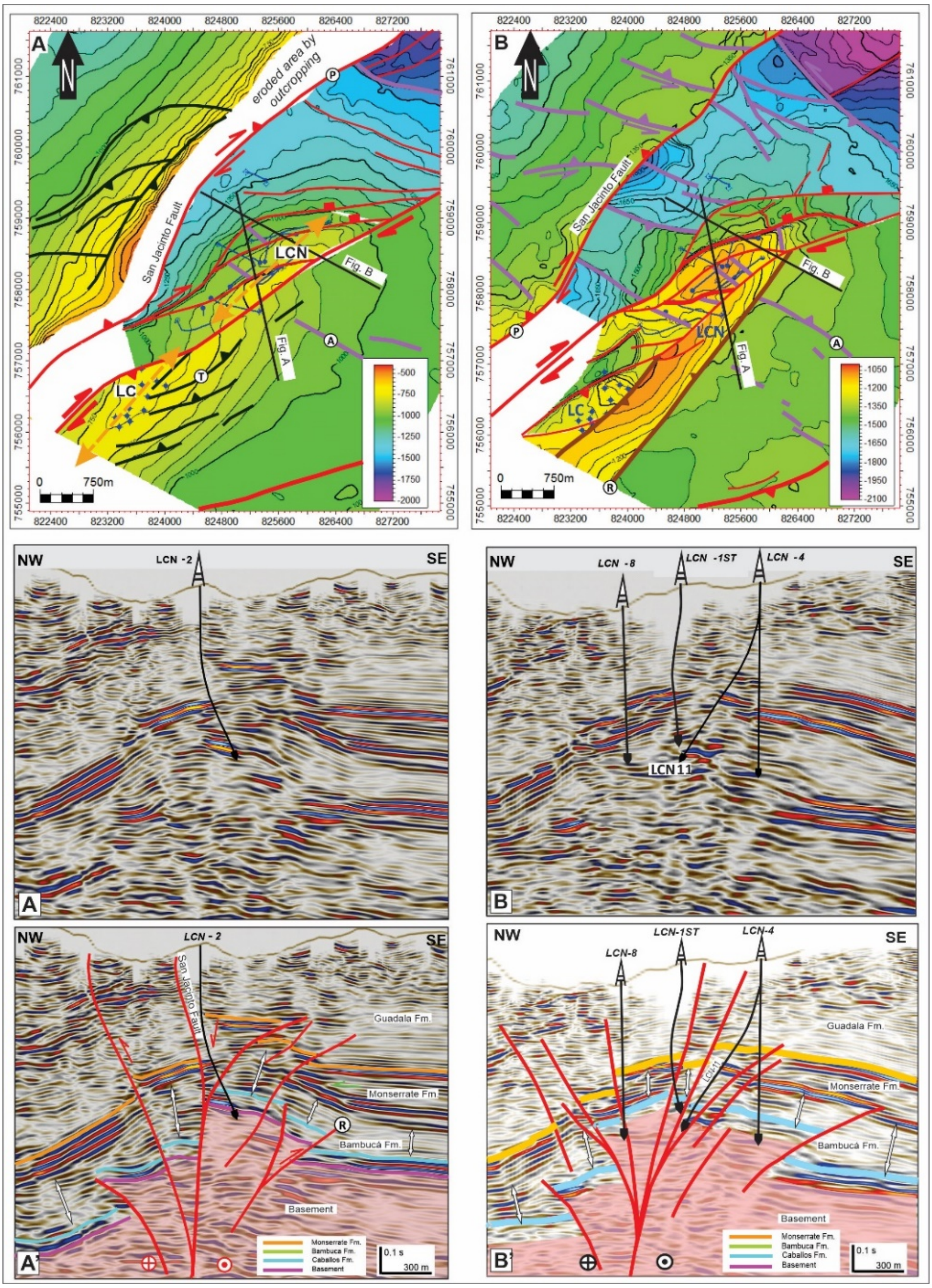

Figure 8 - A: Time-slice structural map of the La Cañada (LC) and La Cañada Norte (LCN) fields at the top of the Monserrate Formation, showing a right-horse-tail termination. The black lines show the position of the seismic lines in C and D. B: Structural map at the top of the basement (from Mantilla et al., 2016) The displacement of the anticline axis (orange line) can be seen. Seismic section of dip showing the structural behaviour of the La Cañada Norte field. A (uninterpreted) A´(interpreted) across the LCN-2 well. B (uninterpreted) B´ (interpreted): across the LCN-8, LCN-1ST and LCN-4 wells. The white double arrow identifies the thickness of the Bambuca Formation.

Preliminary interpretation of the two strike seismic lines across the La Cañada (LC) and La Cañada Norte (LCN) fields show duplicated flakes of the Basement and Monserrate Formation (Figure 10).

The Bambuca Formation mechanical behavior

The Bambuca Formation overlies the La Luna Formation with onlap-like terminations, probably due to a) an effect generated by a lateral rate of change of lithological deposition, or b) they could

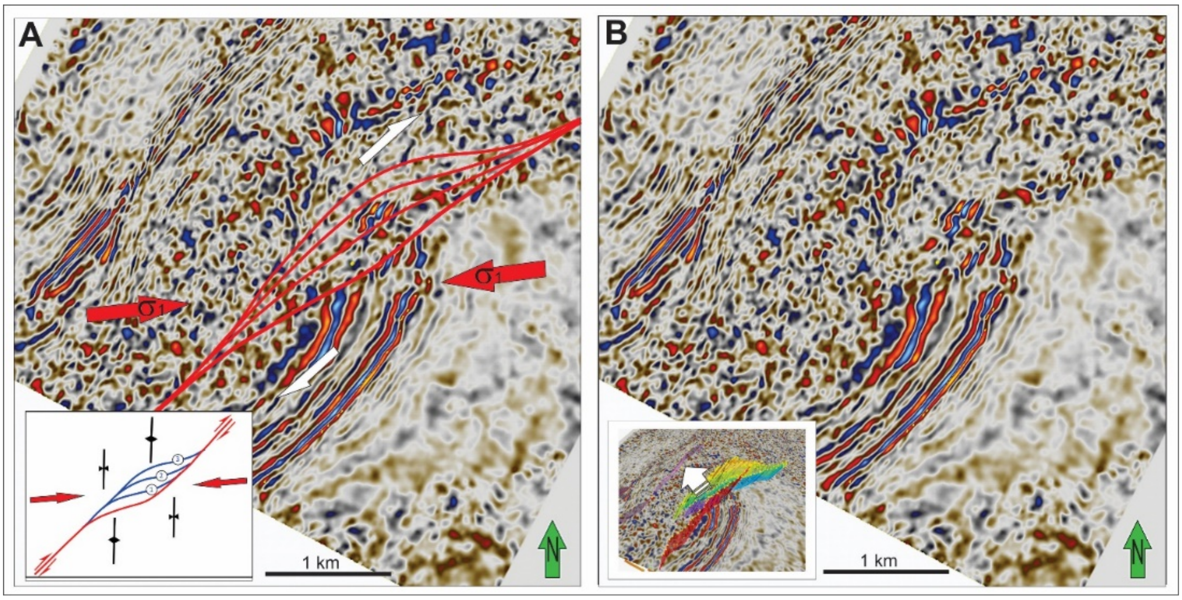

Figure 9 - A and B (uninterpreted) are time slice seismic images of the La Cañada Norte field showing a transpressive segment of the SJF with subordinate dextral displacement. Inset shows a schematic model of the SJF segment with the position of the principal maximum horizontal stress. Inset: View of the projected interpretation in depth showing the bedding dipping to the northwest (white arrow).

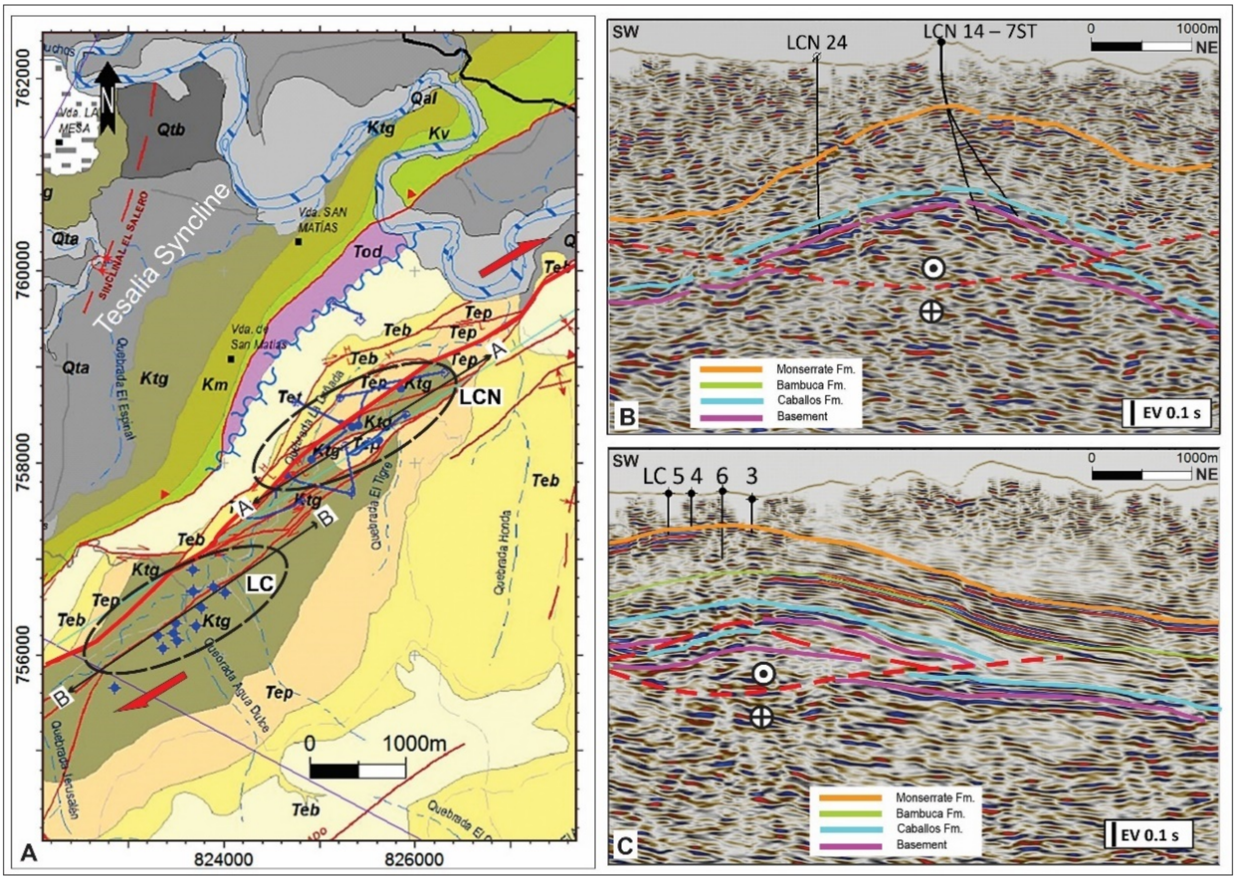

Figure 10 - A: Geological surface map of the La Cañada and La Cañada Norte oil fields (see references in Figure 2) with the localization of the lines C and D. C and D: Preliminary interpretation of the two strike seismic lines across the La Cañada (LC) and La Cañada Norte (LCN) fields.

show evidence of sintectonic growth strata on a local paleo-high not recognised in other areas of the basin (Figure 11).

The vertical compression due to the loading of the thicker overburden on the shales of the Bambuca Formation determines their ductile behavior that favors flow from the synclines with a decrease in their thickness towards the thicker flanks (Figure 11). The Bambuca Formation shows strong changes in thickness depending on

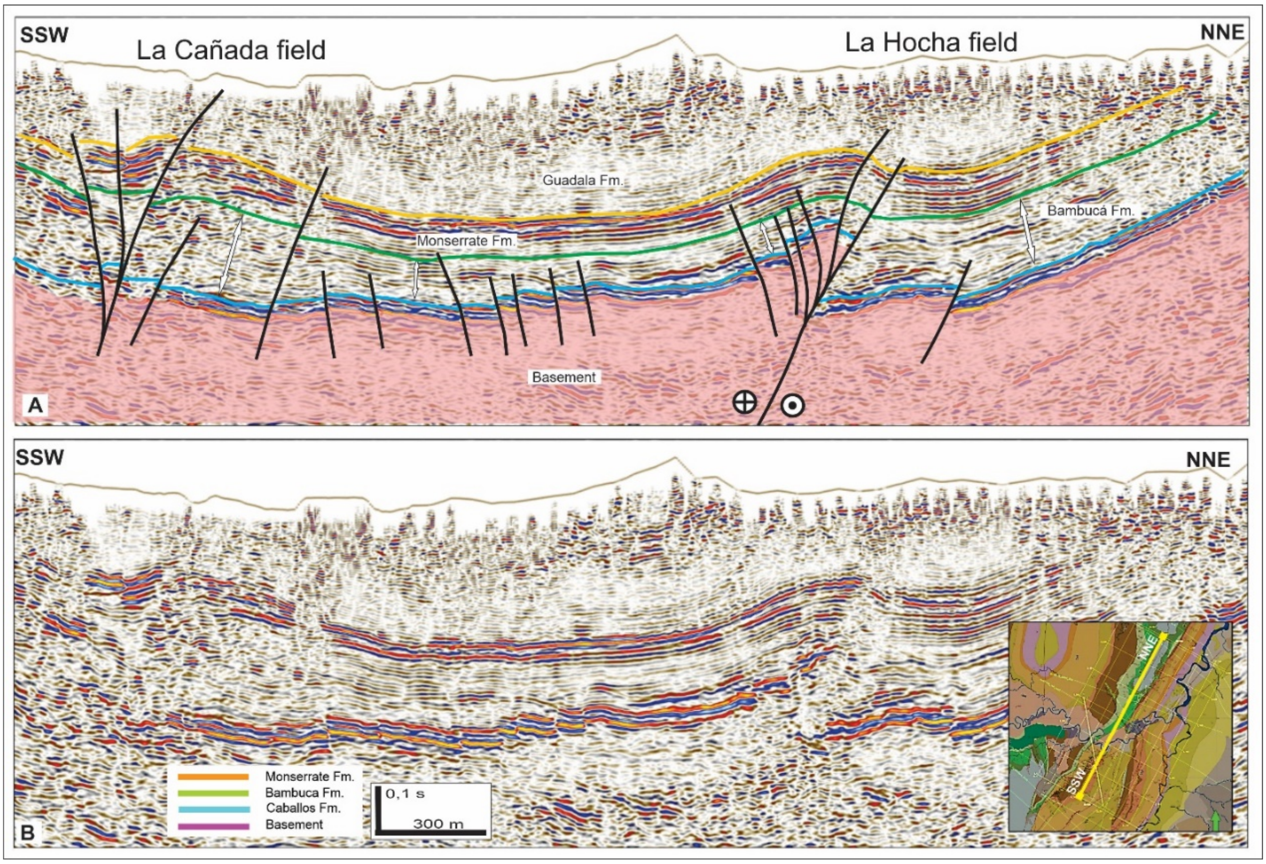

Figure 11. A (B uninterpreted): Regional strike seismic line along the southern LC until the northern LHH fields showing thickness variations of the Bambuca Formation (white double arrows) and more affected underlying basement and adjacent sequences.

its position in the synclines or anticlines due to its flow during the post-depositional history.

Its rheological nature, favoured by the superimposed load of the overlying sedimentary column, causes accommodation movements and ductile adjustments. For this reason, the Bambuca sequence shows a lower minor development of thicknesses in the core of the synclines and higher thicknesses in the anticlines. The vertical load of the overburden pushes the ductile shales towards the anticline flanks. In the La Hocha field, this shale sequence also has subordinate folds caused by detachments.

The lack of deformation expression of the faults within the shales of the Bambuca Formation is interpreted as related to its ductile behaviour. This mechanical behaviour, caused throughout the overlying sedimentary sequence, is associated with this change in thickness, producing: a) smooth and elongated synclines, b) anticlines with elongated and smooth rear flanks and short front flanks, c) steep thrust faults with detachments in this unit, and d) detachment folds in the sequences overlying the Bambuca Formation. The Bambuca Formation is underlain by several common inverted faults with "pop-ups" affecting the Basement and Caballos Formation with a preferential WNW-ESE orientation (Figure 11).

The presence of gentle synclines with evidence of reduction in bedding thickness along their axis and the formation of tight anticlines near the SJF have been interpreted. In agreement with Schamel (1991), we assumed that the deformation of the competent La Luna-Monserrate seismic sequence corresponds to the influence of detachments controlled by the ductile behaviour of the shales of the Bambuca Formation along the Matambo Fault (Figure 12). The Saldaña, Caballos and Tetuán formations show an identical deformation response with no significant lateral changes in thickness.

The new 3D structural model

Based on the interpretation of the structural map of the top of the Monserrate Formation, a series of anticline folds arranged in echelon (F) can be observed along the footwall block of the SJF, as well as on the hanging wall block of the eastern flank of the Tesalia syncline (Figure 12).

Stratigraphic contrasts of the thicker sedimentary record of the area have a strong influence on the structural evolution of the LHH. The presence of different intermediate décollements surfaces associated with the Bambuca Formation has caused the generation of complex fault geometries and a wide spectrum of disharmonic fold types (e.g. rounded, box, chevron and detachment folds). An important feature of the incompetent beds, particularly the Bambuca Shales, is that they have flowed during the deformation process. As a consequence, buckling or higher order folds are common structures in stiff beds between two thick incompetent beds.

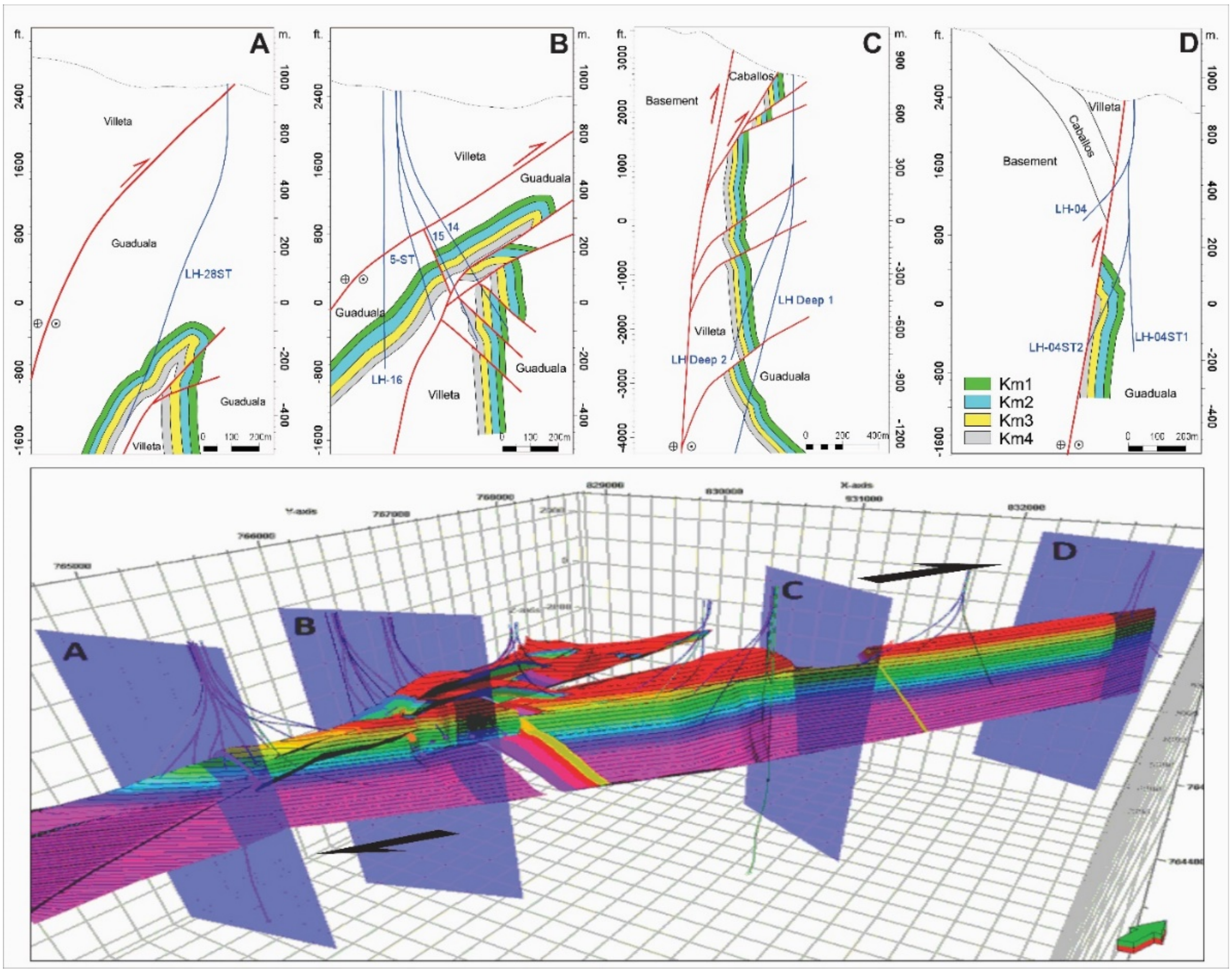

Figure 12 - 3D view of the La Hocha oil field. A, B, C and D are structural sections across the SJF and its eastern footwall.

Different authors (Massoli et al., 2006; Schmalholz and Schmid, 2012, among others) have shown this in the experimental models. In the La Hocha high, the higher-order folding and buckling found in the Monserrate Formation (more competent layers) occur where the Bambuca Formation (more incompetent layers) has thick layers. Incompetent beds can exert a strong control on the distribution and geometry of structures in sedimentary basins (Koyi et al., 2004; Massoli et al., 2006; Simpson, 2009; Callot et al., 2012).

The present interpretation suggests that the faults are sinusoidal with associated sequences, or that they are the product of reactivation of pre-existing faults associated with the basement (Figure 12). This faulting is associated with a predominantly compressive stress field responsible for the strike-slip system with subordinate families of faults according to Riedel shear terminology.

The direction of the maximum stress field (σ1) lies in the bisector between the main faults and the Riedel (R) (see field stress scheme in Figure 4B). This arrangement, oriented at 80° azimuth, generates dextral strike-slip components on the oblique NNE-SSW strikes of the La Hocha fault and the main associated faults. The main horizontal shortening generated by the La Hocha anticline is practically absorbed by the Bambuca Formation. Jiménez et al. (2012) also suggest that the ductile formation changes the orientation of the anticline axis, with almost zero displacements at the level of the Monserrate Formation.

The main features of the new tectonic model of the La Hocha area are simplified into a roughly NW-SE transect (Figure 13).

The results of the present study show the existence of two major tectonic episodes involving strike-slip movements, in which the regional-type San Jacinto and Chusma faults played the main role.

The first episode is associated with the basement deformation formed during the Jurassic-Triassic transtensional tectonic phase (Irving, 1971; Schamel 1991; Velandia et al., 2005; Sarmiento-Rojas et al., 2006). The first uplift pulse in the area is identified at the top of the Monserrate Formation (Maastrichtian).

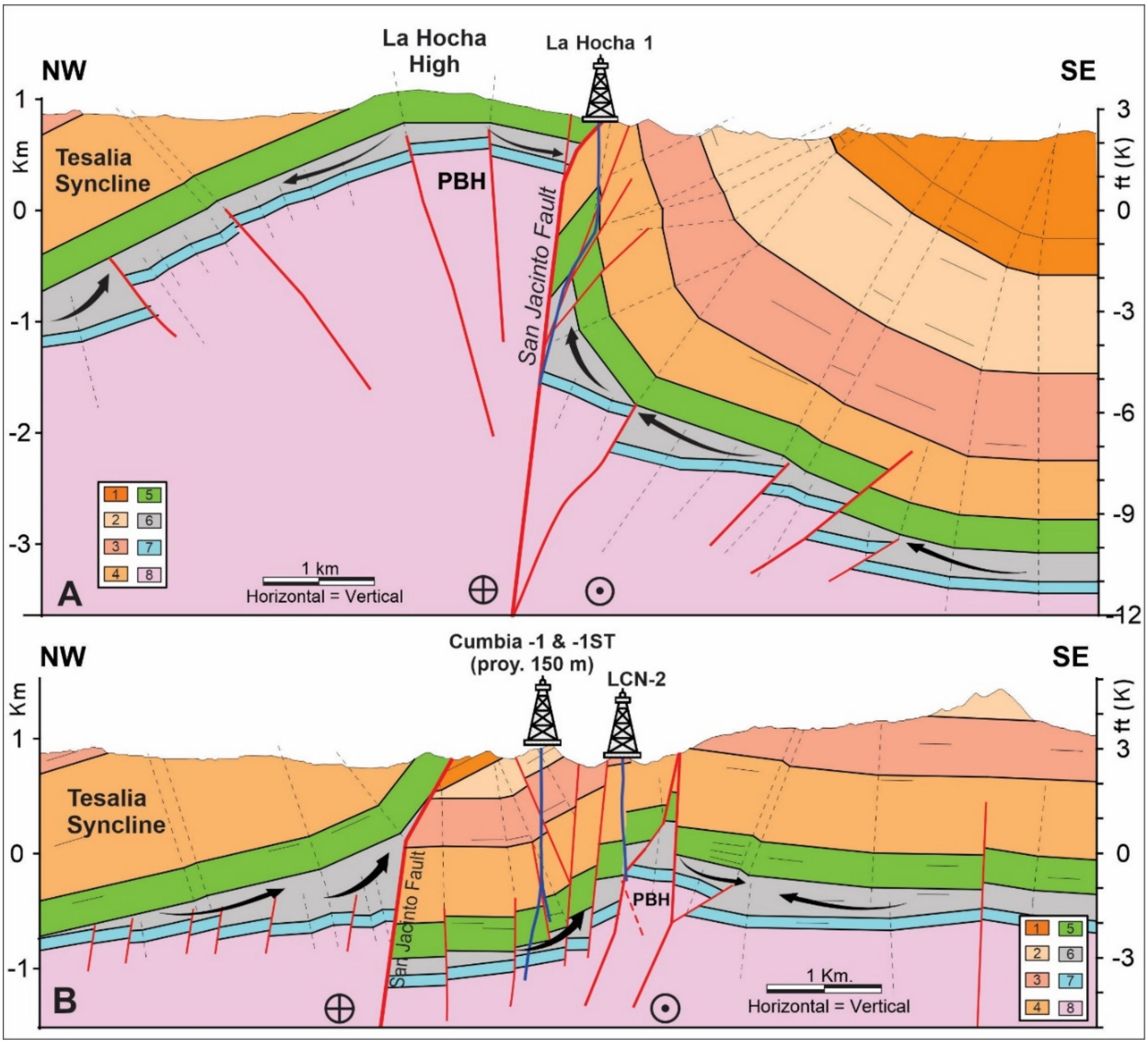

Figure 13 - Structural sections constructed from the seismic sections. A: across the La Hocha field of Figure 9B (see the location in Figure 8C). B: across the Cañada Norte of Figure 9C. 1: Doima-Honda formations; 2: Tesalia-Potrerillos formations; 3: Palermo-Bache formations; 4 Guaduala Group; 5: La Luna-Monserrate formations; 6: Bambuca Formation; 7: Caballos-Tetuán formations; 8: Basement. Black arrows show the shale flow direction. PBH: Paleo basement high.

The second episode produce the reactivation and invertion by a transpression followed by at least three other pulses, chronologically located at the base of the following seismic sequences: a) the Guaduala Group and the Palermo and Bache Formations (Maastrichtian-Paleocene), b) the Tesalia-Potrerillo Formation (Middle Eocene), and c) at the base of the Doima-Honda Formation (Oligocene-Miocene). This second episode probably occurred at the end of the Cretaceous and Paleocene, coinciding with the beginning of the evolution of the Central Cordillera due to the Peruvian Andean Phase (Cobbold et al., 2007). Only major faults associated with the entire sedimentary record were active, while the other faults were continuously absorbed by the ductile deformation of the Bambuca Formation. Salazar (2020) shows secondary Riedel-type strike-slip faults in the Ataco syncline (Girardot subbasin, Figure 1) that were active only up to the Middle Eocene unconformity.

Evidence for a second pulse of deformation involving lateral movement in the area includes the following:

a) Variations in the surface orientation of the SJF strike (Figure 3). This shows preferential transpressive and transtensive segments along the left (more NW-SE orientated) and right (more NE-SW orientated) flexures of the fault, respectively.

b) Identification of high-angle normal faults in the subsurface that compartmentalise the structure of the La Cañada Norte field throughout the sedimentary sequence (from the basement to the Palermo Formation). The Monserrate Formation shows the development of a releasing flexure-type structure associated with dextral displacement (field stress scheme in Figure 4B, and 13).

c) The presence of a structural splay in the SJF in the La Hocha high, composed of the Palermo or Tesalia formations in contact with older rocks (Figure 4A).

d) the arrangement of anticlines of the Monserrate Formation with abrupt termination of the block on the footwall of the SJF.

e) The Matambo fault is associated with thrusting following the strike-slip fault that controls the structure of the La Cañada and La Cañada Norte fields.

CONCLUDING REMARKS

Early structural models of the La Hocha and La Cañada Norte fields proposed the superposition of a series of thrust sheets in duplexes with little overall displacement. In the La Hocha field, the displacement was to the southeast with the development of an antiformal stack associated with a triangular zone; in La Cañada Norte, the displacement is to the northwest.

Nevertheless, Jiménez et al. (2012) interpret it as a transpressive movement of the fault that occurred during the Late Miocene, involving the basement. In this sense, close to the study area, Velandia et al. (2005) show that the Algeciras fault system is a transcurrent structure with evidence of recent Quaternary movements. In the same vein, Fabre (1995) interprets strike-slip movements associated with the Algeciras fault, which formed positive flowering structures and pull-apart basins during the Late Pliocene to the present.

During the action of the Andean tectonic events, a variety of multiscale and diachronic structures are produced on the La Hocha High, associated with geological events related to extensional or transtensional fault inversions. From the analysis of the surface geology, the kinematic structural data and the interpretation of the multi-well controlled seismic survey, there is no evidence for the existence of tectonics associated exclusively with thrusting. Therefore, all the data are more consistent with the transpressional reactivation of the Jurassic-Triassic normal/transtensional faults with dextral strike-slip components.

Nevertheless, the previous evolution of the study area based on 2D balanced sections was usually related to a single stacking of thrust belts detached in the basement due to orthogonal convergence.

However, the present interpretation, based on surface geology, well data and a 3D seismic survey, shows clear evidence of dextral wrenching controlled by earlier normal/transtensional faults associated with the Triassic-Jurassic rifting. In relation to this deformation history, the spatial disposition of fractures and folds and the rheological responses of the different lithologies involved have been considered.

The variations in the angle of incidence of the principal horizontal stress field on the different flexural segments of the SJF determine transtensive scenarios when it turns to the right and transpressive scenarios when it turns to the left. One of these faults displaced the entire sedimentary sequence and separated the La Cañada and La Cañada Norte fields. On the other hand, when the curve turns to the left, transpression contributes to the ductile deformation of the shales of the Bambuca Formation, creating disharmonic folds such as the anticline of the La Hocha field. In terms of their spatial relationship to the main dextral SJF, subordinate faults have been identified as NE-SW dextral Riedel and WNW-SWS sinistral Anti-Riedel fractures. Our interpretation shows that the La Hocha and La Cañada fields may have been united at some point in geological history.

Temporally, we identified at least three main tectonic scenarios involving transcurrent movements over the entire sedimentary sequence: a) basement associated faulting during Jurassic-Triassic rifting with the probable transtensive component. b) Transpressive strike-slip movements that allowed the reactivation and inversion of basement-associated faults in tectonic pulses that occurred during the deposition of the Palermo-Bache and Tesalia-Potrerillo (Eocene) seismic sequences. c) The present surface expression involves both transpressional and transtensional tectonics, generating e.g, a minimum lateral displacement of at least 2.5 km during the Pliocene-Pleistocene in the La Cañada anticline by the separation of its two oil fields.

The greatest variations in the thickness of the shales of the Bambuca Formation are concentrated around the main fault system (P), which cuts through the entire sedimentary sequence.

Subsequent exploration studies failed to demonstrate the presence of thrust sheets that repeated the reservoir section, and instead a large-scale recumbent fold cut by transpressive faults was proposed to explain the structure of the area (Mantilla et al., 2014).

The new tectonic model is highly relevant to petroleum exploration, not only for the La Hocha area, but for the rest of the fields and prospective areas in the Upper Magdalena Valley.

Consequently, this new structural interpretation improves the understanding of the petroleum habitat, traps and migration patterns in the fields, not only locally but also regionally, creating the opportunity to re-evaluate existing fields and generate new development and exploration strategies.

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