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Subsurface Characterization of Structural Traps in the Outer Nunchia Foothills, Colombia

Master Thesis

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Subsurface Characterization of Structural Traps in the Outer Nunchia Foothills, Colombia

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A mi hermoso angelito

Abril Natalia.

"Dripping water hollows out stone,

not through force but through persistence."

Ovid

ABSTRACT

The integration and interpretation of 2D and 3D seismic data, well information, geological maps and public information was used to identify the structural configuration of the outer Nunchia Foothills, to define the structural style and to evaluate the hydrocarbon prospectivity in terms of the structural configuration. A stack of hinterland-dipping monocline to imbricate structures were recognized. Based on the lower detachment levels, the outer Nunchia foothills were divided into three sub-divisions. The basal structures, with detachment in Gacheta Formation and involves Cretaceous rocks to León Formation. The Intermediate structures, with detachment level in Lower to Middle Carbonera, which involves rocks of Carbonera and León Formations; and the upper to surface structures, where the lower detachment is located in the Upper Carbonera and involves the younger rocks. In the outer Nunchia foothills, the reservoir units are involved only in the basal structures, where the southern structure was tested by the Tangara-1 well. The area is therefore classified to be of low hydrocarbon potential in terms of structural traps.

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INTRODUCTION

Structural models in the eastern foothills of the Eastern Cordillera of Colombia

The foothills are one of the areas most studied in the mountain belts because (1) they record the uplift history of the mountain belt, (2) they accommodate the regional shortening that create the mountain chains (Duerto et al., 2006), and (3) in these areas the structures are highly prospective for hydrocarbons accumulations. However, the foothills are also well known for their structural complexity. The harsh topography and steeply dipping bedding generate several problems in seismic acquisition and processing. Therefore, the interpreted structural models of these areas have high uncertainty and there is high potential for missing hydrocarbon accumulations.

The eastern foothills of the Eastern Cordillera of Colombia (EFEC) are considered one of the principal petroleum basins of Colombia (Figure 1). This basin has eight oil fields with more than 3000 MMBL of initial reserves, where the largest oil fields are Cusiana, and Cupiagua. During the last five decades of exploration, the basin has been studied by 2D seismic data, surface geological mapping campaigns, and exploratory wells. 3D seismic is generally acquired when the operator makes a discovery, and only few 3D seismic cubes are acquired during the exploration phase.

Supported by the identification of some transversal zones and changes in structural styles, Bayona et al. (2008); Cortés et al. (2006) and Cortés et al. (2009) divided the EFEC in three areas: North Llanos Foothills, Central Llanos Foothills and South Llanos Foothills (figure 1). The majority of the oil fields in the basin are located in the southern part of the Central Foothills. As a consequence, this area has more public information including: the geometry and kinematic analysis of structures, (Amaya and Galindo, 2008; Cazier et al., 1995; Cediel et al., 1998; Cortés et al., 2009; Linares et al., 2009; Martinez, 2003, 2006b; Rochat et al., 2003), the configuration of oil fields using pseudo-3D structural models (Egbue and Kellogg, 2012; Martinez, 2006a; Rathke and Coral, 1997), and 3D models to predict fracture patterns (Richards et al., 2006).

Based on the structural styles, Martinez (2003, 2006b) divided the area in three zones: (1) Overthrust trend (i.e. Floreña, Pauto, Dele, and Volcanera oil fields), (2) transition zone with isolated structures (i.e. Cupiagua oil fields) and (3) frontal structures (i.e. Cusiana oil field).

The Nunchia Foothills, 22km to the ENE of the Floreña oil field, consist of two main regions: internal and external structure (Rochat et al., 2003). There, two operators tried to extrapolate the Cupiagua play. However, they did not find the reservoir predicted by the structural model. Instead, they found a thicker sequence of the overburden rocks. The Aysisi-1 well (1993), drilled a sequence of the León Formation that is 2.2 times thicker than the foreland thickness and the Tangara-1 well (2004) drilled 3490m of a faulted sequence of the Carbonera Formation. This thickness is 4.1 times thicker than the corresponded foreland thickness.

The seismic data over this area together with information from the Aysisi-1 and Tangara-1 wells, surface geological maps and topographic data available were used: (1) to identify which structures of the outer Nunchia foothills involve the reservoir rocks; (2) to define the structural geometry and the sequence of thrusting of outer area of the Nunchia foothills; (3) to identify the structural style in the Nunchia foothills, and; (4) to identify the variability of the structures along the strike.

The surface analysis was done in ArcGis, the subsurface interpretation in Petrel and the evaluation of the 3D structural model in Move. The work was developed in time domain, because there are too few wells in the area to generate a consistent velocity model.

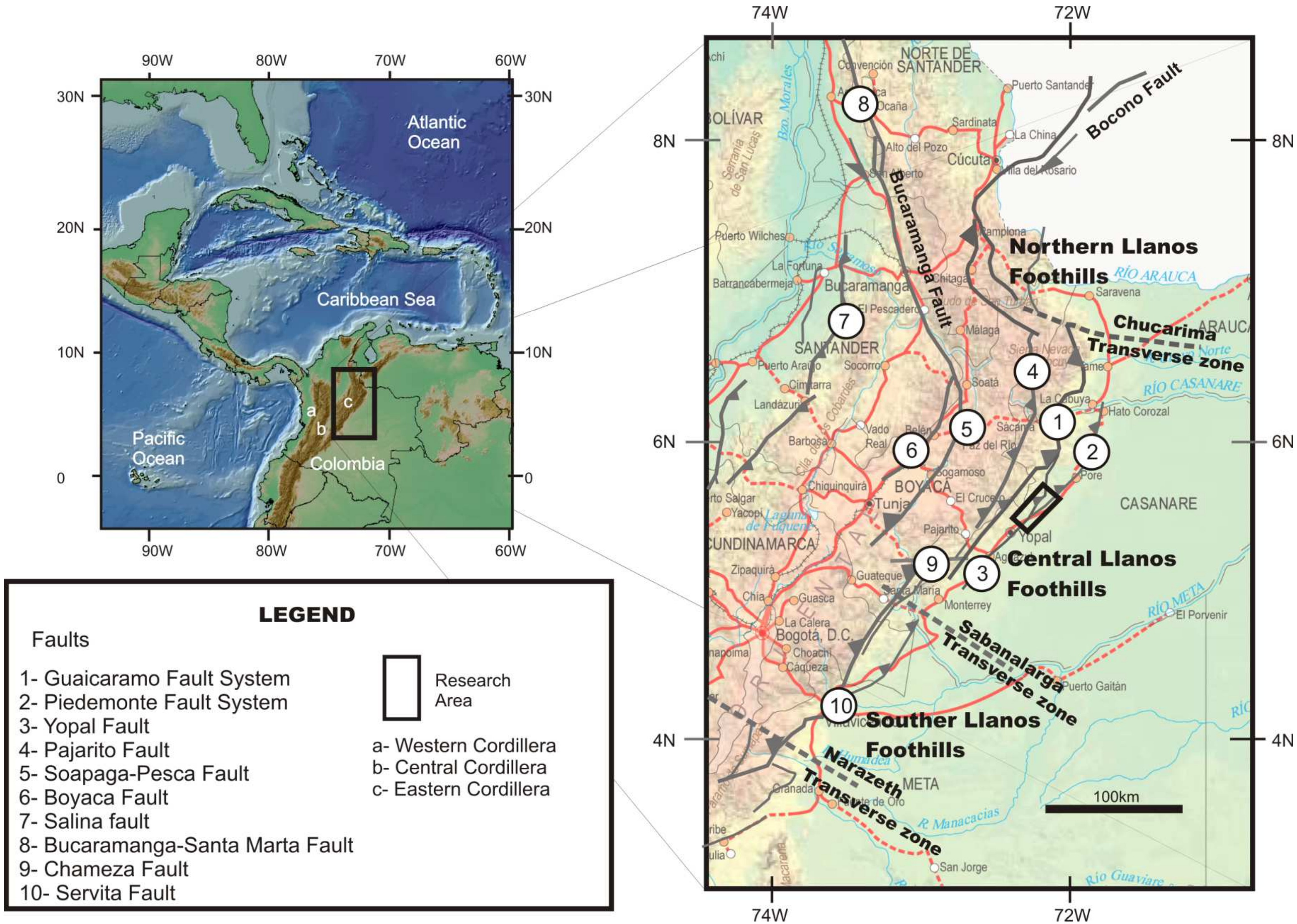


Figure 1. General location of Northern Andes, the eastern foothills of the Eastern Cordillera and the location of the study area.

The mountain front of the Nunchia area is divided in two principle regions, the higher foothills and lower foothills. They are separated by the Guiacaramo fault system. At the same time, the lower foothills are divided in two areas, the inner antiformal stack and outer imbricate zone, which is the focus of this study.

The outer imbricate zone of the Nunchia foothills is characterized by thin-skinned deformation. It is a stacked monocline to imbricate structure with separate detachment levels. Based on the identified geometry, the imbricate structures a break-backward sequence with separated detachment level is proposed. The outer Nunchia Foothills are divided into three sub-divions, based on the detachment level: (1) basal structures, defined as having a detachment in the Gacheta Formation; (2) intermediate structures, with detachments in both C-8 (Lower Carbonera Formation) and C-6 (Middle Carbonera Formation), and; (3) upper to surface structures with a detachment level in C-2 (Upper Carbonera Formation).

Along strike, the Outer Nuchia Foothills become deeper to the north and the distance between the inner antiformal stack and outer imbricate region widens.

Although, to understand the real configuration of the Nunchia foothills it is necessary to integrate the outer and inner regions, the inner region is currently confidential due to oil exploration activity. Future studies that are able to integrate these areas would allow for a better understanding of the geometry and kinematic architecture of the Nunchia foothills.

The contribution of this research will both aid the regional understanding of the EFEC and will evaluate the hydrocarbon prospectivity of the area in terms of the structural configuration.

GEOLOGICAL SETTING

Regional tectonic setting

In Colombia, the Andes mountain belt is divided in three cordilleras: Western Cordillera, Central Cordillera and Eastern Cordillera. They are separated by two inter-mountain valleys: The Cauca Valley and Magdalena Valley.

In the Triassic to Early Cretaceous, the Magdalena Valley, the Eastern Cordillera and Llanos foreland of Colombia were part of an asymmetrical graben related to a back-arc basin (Etayo-Serna et al., 1976; Fabre, 1983; Sarmiento-Rojas, 2001; Sarmiento-Rojas et al., 2006). Sarmiento-Rojas et al. (op cit) recognized five different extensional pulses: three events are related to Triassic-Jurassic and two to the Cretaceous: Berriasian-Hauterivian and Aptian-Albian.

Bayona et al. (2008); Colleta et al. (1990); Cooper et al. (1995); Dengo and Covey (1993); Mora et al. (2008); Restrepo-Pace et al. (2004); Restrepo-Pace and Villamil (1997); Roeder and Chamberlain (1995) Tesón et al. (2013) and Toro et al. (2004) have proposed different models to explain the uplift of the EC. The models vary between tectonic inversion and major super-crustal low angle thrusting that loads the cratonic foreland (Figure 2). The same authors and Kroonenberg et al. (1990) proposed that the main deformation is related to the Miocene to Holocene Andean orogeny, with a principal deformation pulse in the Upper Miocene-Pliocene. However, some authors (Bayona et al., 2008; Cortés et al., 2006; Cortés et al., 2009; Restrepo-Pace and Villamil, 1997) suggest that some deformation pulses started in the Late Cretaceous-Paleocene to Oligocene, related to pre-Andean deformation.

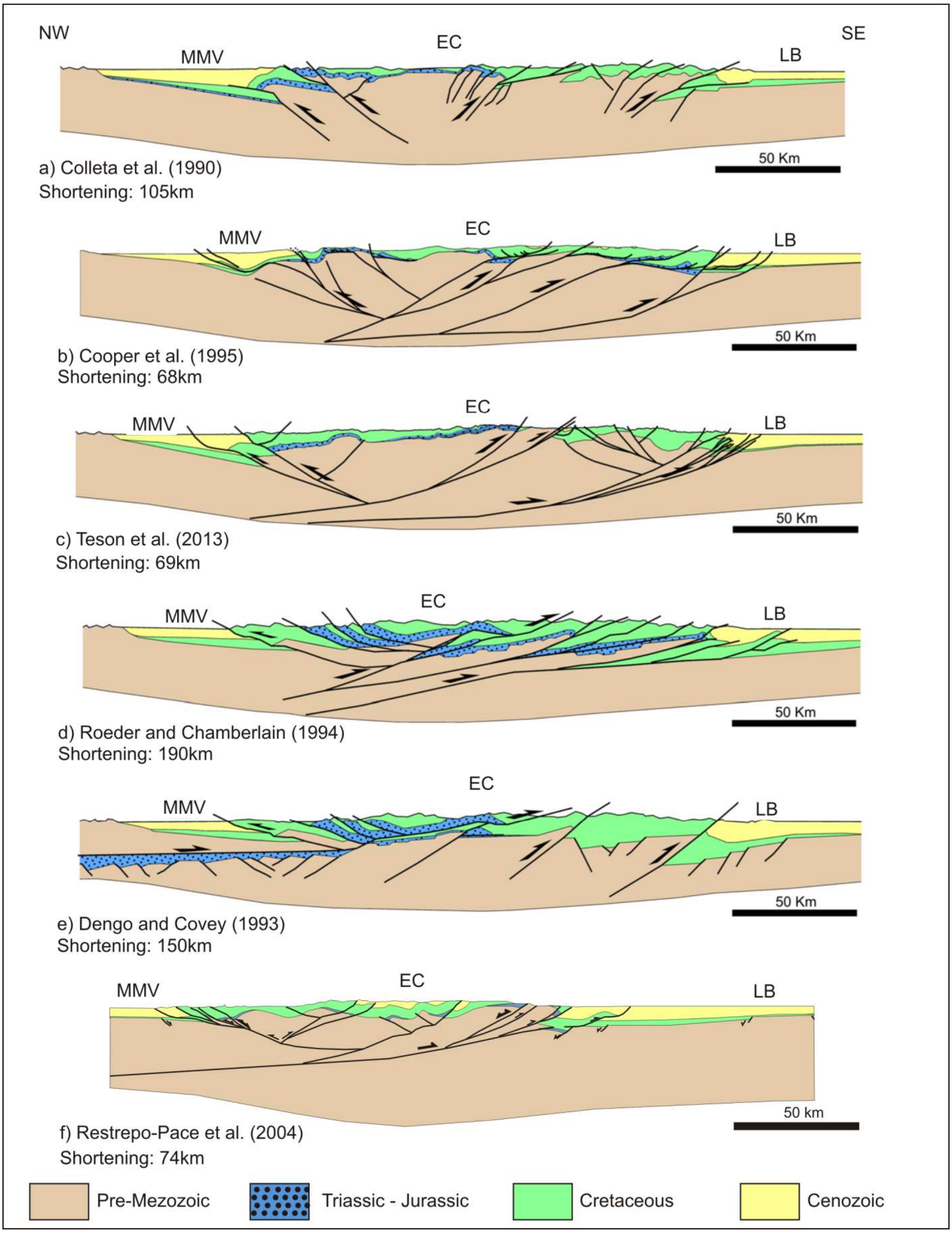


Figure 2. Some models proposed to explain the origin of Easter Cordillera. Models (a), (b) and (c) propose a theory of tectonic inversion. Model (d) supra-crustal thrust and models (e) and (f) a combination between tectonic inversion and supra-thrusting adapted from Tesón et al. (2013) and Restrepo-Pace et al. (2004).

The eastern foothills of the Eastern Cordillera (EFEC) present variations in structural style along strike. Even though no basement rocks are exposed, three transverse zones allow the division of the EFEC in the South Llanos Foothills, Central Llanos Foothills and North Llanos Foothills (Bayona et al., 2008) (figures 1 and 3). Tesón et al. (2013) determined that the EFEC has today two stress regimes: transpressional in the South Llanos Foothills and compressional in the Central and North Llanos Foothills.

The South Llanos Foothills are limited to the south by the Nazareth transverse zone and to the north by the Sabanalarga transverse zone. It has a predominant along strike NNE orientation, with around 147 km length and variable width of 14 to 30km. The studies by Casero et al. (1995); Mora et al. (2010); Parra et al. (2009) and Rowan and Linares (2000, 2005) show that the structures of the South Llanos Foothills are highly influenced by pre-existing structures. In the southern part, the structures comprise of flower structures and anticlines generated by the Algeciras transpressional fault. To the north, the structures are related with thick-skinned deformation in the inner part and thin-skinned deformation basinward (Mora et al., 2010)

The North Llanos Foothills are located between the Cucharima transverse zone and the Bocono Fault. This zone has a boomerang shape with a predominant along strike N20W orientation, a length of 81km and width of 40km. Bayona et al. (2008); Cortés et al. (2006); Cortés et al. (2009) and Corredor (2003) proposed thin-skinned deformation with an inversion structure in the frontal fault.

The Central Llanos Foothills (CLF) are located between the Sabanalarga and the Chucarima transverse zones and is the principal zone of interest in this study. In this zone, the Eastern Cordillera changes gradually in direction from NNE to NNW. This is the longest zone with 270km length and large, variable width along strike (Figure 3 and 4). In the southern part, the

CLF has a width of 22km that decreases progressively to 9km around Yopal city, to the north. From Yopal, it becomes gradually wider again, reaching 36km to the north. The CLF holds the largest number and biggest oil fields in the EFEC. As a consequence, hundreds of wells have been drilled and thousands of km of seismic information have been acquired to develop these resources.

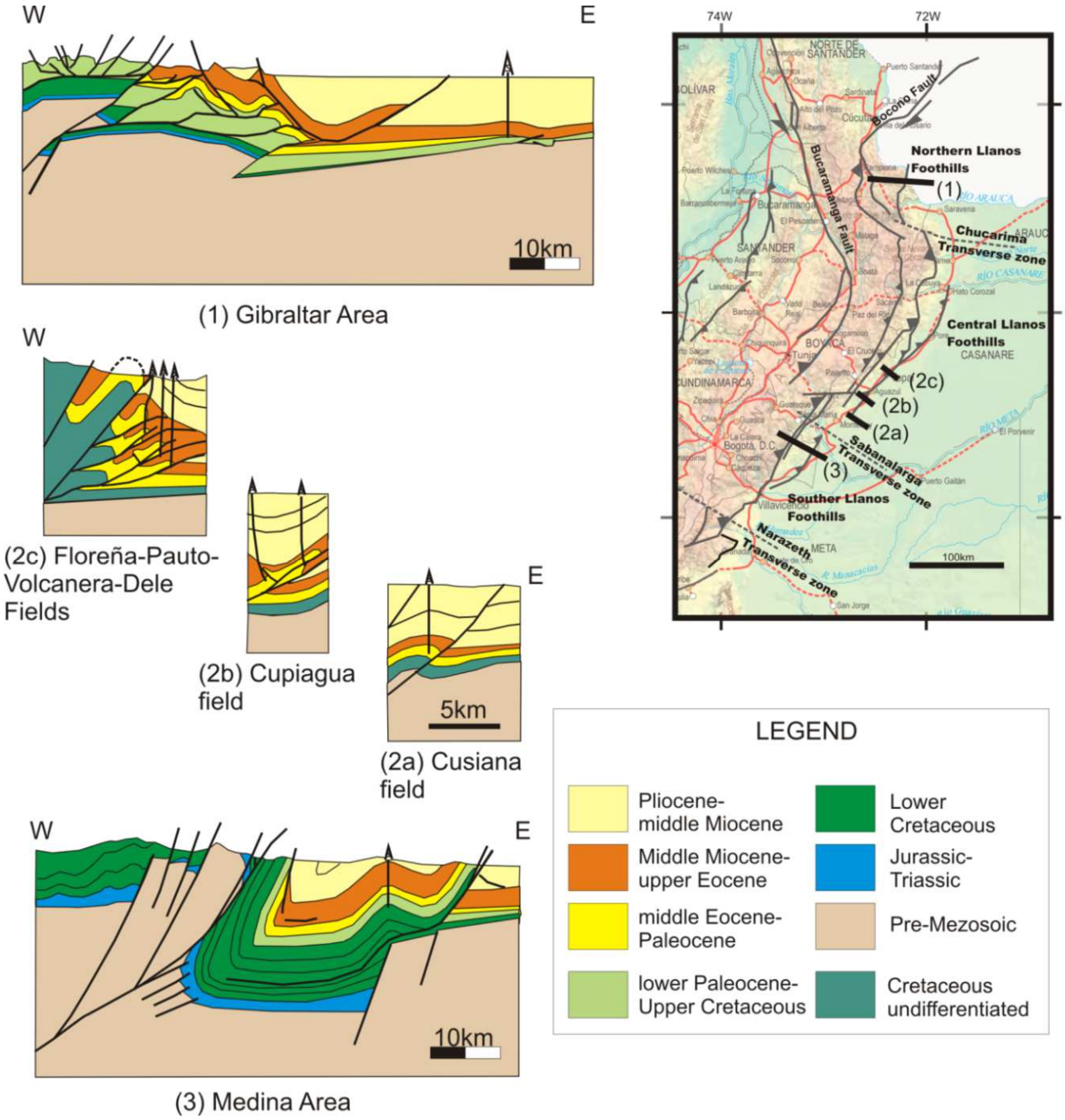


Figure 3. Cross sections showing the lateral variation along strike of the eastern foothills of the Eastern Cordillera. 1) North Llanos Foothills (Bayona et al., 2008), 2) Central Llanos Foothills (Martinez, 2006b) and 3) South Llanos Foothills (Rowan and Linares, 2000)

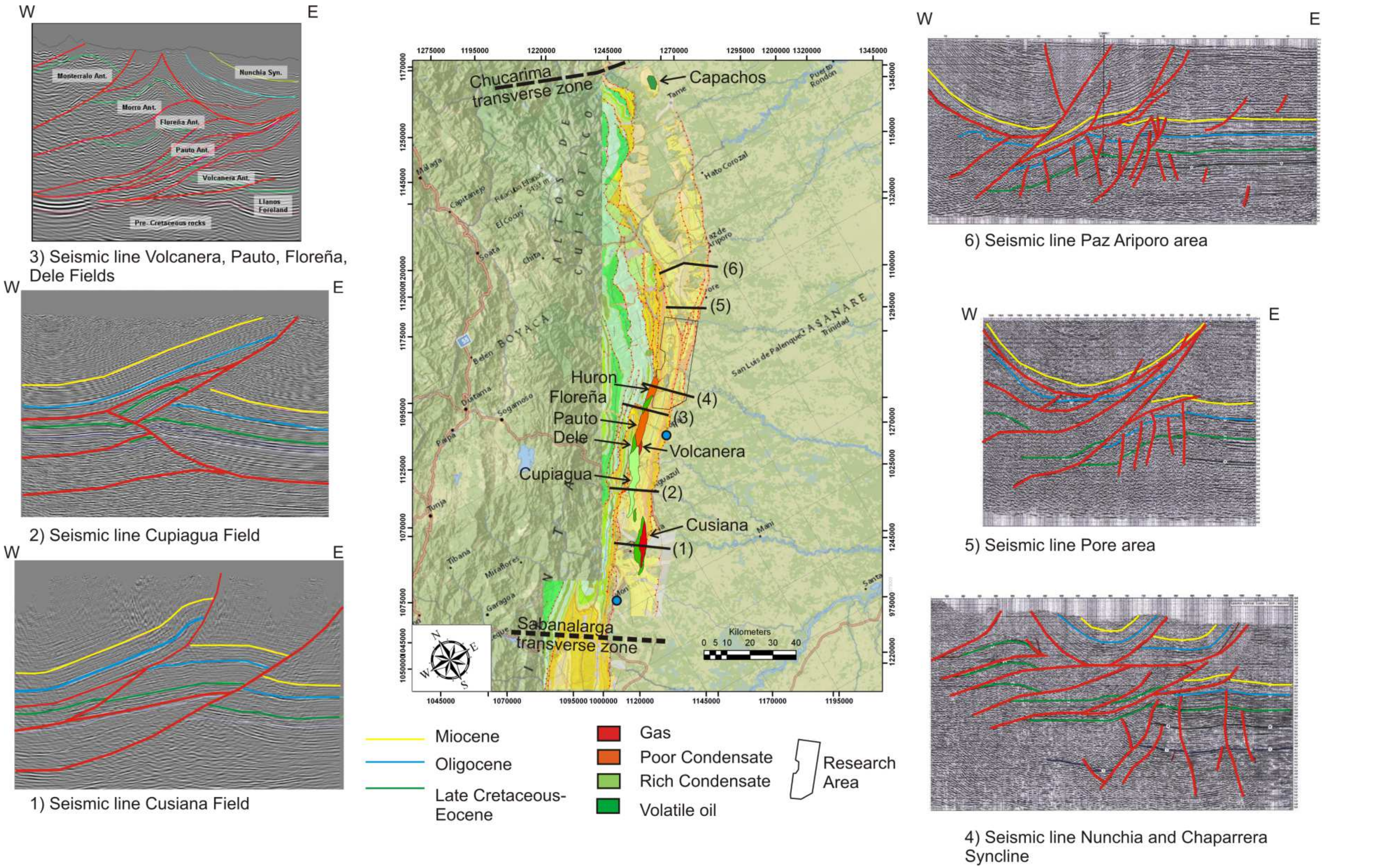


Figure 4. Seismic interpretation and structural styles along strike in the Central Llanos Foothills. Adapted from Cediel et al. (1998); Martinez (2003, 2006b) and Linares et al. (2009)

Although the traps in the CLF are essentially contractional fault-related folds (Rochat et al., 2003), during the last 60 years the structural models/interpretations have varied from thin-skinned to inversion tectonics (Martinez, 2003, 2006b). In the region between Cusiana to the Huron oil fields, Martinez (op. cit.) divided the area into three deformation zones from west to east (figures 3): Overthrust (antiformal stack Linares et al. (2009)), transitional and frontal. The overthrust zone is characterized by a series of duplexes in a triangular zone, with elongated backlimbs and tight to overturned frontlimbs (Pauto complex, which is cmposed for the Volcanera, Dele, Pauto, Floreña and Huron oil fields). The transitional zone is a low relief, high amplitude, tight asymetric structure (Cupiagua oilfield). Finally, the frontal zone is described by large, asymetrical hanging wall structures (Cusiana oil field).

Tectono-stratigraphic setting

In the EFEC a Cretaceous – Cenozoic sedimentary sequence with multiple unconformities that overlay in unconformable contact a sequence of Ordovician shales have been reported by wells in the area (Amaya et al., 2006; Barrero et al., 2007; Cazier et al., 1995; De'Ath, 1995; O'Leary et al., 1997; Ramon and Fajardo, 2006) . Two types of deposits have been identified post-rift and foreland (figure 5). The post-rift deposits are represented by the Une and Gachetá formations, while the foreland deposits are represented by the Guadalupe, Barco, Los Cuervos, Mirador, Carbonera, León and Guayabo formations. The foreland deposits are grouped in five tectono-stratigraphic sequences (Bayona et al., 2008).

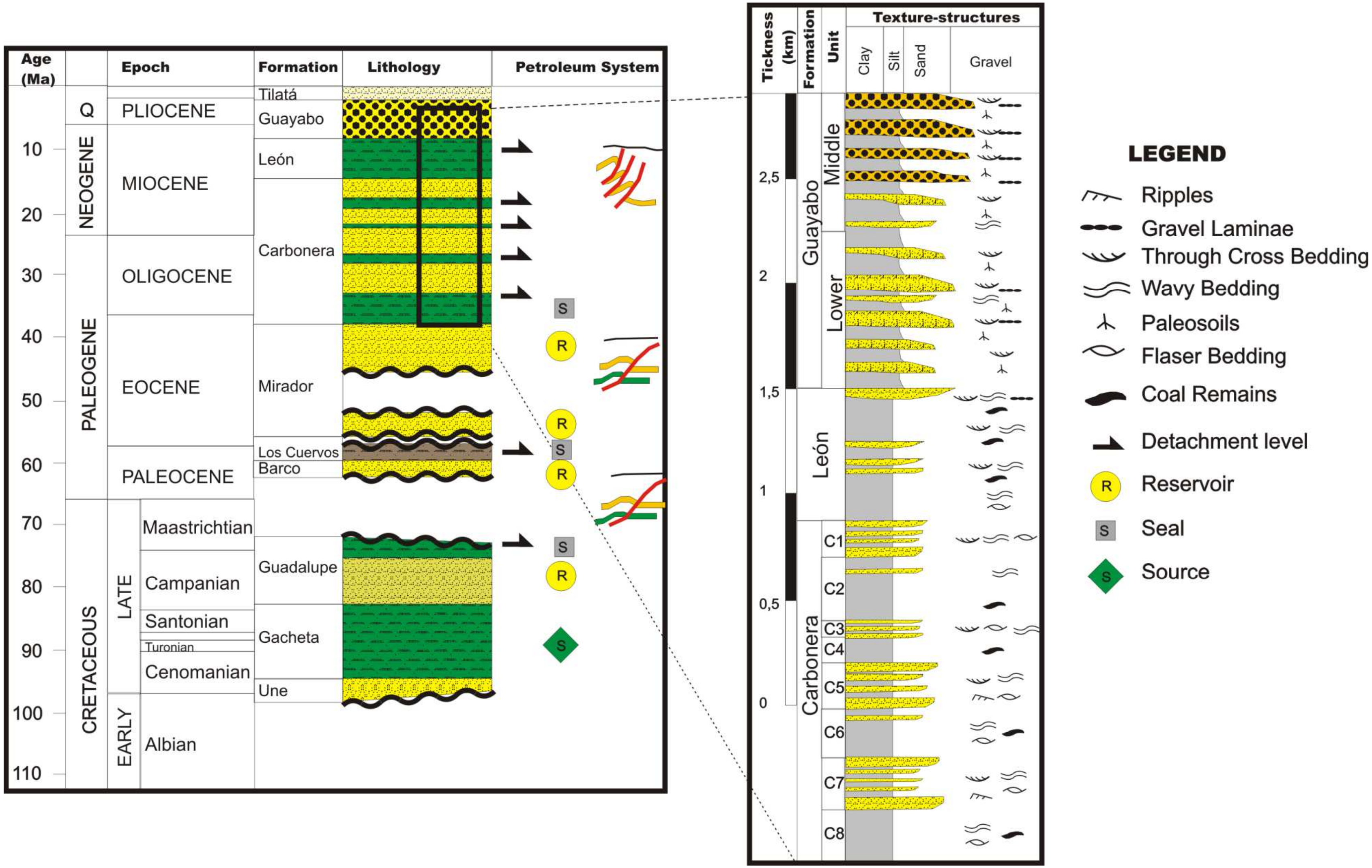


Figure 5.General stratigraphic column for the study area. Adapted from Barrero et al. (2007); Martinez (2006a) and Ramirez-Arias et al. (2012)

Foreland deposits

Guadalupe Formation

This Formation is divided in two units; a lower unit (122 to 152m thick) which consists of a package of shallow marine shelf sandstone with intercalations of phosphatic-rich sandstones and the upper unit, which is comprised of a sequence of claystones intercalated with siltstones.

The sandstones of the Guadalupe Formation are the lower reservoir targets in the EFEC. These sandstones are lithoarenites with porosities between 4 to 20% and were deposited during the Santonian to Campanian.

Barco Formation

The Barco Formation is a progradational estuarine unit composed of sandstones with some intercalations of marine claystones. This unit is one of the reservoirs in the EFEC with porosities between 2 to 12.5% and a thickness of 80 to 130m.

Los Cuervos Formation

The top seal for this unit is represented by the continental claystones and siltstones of Los Cuervos Formation. This unit has a thickness of 140m.

Mirador Formation

The Mirador Formation is a succession of of quartz-arenites deposited in the Late Miocene (thickness of 130 to 160m). This Formation is divided into Lower Mirador and Upper Mirador units.

This Formation is the principal reservoir unit in the EFEC. It contains more than 50% of the oil reserves tested in the basin (Amaya et al., 2006; Cazier et al., 1995). The porosities vary from 2-12.5% with permeabilities up to 1 darcy (O'Leary et al., 1997).

Carbonera Formation

This Formation is a succession of claystones and sandstones that are divided into eight units, where the C-1, C-3, C-5 and C-7 represent the continental rich sandstones units and the C-2, C-4, C-6 and C-8 the claystones deposits. These deposits recorded the initial uplift of the EC (Parra et al., 2009). Across the area, these units vary in thickness. They are thicker and coarser to the west and thinner to the foreland. The lower Unit, C-8 is the seal rock for the principal reservoir in the basin.

León Formation

The León Formation is a dark laminate claystone and mudstone with marine fauna, molluscs and foraminifera. It has a thickness of between 500 to 650m. This unit was deposited in the Middle Miocene.

Guayabo Formation

The Guayabo Formation represents the molasse deposits of the uplift of the Eastern Cordillera. In the EFEC the Guayabo Formation can reach more than 1.6km in thickness and is divided in two units. The lower unit is an intercalation of thick bed sandstones with claystones. The Guayabo Formation was deposited from Middle to Late Miocene to Pleistocene.

DATA

This research is based on 3D seismic, 2D seismic, two exploratory wells and three geological maps (figure 6). This information was kindly provided by the Colombian Hydrocarbon National Agency (ANH) to the author, to improve the regional understanding of the area and to re-evaluate its hydrocarbon prospectivity in terms of the structural configuration.

Seismic data

The research was focused on the interpretation of the seismic information available in the area. The Tangara-3D seismic cube has dimensions of 40km x 14,5km, and an area of 533,5km^2. This was the first exploratory 3D seismic with sparse design in the EFEC area. Table 1 shows the principal information and the parameters of the 3D seismic survey. Additionally, 511km of 2D seismic, represented by 24 seismic lines complemented the information of the study area. These were gathered in four vintages acquired from 1989 to 1993 (table 2). Figure 7 shows a comparison between the 3D and 2D seismic surveys. The Tangara-3D survey and the 2D seismic available can be classified as fair to poor. Poor seismic quality is the result of geological complexity and technical issues, which are discussed below.

Table 1. Parameters of the 3D seismic available

Vintage	Km	Process	Length	Time recorded	Sample interval
Tangara	area	PSTM	39.8km	7s	4
IL				XL	
Number	interval	Length	Rotation from north	Number	interval
798	50m	20km	128.3	801	25

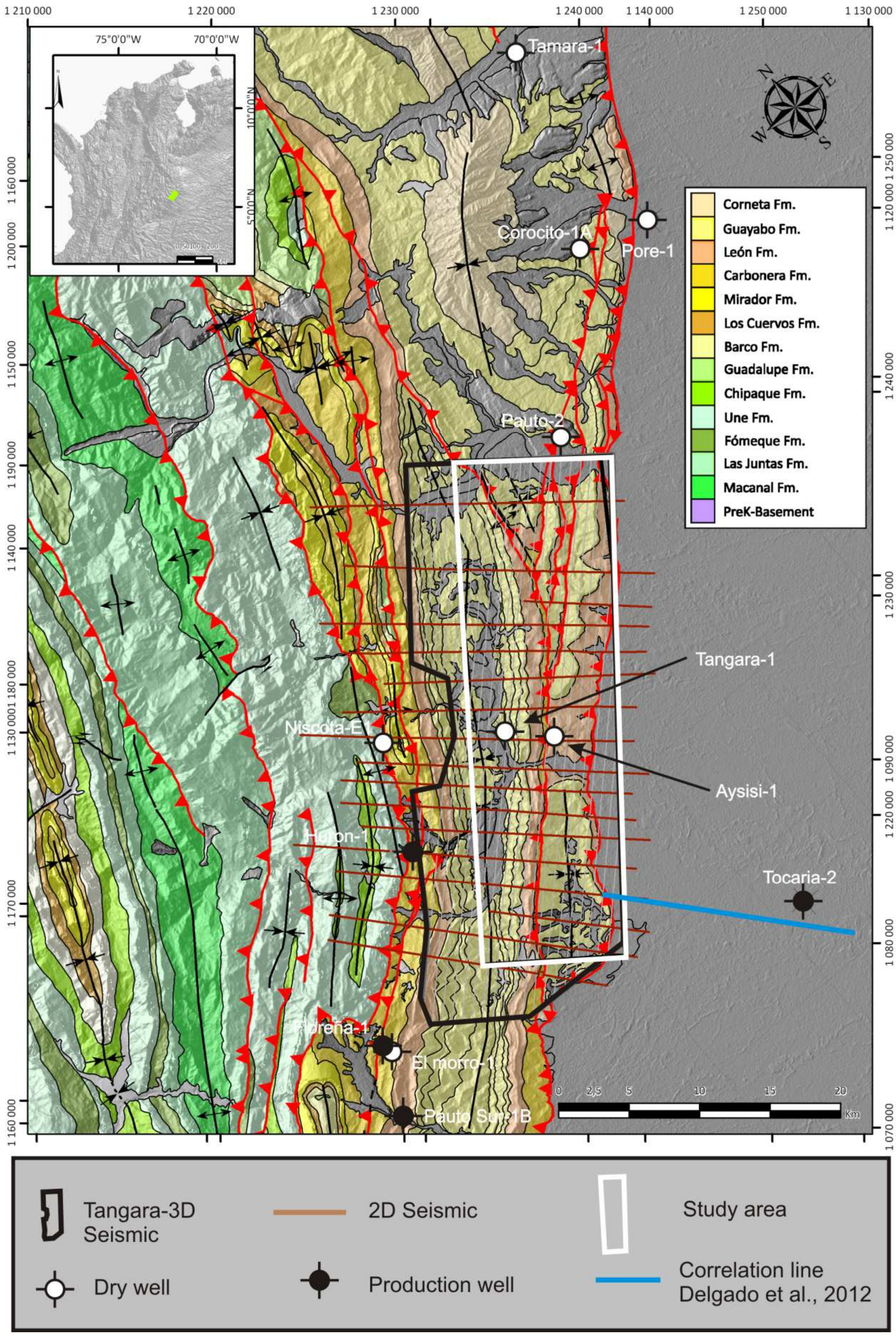


Figure 6. Location of the study area and information available.

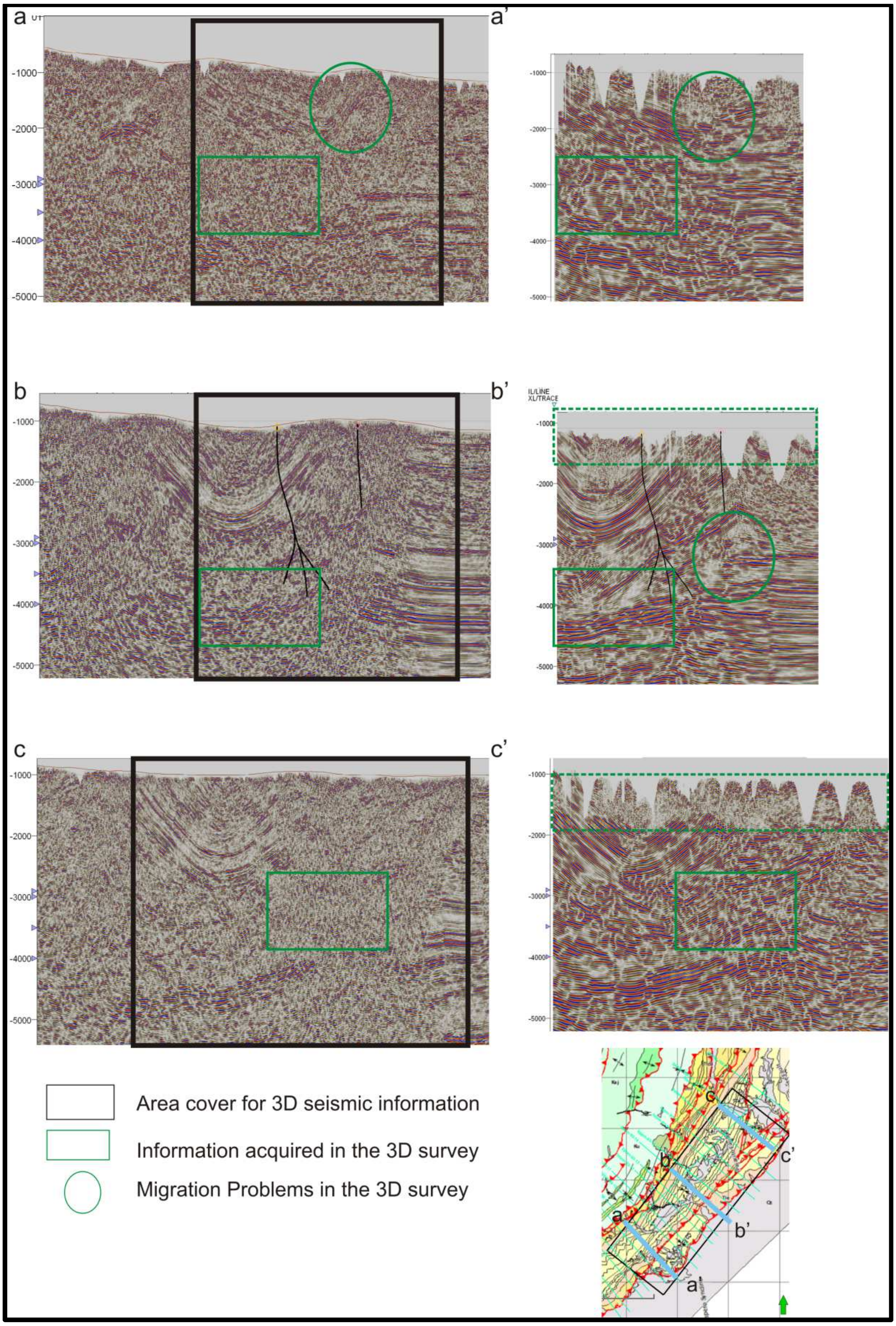


Figure 7.Comparison between 2D and 3D seismic using the same scale and location. The lines are displayed from south to north. Lines a, b, and c correspond to 2D seismic. The letters a', b' and c' are related to the 3D seismic image.

Vintage	Number lines	Km	Array type	Sample interval
Pauto tamara-1989	2	17.8	Symetric	4
Pauto-1990	2	35.8	Symetric	4
Pauto-1992	3	60.4	Symetric	4
Piedemonte-1993	17	40	Symetric	4

Table 2. Seismic vintages and parameters of the 2D seismic used

Geological complexity

1- ***Dips:*** High structural dips (35 to 75 degrees) in the surface and in the subsurface forelimbs.

2- ***Depositional system:*** The stratigraphic sequences have contain a high percentage of continental deposits. These deposits are characterized by low continuity and thickness variations in all directions.

3- ***Structural complexity:*** The foothills exhibit a series of imbricate structures. These structures have high dip and complex geometry that cannot be well illuminated in the seismic.

4- ***Lateral or oblique ramps:*** These discontinuities along the strike can create high dips and sharp changes in the structure's geometries that are usually not well defined in the seismic.

Technical issues

1- ***Acquisition parameters:*** Theoretically the sparse 3D seismic increases the number of channels and uses wider receiver line spacing to obtain the same result than a conventional 3D seismic (Estrada and Jaramillo, 2003). Due to the small number of shots, this design is recommended during the exploration phase. Although, the study does not compare the two methods, the overall results allow the seismic to be classified as poor to acceptable. However, during the study, some anomalies along strike were found.

2- ***Noise and static attenuation:*** Several advances have been made to reduce the noise and static problem generated by the topography and lithology. However, they are not perfect and the processor, if using aggressive filtering techniques can remove important information during processing.

   Taking into account that the seismic was processed in 2003, it could still be improved using leading edge process technology.

3- ***Seismic fold:*** Although the seismic processing report was not available, it is highly recognized that the boundaries of the seismic cube have a problem of seismic fold. Additionally, the high dips in the forelimbs and back limbs of the structures required longer receiver cables to acquire the signal. The parameters of the Tangara-3D may have not been enough to capture all of the reflections from the steep subsurface structures.

4- ***Velocity control:*** The seismic data available is a post stack time migration (PSTM) survey that was controlled by two wells. These wells are located in the middle of the seismic cube and are separated by 3.4km following the dip direction. Thus, the low velocity control makes it difficult to generate an accurate velocity model and therefore, an accurate seismic image.

5- ***Migration 2D line:*** Although the 2D seismic lines are longer and record reflection with high dips, these seismic lines contain several reflection out of the plane, increasing the noise and reducing the seismic quality

Well data

Two exploratory wells were used in the 3D structural model: Aysisi-1 and Tangara-1 (table 3). The information available from these wells were reports, directional surveys, check shots or VSP logs, and well tops information.

The Aysisi-1 well was drilled by Occidental of Colombia in 1993 with a total depth (TD) of 2143m (7032ft). The well targeted the Eocene sandstone of the Mirador Formation. However, the well only penetrated rocks of the Guayabo to upper Carbonera Formations. The Tangara-1 well started in 2004 and was abandoned in 2006 after 656 days of work. The objective was the sandstones of the Mirador and Barco Formations, included in an imbricate thrust sequence of the Piedemonte fault system. This well has four mechanical side tracks (Tangara-ST1, ST4 and ST5) and two geological side tracks (ST-2 and ST3). The well encountered mainly rocks from the Guayabo and Carbonera Formations that exceeded original prognosis. The reservoirs rocks were reached by the sidetracks ST-1 and ST-2, in a sequence below the Piedemonte fault system. These reservoirs were water bearing.

Well	Operator	Year	GL	RTE	TD		ST type
					m	ft	
Aysisi-1	Occidental	1993			2143	7032	
Tangara-1	Hocol	2004-2006	1140.91	1774.5			Mechanic
Tangara-1ST	Hocol	2004-2007	1140.91	1774.5	5564	18254	
Tangara-1ST2	Hocol	2004-2008	1140.91	1774.5	5794	19010	Geologic
Tangara-1ST3	Hocol	2004-2009	1140.91	1774.5	4952	16247	Geologic
Tangara-1ST4	Hocol	2004-2010	1140.91	1774.5	5224	17140	Mechanic
Tangara-1ST5	Hocol	2004-2011	1140.91	1774.5	5097	16724	Mechanic

Table 3. Wells include into this research.

The well tops of Corocito-1, Pore-1 and Tamara-1 wells were included for the analysis of the stratigraphic thickness (see observation chapter). These wells drilled the León, Carbonera and Mirador formations in the foreland area.

Well top uncertainty

The basin contains a 4km thickness of continental sediments and around 0.6km of marine sediments. They are easily distinguished based on their lithological properties. Some of these Formations are divided internally into units due to strong contrasting lithologies, e.g. The Carbonera Formation, which is divided into eight units. Usually during drilling in imbricate zones, the operator uses palynology *in situ* and logging while drilling (LWD) to help identify the top of a formation.

The definition of the units in the Carbonera Formation is one of the most critical aspects of well operations. In these units different casings are set and the last unit, C-8, is the top seal of the principal reservoir. The recognition of these tops is critical as to not damage the reservoir and to take the right decision when changing the drilling bit or setting the casing. However, the low lateral continuity, thickness changes and several faulted zones makes this work very challenging.

The palynological zonation for the Llanos Basin is a vital tool to solve stratigraphic problems, test structural models and to identify lithological units (Jaramillo and Rueda, 2004; Jaramillo et al., 2011; Jaramillo et al., 2006). However, the resolution of the palynological zones has a range between 2 to 10 million of years, which gives a considerable measure of uncertainty in dating. Additionally, the re-working of the units and the caving during drilling can contaminate the samples, increasing the uncertainty of the sample dating and therefore, the identification of the stratigraphic tops.

Surface geological maps

Three versions of geological maps and key publications (Bande et al., 2012; Ramirez-Arias et al., 2012; Tesón et al., 2013) allowed identification of different lithological contacts and faults on the surface.

METHODOLOGY

This research is divides into two sections, surface analysis and subsurface analysis.

Surface analysis

The surface analysis is based on the examination of a digital elevation model (DEM) of 30m resolution, existing geological maps and public information. This work was carried out in ArcGis with the objective of identifying the direction and relationships of the principal structures and faults. Additionally, it allowed the identification of changes in the mountain front and the recognition of western boundary of the foreland basin.

Subsurface analysis

The subsurface analysis was based on stratigraphic correlation and seismic interpretation of the data available. This data was tied to the surface geological map during the seismic interpretation.

Stratigraphic correlation

The stratigraphic correlation is supported by the analysis of the well data and surface information available in the foothills and foreland areas. For the foothills area the stratigraphic sequence is represented by the Tangara-1, Aysisi-1 and the rocks exposed in the Nunchia syncline (Ramirez-Arias et al., 2012). Whereas, the foreland area is represented by the Pore-1, Corocito-1A and Tamara-1 wells, and the study of Delgado et al. (2012).

This correlation concentrated on the identification of thickness variability in the stratigraphic sequence, the identification of the regional structural level's depth, and seismic facies recognition for the foreland sequence.

No e-logs were available, only the reported well tops were included in this analysis. The well tops are shown in measured depth (MD) and true vertical depth subsea (TVDss). In the study, the thickness of the units and formations were calculated using the TVDss value; because this value is the closer measurement to the real true stratigraphic thickness (TST). The values from TVDss are displayed with the negative symbol (-) to facilitate the differentiation between the MD and TVD values.

Subsurface structure

Taking into account that the principal source of uncertainty in a balanced cross section is the shape and thickness of the initial stratigraphic wedge involved in the deformation (Allmendinger and Judge, 2014), this research had an ambitious aim of generating a 3D structural model using the 3D seismic cube, Tangara 3D.

The model had three steps: 1) integration of the surface and subsurface data, 2) generation of a structural framework and 3) populate with the stratigraphic framework.

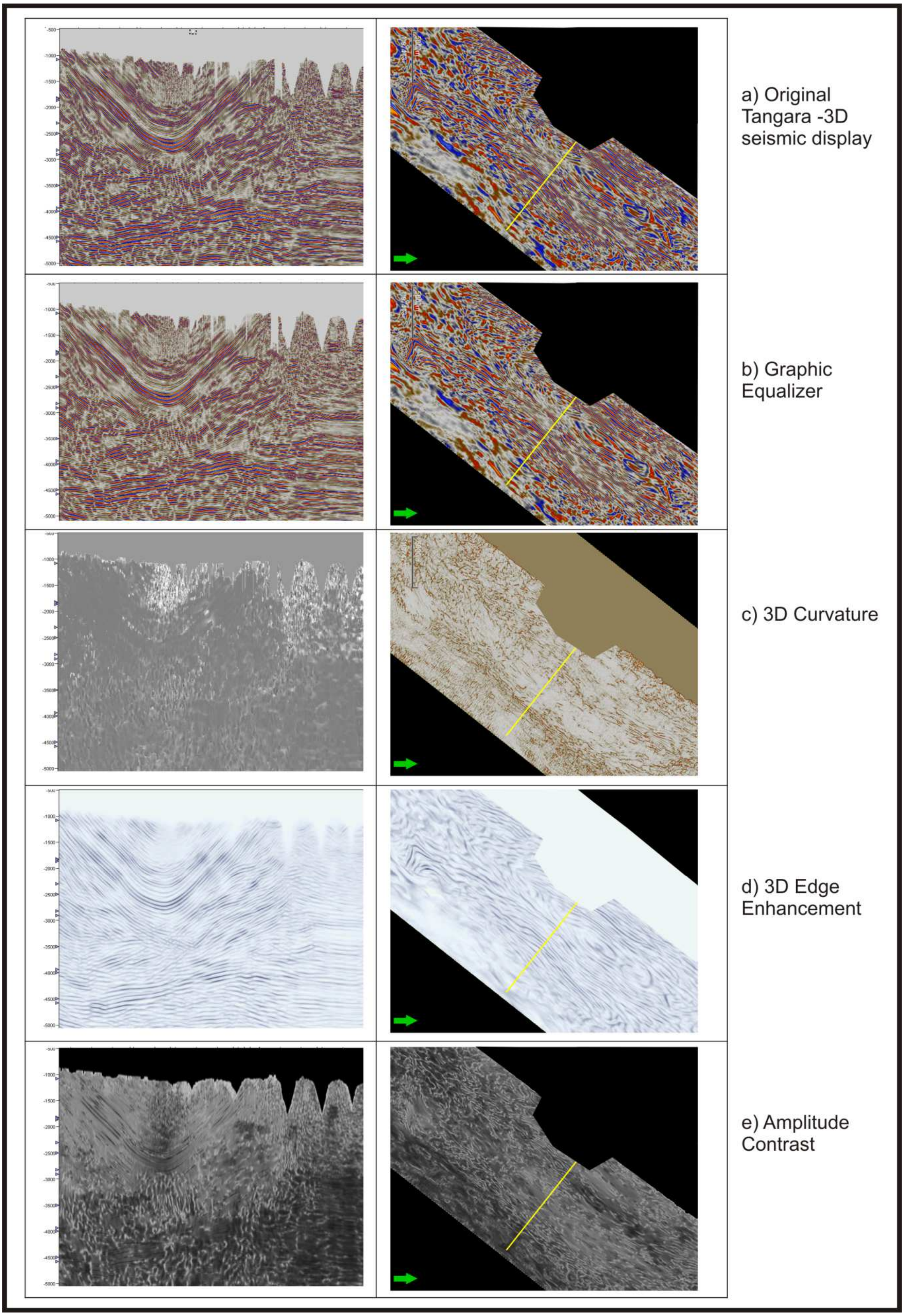
Integration of the surface and subsurface data

The seismic, well and surface geological data were compiled and interpreted using Petrel. To avoid distortion in the geometry of the 3D seismic data, the study was set to the original coordinate system of the seismic (Colombia Bogota datum zone). Additionally, the research uses the same unit convention established for the oil industry in Colombia, where the surface distance is in meters, the depth in feet, and velocity in feet/second. The seismic reference datum was set at 6561ft (2000m).

The 3D seismic has high amplitude. Therefore, to improve the seismic image or identify the discontinuities, seismic attribute analyses were applied in Petrel. Table 5 and figure 8 show the attributes tested and the principal characteristics of them. In summary, the interpretation was conducted in the cube generated with graphic equalizer attribute. This attribute improved the seismic image decreasing the frequency from noisy data. Although, the attributes: variance, edge enhancement, chaos and ant track allowed to recognized some structural features in the Nunchia syncline, these attributes do not work in the imbricate zone.

Seismic attribute	Operation	Objective
3D Edge Enhancement	Enhance edge detectiobn by emphasizing larger and planer features	Identify most frontal fault
Antitrack	Extract faults from pre-processed sesimic volumes.	Reveals discontinuities in seismic data either related to stratigraphic terminations or structural lineaments
Amplitude contrast	Uses the Sobel filter to isolate areas with amplitude discontinuities.	Identify faults
Chaos	Maps the "chaoticness" of the local seismic signal from statistical analysis of dip/azimuth estimate.	Identify faults
3D Curvature	Describes how bent a curve is at a particular point. Enables the detection of subtle structural changes in dip-saturated data.	Fault lineament detection, in particular in dip saturated data. Helps indentifying upthrown and downthrown sides of a fault
Variance	Signal coherency analysis: Estimates trace to trace variance (1-semblance). Amplitude Invariant (but not orientation invariant)	Fault detection from continuous variance response. Gas chimney mapping
Dip ilumination	Highlights structural geology with the use of lighting and dip field estimation	Fault identification
Edge	An edge enhancement method taht is based on statistical methods	Kind bands identification
Graphic equalizer	Seismic data bandwidth filtering : Applies a bandwidth filter with frequency indexed weighting as per defined in the equalizer	Reduce frequencies from noisy seismic

Table 4. Seismic attributes tested in this work to identify the discontinuities (faults) and improve the quality of the seismic image. Information extracted from Petrel® software and manuals.


a) Original Tangara -3D seismic display
b) Graphic Equalizer
c) 3D Curvature
d) 3D Edge Enhancement
e) Amplitude Contrast

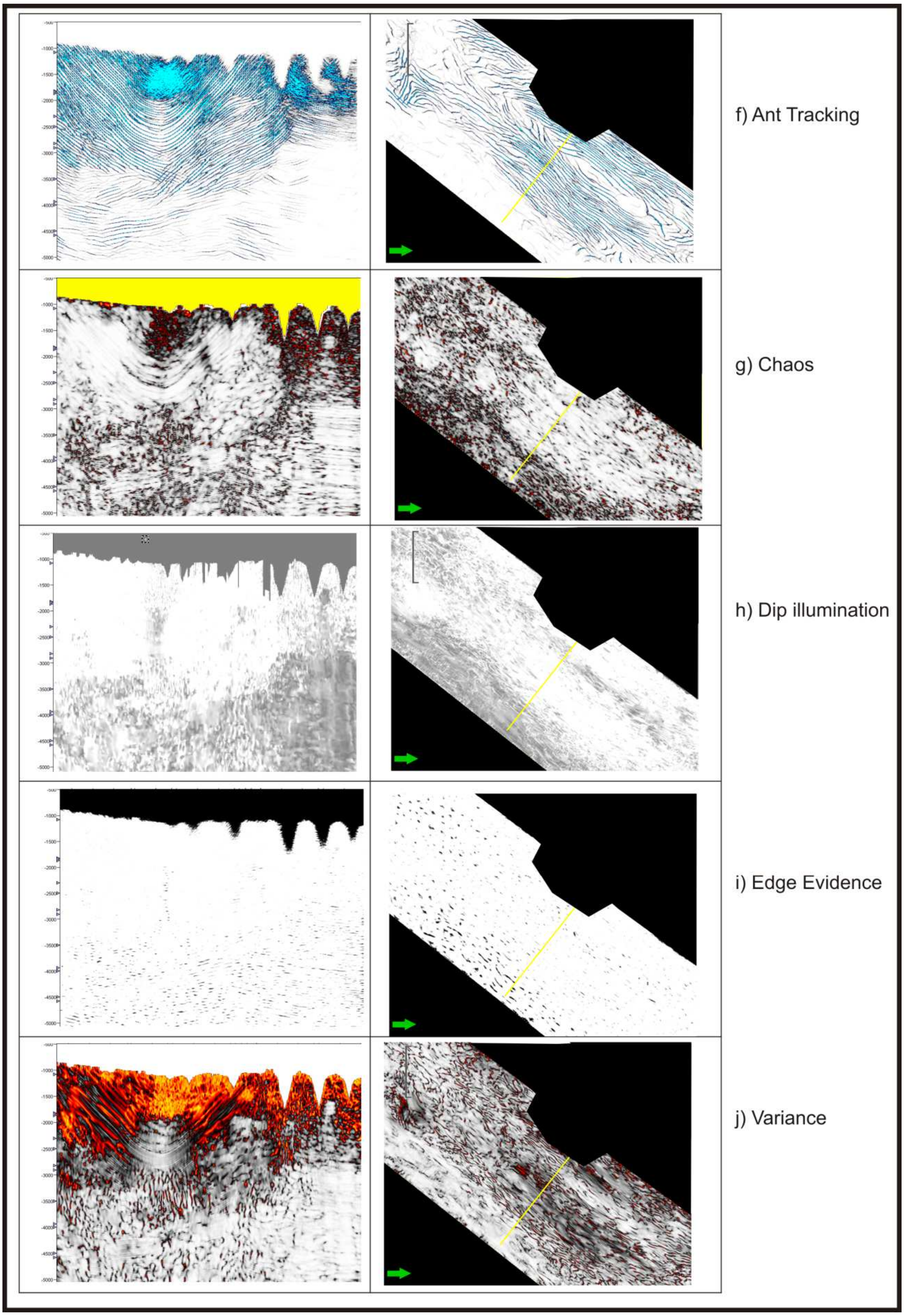


Figure 8. Examples of the seismic attributes tested to improve the interpretation of the structural framework.

During the subsurface interpretation, the workflow described by Tearpock and Bischke (2003, chapter 9) and the terminology described by McClay (1991) was applied.

Structural framework

Taking into account the interpretation was made in time domain, an approximation of 1:1 in vertical exaggeration was generated. In this, case the velocity was calculated from the deeper well, Tangara-1ST.

Therefore:

$$v = \frac{d}{t} = \frac{SRD + TD\ (in\ TVD)}{1WT\ second\ from\ SRD} = \frac{7012m}{1.9412s} = 3612.4\ m/s$$

This relation was used to calculate the vertical scale in the seismic profiles, e.g. for a horizontal scale of 1:50000, the vertical scale was calculated as 2.8s/in.

Knowing that in 1second represent 3612.4 meters, so:

$$VE = 3612.4m * \frac{1cm}{500m} * \frac{1in}{2.54cm} = 2.8in$$

On the other hand, to identify the fault plane, this work used the techniques descripted by Shaw et al. (2005). In this methodology, the fault identified in the dip line (figure 9) is confirmed and interpreted through the crossing points of the diagonal lines, generating fault planes. Finally, the interpretation of fault is completed continuing the same methodology along the strike of the fault.

Stratigraphic framework

The initial methodology was to generate a full structural framework for the whole area, which must be filled with the stratigraphic succession, respecting the lateral thickness change. However, during the development of the research, this methodology had to be modified.

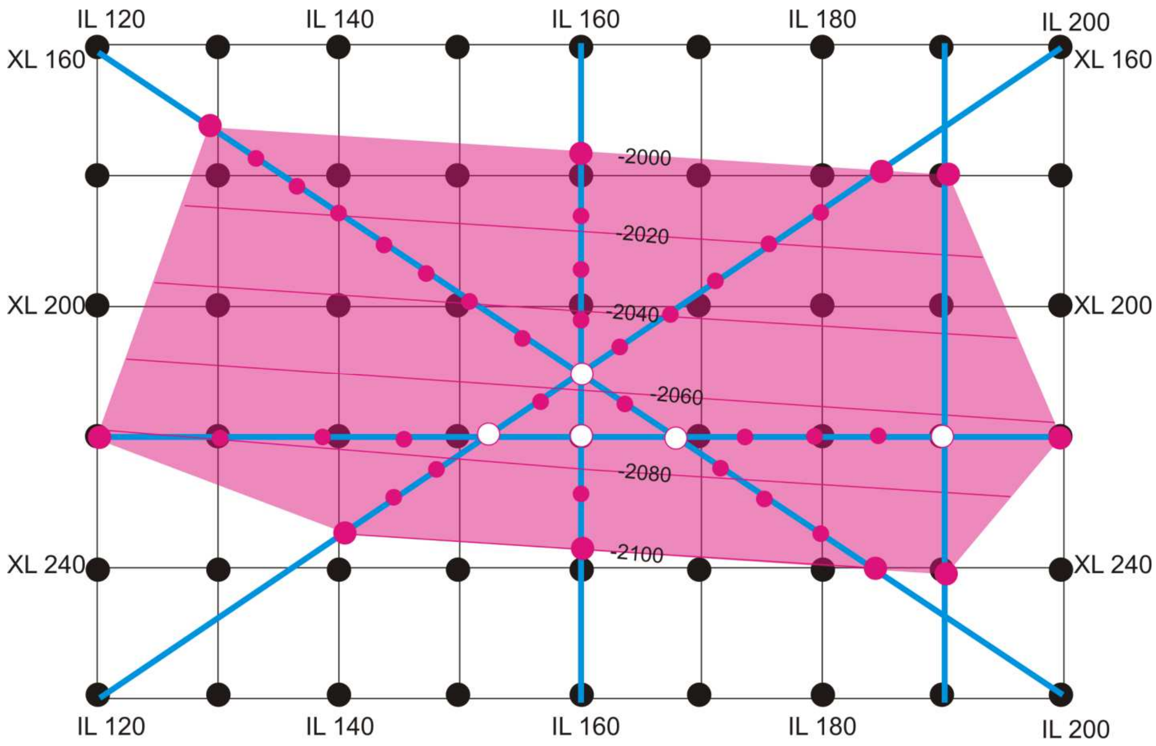


Figure 9. Methodology to identify the fault surface in 3D. Red points show the extreme point of the fault identified in an aerial view. Adapted from Tearpock and Bischke (2003) figure 9-18.

Modification of methodology

Starting from the area where the wells are located, the interpretation of the dip lines was done every kilometre. In this case, the structural and stratigraphic framework was interpreted in every line before move to the next section. To do the extrapolation of the faults, the methodology explained was followed (figure 9). If any inconsistencies were found in the structural framework, a control line between the two lines was generated.

Because of the structural complexity and relative poor quality of the seismic, the model assumed constant bed thickness and flexural slip deformation.

3D Model consistency analysis

To check the inconsistency of the interpretation, an analysis of fault displacement was conducted and random cross-sections were generated with Move software. This method calculates the cutoffs of the fault in the hanging and footwall.

The cutoffs permitted calculation of the throw of the faults and with recognizing the principal orientations, displacements and other statistical information from the study area.

DESCRIPTION OF THE MOST FRONTAL PART OF THE NUNCHIA FOOTHILLS

Surface geology

The geological map shows that the axis of EC changes in direction from NE to NNE in this area (figure 10). This change does not affect the whole mountain. The biggest directional changes are located in the central part of the Cordillera (N36E to N13E), and it decreases progressively towards the foreland, where the structures keep almost the same direction (N40E).

Geologically, the mountain front exposes rocks from Cretaceous to Pleistocene (figures 11). A marked change in topographic expression highlights the division between the lower and upper regions. The higher region is composed principally by Berriasian to Cenomanian sedimentary rocks, where the Une and Lutitas de Macanal formations represent the largest portion. Three principal faults were recognized, from east to west: Santa Maria, Paya-Pajarito fault and Guaicaramo fault systems. The structures are long and have an angular relationship with the faults of 10º.

The lower region, where is located the study area, is composed mainly of Cenozoic deposits of the Guayabo, León and Carbonera formations. Four principal structures can be recognized: Nunchia syncline, Zamaricote syncline Chaparrera syncline and Cardenalito monocline.

The southern structure is the Nunchia syncline. It is bound to the west by the Guaicaramo Fault and to the east by the Yopal Fault. In the north of the study area, the Nunchia syncline is replaced by the Zamaricote syncline (figure 12b). The Nunchia syncline is around 105km long and dies to the north of the study area, where it is replaced by the Zamaricote syncline.

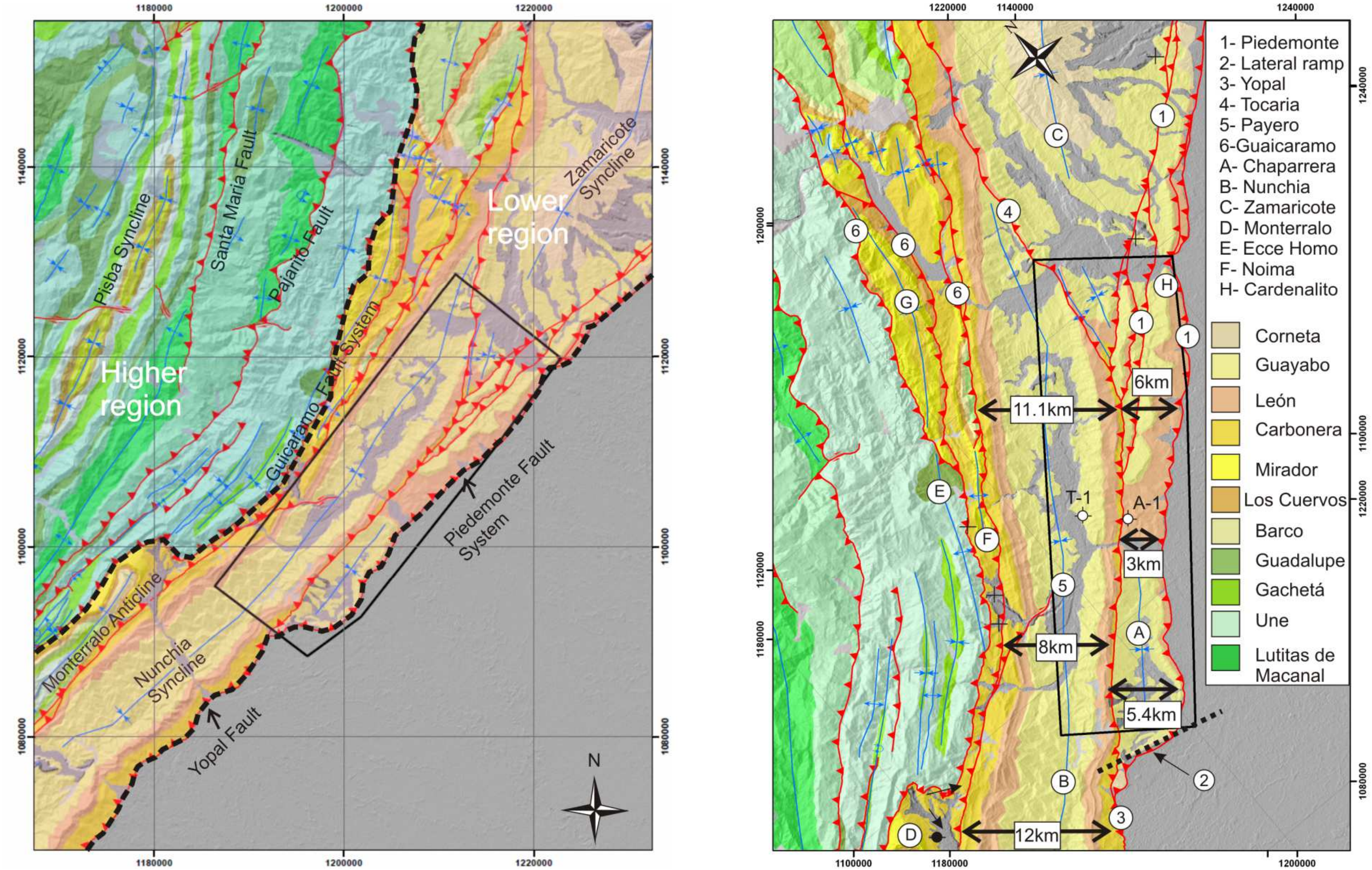


Figure 10: Surface geology of the mountain front in the Nunchia foothills area. Left image (a) shows the different regions in the mountain front. Right image (b) geological map of the study area which shows the structures and fault in the study area Green color represent Cretaceous rocks and yellow colors the Cenozoic deposits; north rotated 40º anticlockwise. The number shows the names of the faults and the letters the name of the structures. A-1= Aysisi-1; T-1= Tangara-1.

Based on its characteristics and axial surface direction changes, the syncline can be segmented in three areas: (1) In the south, asymmetric structure with a axial surface direction of N50ºE, 12km width and dips of between 20º to 30º in the eastern flank and 40º to 60º in the western flank. The flanks expose rocks from the middle Carbonera to Guayabo formations. (2) Near to the inflexion point of the Guaicaramo Fault, with a axial surface direction of N40ºE, 8km width and dips between 40º to 50º in the eastern flank and 40º to 65º in the western flank. The flanks expose rocks from the upper Carbonera to Guayabo formations. (3) Near to the Tocaria Fault, the structure reaches a width of 11.1km and becomes symmetrical with dips around 40º in the flanks. However, to the north of this point, the axial surface of the structure change to N20ºE and the hinge line rises up.

The Zamaricote syncline is bound to the west by the Guaicaramo fault system, to the east by the Piedemonte fault system, and to the south by a Tocaria fault, which has a hinterland-vergent thrust. The structure has a 120km length and becomes progressively wider until it reaches a maximum width of 32km. Differing from the Nunchia syncline, the Zamaricote syncline exposes rocks from the Corneta Formation (younger) in the axis of the syncline, representing an increase in space of accommodation.

The Chaparrera syncline is located to the south of the study area. This is a small symmetric syncline with N45ºE direction, 14.5km length and a maximum width of 5.4km. The syncline exposes principally rocks of Guayabo Formation and in the eastern flank, rocks of the León Formation. The hinge line rises up near the Aysisi-1 well.

The Cardenalito monocline structure is the most frontal structure. It is a hinterland-dipping structure that starts near to the Aysisi-1 well and plunges to the north until it becomes the eastern flank of the Zamaricote structure. In the south, the structure exposes rocks of the León Formation and involves rocks of the Guayabo Formation to the north.

Finally, the foreland basin is represented by quaternary flat deposits. This region is bounded to the west by the Yopal Fault or by the Piedemonte Fault System.

It is important to highlight that in the area where the EC changes direction, it affects the lower region. (1) The Nunchia syncline is narrower, the limbs are steeper and the axial surface changes in direction, (2) the hinge axis of the Chaparrera rises up and it becomes the Cardenalito monocline, (3) a sinistral strike-slip fault, Payero, cuts the western flank of the Nunchia.

Subsurface geology of the Nunchia foothills

Stratigraphic correlation

There are only two wells located in the study area, Tangara-1 and Aysisi-1. These wells drilled through a repeated sequence of continental sandstones and claystones of the Carbonera and León formations.

The Aysisi-1 well reached a total depth (TD) 2143m (7032ft). It has an average inclination of 5.2º with a SE direction. The tops reported show three faults located in the León Formation. In this well, only the units C-1 and C-2 of the Carbonera Formation were drilled. They have an average drilled thickness of 282m and 103m respectively.

The Tangara well has five sidetracks, two of them due to changes in the geological target (ST2 and ST3). The Tangara-1 and Tangara-1ST reached a TD of 5571m (18278ft). These wells have a predominant direction of 127º in azimuth. The well Tangara-1 has an average inclination of 20º, while the Tangara-1ST has an inclination of 18º that drop to 4º in the last 840m. The Tangara-1ST2 is a geological sidetrack that tried to reach the Mirador Formation in a higher position. The ST has a direction of 134º in azimuth with 36º of inclination. The Tangara-1ST3 is a geological sidetrack that was planned to penetrate the Mirador Formation present in the hanging wall of the Pardillo Fault. Finally the ST4 and ST5 were mechanical sidetracks. The last ST was abandoned due to mechanical problems.

Some anomalies were found in the Tangara-1 well tops. These anomalies are related to inconsistences in the unit thickness or possible overturned sections (figure 11 and 13). Therefore, the wells tops were gathered in different packages confined by faults or in the tops where the well does not follow the normal stratigraphic succession. This method was invented to organise the well tops and to allow for easier correlation between the sidetrack wells.

The most outstanding anomaly in Tangara-1 and 1ST is located between the packages VI to IX (figure 11). The package VI starts in the C-3 unit and follows the normal stratigraphic succession until the C-8 unit, where the top of the C-7 unit. No faults were recognized. The stratigraphic succession continues in reverse sequence reporting the C-6 unit (Package VII). After that, the well found the C-7 unit in a normal succession (package VIII). Finally, the sequence is faulted to the C-1 unit. The packages IX contain the C-1 to C-7 units. However, entire package is only 84m.

The same anomalies were found in the Tangara-1ST2 and Tangara-1ST3, ST4 and ST5 (figure 12). In the Tangara-1ST2, this section is reported as a normal package (IV) 730m of the C-4, C-5 and C-6 units, where the C-6 has an anomalous thickness of 536m. On the other hand, in the Tangara-1ST3, ST4 and ST5 the section is recorded by C.1 to C5 units in a normal stratigraphic succession but has an anomalous thickness of 955m.

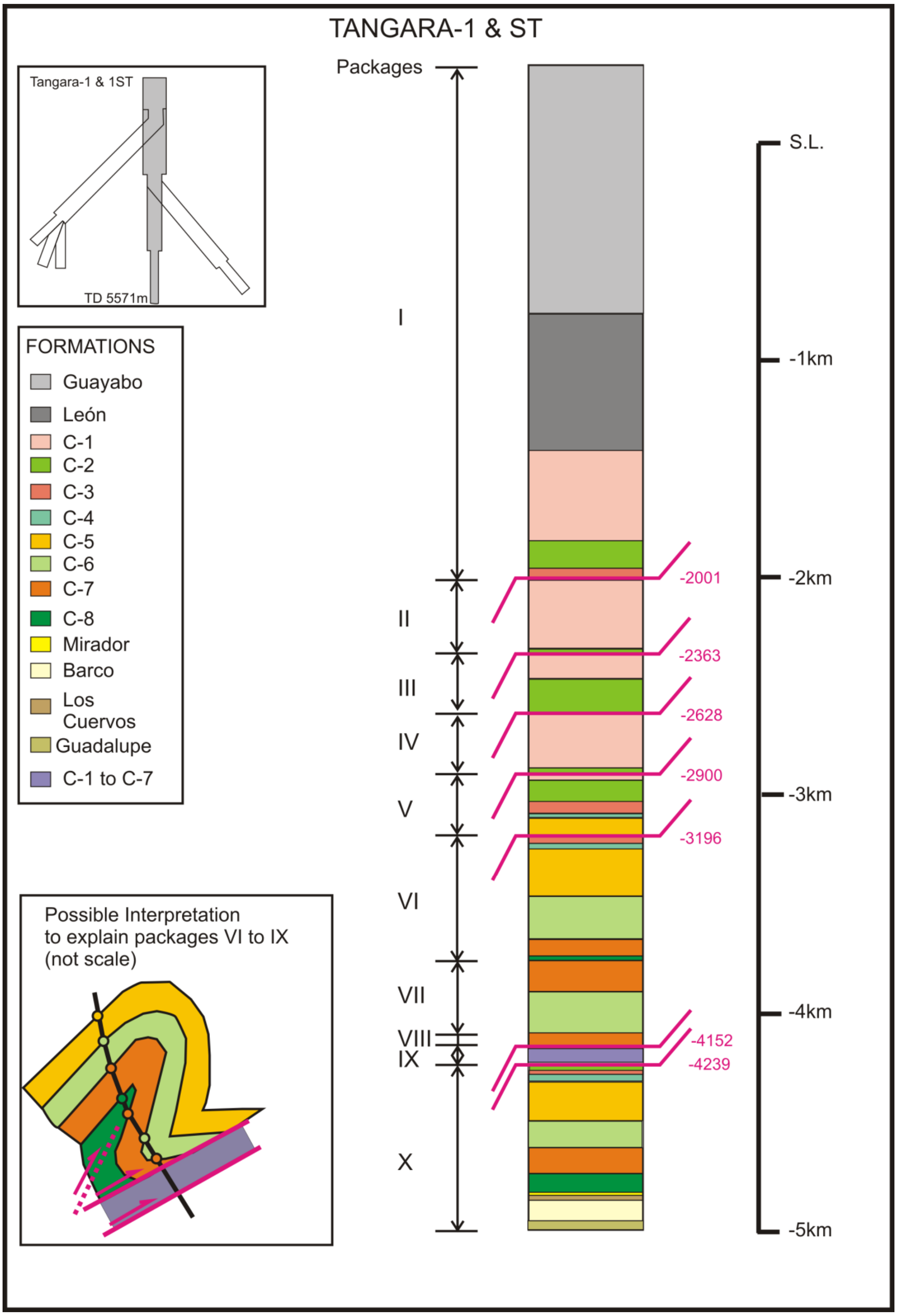


Figure 11.Stratigraphic column reported in the well report for the Tangara-1 and Tangara-1ST wells.

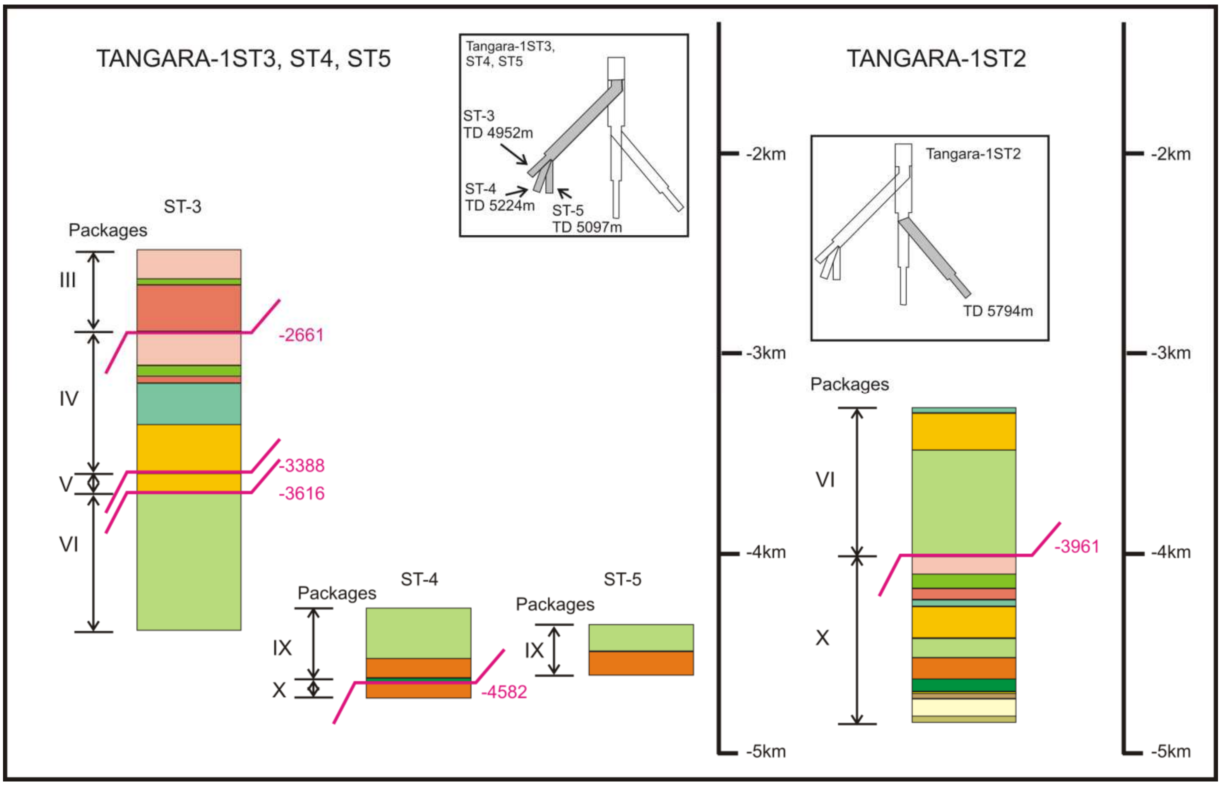


Figure 12. Stratigraphic column reported in the well report for the Tangara-1ST2, Tangara-1ST3, Tangara-1ST4 and Tangara-1ST5 wells.

Thickness from Tangara-1 wells and Asisi-1 well

The thickness of each unit and Formation was calculated from the units that are not faulted (table 8). These values were calculated in TVDss, which is the closest to the TST. Table 8 shows the thickness of the León, Mirador, Los Cuervos and Barco formations and highlights the differences in thickness in the units of the Carbonera Formation.

The Table 8 shows that the C-2, C-3, C-5, C-6 and C7 units, and Mirador, Guadalupe and Barco formations are thicker to the west; whereas, the C-4 Unit has a similar thickness.

Formation	ST	ST3	ST3	ST	ST	ST2	ST4	ST	ST2	Statistics		
	I	III	IV	V	VI	VI	X	IX	X	Average	Max	Min
Upper Guayabo												
Lower Guayabo												
León	-782.1									-782.1		
C1	-416.4									-416.4		
C2	-127.5	-176.0	-129.3	-114.8					-76.8	-124.9	-76.8	-176.0
C3			-62.9	-53.0				-31.3	-48.5	-48.9	-31.3	-62.9
C4			-27.4	-23.3	-27.5			-31.7	-29.2	-27.8	-23.3	-31.7
C5					-215.2	-183.3		-177.1	-156.1	-182.9	-156.1	-215.2
C6					-203.0			-127.3	-114.0	-148.1	-114.0	-203.0
C7					-72.9		-119.8	-114.8	-99.7	-101.8	-72.9	-119.8
C8								-86.2	-74.3	-80.2	-74.3	-86.2
Mirador								-14.5	-5.2	-9.9	-5.2	-14.5
Los Cuervos								-27.0	-22.9	-25.0	-22.9	-27.0
Barco								-144.5	-97.1	-120.8	-97.1	-144.5
Guadalupe												
Gacheta												
Lower Sand												

Table 5. Thickness values extracted from the Tangara-1 wells. Negative are used to show that values were generated from TVDss measurements.

Well Correlation

The stratigraphic sequences reported in the Aysisi-1 and Tangara-1 well have high variability in thickness. It could be caused by faulting, the deviation of the well, difficulties in the recognition of the unit (based on lithological and palynology), or simply, actual changes in thickness.

Therefore, a correlation between the Tangara-1, Tangara-1ST wells and the Aysisi-1 well was generated (figure 13). It shows at least six structures: (1) **Gavilán**. This structure is represented by the gathering of the package X in the three side tracks of Tangara-1 well. This is the only structure that includes the reservoir rocks in the deformation. (2) **Tangara.** It consists of packages VI in Tangara-1ST3, ST4, and ST5; the packages VI, VII, VIII and IX of the Tangara-1&ST; the package VI in Tangara-1ST2; and the package IV in Aysisi-1 well. This structure is related to the Pardillo fault.

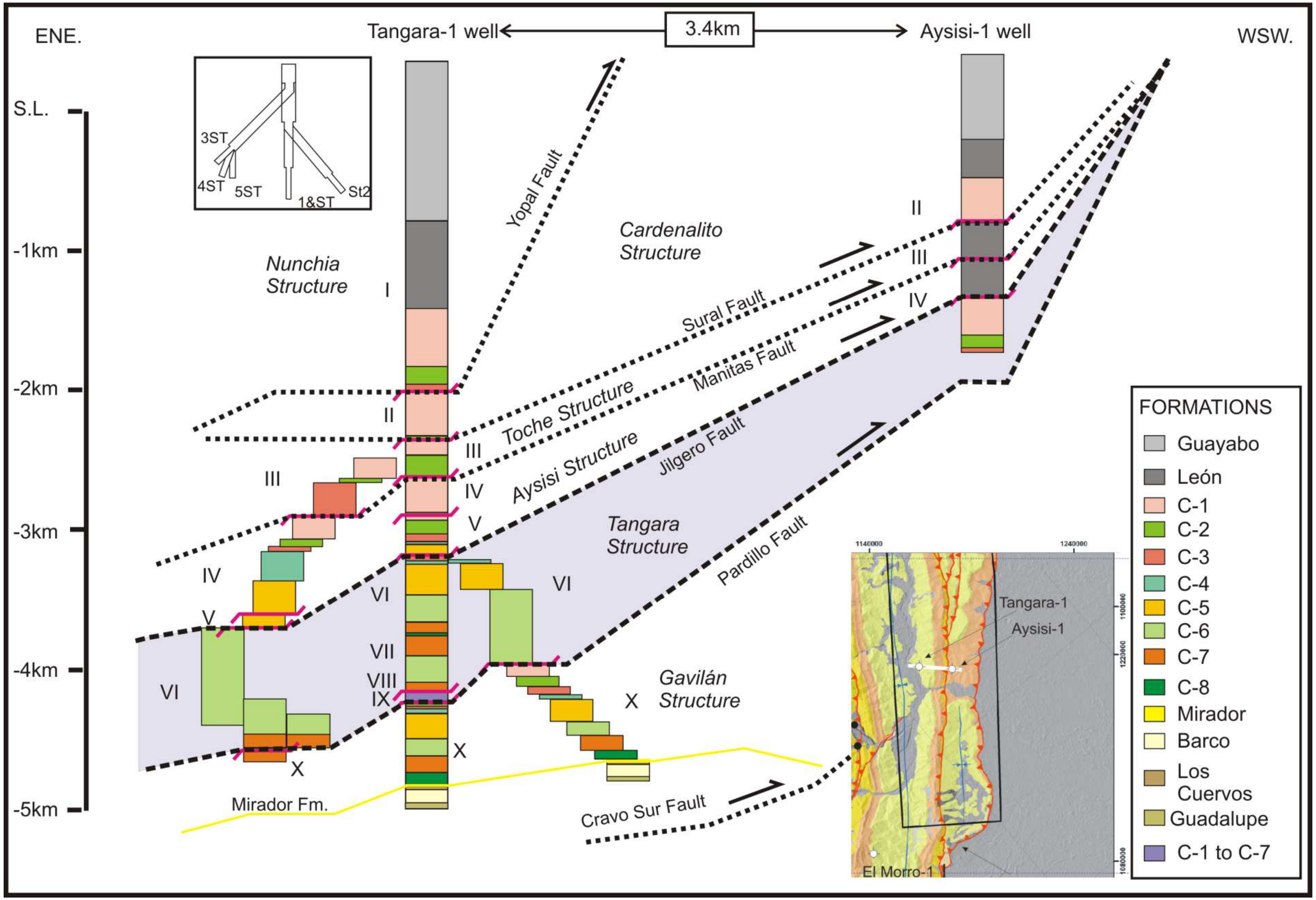


Figure 13. Well correlation between Tangara-1, Tangara-1 sidetracks and Aysisi-1 well. No horizontal scale was used. Depth in TVDss.

Although the Tangara-1ST reports a reverse stratigraphic sequence in this zone, the Tangara-1ST3, ST4 and ST5, drilled in the back-limb of the structure do not support it. Instead, it only shows a thick sequence of the C-6 Unit. (3) **Aysisi.** It is related to the Jilgero Fault and it is represented by the packages V and VI in Tangara-1ST3, ST4 and ST5, IV and V in Tangara-1&ST; and the package III in Aysisi-1 well. (4) **Toche**. It is generated for the aggregation of packages III in Tangara-1&ST and II in Aysisi-1 well. This structure is associated to the Manitas Fault. (5) **Cardenalito**. This structure is related to the packages II in the Tangara-1 and I in the Aysisi-1 well. This structure is related to the Sural I Fault and its surface expression is a hinterland-dipping monocline. (6) **Nunchia**. This structure is represented by the package I of the Tangara-1 well. This well drilled the eastern flank of the Nunchia syncline.

Furthermore, to observe the lateral changes between the Nunchia foothills and the foreland, results from the study by Ramirez-Arias et al. (2012)

from the Nunchia syncline were integrated in the study as well as formation thicknesses reported in some well of the foreland basin.

Foreland sequence

The Formation and Unit thicknesses were extracted from the well top of the Corocito-1A, Pore-1 and Tamara-1 wells (Table 6). The northern well is Tamara-1, located 48km to the North. The Corocito-1A well is located 34.8km to the NNE and the Pauto-1 37.8km to the NNE (figure 6). The well Corocito-1A has a repetition of the Guayabo Formation. Therefore, the rocks located in the hanging wall were removed from the analysis and the values used are in TVDss.

Formation	Foothills			Foreland		
	Ramirez *etal*	Tangara-1	Aysisi-1	Corocito-1	Pauto-2	Tamara-1
	m	TVDss		TVDss	TVDss	TVDss
Upper Guayabo	680				-1505.7	-3968.2
Lower Guayabo	760			-714.1	-1542.3	
León	640	-782.1		-517.2	-376.4	-469.1
C1	180	-416.4	-282	-30.8	-166.1	-216.1
C2	300	-124.9	-103	-72.8	-67.1	-76.8
C3	80	-48.9		-52.4	-48.8	-54.3
C4	120	-27.8		-95.7	-76.2	-22.9
C5	220	-182.9		-95.7	-79.9	-184.4
C6	240	-148.1		-84.7	-101.5	-24.7
C7	260	-101.8		-79.2	-88.4	-94.8
C8	260	-80.2		-57.9	-44.2	-158.8
Mirador		-9.9		-48.7	-57.9	-81.7
Los Cuervos		-25.0			-23.8	-12.8
Barco		-120.8			-82.9	-48.2
Guadalupe					-111.3	
Gacheta					-164.3	
Lower Sand					-39.3	

Table 6. Thickness correlation between the foothills and foreland areas. Negative values are used to highlight that values correspond to TVDss measurements.

Foothills sequence

The foothill sequence is based on the average thickness calculated from the Tangara-1 and Aysisi-1 wells (table 5) and the unit thickness reported in the Nunchia Syncline by (Ramirez-Arias et al., 2012) (figure 5). They report a sequence that starts in the Middle Guayabo and finalized in the C-8 Unit of the Carbonera Formation (table 6).

Foothills -Foreland Correlation

Table 6 shows the units extracted from the wells and the surface. The values used for the Tangara-1 well are related with the average thickness calculated in table 5.

The following observations can be extracted from the table:

1- The Guayabo Formation is thicker to the west and to the north

2- The León Formation and the Units of Carbonera Formation are thicker to the west.

3- The Mirador has a thicker section to the north in the foreland area.

4- The Mirador Formation has a thinner thickness value in Tangara-1.

5- Los Cuervos and Barco formation are thinner to the North.

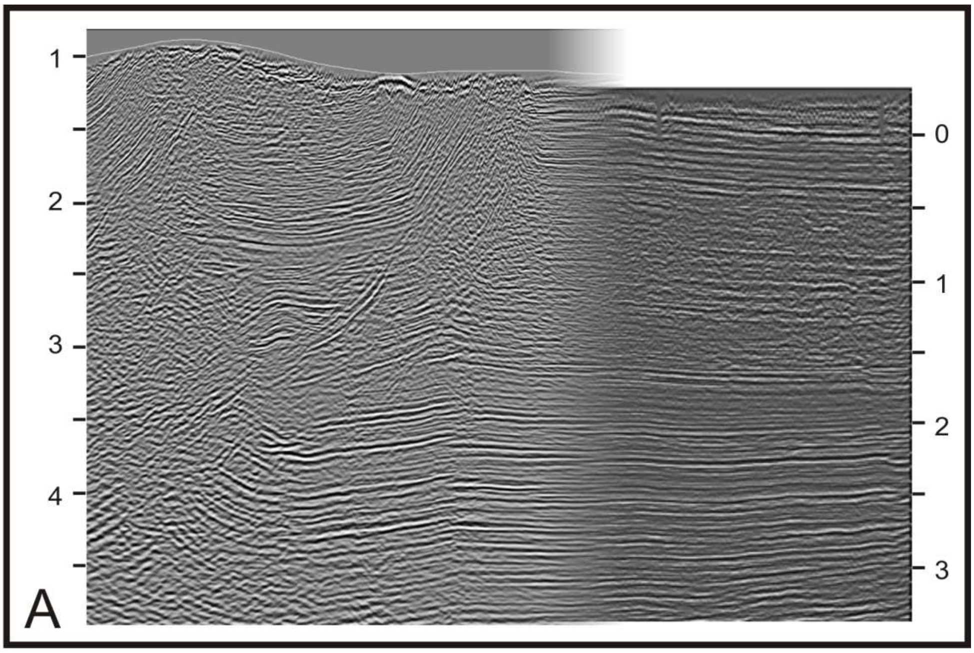
Seismic interpretation

Foothills and foreland correlation

Two regions have been recognized: The Nunchia foothills to the west and the Llanos foreland to the east. In the study area the nearest well located in the foreland is the Tocaria-2 well (figure 6). However, no well information or seismic imaging was available in this area to identify the foreland deposits. A solution was to merge an interpretation made in the foreland by Delgado et al. (2012) with a seismic line available for this study, as shown in figure 14. It permitted the identification and tie of the different formations in the foreland. Additionally, it allowed identifying for every formation, the seismic character, depth and seismic thickness.

Taking as reference the seismic reference datum of the project (2000m), the top of the León Formation was detected at 3125ms, Carbonera Formation at 3515ms and Mirador Formation at 4050ms. Therefore, the thickness of the León and Carbonera formations is 390ms and 535ms respectively. These values are in two-way-time (TWT).

Table 11 and figure 13 show the seismic facies and seismic patters for the different formations in the foreland deposits. Although, the 3D seismic is characterized by high amplitude reflections, the patterns and seismic facies can be recognized in 2D and 3D seismic data.



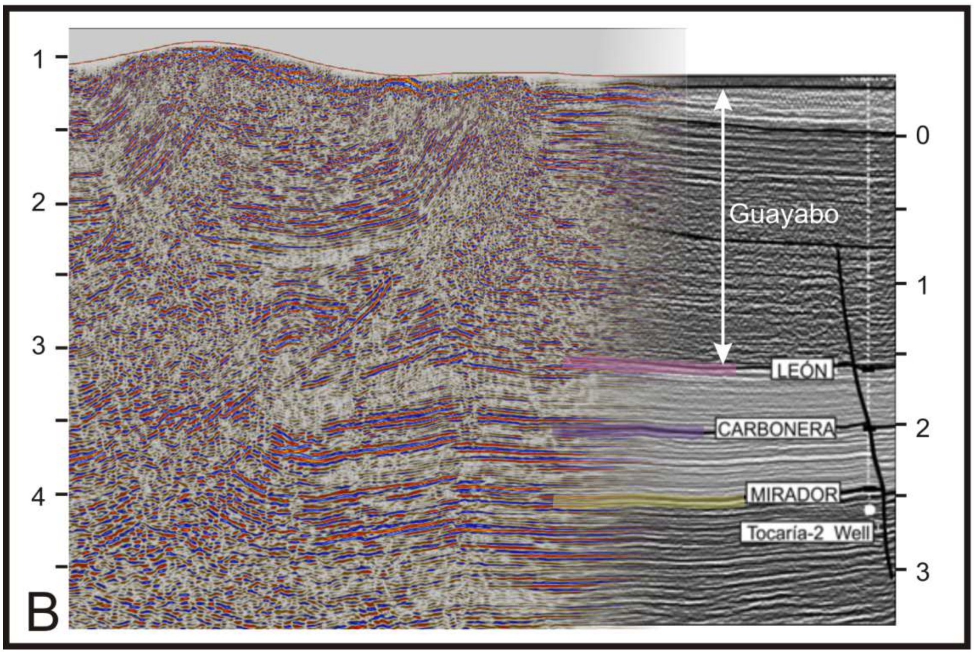


Figure 14. Seismic correlation between the study area and the foreland basin. Right image figure 5 by Delgado et al. (2012) and left image 2D seismic section over the study area. (A) figure correlation without interpretation (B) section interpreted and extrapolated to the study area. The left image used a different color bar to show the different seismic character of every Formation. See figures 6 or 17 to location of the correlation.

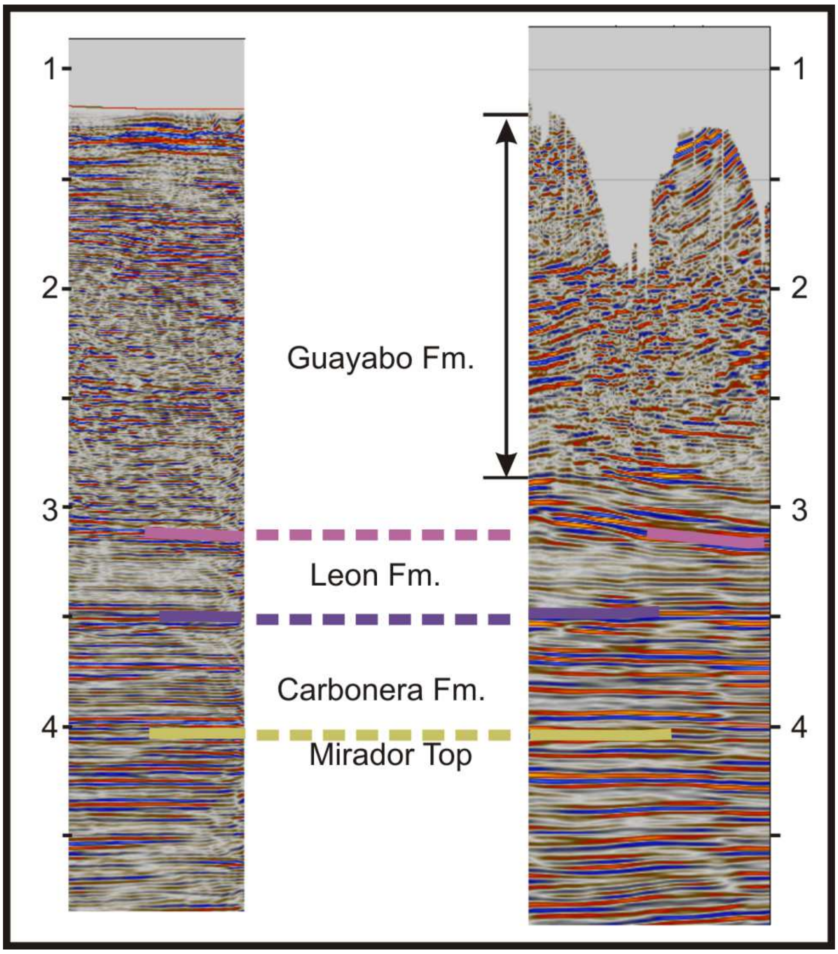


Figure 15. Seismic facies identified for the foreland in the study area.

FORMATION	CONTINUITY	AMPLITUDE	FREQUENCY	PATTERN
Guayabo	Discontinuous	High	Medium	Subparallel
León	Continuous	Low	High	Almost free
Carbonera	Medium	Medium	Medium	Subparallel
Mirador and Cretaceous	Continuous	High	Low	Subparallel

Table 7. Characteristics of the seismic facies identified for the foreland in the study area.

On the other hand, in the foothills zone, these patterns can be recognized only in the Nunchia and Chaparrera syncline. There, the León Formation is a package almost free of reflections with low amplitude and high frequency; and the Upper Carbonera Formation is characterized by strong reflections with high amplitude and low frequency.

Below these surface structures, it is not possible to recognize seismic patterns. This zone is characterized by reflections with high amplitude and low continuity in the N-S and E-W directions. However, three thin packages of high frequency and medium continuity could be documented. They are related to the C-1 unit, C-3 to C-5 interval and C-7 unit.

Below the deformation zone, a non-deformed package with strong reflections, low frequency and high amplitude is easily recognized. This package has a thickness of around 4000ms.

General Configuration

The subsurface structural configuration of the most eastern part of EFEC was defined through the interpretation of the Tangara-3D seismic survey and some 2D lines within the study area (figure 17). The Yopal Foothills area is located 15km to the east from the southern part of the study area (figure 17). In this zone are located the Pauto -Floreña, Dele and Volcanera oil fields, where different authors have proposed triangular zones (Martinez, 2003, 2006b) or antiformal stack structural configurations (Egbue and Kellogg, 2012; Linares et al., 2009).

A southern 2D seismic line was interpreted schematically in this area (figure 18). It can be interpreted as an antiformal stack with active-roof duplex. This zone has a foreland-vergent thrust system where the structures have a predominant strike direction of 40º in azimuth direction (figure 18)

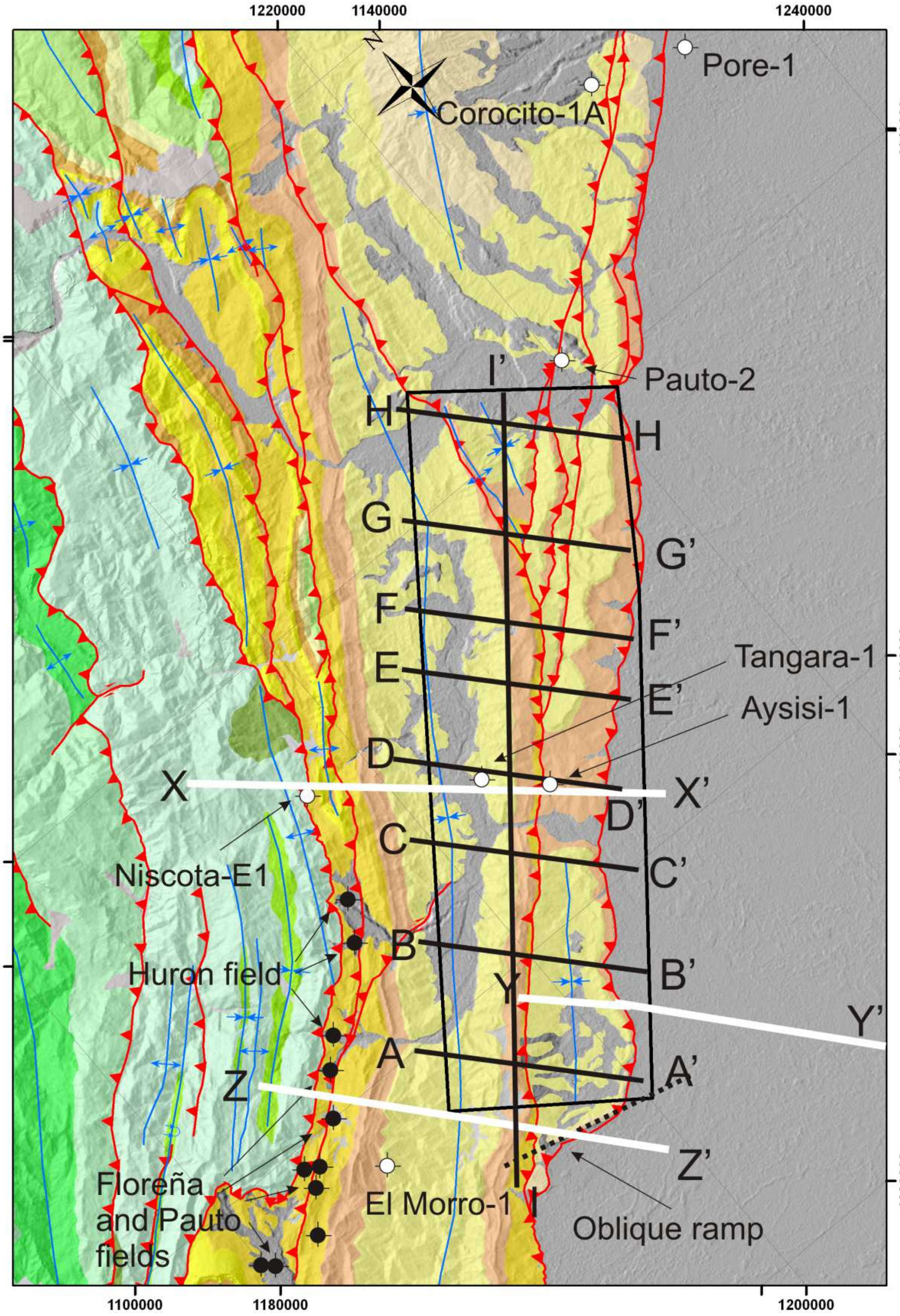


Figure 16. Location of cross sections located in the study area. X-X' shows the regional configuration of the Nunchia foothills; the section Y-Y' a correlation with the foreland basin; and the sections A-A' to F-F' the structure configuration of the east area of the Nunchia foothills.

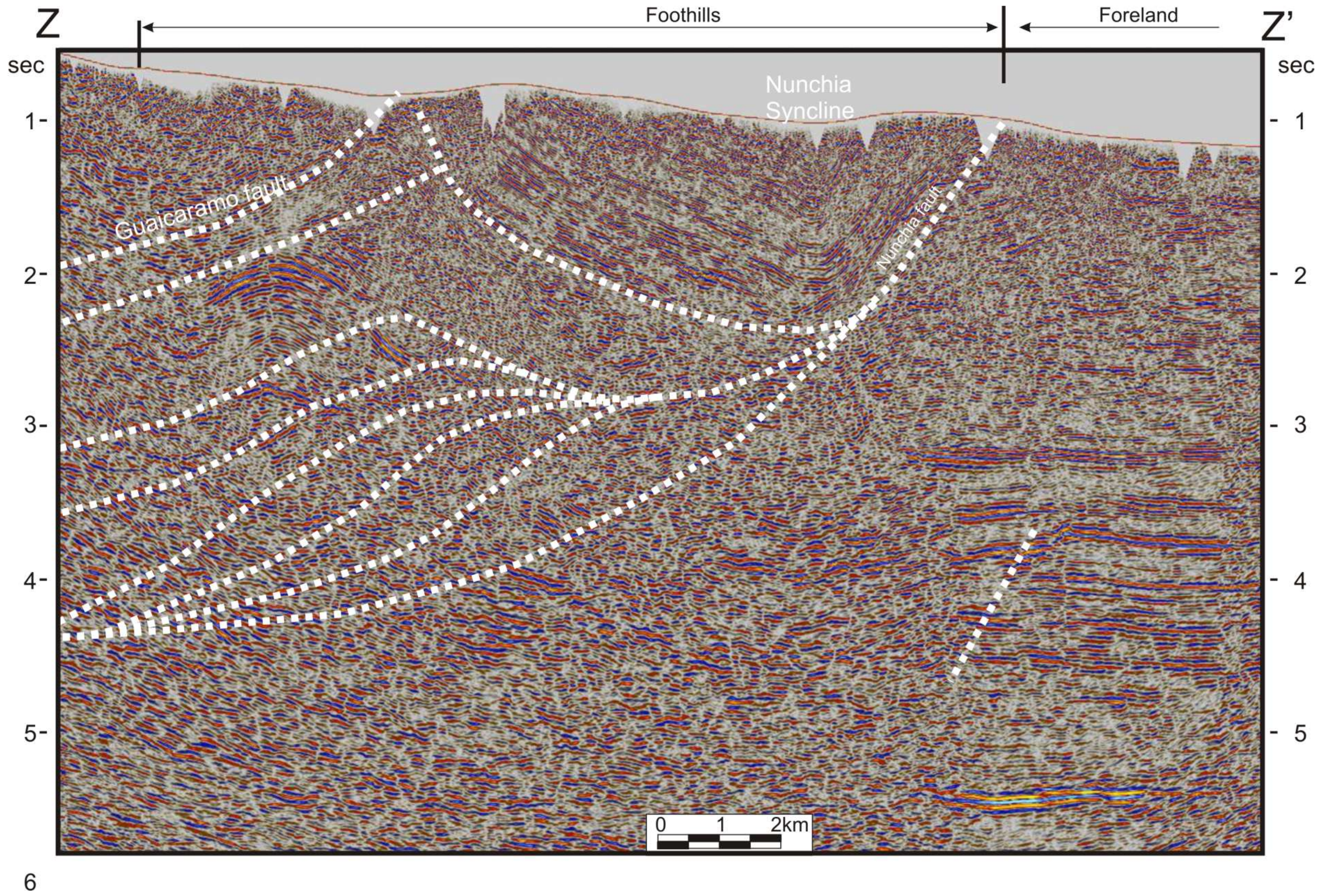


Figure 17. Section Z-Z' showing the general configuration of the Yopal foothills region. Two areas are defined: West area and Nunchia syncline.

Nunchia foothills

The west limit of the Nunchia foothills is the Guaicaramo fault system and in the east, the un-deformed section of the foreland area. A 2D seismic line was schematically interpreted to define the configuration of the Nunchia foothills (figure 18). It is characterized as a hinterland dipping duplex, foreland-vergent thrusts with flat and ramp trajectory. Geometrically, it can be divided in two areas: inner and outer, where the Nunchia syncline is located between them.

Although, this work is focussed in the outer area, the 2D seismic line allows seeing that the inner zone follows the antiformal stack configuration described in the Yopal Foothills (figures 18 and 19). The deformation in this area includes upper Late Cretaceous to Oligocene rocks, which are confirmed by the results of Niscota-E1, Huron-1, Huron-2 and Huron-3 wells (De Freitas, 2010) This area has confidential restrictions due to oil exploration works. Therefore, it will not be interpreted in the seismic sections

The outer zone represents the most frontal deformation zone of the EFEC in the Nunchia region. It is characterized as stacked imbricate structures with active roof duplex. Eleven structures were interpreted in the study area (figure 19). They are fault-related structures in a foreland vergent thrust system that generates monoclines or asymmetrical anticlines with hinterland-dipping and small frontal limbs. Additionally, two structures related to a normal fault were identified in the north of the study area. Based on the detachment levels, the structures were classified as basal, intermediate and upper to surface structures. In the south, the outer zone has 9.5km width, that increases to the north to around 12km (sections A-A’ to F-F’, figure 20 to 39). Two wells have been drilled in this area: the Tangara-1 and Aysis-1. The results of these wells are described in the stratigraphic correlation section.

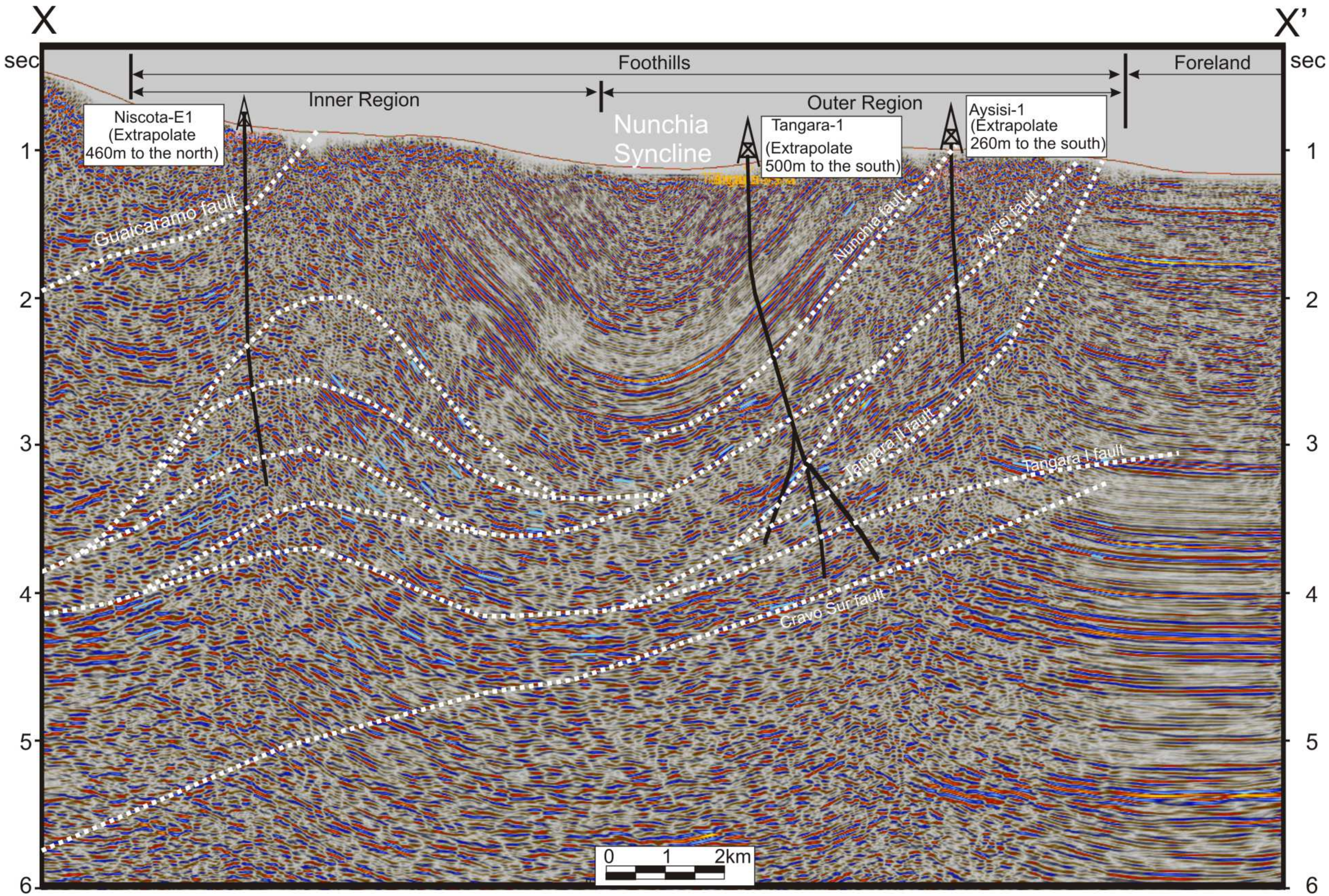


Figure 18. Section X-X' showing the general configuration of the Nunchia foothills region. Three areas are defined: West area, Nunchia syncline and East area

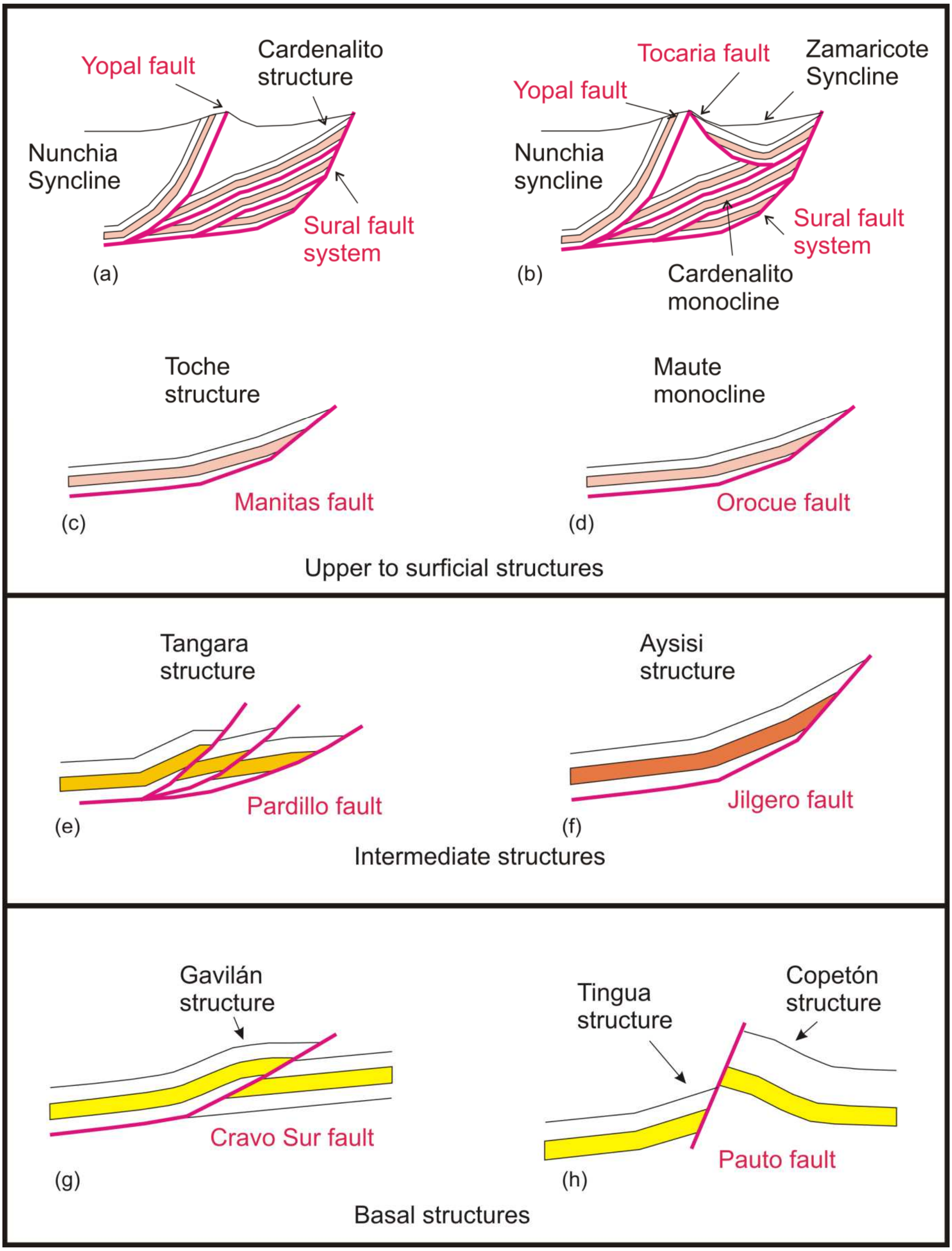


Figure 19. Sketch of structures interpreted in the outer zone of the Nunchia Foothills. The basal structures involves reservoir rocks (yellow) , the intermediate structures only Carbonera and León Formation (Orange) and the upper to surface structures, rocks from upper Carbonera, León and Guayabo formations.

Stratigraphic levels of thrust detachments

The outer zone of the Nunchia foothills is characterized by a stacked imbricate structures with different detachment levels. The faults present a flat and ramp thrust trajectory where basal detachments are related to the Gachetá Formation or the units of the Carbonera Formation. The upper detachment is in the León Formation. The Tangara-1 and Aysisi-1 wells show several repetitions in the Carbonera and León Formations, especially in the clay to silty units C-2, C-6 and C-8 (figures 11 to 13). It is confirmed by the cross section A-A' to F-F' (figures 21 to 29) where the flats are related to claystone units of the Carbonera Formations and León Formation.

The basal and intermediate structures increase their structural elevation to the north, reaching maximum structural elevation around the Tangara-1 and Aysisi-1 wells (section D-D', figures 26 and 27). In this area, the Pardillo and Jilgero faults join the faults of the upper structures and are exposed at the surface (figures 10). These faults comprise the Piedemonte fault system, which is the eastern limit of the Nunchia foothills.

The Table 8 shows the structures, the faults related and their detachments level.

Structure	Fault	Detachment		Surface expresion
		Basal	Upper	
Gavilán	Cravo Sur	Gachetá?	León	No
Tangara	Pardillo	C-8	León	Yes
Aysisi	Jilgero	C-6	León	Yes
Maute	Orocue	C-2	-	Yes
Toche	Manitas	C-2	-	Yes
Cardenalito	Sural	C-2	-	Yes
Nunchia	Yopal	C-2	-	Yes

Table 8. Detachment levels identified for every fault in the seismic interpretation.

Subsurface structure

In order to explain the variation in the structural geometry along strike of the east area of the outer zone of Nunchia Foothills, nine sections were extracted from the seismic interpretation (figures 18 to 26). The sections A-A to H-H' represent seismic lines in dip direction from south to north respectively; while the section I-I' shows a seismic section along strike. The sections were interpreted with a horizontal scale of 1:40000 and vertical scale of 3.5 s/in to generate and approximate 1:1 relationship. Therefore, the angles described are approximates. The faults interpreted in the sections are foreland-vergent thrust, with exceptions of Payero (strike-slip fault), Tocaria (back-thrust fault) and Pauto (normal fault)

The sections are described from depth to surface using the structures and fault names shown in the figure 20. The structural relief is calculated using the lower unit involved in each respective structure.

Section A-A'

Section A-A' (figures 20 and 21) is located in the southern part of the Nunchia foothills, exactly 3km to the north of the fault with an E-W direction that bounded the Chaparral syncline (figure 16). The deeper structures have small structural relief. They are represented by the Cravo Sur, Pardillo and Jilgero faults, which generates hinterland-dipping monoclines (Gavilán, Tangara and Aysisi respectively). The fault ramps are straight with dips between 20º to 25º. The monoclines have 1 to 2km length with dips of 10º to 18º. The faults are covered by the Guayabo Formation generating an angular unconformity. The upper structures are represented for the Yopal and Sural faults which generate the Nunchia and Chaparral synclines respectively. The Yopal Fault was controlled using a 2D line, because the seismic quality in the firsts 1.8 seconds is poor (figure 7a). The Gavilán structure is the only one to contain reservoirs units.

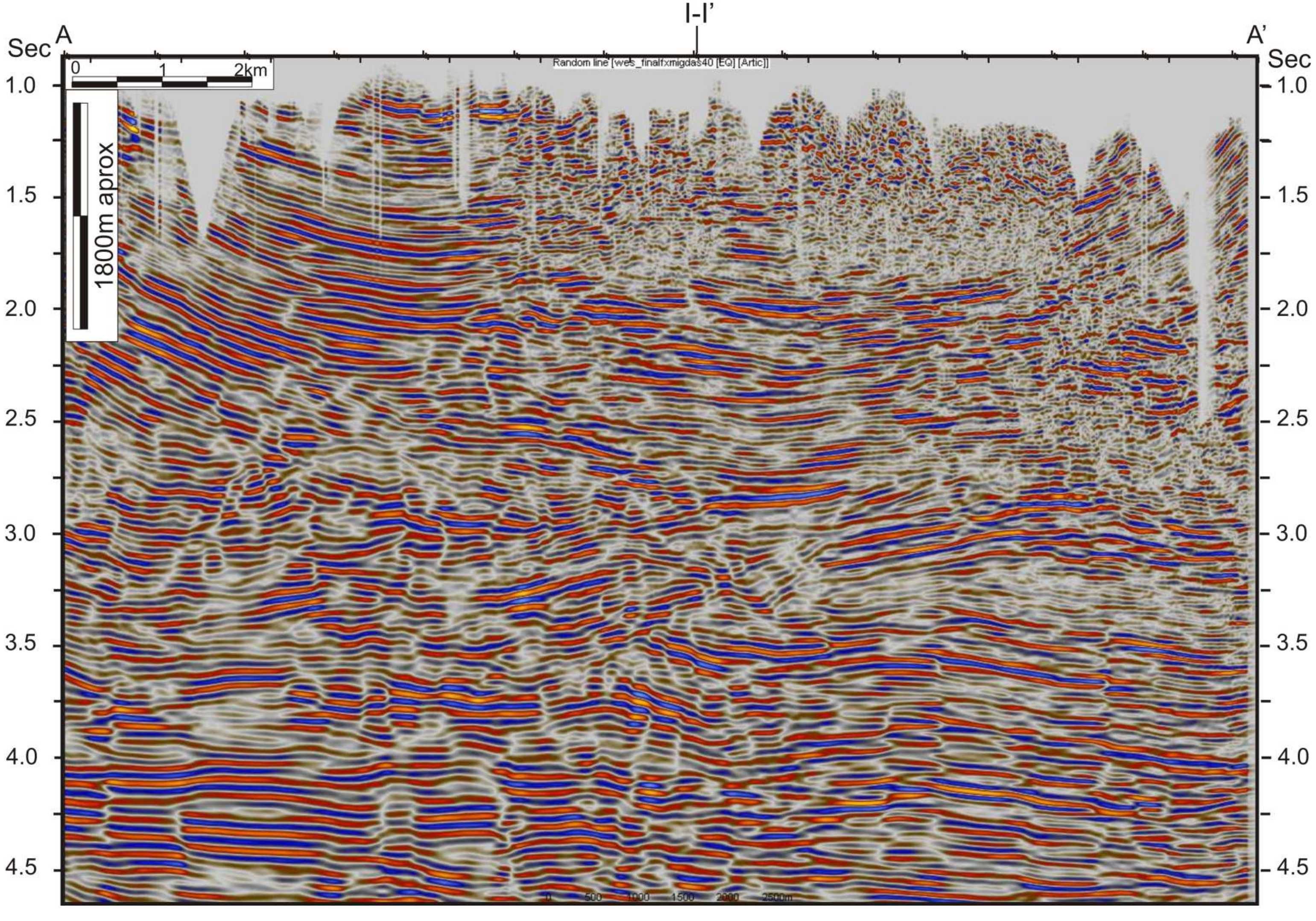


Figure 20. Cross section A-A' without interpretation

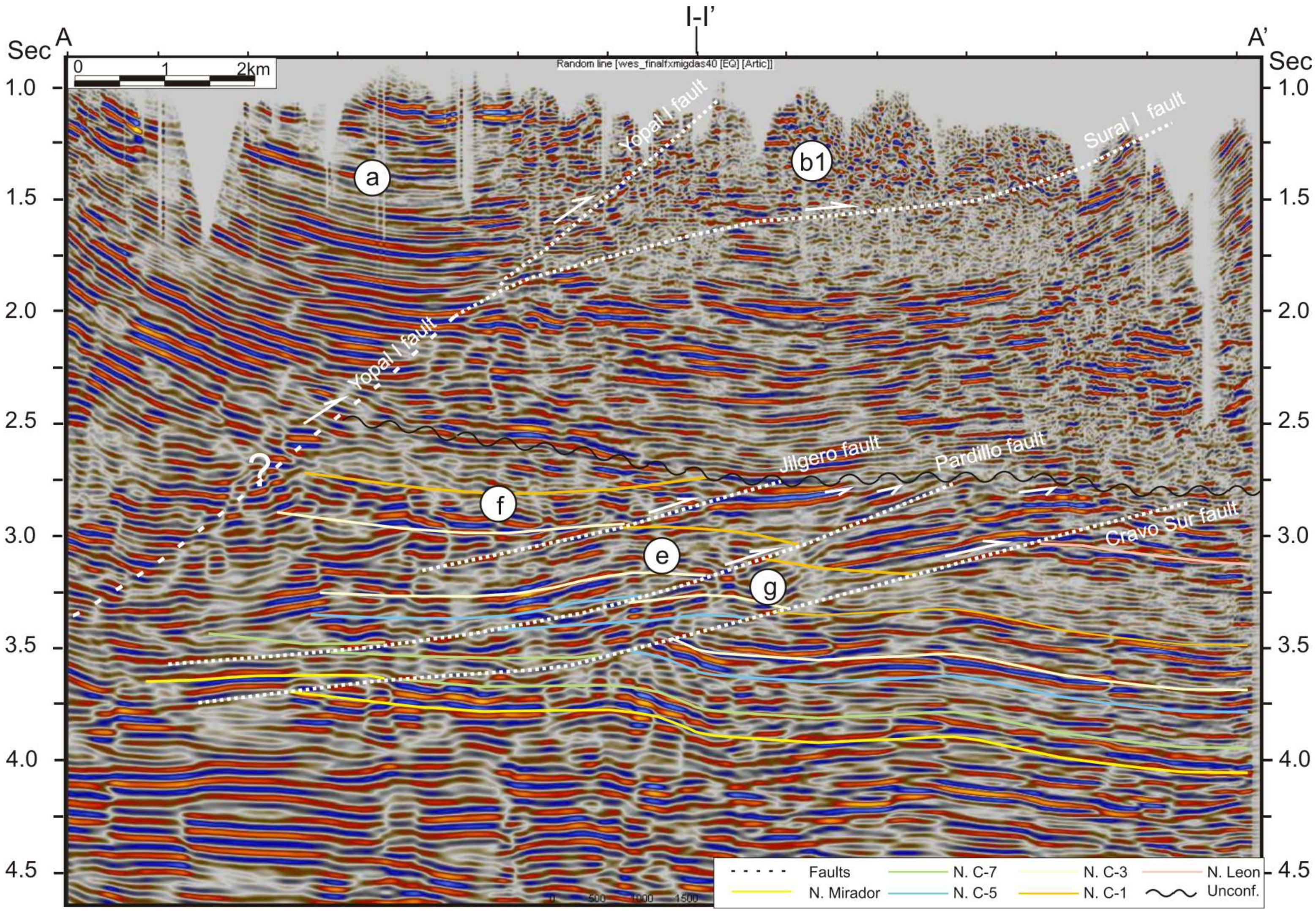


Figure 21. Cross section A-A' with interpretation. In letters are shown the name of the structures: (a) Nunchia; (b1) Chaparral; (e)Tangara; (f) Aysisi; and (g) Gavilán.

Section B-B'

Section B-B' (figures 22 and 23) is located 5.3km NE of the previous section. The basal structure is a hinterland-dipping asymmetrical anticline with small structural relief. The back-limb has a 3.4 km length with 15º dip and the fault footwall ramp of 30º. The intermediate structures are the Tangara and Aysisi hinterland-dipping monoclines. The Tangara structure is a break-backward imbricate structure with common lower detachment in the C-8 unit. The lower monocline have a dip of 20º while the upper monocline 25º. The Jilgero Fault cuts the Tangara structure, generating an Aysisi monocline, which has a limb length of 6km with a dip of 25º. The upper structures are the hinterland-dipping monocline Toche and the asymmetrical anticline Maute. The Toche's limb has a 3km length with a dip of 30º, while the back-limb of Maute structure has 2km length and 35º dip. The Orocue Fault shows an intermediate footwall flat that generates the base of the Chaparral syncline. The surface structures are Chaparrera and Nunchia synclines. The Yopal Fault generates the eastern flank of the Nunchia syncline, which has an approximate dip of 60º. The eastern and western flanks of the Nunchia syncline are cut by two faults. Based on the geological map and the time-slice interpretation (figure 30 and 31), they are left-lateral strike slip faults with a normal component. The Chaparrera syncline is generated by the interaction of Orocue-Manitas faults and the Sural I fault. The seismic image in the first second is poor, consequently, the Sural Fault was instead controlled by the geological map and the Orocue-Manitas faults are not recognized on surface.

The basal structure includes rocks from Cretaceous to the León Formation; The Tangara structure from the C-8 unit to the León Formation; the Aysisi structure from the C-6 unit to León Formation; the Toche and Maute structures from the C-4 unit to León Formation and the Chaparrera and Nunchia synclines from the C-2 unit to Guayabo Formation.

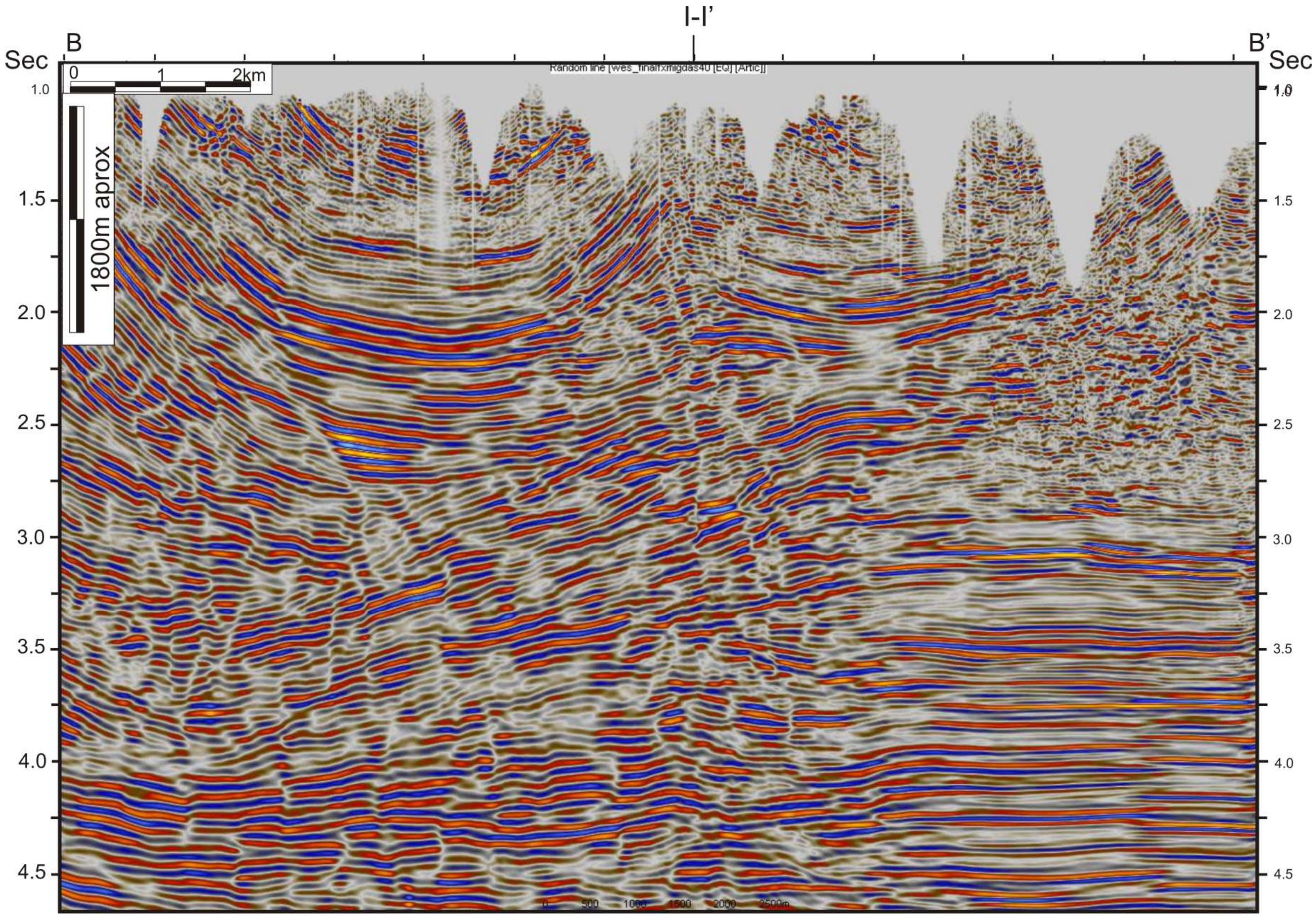


Figure 22. Cross section B-B' without interpretation

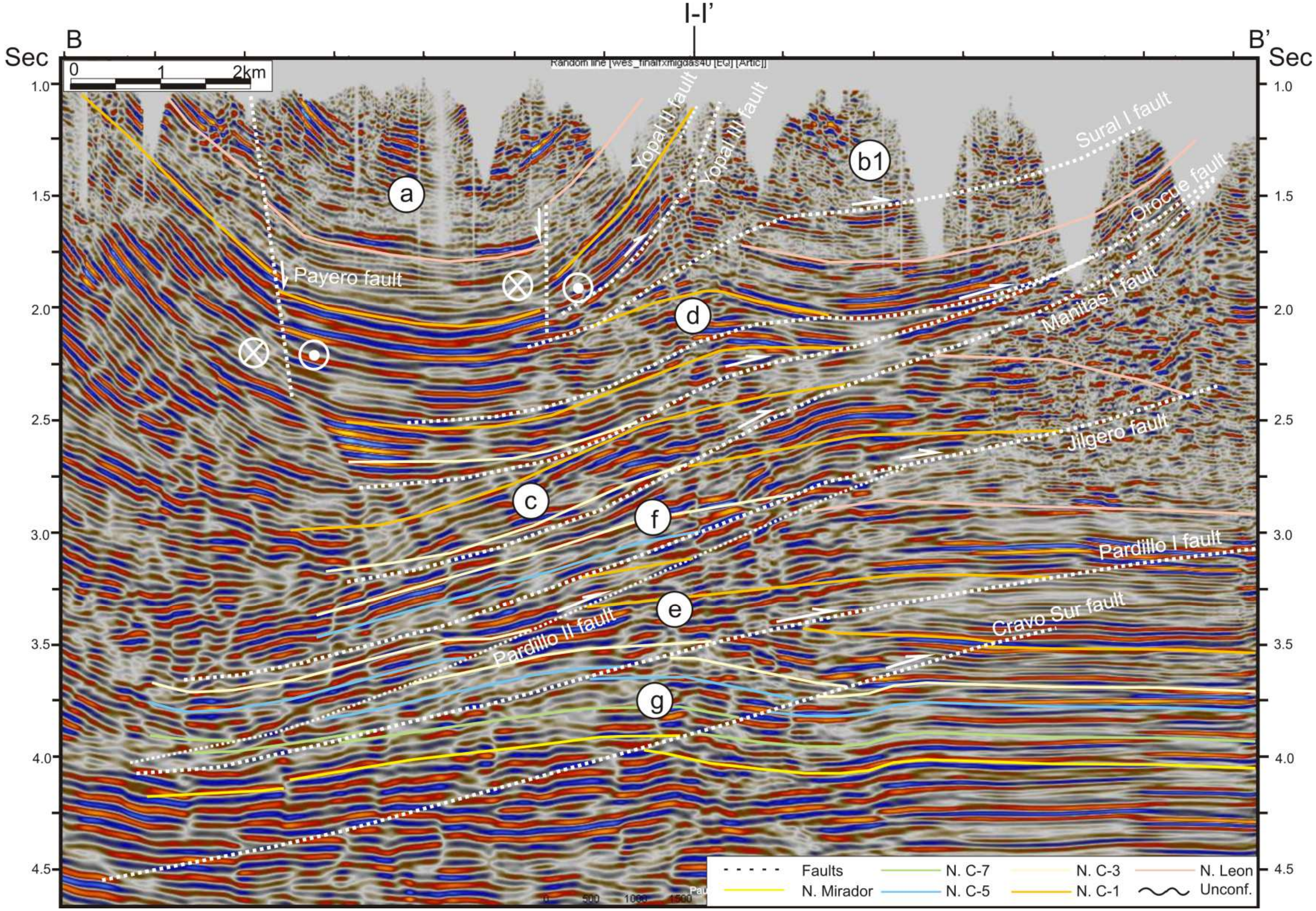


Figure 23. Cross section B-B' with interpretation. In letters are shown the name of the structures: (a) Nunchia; (b1) Chaparral; (e)Tangara; (f) Aysisi; and (g) Gavilán.

Section C-C'

This cross section (figures 24 and 25) is located 4.8km to the north of section B-B'. The basal structure, Gavilán, is a hinterland-dipping asymmetrical anticline with a back-limb of 6,8 km length and 15º of dip. The forelimb has 450m length with 25º dip. In this section, the structure reached a structural relief of 250ms TWT (~900m). The stratigraphic wedges involved in the deformation are Cretaceous rocks to León Formation. The intermediate structures are Tangara and Aysisi. The Tangara is a break-backward imbricate structure with common detachment in the C-8 unit. The upper thrust sheet is a hinterland-dipping monocline 4.5km in length with 35º dip, while the back-limb of the lower thrust sheet has a 3.2km length with 30º dip. The Tangara structure reaches in this point 0.6 second TWT (~1.8km): The Aysisi structure covers the Tangara structure. It is a hinterland-dipping monocline with a long footwall flat in the C-2 unit. Superimposing on this structure are the hinterland-dipping monoclines of the Toche, Maute, and Cardenalito structures. The units involved are upper Carbonera and León Formation. In this area the Chaparral syncline is replaced by the Cardenalito monocline. The Nunchia syncline is asymmetric with steep dips in the west flank, where is cut by the Payero fault.

Section D-D'

In section D-D' are located the two wells available in the study, Tangara-1 and Aysisi-I (figures 26 and 27). The Tangara-1ST and Tangara-1ST2 drilled the reservoir rocks located in the Gavilán structure; while the Aysisi well drilled only the León Formation and the upper part of the Carbonera Formation. In this region, the Cravo Sur structure is a hinterland-dipping monocline, with a limb of 5km length and a structural relief of 326ms TWT (~1.2m).

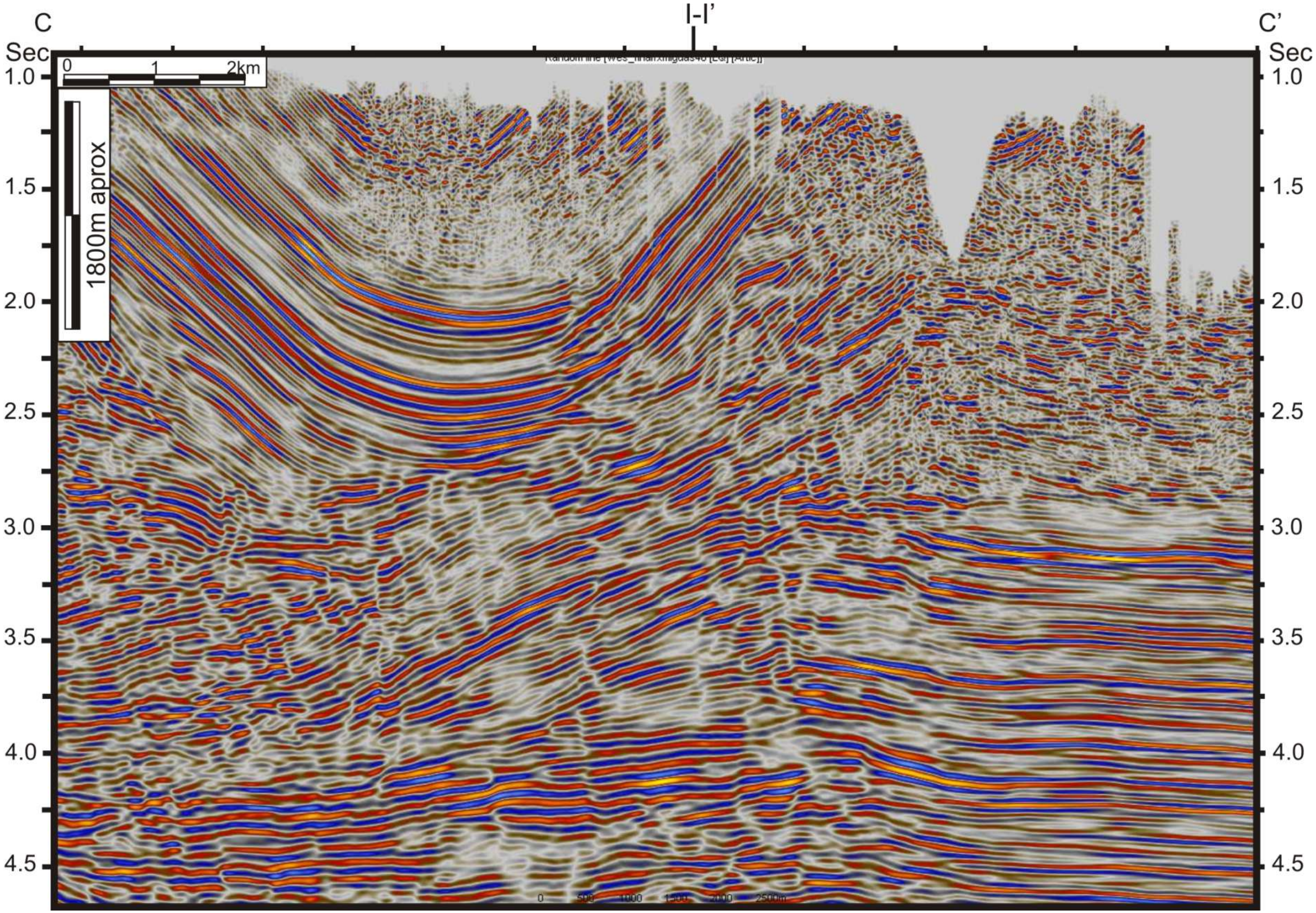


Figure 24. Cross section C-C' without interpretation

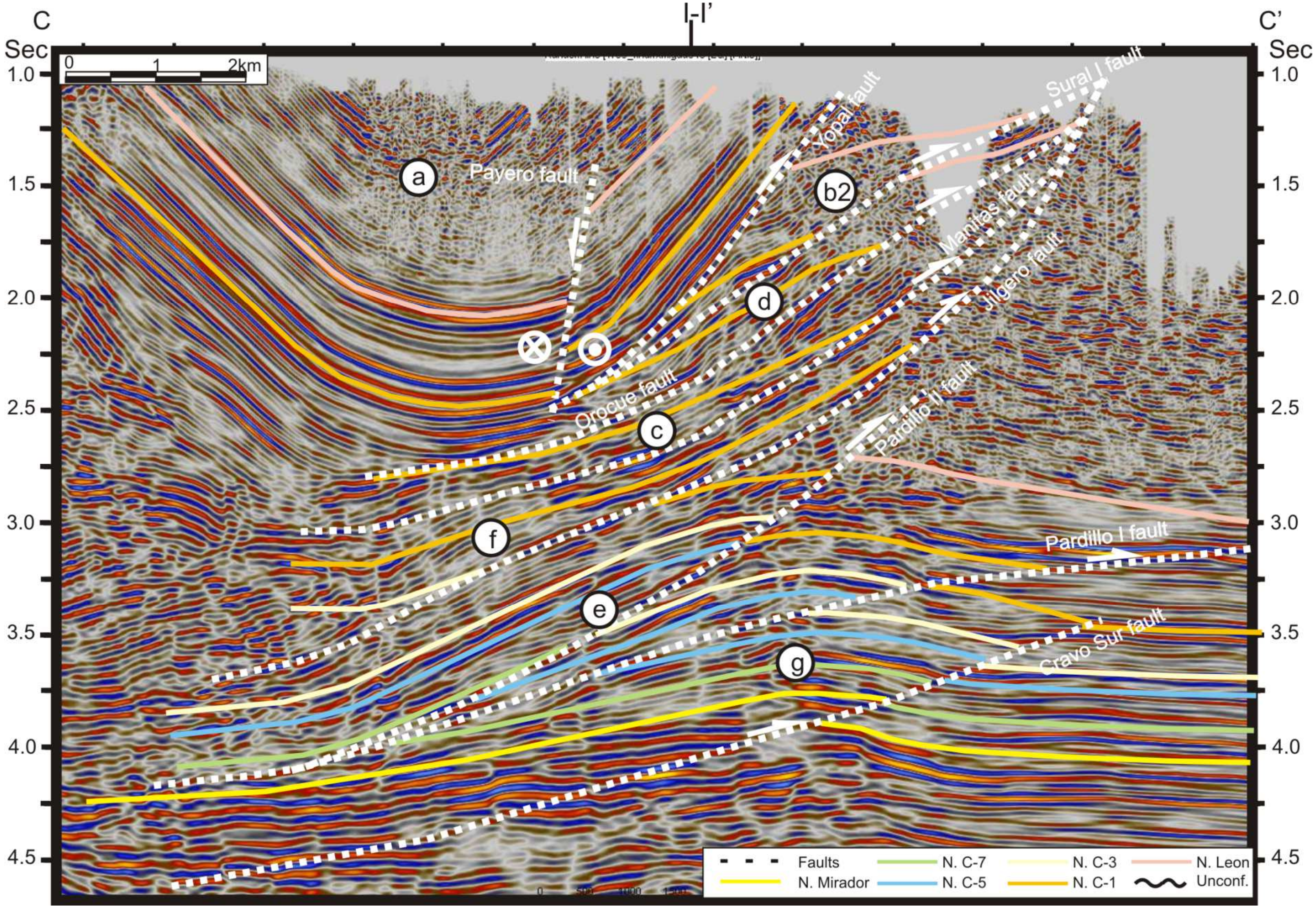


Figure 25. Cross section C-C' with interpretation. In letters are shown the name of the structures: (a) Nunchia; (b1) Chaparral; (e)Tangara; (f) Aysisi; and (g) Gavilán.

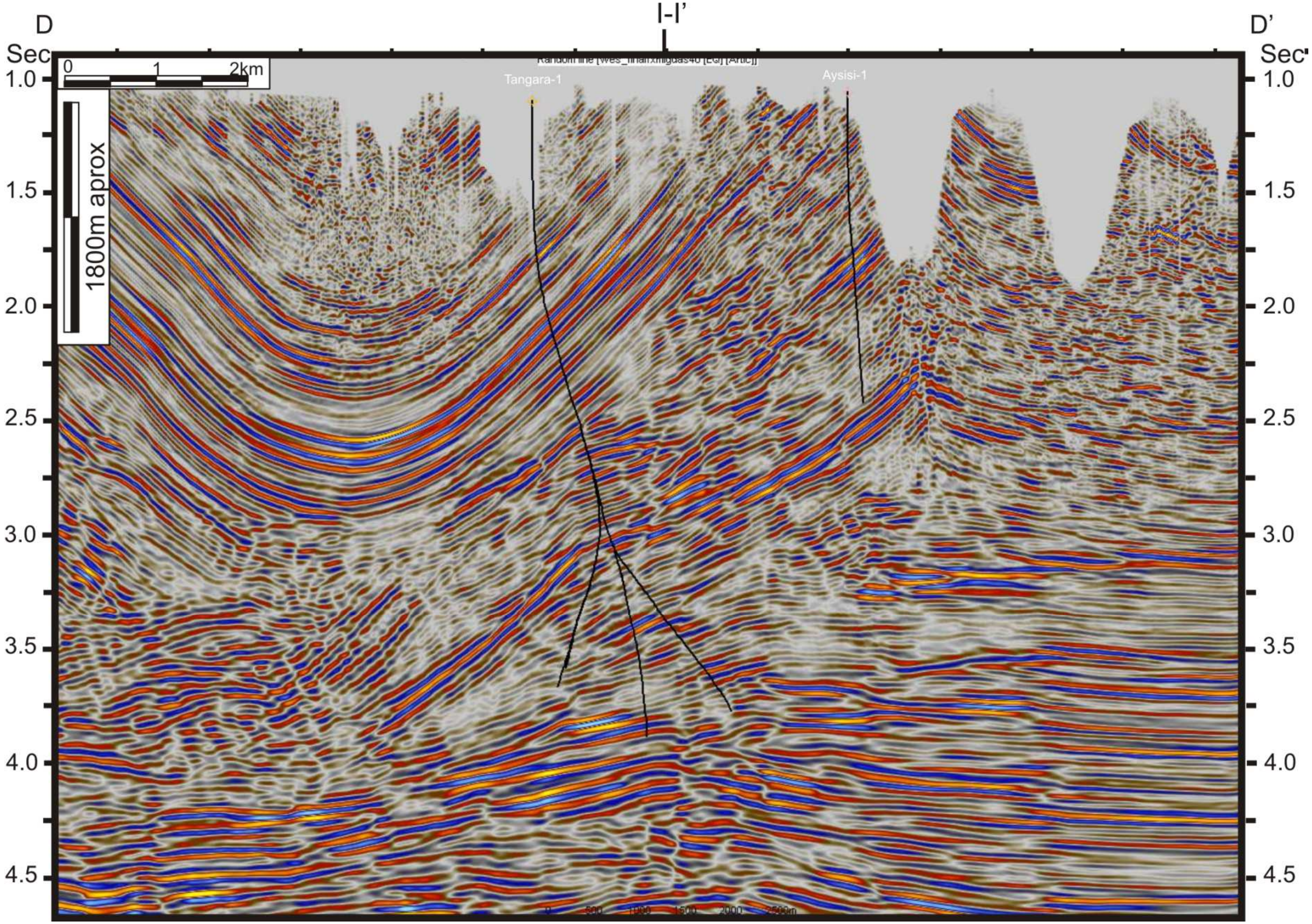


Figure 26. Cross section D-D' without interpretation

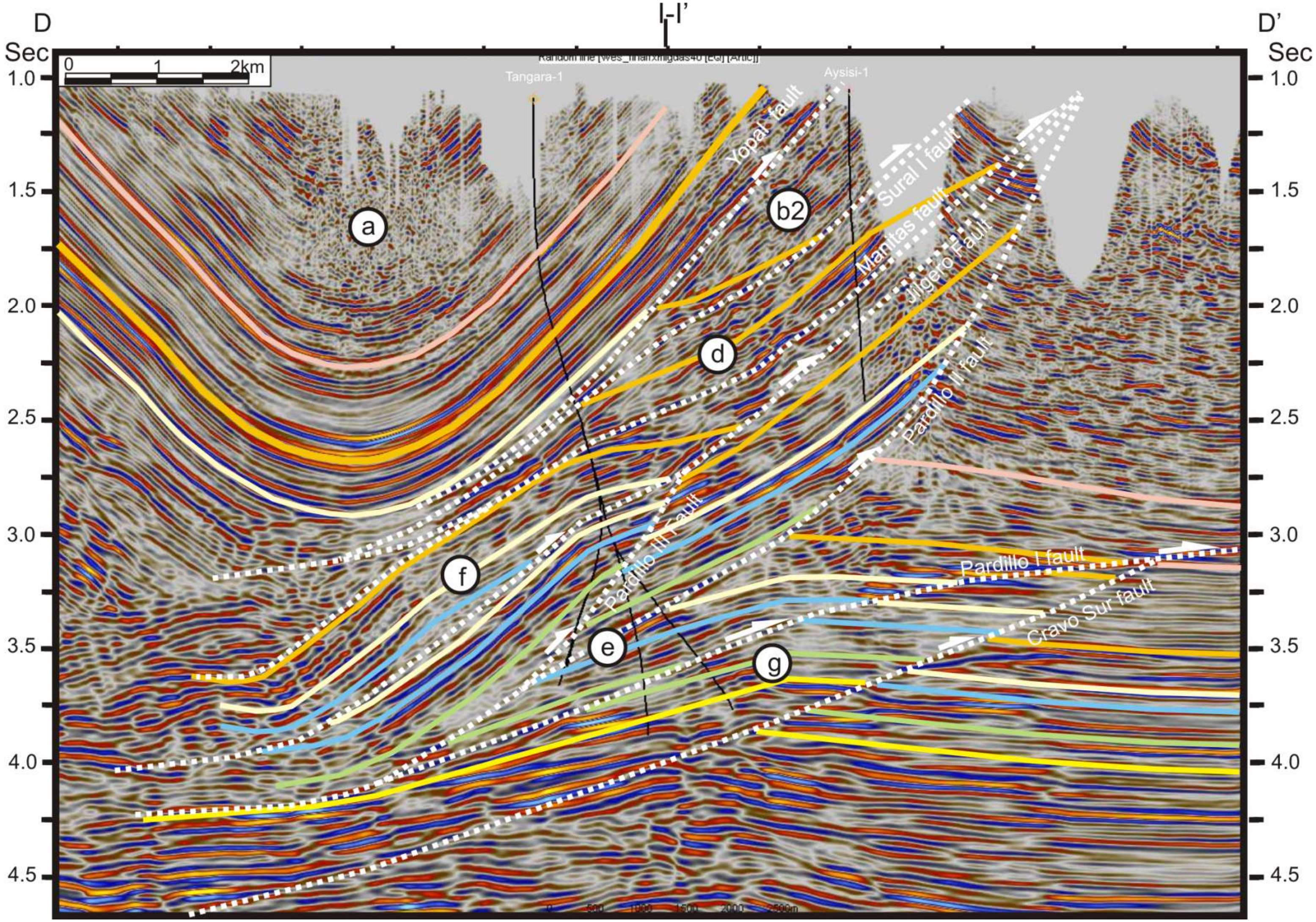


Figure 27. Cross section D-D' with interpretation. In letters are shown the name of the structures: (a) Nunchia; (b1) Chaparral; (e)Tangara; (f) Aysisi; and (g) Gavilán.

The Tangara structure is cut by two faults, Pardillo II and III, where the Pardillo II fault reaches the surface generating a steep hinterland-dipping monoclines with a structural relief of 1,16s TWT (~2km).

The Pardillo III fault is the western fault of the Tangara structure. It cuts the structure where the wells are located. No evidence of overturned folds was observed. The Aysisi structure is a steep hinterland-dipping monocline with a lower detachment in the C-6 unit and upper detachment in the León Formation. This fault joins the upper fault near to the surface. The faults Manitas and Sural generate hinterland-dipping monoclines with dips between 45 to 50º dip. The units involved are C-2 to Guayabo Formation.

<u>Section E-E'</u>

This section (figures 28 and 29) is located 4.3km to the north of the previous section. In this The Cravo Sur fault has a sub-thrust structure that increment the footwall ramp to 35º inclination. Although, the ramp is steeper, the Gavilán structure decreases the structural level to 290ms (~520m). The Caño Sur structure decrease the structural relief; whereas, the Tangara structure reaches his maximum structural relief reaching 1.1sec. Moreover, the Tnagara I fault has a new branch, Tangara I-a fault, with small displacement. The Tangara structure keeps its characteristics of the previous section. However, a new splay of the Pardillo I Fault is formed. The structure related to Aysisi Fault is a hinterland-dipping monocline of 4km that involves rocks form Mirador Formation in the west to León Formation if the east. The Manitas, Sural and Yopal Fault generate an imbricate structure with common detachment in the C-2 unit. The fault ramps increase the dip angle from east (40º) to west (50º). Some thickness changes are recognized in the west flank of Nunchia syncline, which are related to a strike-slip fault.

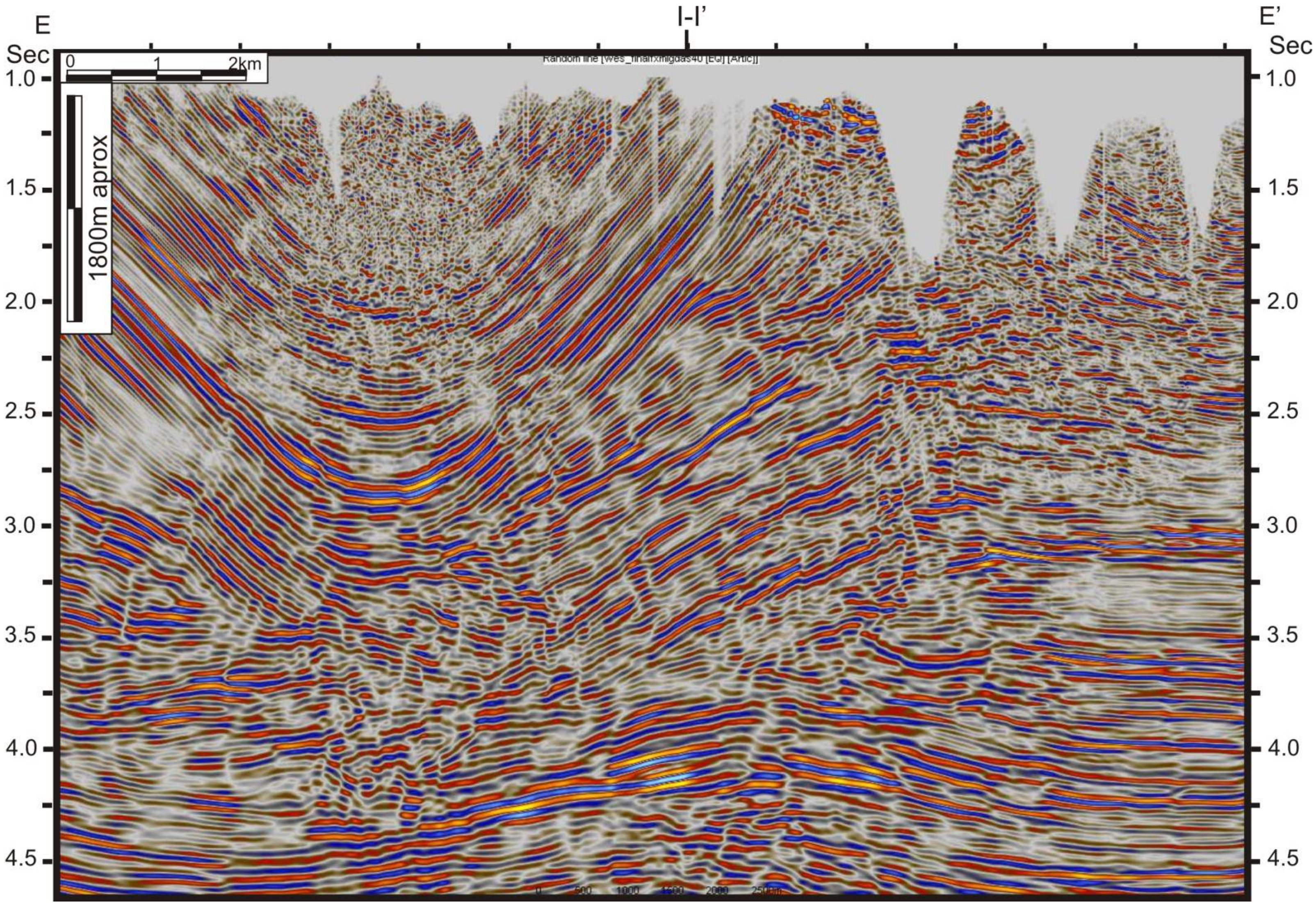


Figure 28. Cross section E-E' without interpretation

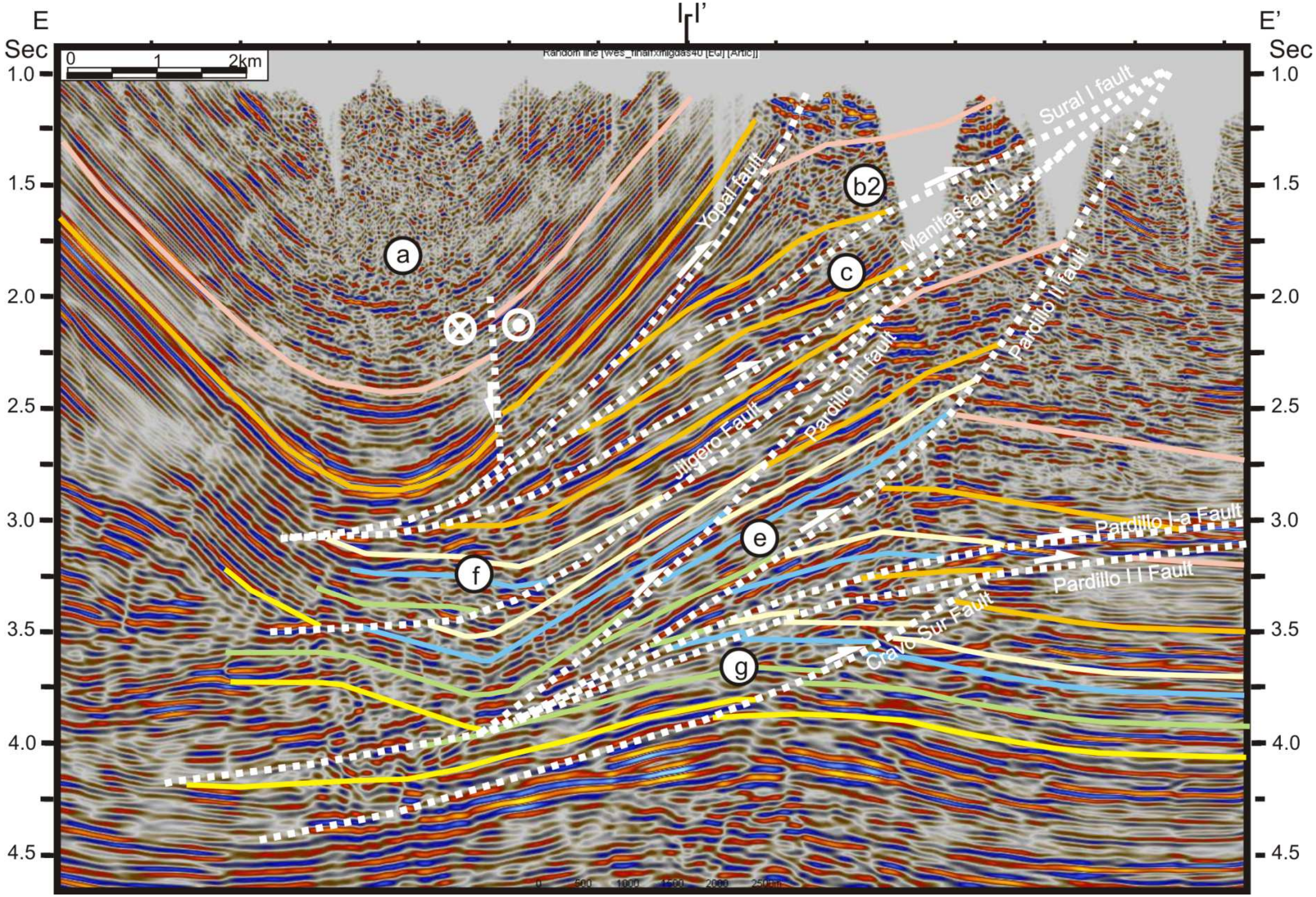


Figure 29. Cross section E-E' with interpretation. In letters are shown the name of the structures: (a) Nunchia; (b1) Chaparral; (e)Tangara; (f) Aysisi; and (g) Gavilán.

Section F-F'

The section is located 2.8km to the north of the previous cross section. This section presents a drastic change in the structural style. The basal structure is a normal fault that contains rocks of Mirador and Carbonera formations (figure 30-31).

The hanging-wall generates the hinterland-dipping monocline, Tingua structure, which involves the reservoir rocks; while the footwall generates a foreland-dipping monocline structure, Copetón. The back-limbs of the Tangara structure are transported to the foreland by the Pardillo II and III fault. The ramps of these faults have a dip around 45º and back-limbs parallel to the fault. The Aysisi structure is a monocline with a long local detachment in the C-6 unit. This structural sheet involves reservoir rocks in the west to León Formation in east. The Manitas and Sural faults generate the Toche and Cardenalito hinterland-dipping monocline that involves in the deformation, rocks from C-2 unit to Guayabo units. The Yopal is the steepest fault and generates the western flank of the Nunchia syncline.

Section G-G'

This section (figure 32-33) is located 4.3km to the north of the previous section. In general, the structures are similar to the F-F' section. The basal fault increases the displacement, while the Tangara structure decreases in structural relief. The western limb moves towards the foreland, generating a small compartment between the Pardillo II and III faults. The Aysisi structure has the same behaviour as in the previous section. The Manitas Fault involves the Mirador Formation to the west and reaches the surface to the east. While the Sural fault splays in Sural I and Sural II faults and involves rocks from C-2 to Guayabo Formation. A new back-thrust, Tocaria Fault, is interpreted. It decapitated (cross-cuts) the Nunchia structure.

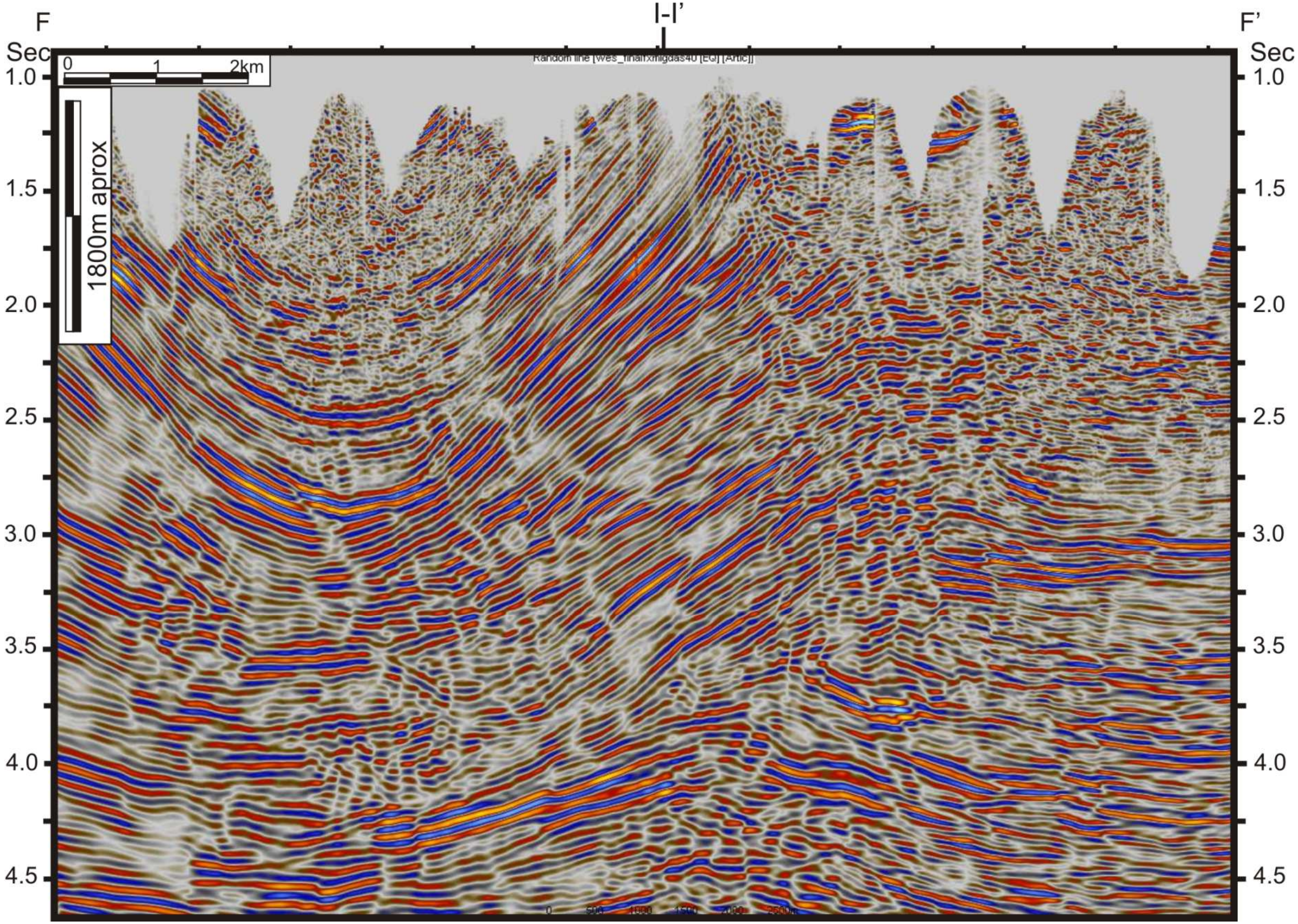


Figure 30. Cross section F-F' without interpretation

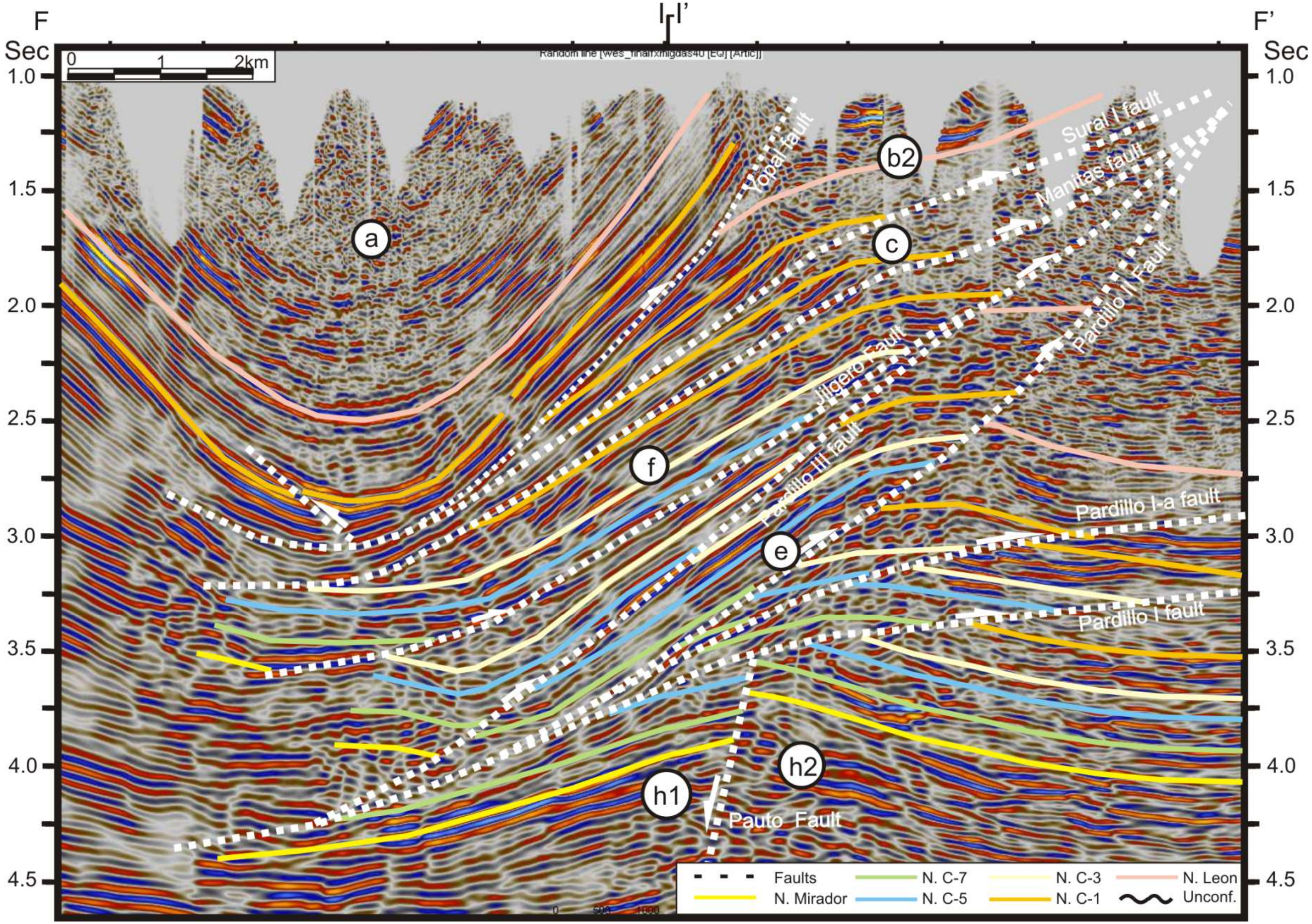


Figure 31. Cross section F-F' with interpretation. In letters are shown the name of the structures: (a) Nunchia; (b1) Chaparral; (e)Tangara; (f) Aysisi; and (g) Gavilán.

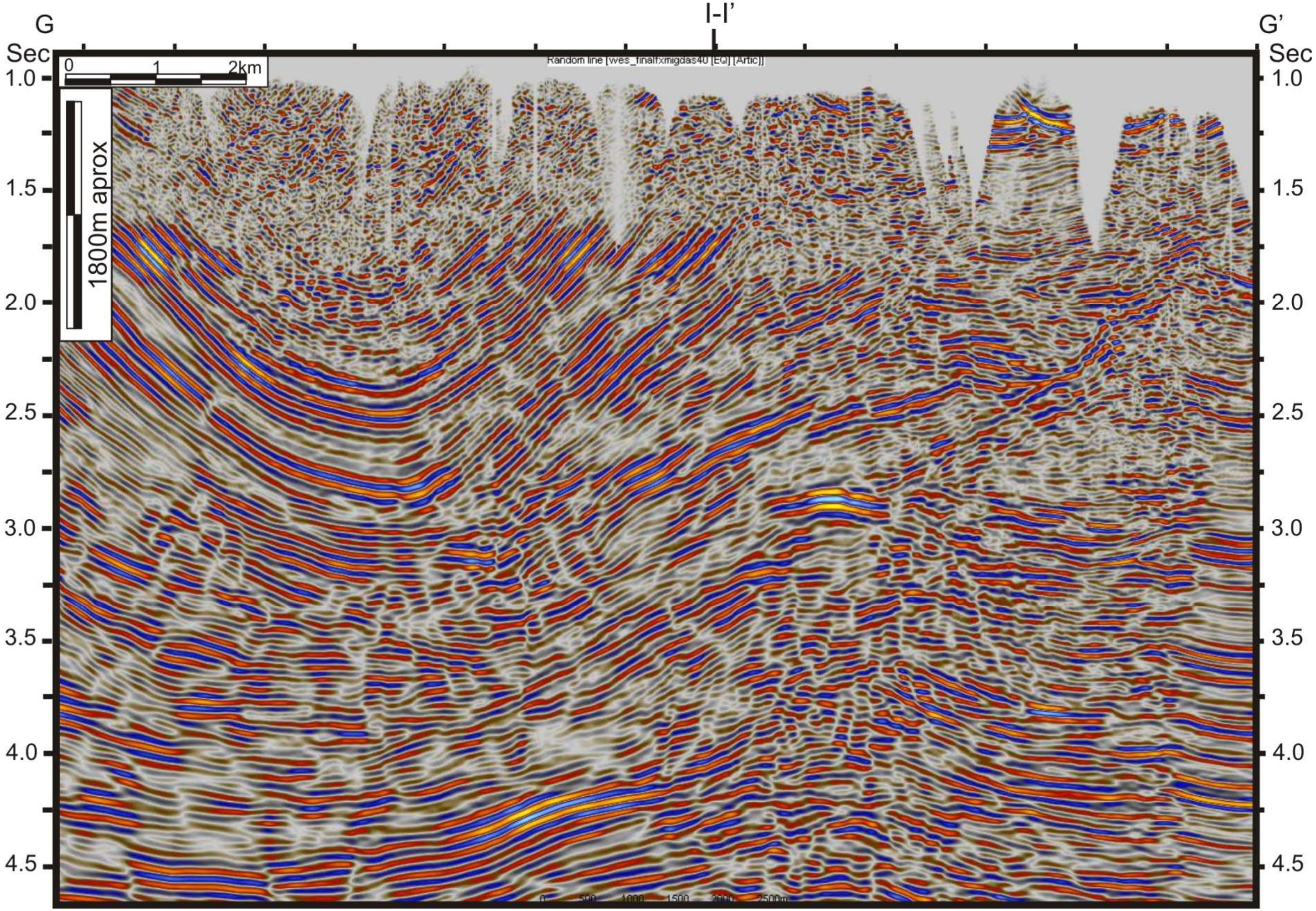


Figure 32. Cross section G-G' without interpretation

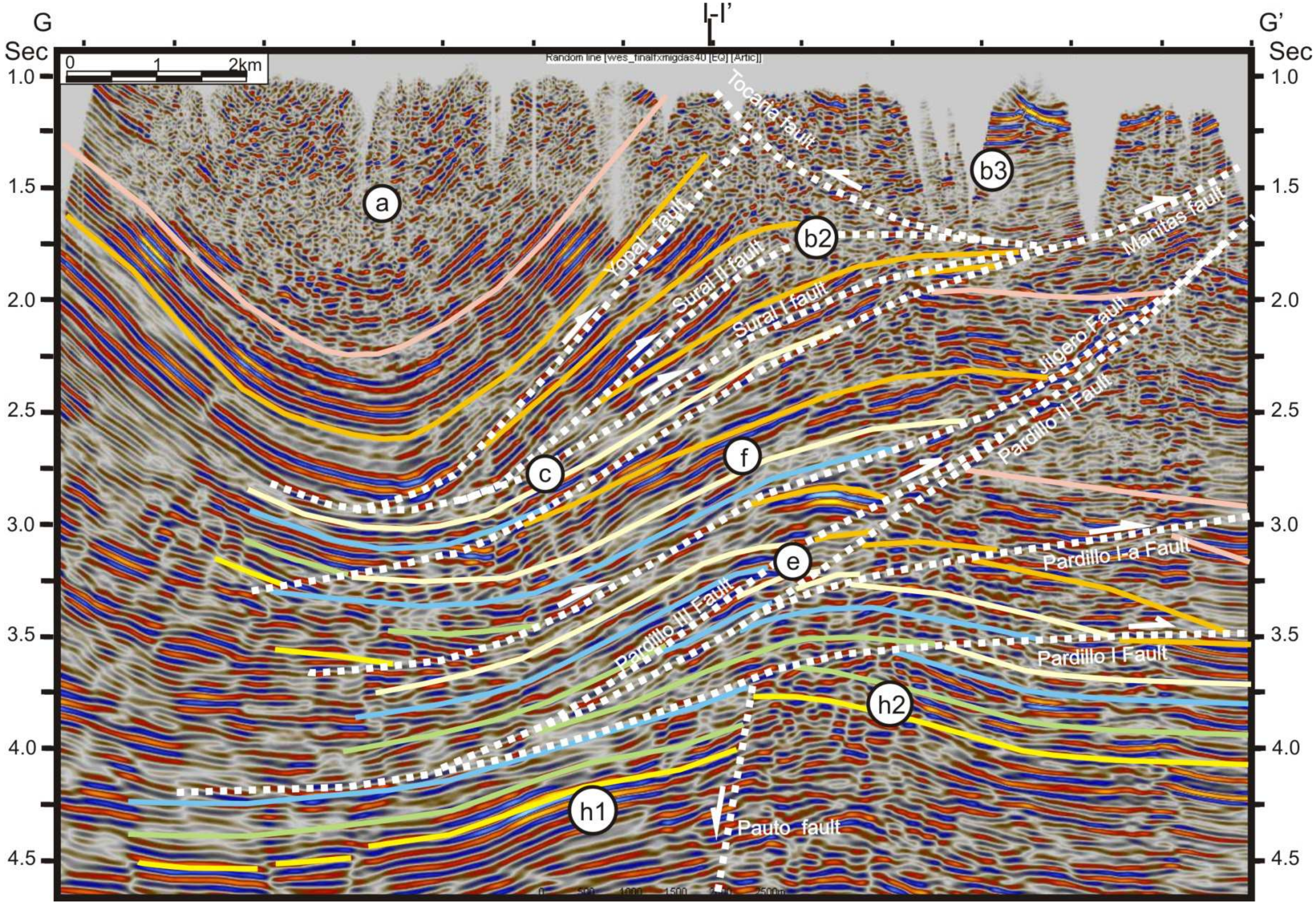


Figure 33. Cross section G-G' with interpretation. In letters are shown the name of the structures: (a) Nunchia; (b1) Chaparral; (e)Tangara; (f) Aysisi; and (g) Gavilán.

Section H-H’

Section H-H’ is located 5.3km to the north of the previous section. In this region the structures are broader than in the previous section.

The Tangara structure is reducing in structural relief and the Pardillo II fault disappears altogether. In this area the Asysis structure is a break-backward imbricate structure with common detachment level. The structure is transported towards the foreland reaching a maximum structural relief of 900ms TWT (1.6km). It generates an asymmetrical hinterland-dipping anticline, where the back-limb has 5.3km length and 20º to 25º dips. The Jilgero II Fault cut the backlimb generating a monocline. In this area, the Aysisi structure involves rocks from Mirador in the west to León in the east. This structure is superimposed by the Manitas, Sural I, Sural II and Sural III faults. These have a common detachment in the C-2 unit and generate an imbricate of hinterland-dipping monoclines with dips between 20º to 30º. In this area, the Nunchia syncline has a 6km width and the Zamaricote, an 8km width.

Section I-I’

The section I-I’ is a strike section over the study area. It shows the variation and the interaction of the different structures along strike. The area can be divided in three zones, basal, intermediate and upper to surface structures. In the south the basal structure is represented by the Gavilán structure and in the north by the Tingua structure. They are separated by a lateral ramp that changes the structural style of the basal zone, from thrusting to normal fault. The intermediate structures are Tangara and Aysisi. They are widespread across the whole area. The lower structure, Tangara reaches the highest region around the Tangara-1 well. After that, the structure plunges to the north progressively. The Aysisi structure involves rock from C-6 to the León Formation in the south; in the central area involves rocks form C-2 to the León Formation and to the north, involves rocks from C-6 unit to the León Formation. The upper structures superimpose the Aysisi structures, involving rocks from C-2 unit to the Guayabo Formation. To the north of the G-G’ section, all structures are deepening to the north and a new fault, the Tocaria Fault, with back-thrust direction cross-cuts the Yopal fault system.

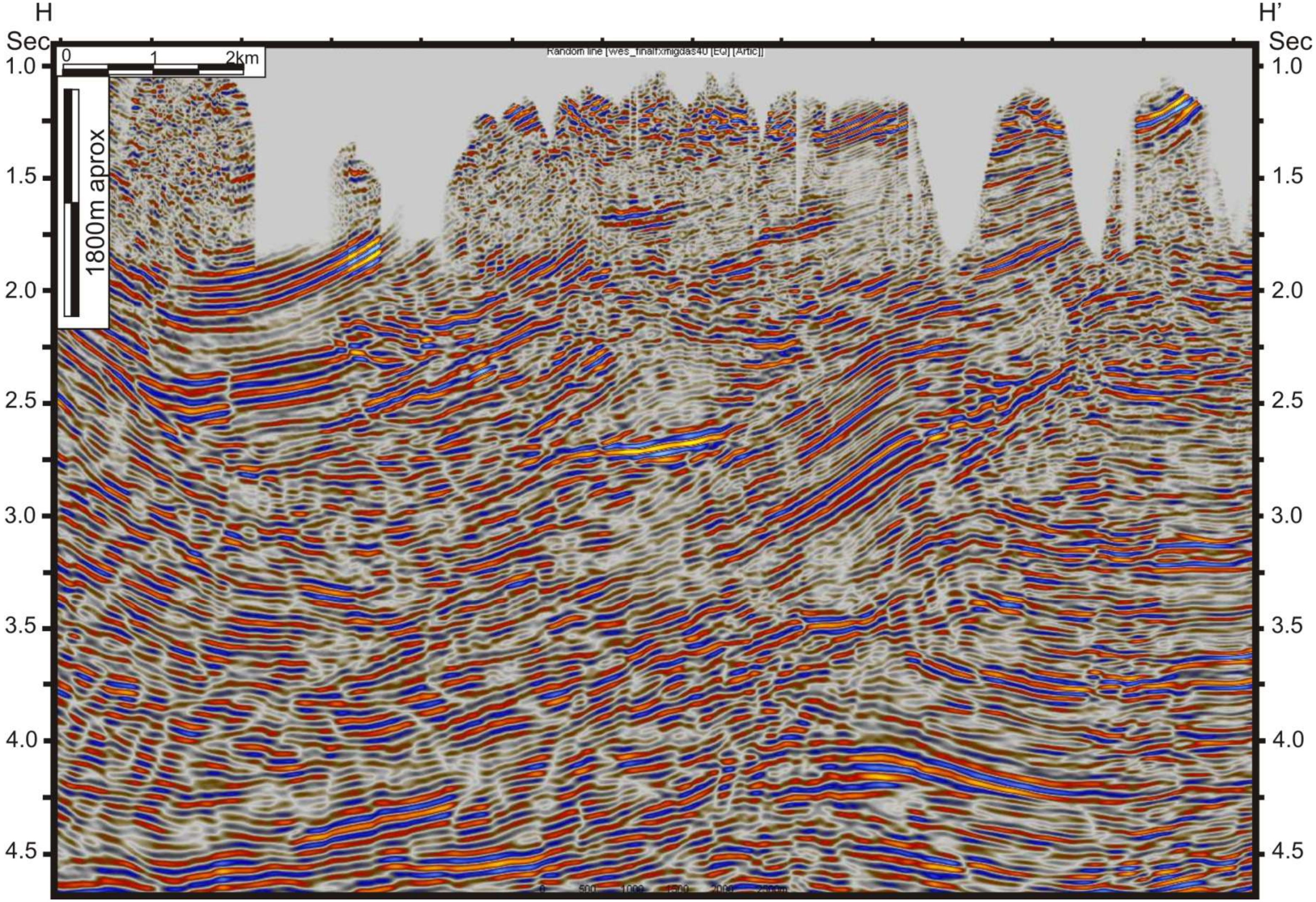


Figure 34. Cross section H-H' without interpretation

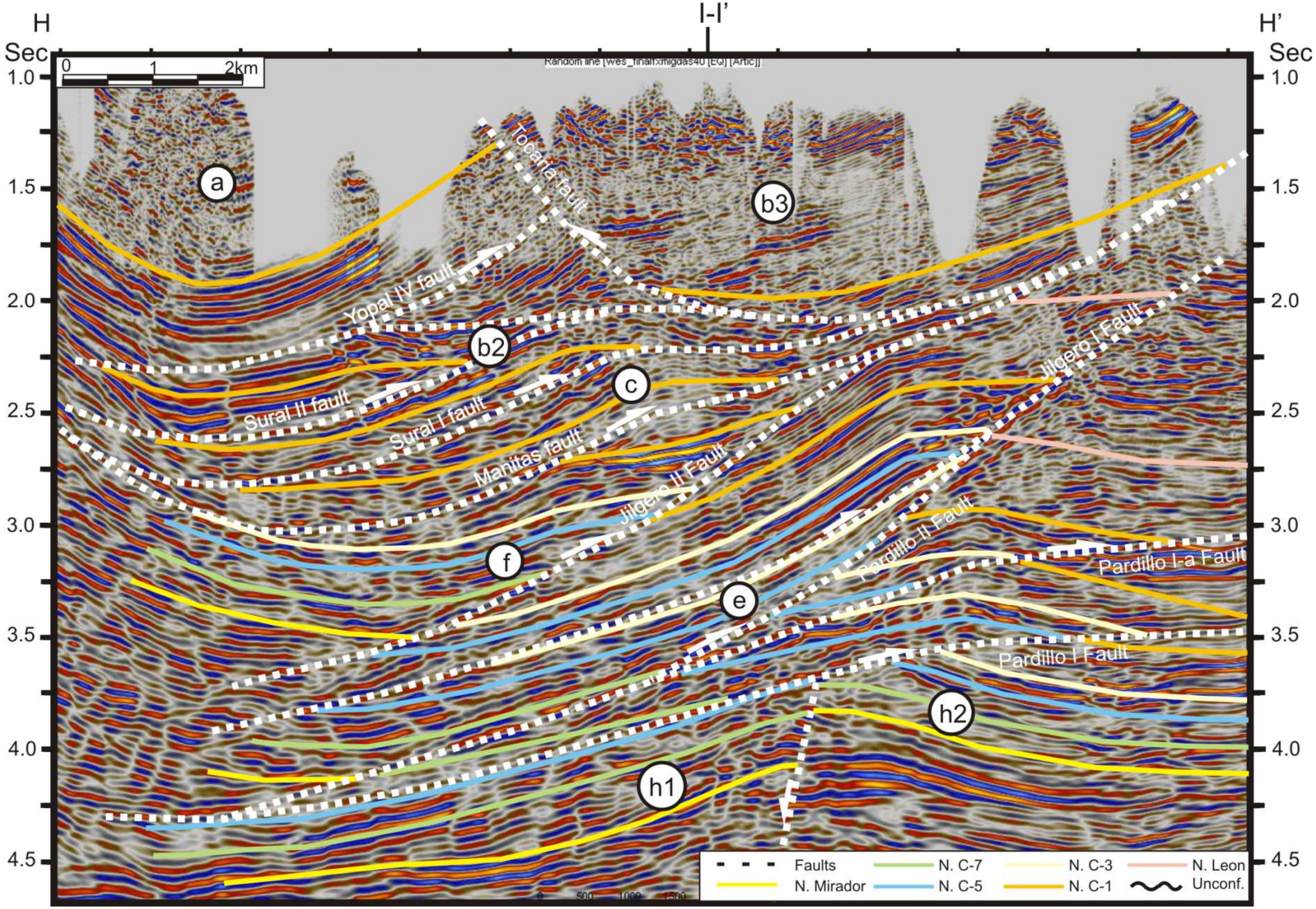


Figure 35. Cross section G-G' with interpretation. In letters are shown the name of the structures: (a) Nunchia; (b1) Chaparral; (e)Tangara; (f) Aysisi; and (g) Gavilán

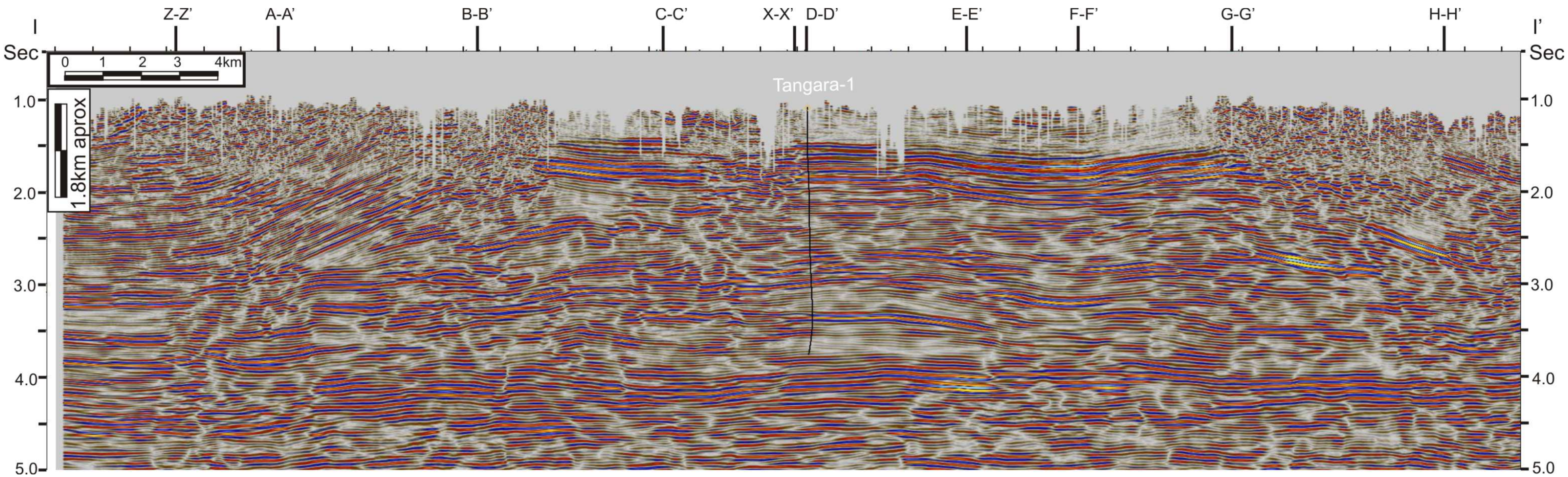


Figure 36. Cross section I-I' without interpretation

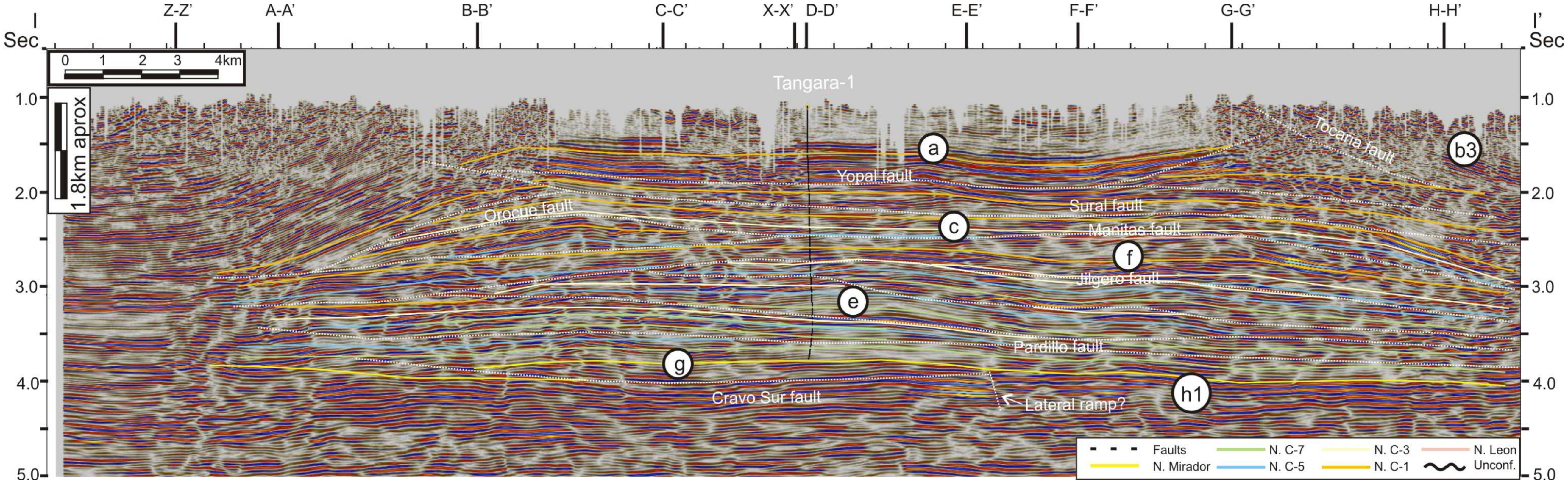


Figure 37. Cross section G-G' with interpretation. In letters are shown the name of the structures: : (a) Nunchia; (b3) Zamaricote; (c) Toche; (d) Maute; (e)Tangara; (f) Aysisi; (g) Gavilán; (h1) Tingua.

Time-Slice interpretation

Although, several seismic attributes were applied to the Tangara-3D seismic cube, the poor quality of the data did not allow produce a good result for the outer imbricate zone. However, some attributes showed structural features in the Nunchia syncline (figure 39). The attribute, Variance, shows the best seismic image for structural interpretation.

As a result, the interpretation of structural features in the Nunchia syncline was generated using the Variance attribute. It aided the interpretation of: one family of faults (blue), two lineaments (green and orange), and the hinge line for the Nunchia syncline (yellow) (figure 40). The fault family has N80E-W80S direction with left-lateral displacement. The family is composed for three faults, where the second fault corresponds to the Payero Fault, which is identified in the geological map. Fault (3) disappears at time-slice -2316ms and Fault (1) disappears at time-slice -2432ms. Two green lineaments were interpreted to the north of the Nunchia syncline. These lineaments have a N5°W-S5°E to N10°W-S10°E orientation; the lineament (1) is interpreted in all time-slices, while the lineament (2) is recognized only at time-slice -2432ms, which had an observed orientation of N65°E-S65°W. Finally, the hinge line of the Nunchia syncline was interpreted. In the south, the hinge line has a direction of N30°E. It changes after the Payero Fault (fault (2)) to N25°E and near to the green lineament (1) reaches a new direction of N15°E.

The direction of structures, the fault direction and movement, and some lineaments (green) may be analogous to those expected in a strike-slip setting. However, the low number of faults identified is not sufficient enough to evaluate if the area is influenced by strike-slip movement. Therefore, the faults are interpreted to have formed to accommodate the displacement generated by the bend in the EC.

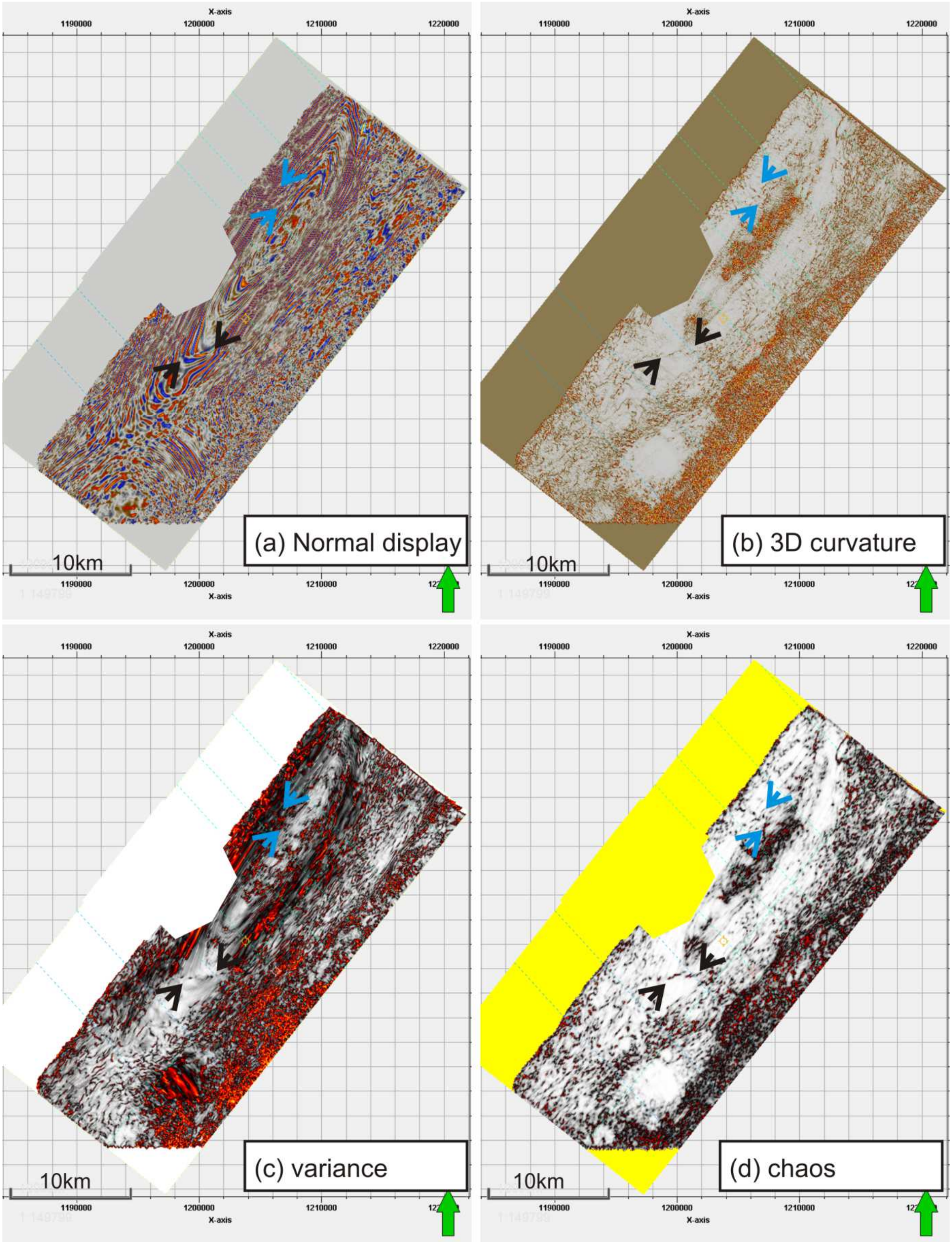
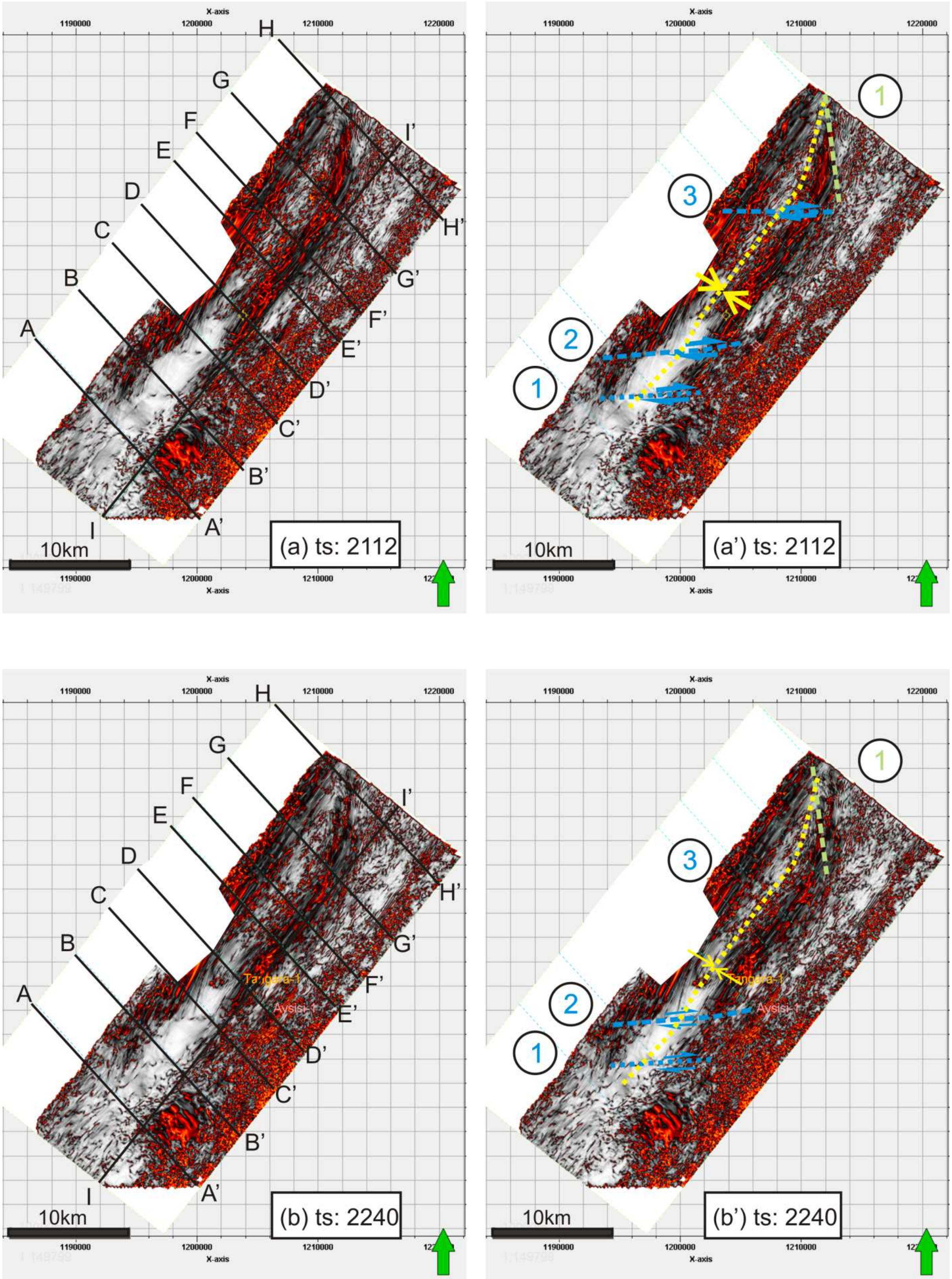


Figure 38. Best time-slice section (-2316ms) of the Tangara-3D. It shows a comparison between the best imagines obtained in in the seismic attributes


X-axis
1190000
1200000
1210000
1220000
A
B
C
D
E
F
G
H
I
A'
B'
C'
D'
E'
F'
G'
H'
I'
10km
(a) ts: 2112
(a') ts: 2112
1
2
3
(b) ts: 2240
(b') ts: 2240
Tangara-1

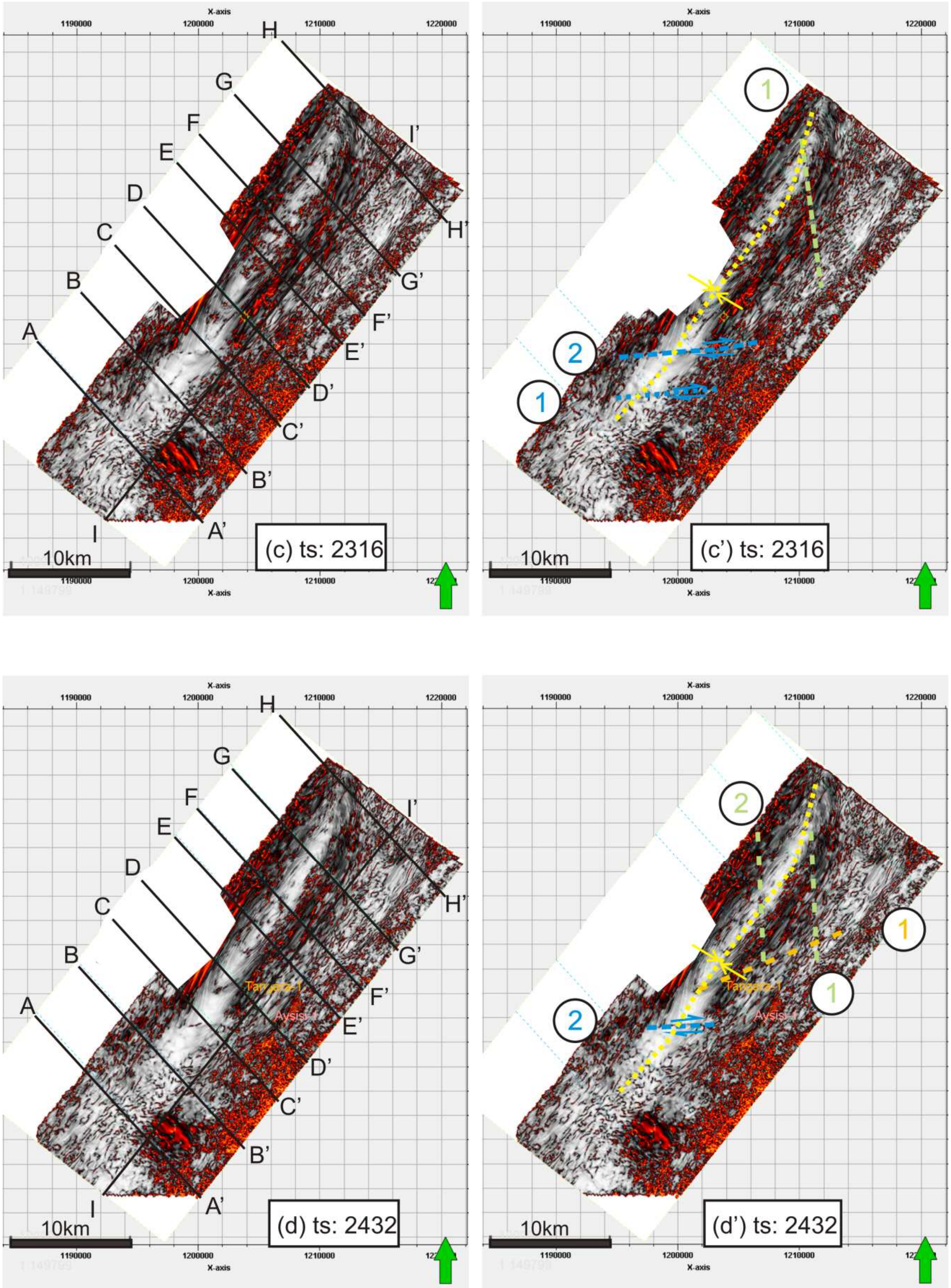


Figure 39. Lineaments and fautls identified in the time slices using the variance seismic attributes. Blue: faults , green and orange lineaments, and yellow the axis of the structure.

Subsurface maps

The interpretation allowed for the generation of surfaces at different stratigraphic levels. Firstly, they were used to create the pseudo-3D model and to generate structural maps in TWT, to evaluate the geometry and lateral continuity of the structures. Secondly, these maps were used to identify the location of the reservoir units, in the basal structures and verify their absence from intermediate structures. Five maps are displayed to show the configuration of Gavilán, Tingua, Copetón, Tangara and Aysisi structures.

Gavilan, Tingua and Copetón Structures

These are the only basal structures observed to contain the reservoir rocks in the outer Nunchia foothills (figure 41). The Gavilán structure is located in the south. This is an asymmetrical hinterland-dipping faulted anticline, with a gentle dipping back-limb. The structure is generated by the Cravo Sur Fault and is bound to the south and north by lateral or oblique ramps. This structure was tested by the Tangara-1ST and Tangara-1ST2 wells. In this zone, the structure is cross-cut in the lower Carbonera level by the Pardillo I fault (figure 42). The Tingua and Copetón structures are located to the north. They are related to a normal fault, Pauto, which dips to the hinterland. Tingua structure is small faulted anticline located in the footwall of Pauto Fault; while the Copetón structure is located in the hanging-wall. It is a 3-way closure anticline with a length of 10km. The figure 41 shows the relation between the Gavilan structure and the foreland deposits; and the configuration of the Tingua and Copetón structures.

Tangara imbricate structure

The Tangara structure is located across the whole study area (figures 43 to 46). Two different structural levels, C-7 and C-5, are displayed to show the movement and configuration of the structural sheets as well as a comparison between the two units.

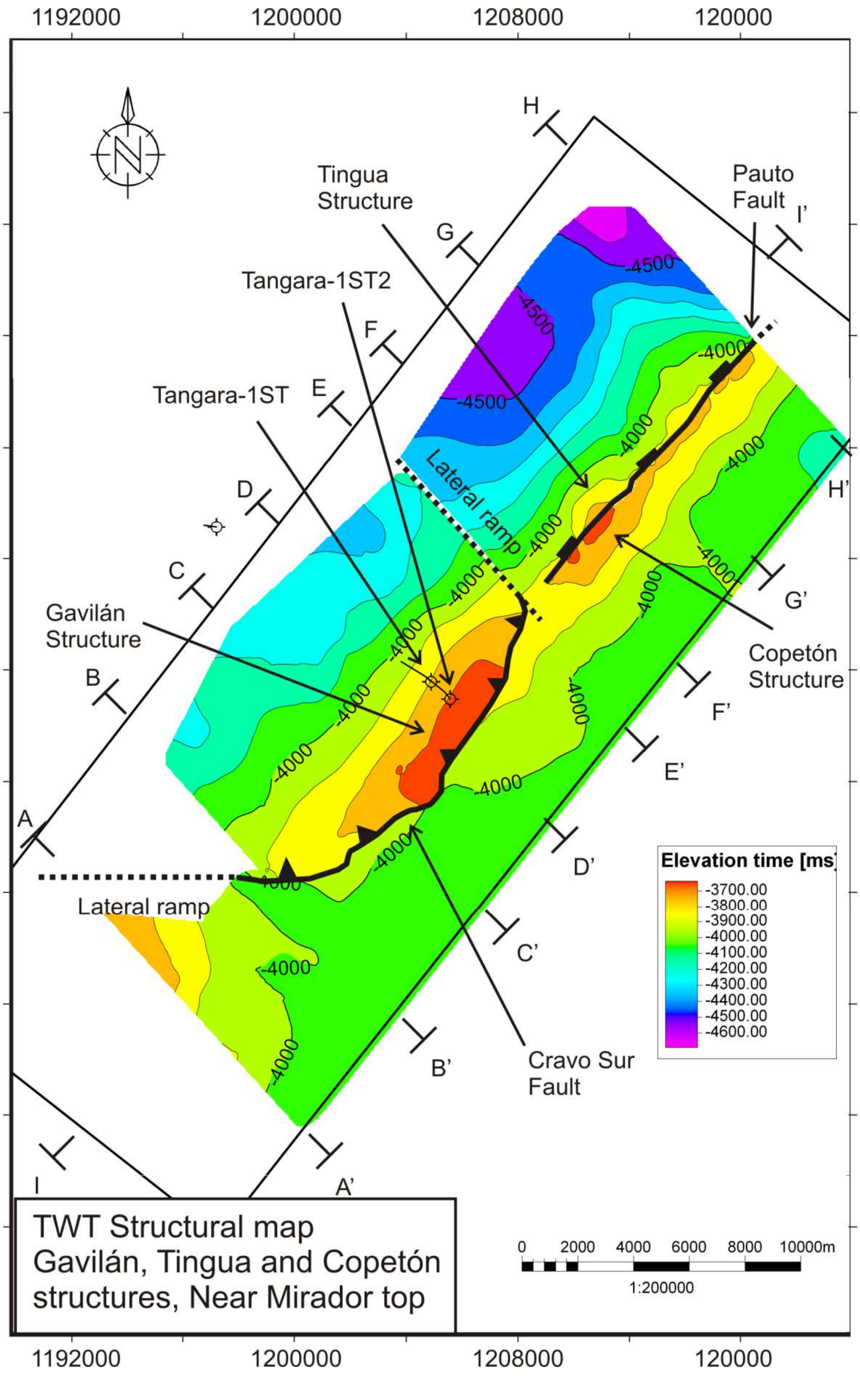


Figure 40. TWT Structural map near top Mirador Formation, for the basal and foreland deposits.

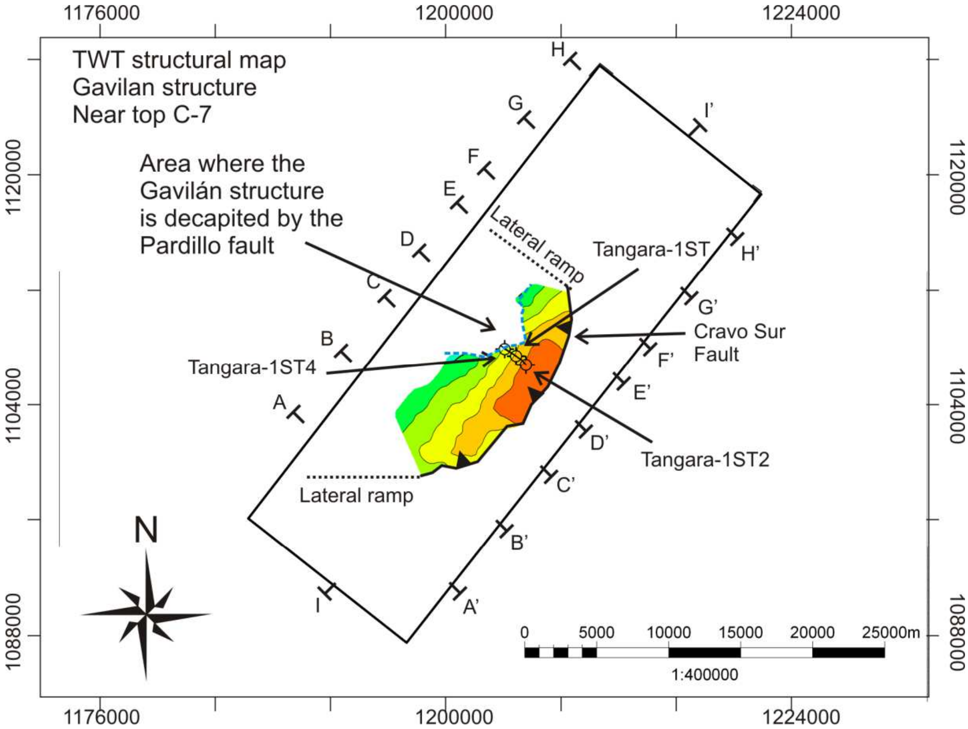


Figure 41. TWT Structural map near top C-7 unit in the Gavilán structure. It shows the are where the structure is decapitated by the Pardillo faults.

The imbricate structure is a hinterland-dipping monocline that is cut by three faults, Pardillo I-a, Pardillo II and Pardillo III (figures 43 and 45). The upper structural sheets generate steep monoclines, where the maximum structural relief is located in the location of the Tangara and Aysisi wells. The general configuration of the imbricate structure does not have any significant geometrical variability between the different levels (figures 44 and 46). However, three aspects can be highlighted: (1) the frontal part of the Pardillo I fault in the C-5 level, is located around 4km from the C-7 unit in the direction of the foreland. (2) The maximum structural relief is reached by the C-7 level related to the Pardillo II Fault. (3) The faults' strike in the C-5 level is straighter than the C-7 level. This is more clear in figures 44 and 46, where each structural sheet is shown individually. The Tangara I compartment in the C-7 level is small and has a "snake" form, while the C-5 level present a faulted anticline with long back-limb in the south area. In the north, the back limb is decapitated.

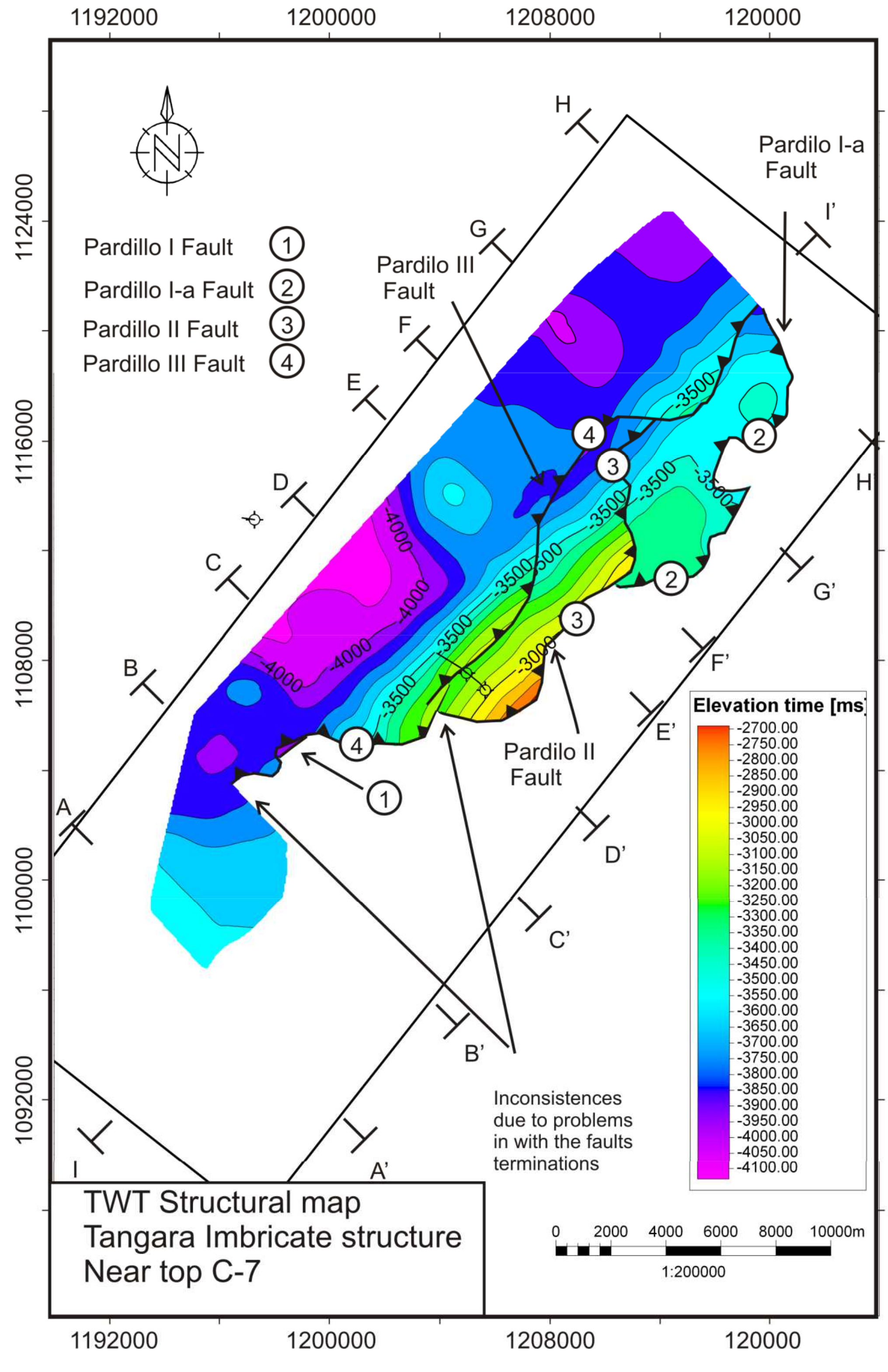


Figure 42. TWT Structural map near top C-7 unit, for the Tangara imbricate structure.

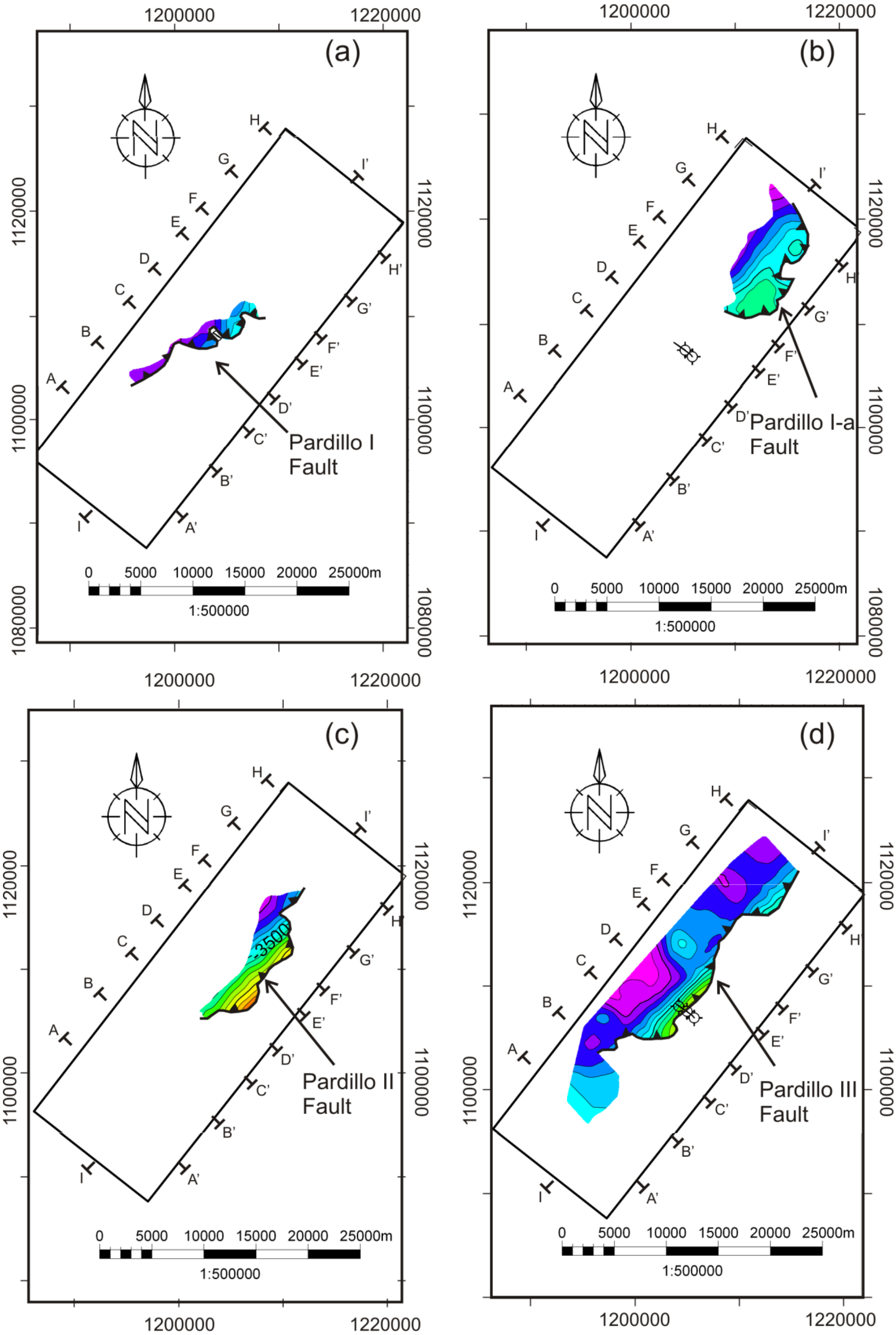


Figure 43. Structural map TWT of the compartments of Tangara imbricate structure, near top C-7 unit.

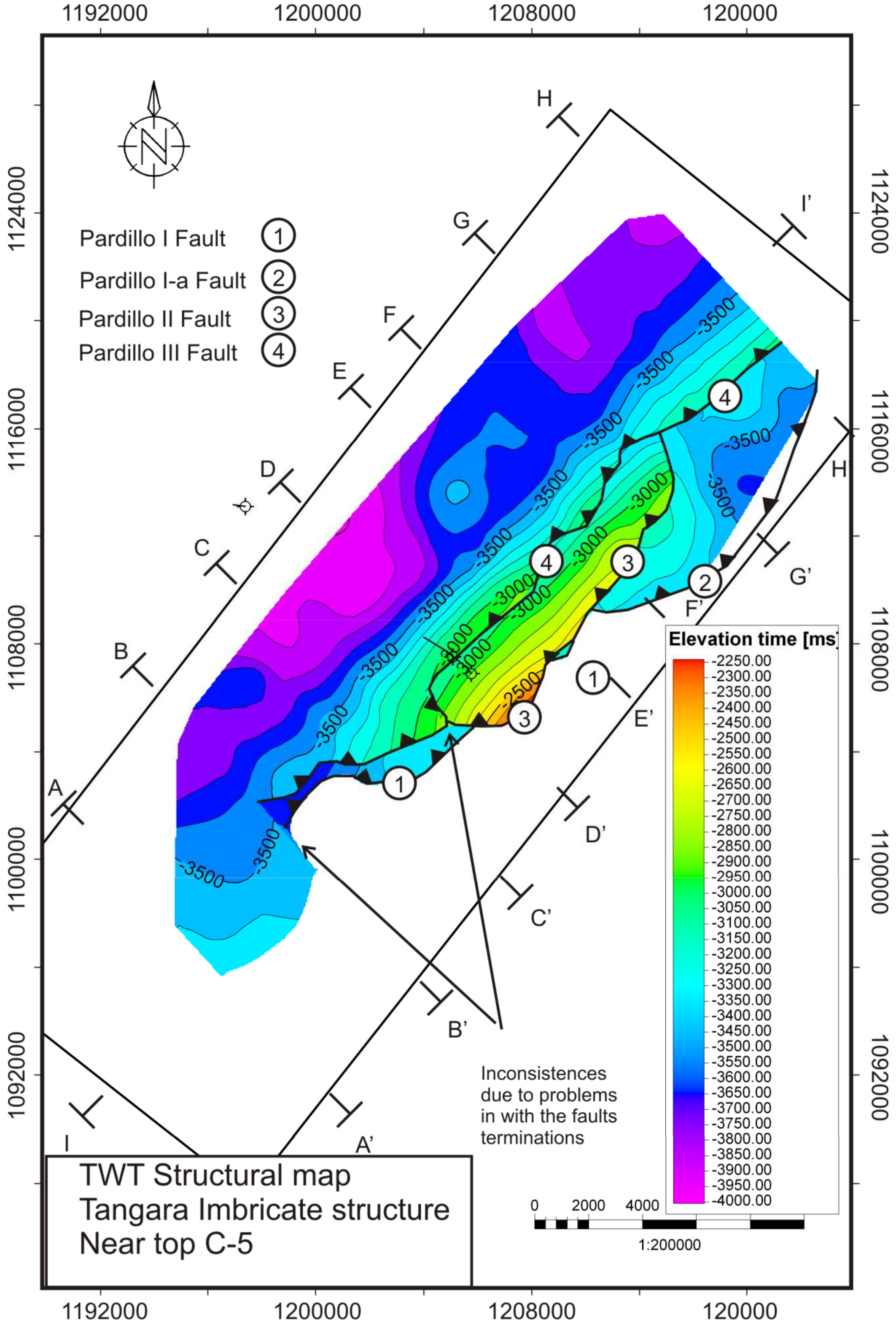


Figure 44. TWT Structural map near top C-5 unit, for the Tangara imbricate structure.

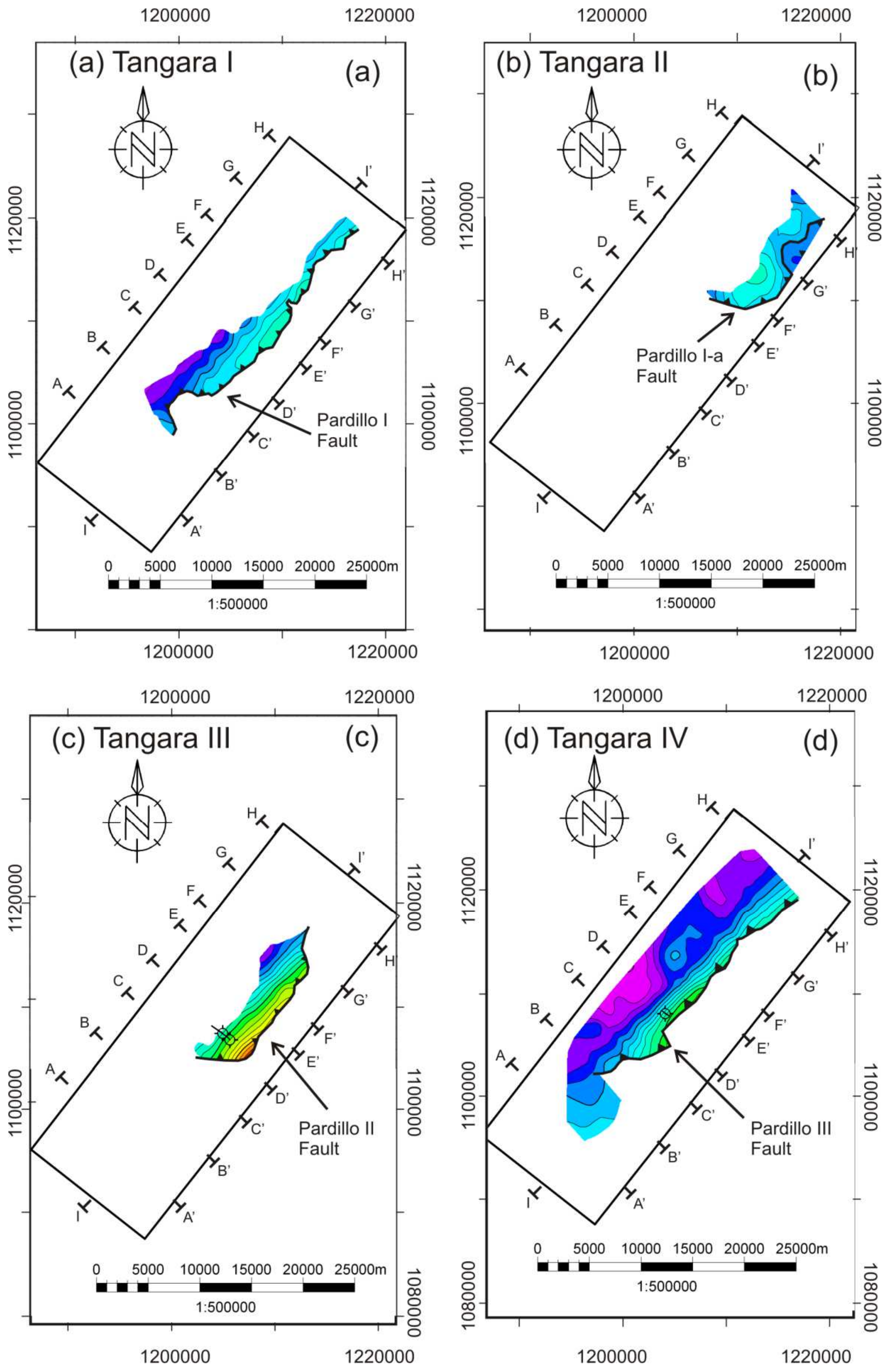


Figure 45.Structural map TWT of the compartments of Tangara imbricate structure, near top C-5 unit.

The Tangara II compartment is located to the north of the study area. Here it is possible to see that the displacement in the upper units is moving to the foreland. The Tangara III compartment shows a steep hinterland-dipping monocline without significant changes. Finally, the Tangara IV is the longest structural sheet, and in this case the Pardillo III fault has a straighter shape.

Aysisi structure

This structure superimposes the Tangara imbricate structure. Figure 46 shows that in the C-3 unit of the Carbonera Formation the structure is a faulted anticline that has the maximum structural relief between the cross section F-F' to G-G'. Between the sections C-C' and E-E' the fault has a sigmoidal shape.

Summary of observations for the structural configuration of the east zone of the lower Nunchia foothills

In the east zone of the lower Nunchia foothills, the following characteristics were extracted from the seismic interpretation, well correlation and subsurface maps

1- The faults have a flat-ramp trajectory with ramps between 25° to 30°.
2- The faults do not present evidence of bending.
3- The structures have different base detachment levels, Gachetá, C-8, C-6, C-4 and the León Formation.
4- The faults do not join in a common upper detachment level
5- The upper imbricates do not shows evidence of bending due to lower structures
6- Two Lateral ramps changes the change the structural style and configuration of the area. In the south, the structure is a thrust that involves Cretaceous rocks to Oligocene rocks, while in the north is a normal fault, the Pauto fault generated during the Oligocene.

7- The lower duplex involves the lower Carbonera Formation, while the upper structural sheets comprise the upper Carbonera unit and the Leon Formation.

8- In the south, the outer Nunchia foothills are narrower than in the north.

9- In the south, the lower structures are associated with the Tangara fault system and the Cravo Sur fault; while the upper structures are associated to the faults: Aysisi, Orocue, Manitas, Sural I and the Yopal fault system

10- In the north, lower structures are associated to the Pauto fault, Tangara fault system, Aysisi and Manotas faults. The upper structures are related to the Sural fault system, Yopal fault, and Tocaria back-thrust.

11- In the area where the EC changes in direction, the lower structures reach the maximum structural relief and a series of left-lateral strike slip faults accommodate the shortening in the Nunchia syncline.

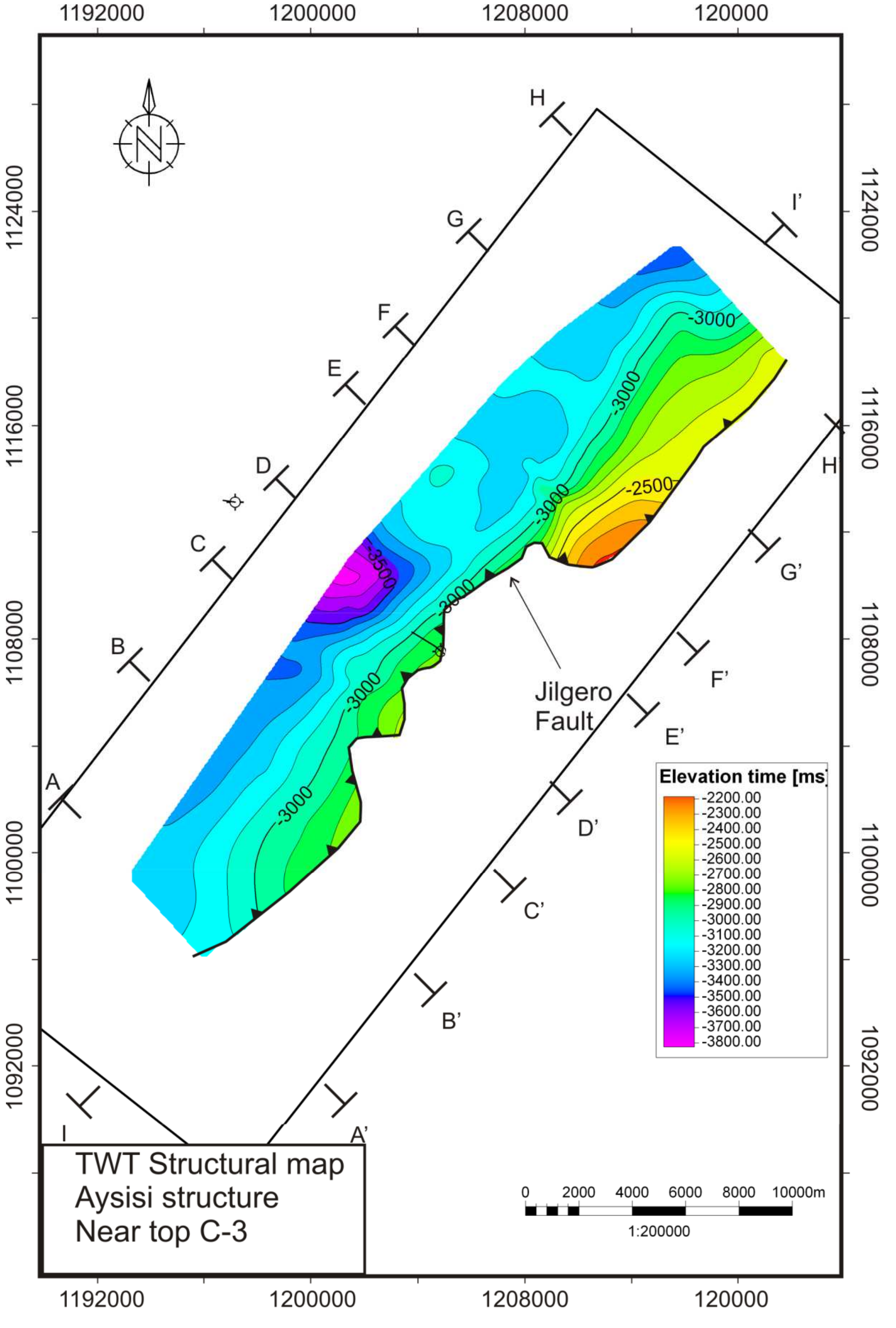


Figure 46. TWT Structural map near top C-3 unit for the Aysisi structure

3D structural model of the outer Nunchia foothills

To verify the interpretation, the fault and surface horizons were exported to Move to check the consistency of the model (figure 47). To verify the interpretation, six cross sections were extracted from the model (figures 48 to 51) and a displacement analysis of the basal and lower structures was generated (figure 52).

Figure 47 shows the structural framework for the basal and intermediate structures in the outer Nunchia foothills, while figure 48 shows the location of the cross sections generated. The cross sections highlight three types of error: interpretation (red cicles), continuity of surfaces (blue) and inconsistencies in traced fault tip extent, for example between 2D seismic lines where it could not be interpreted (green) (figures 48 to 52).

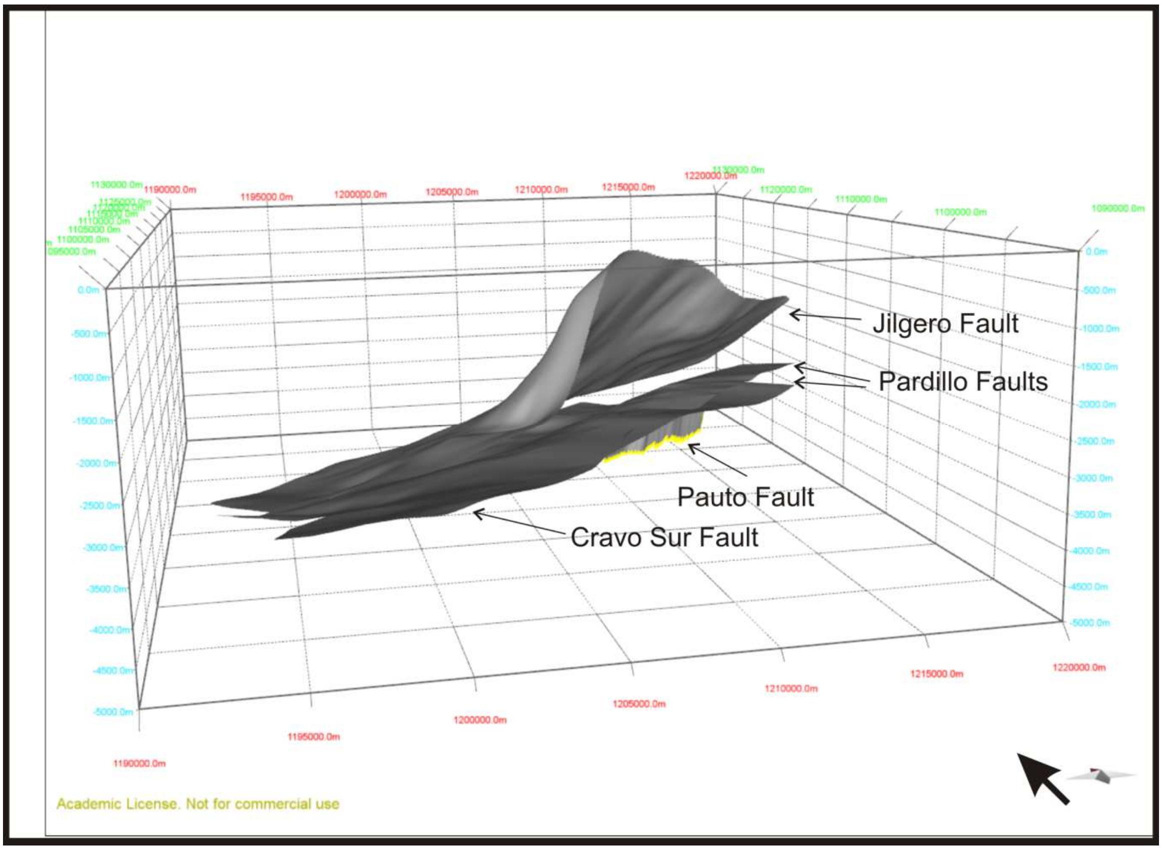


Figure 47. Structural framework model for the basal and intermediate structures of the outer Nunchia Foothills

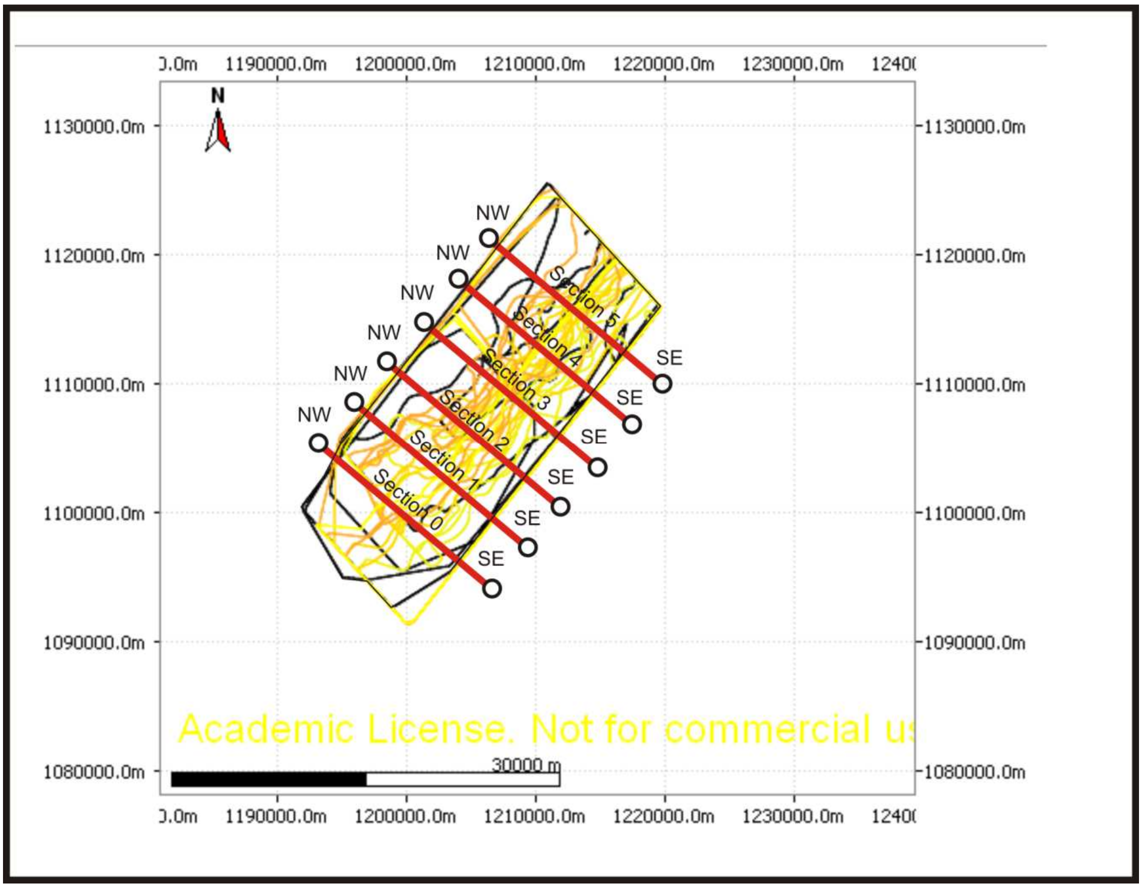


Figure 48. Location of the random cross sections generates to check the consistence of the structural model.

The interpretation errors in section 1 are related to the merging of the C-5 and C-7 units (figure 49, Section 1a) and due to a local flat on the C-5 surface that increases the displacement. In section 2 (figure 49), error is related to the length of the C-7 ramp; and in section 5, with the fault displacement, in this case the displacement represents a normal fault.

The same types of errors were found in the displacement analysis (figure 52). The principal error is related to the termination of the faults. Interpretation errors are associated to the Pardillo I fault in the C-7 level, where the displacement changes suddenly to reverse form.

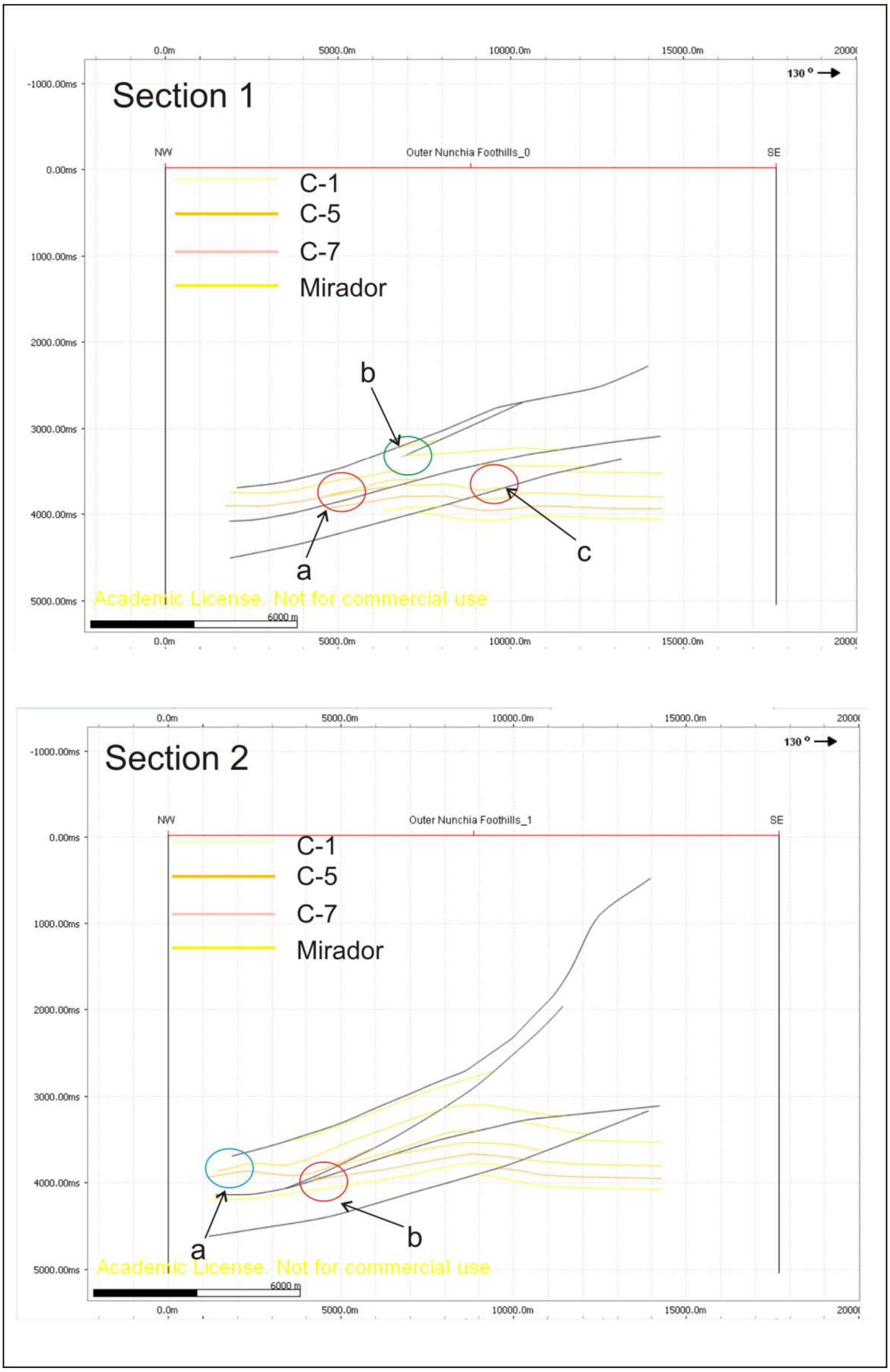


Figure 49. Sections 1 and 2 generated in Move software

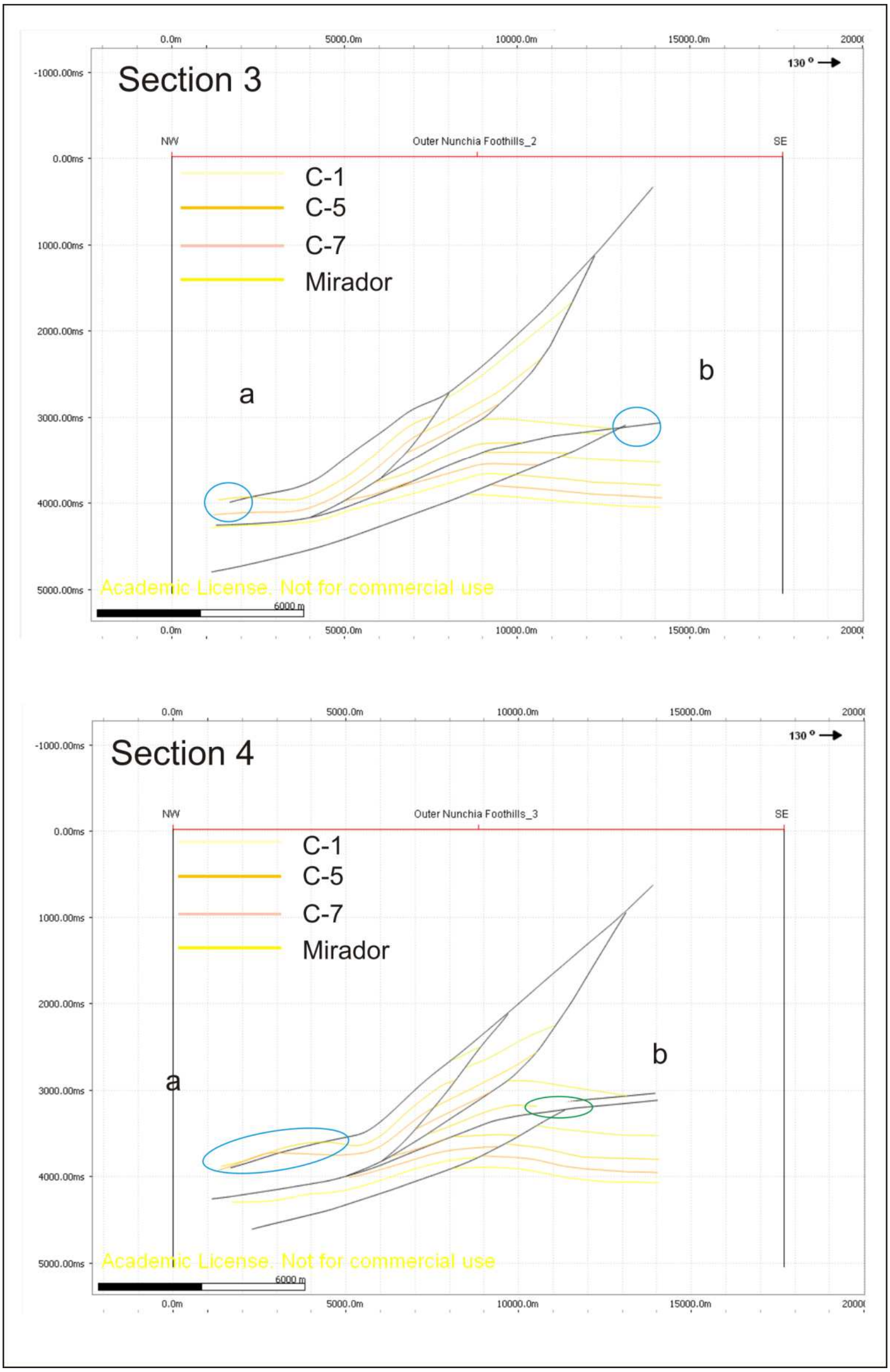


Figure 50. Sections 3 and 4 generated in Move software

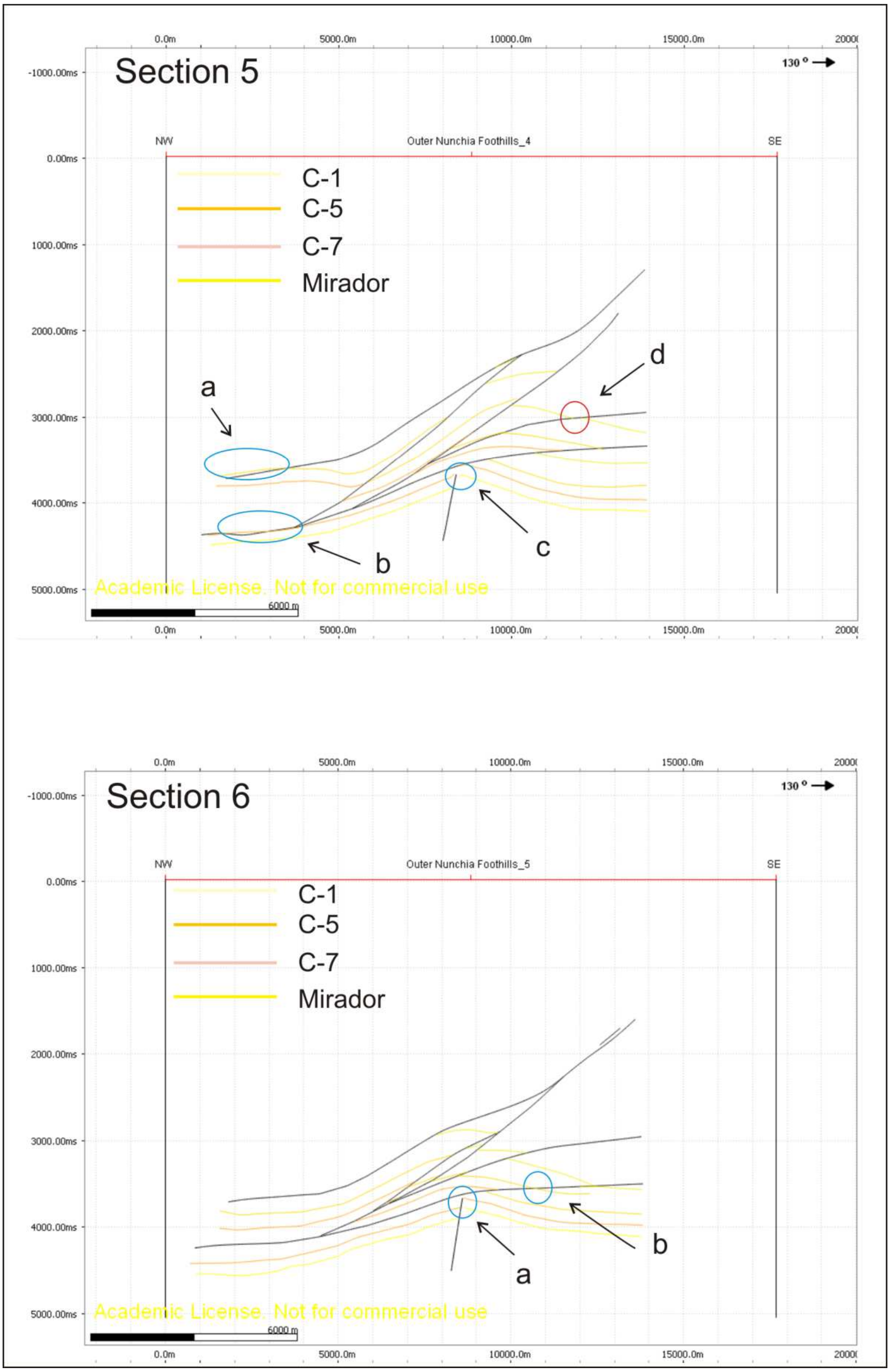


Figure 51. Sections 4 and 5 generated in Move software

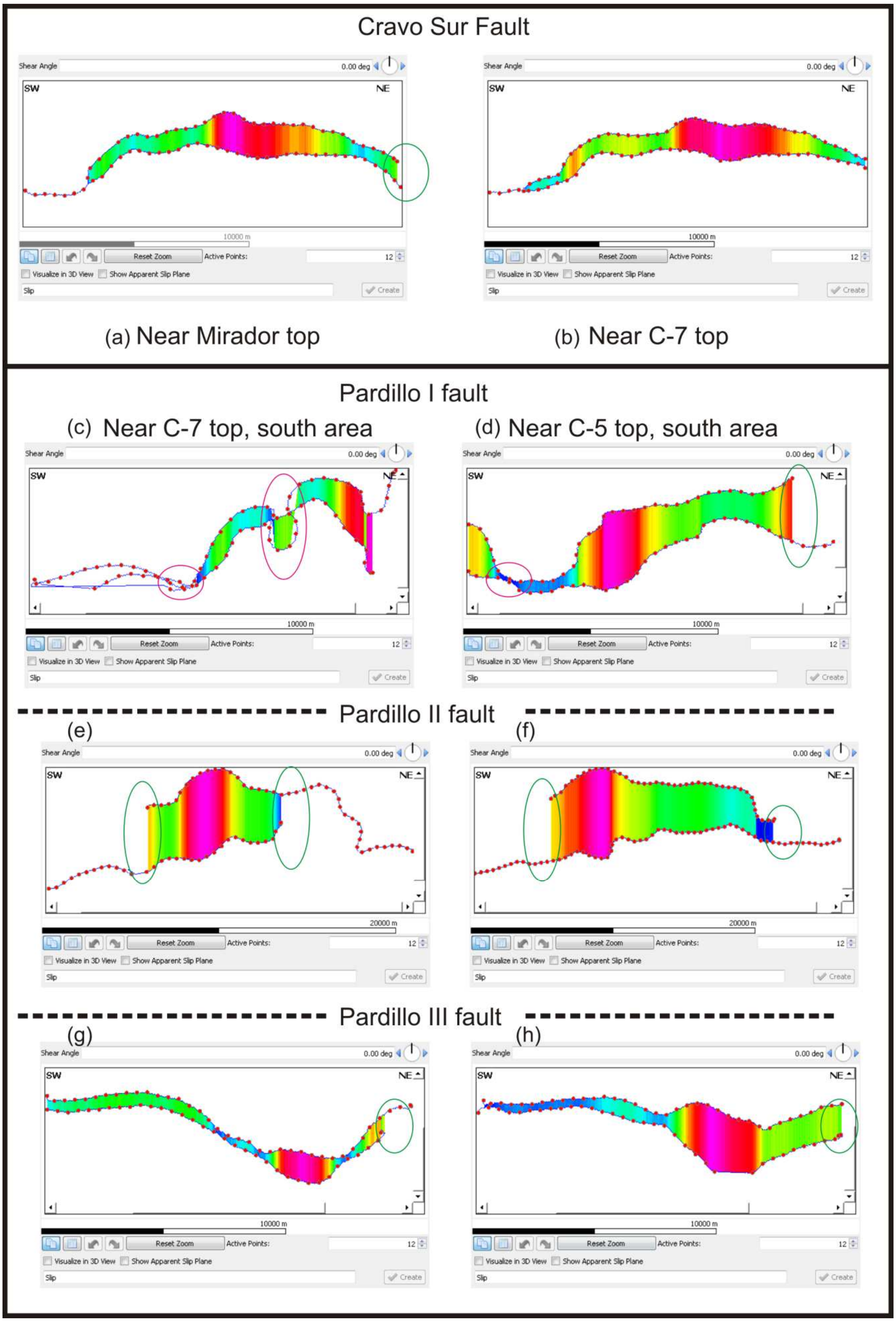


Figure 52. Displacement analysis of the Cravos Sur, Pardillo I, Pardillo II and Pardillo III faults.

Discussion

Configuration and structural style

Three studies in this area show the structural style, Cediel et al., (1998) and Rochat et al. (2003) to be thin-skinned, while Tesón, et al. (2013) show a thick-skinned to inversion tectonic structural style (figure 53).

In this study the Nunchia foothills are divided in two areas: outer and inner. The outer area follows the structural style identified in the Pauto complex, antiformal stack, while the outer area show an stacked of hinterland-dipping imbricate structures. The detachment level allows the distinguishing between the structures: Basal structures, intermediate structures and upper to surface structures (figure 19). The basal structures have a detachment in the Gachetá Formation and are the only structures that involve the reservoir rocks into the deformation; the intermediate structures have the lower detachment in the Lower to Middle Carbonera Formation (C-8 and C-6); and, the detachment for the upper to surficial structures is the Upper Carbonera (C-4? And C-2). The compressional structures are hinterland-dipping monoclines or asymmetrical anticlines characterized by long back-limbs and gentle dip. Therefore, a thin-skinned structural tectonic style is proposed for this area. It supports the interpretations of Cediel et al., (1998) and Rochat et al. (2003).

Tesón, et al. (2013) shows that the structures corresponding to the Outer Nunchia Foothills are related to inversion structures (figure 53 C). The Yopal and Piedemonte fault system are faults with steep ramps that involve basement rocks into the deformation. Although, this interpretation is more prospective in term of hydrocarbon exploration, it does not match with the result of the Tangara-1 well and the seismic responses of the Tangara 3D.

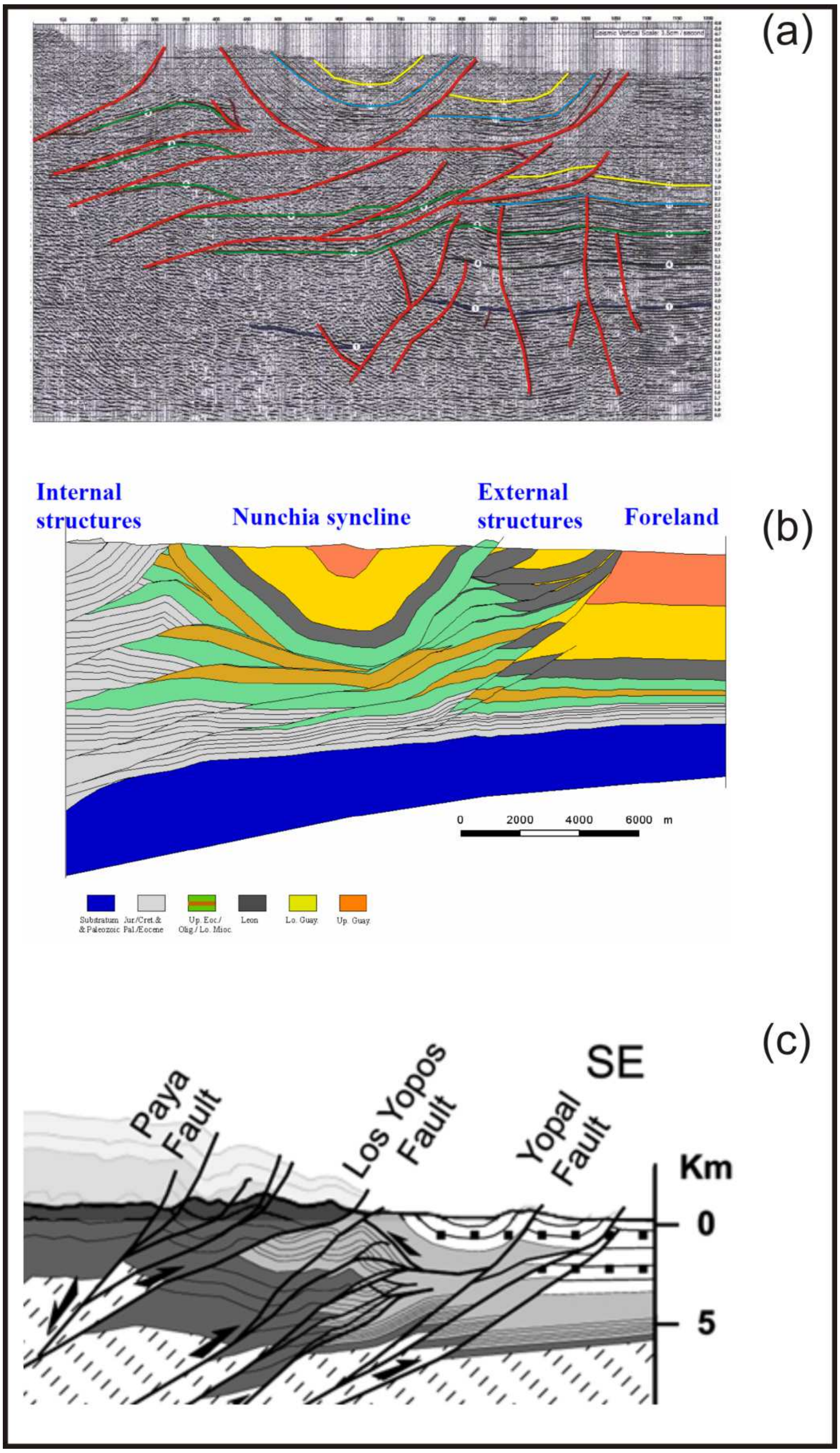


Figure 53. Structural styles proposed in the study area, Thin-skinned proposed by Cediel et al., (1998) (a) and Rochat et al. (2003) (b) and thick-skinned by Tesón et al., (2013) (C). (Compiled from Cediel et al., 1998; Rochat et al. 2003; Tesón et al., 2013)

Structural configuration and structures of the Outer Nunchia Foothills

The Nunchia foothills are divided into inner and outer structures (internal and external structure for Rochat et al., (2003)). The inner structures are a prolongation of the antiformal stacked documented in the Pauto, Floreña, Dele, and Volcanera area (Linares et al., 2009; Martinez, 2003, 2006b; Rochat et al., 2003), while the outer structures comprise of stacked monoclines to imbricate structures. Figure 54 proposes a model for this region, where the reservoir rocks, represented by the yellow layer are located principally in the inner structures.

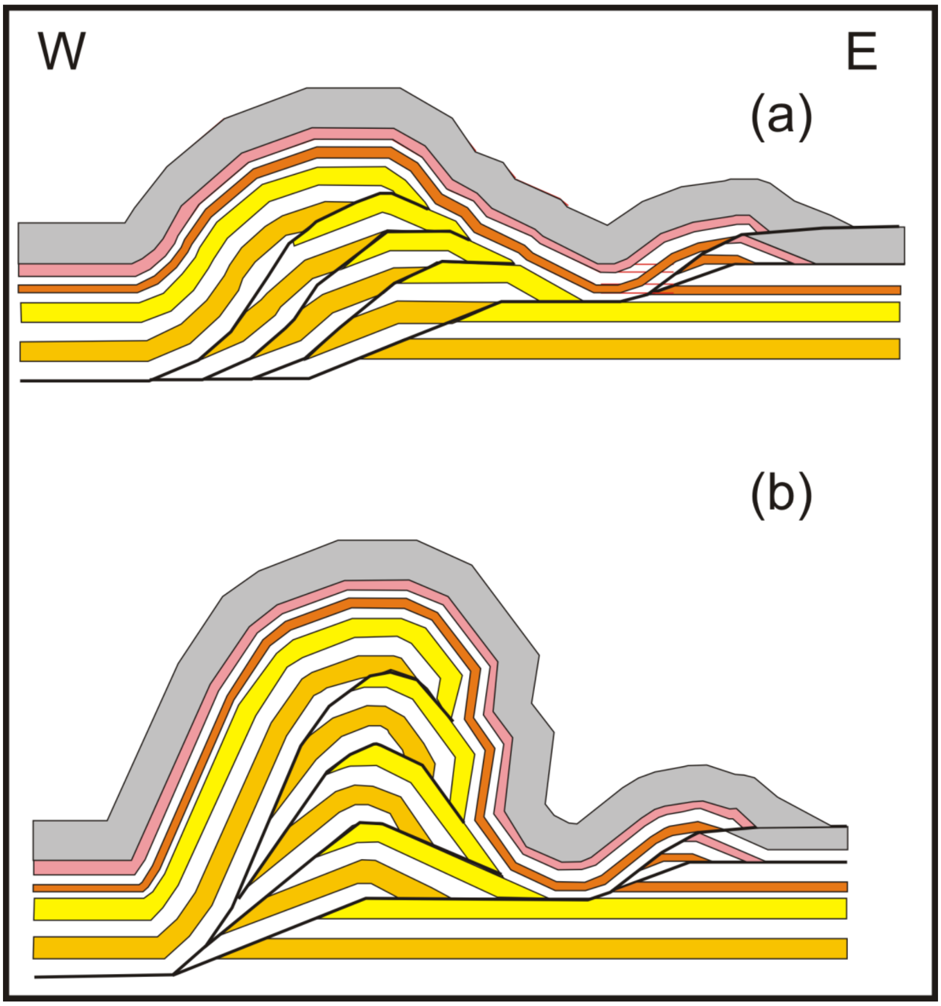


Figure 54. Model to explain the configuration of the Nunchia Footthills. (a) hinterland-dipping antiformal stack; (b) foreland-dipping antiformal stack.

The region is affected by the change of direction of the EC. It generates a change in the geometry of the Nunchia syncline, the generation of some strike-slip fault (Payero fault) and the increase of the structural relief in the intermediate structures of the outer Nunchia foothills. The model shown in figure 54-b explain the changes generated in the Nunchia syncline and the outer Nunchia Foothills area.

Therefore, taking into account the configuration of the lower foothills and the structural style, the Nunchia foothills is a combination of the overthrust (inner zone) and frontal structures (outer zone) proposed by Martinez (2003, 2006b).

The stratigraphic correlation and seismic interpretation allowed separation of the structures in three zones, based on the lower detachment. The basal structures are the only structures that contain the reservoirs in the deformation. The intermediate structures, with lower detachment in the C-8 or C-6 unit involves the Carbonera to León Formations into the structures. Finally, the upper to surface structures, involves rocks from Upper Carbonera to Gauyabo Formation.

The stratigraphic correlation show lateral variation to the north and to the west directions. The Carbonera units become thicker to the west, which can represent the source of the syn-deformation units in the basin. This matches with the Martinez (2003. 2006b) interpretation. He proposes that the two initial deformation events affect the lower Carbonera (C-6 toC-8 units) and middle Carbonera (C-5 unit) to Guayabo Formation.

The structures plunge to the north. It is recognized by the deposit of a Corneta Formation in the axial surface of the Zamaricote syncline. In the same way, the correlation shows that the units becoming thicker to the north. It implies that this region has a major space of accommodation. This extra space of accommodation is interpreted as isostatic result of the uplift of the EC. To the north, the EC reaches the highest elevation, the Sierra Nevada del Cocuy. This area is composed of 21 picks with elevations between 5000m (Ritacuba Blanco pick) to 4800m (Portales pick).

Sequence of deformation of the structures in the outer Nunchia foothills

The seismic sections interpreted show that the faults have a flat-ramp trajectory with ramps between 25° to 30°. The faults do not present evidences of bending. Additionally, the structures have different detachment levels, Gachetá, C-8, C-6, C-2 and León Formations. Based on the geometry, the imbricate structures involved in the stack are break-backward stacks separated by detachment levels are proposed. The monoclines located in the upper structures represent the end-member of the Nunchia Foothills. Therefore, the model proposed by Egbue and Kellogg, 2012, where the EFEC has an active-roof duplex is validated in this research.

Future works

Although the research allowed the generation of a structural model for the outer Nunchia Foothills, it has some inconsistencies. An update of the seismic interpretation and structural restoration would improve the structural model.

Additionally, the study should involve the inner zone, to evaluate the complete configuration of the Nunchia foothills.

A research focus on the quality of the seismic data must be done to evaluate if the sparse design can be acquired in the EFEC. If positive results are found, it would be used by operators in the area as a cost-effective method of acquiring 3D seismic.

CONCLUSION

1. The outer Nunchia foothills are comprised of stacked hinterland-dipping monoclines to imbricate structures, developed in a thin-skinned structural style.
2. The structures can be classified based on the lower detachment level as basal, intermediate or upper to surface structures.
3. The imbricate structures located in the intermediate structures are break-backward sequence with common detachment levels.
4. The end-member of the Nunchia foothills is an active-roof duplex, which is represented for the upper to surface structures in the outer Nunchia foothills
5. At least two lateral ramps affect the structural configuration of the lower Nunchia foothills.
6. The Carbonera, Leon and Guayabo formations are syn-deformation deposits, with lateral thickness variation, increasing to west and to north.
7. The hydrocarbon prospectivity in the outer Nunchia foothills is low because the reservoir rocks are involved only in the basal structures. In the south, this structure was tested by the Tangara-1ST2 wells and Tangara-1ST2 wells.
8. The current seismic quality of the Tangara-3D and the geological complexity prevent construction of a consistent 3D model. Only, a pseudo-3D model can be generated.

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