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The role of inherited structures in a foreland basin evolution. The Metán Basin in NW Argentina

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ABSTRACT

The foreland basin of the Central Andes in NW Argentina is formed by partially unconnected basins limited by uneven high ranges. The Metán Basin is located in the foothills of the Central Andes in NW Argentina between the Eastern Cordillera, the Sierras Pampeanas and the Santa Bárbara System. This basin resulted from a Cretaceous to Paleogene rifting event and from two Neogene to Quaternary foreland basin stages. For this study field data, log well, seismic reflection and satellite images have been interpreted. The propagation of deformation in this sector of the Andes is influenced by inherited structures (e.g. Cretaceous extensional faults), which have been reactivated during Andean compression as high angle and oblique reverse faults. Deformation does not advance regularly throughout the foreland in a normal forward sequence but jumps across inherited faults. Fault reactivation has resulted in uplift of basement cored ranges and hanging wall anticlines that divided the foreland into small basins (e.g. the Metán Basin).

1. Introduction

The geometry and evolution of the space of a basin and its sedimentary infill are strongly controlled by several factors related to subsidence mechanisms. In an "Andean type" plate convergent margin (Dewey and Bird, 1970) as in other orogenic systems, the proximal parts of the foreland basin are progressively incorporated into the orogen as the thrust front propagates forward. These parts then become piggyback or the entire foreland is compartmentalized becoming a broken foreland depending on the structural style (Jordan et al., 1983; DeCelles and Giles, 1996).

Structural discontinuities from earlier tectonic cycles may play a major role in the way that deformation propagates and in the way that ranges uplift, affecting the development of the foreland classical piggyback sequence (Ramos, 1999b). If this is the case, tectonic load could change dramatically from shallow detached thrusts to thick basement ranges. The Central Andes provides good examples for the two situations: 1) A thin-skinned fold and thrust belt develops in the Subandean system in Bolivia, where thrust sheets detached at shallow depth are raised and transported eastwards, and where deformation propagates towards the foreland (Roeder, 1988; Baby et al., 1992; Echavarria et al., 2003; Uba et al., 2009). 2) A thick-skinned thrust system is developed in the Santa Bárbara and the Sierras Pampeanas in NW Argentina (González Bonorino, 1950; Allmendinger et al., 1983; Jordan et al., 1983), where crustal discontinuities related to Palaeozoic orogenies or to Cretaceous extensional faults are easily reactivated when subjected to shortening, giving rise to high positive reliefs.

The Metán Basin has been studied by many authors. Mon (1976) described the control of inherited oblique faults on the structure resulting from Late Pliocene to Early Pleistocene deformation. Grier et al. (1991) highlighted the regional role of the tectonic inversion of the Cretaceous extensional fault system. Cristallini et al. (1997) evaluated the structure of the basin by reprocessing seismic reflection lines and using well data, some of which are also included in this study. These last authors showed that the structure of the basin comprises a series of half grabens filled with Cretaceous red beds. They also interpreted several deep, east dipping reflections as master shears, attributed to the Cretaceous rift system and to their subsequent reactivation as thrusts. Vergani and Starck (1981) studied a larger area embracing part of the Eastern Cordillera immediately to the west of the Metán Basin and proposed a deep cross section. Mon et al. (2005a) described structural sections of the Metán Basin including the Sierra de Metán and Cerro Colorado.

The present study seeks to elucidate the structure of the Metán Basin in order to better understand its evolution and the factors controlling the development and the deformational sequence of this basin.

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2. Geological setting

The Metán Basin lies in the foothills of the Central Andes, in NW Argentina between 25–26° south and 65–64°30′ west. The area is located between three geological provinces: the Eastern Cordillera, the Sierras Pampeanas and the Santa Bárbara System (Fig. 1). These units are formed by basement blocks and Cretaceous inverted half grabens with deep detachments (González Bonorino, 1950; Bianucci et al., 1981; Grier et al., 1991; Kress, 1995; Cristallini et al., 1997). By contrast, the Subandean system, located further North, in the Bolivian border (Fig. 1), is formed by a thin-skinned fold and thrust belt that is detached in the Palaeozoic succession at a shallow depth (Roeder, 1988; Baby et al., 1992; Uba et al., 2009). This change in the tectonic style correlates with both a southward pinch-out of the Palaeozoic basin and the superposition of the foreland on the Cretaceous rift basin to the south of 24° S (Allmendinger et al., 1983; Comínguez and Ramos, 1995). The upper crust in this region has strong discontinuities due to inherited structures related to tectonic events from the early Palaeozoic (Rapela et al., 1998). These structures were reactivated several times. One of these reactivations occurred during the Late Cretaceous, when extension in the retroarc produced the Salta Rift Basin (Salfity, 1982; Galliski and Viramonte, 1988; Salfity and Marquillas, 1994).

The Metán Basin is located to the North of the present flat-slab subduction where the Nazca oceanic plate changes its dip from flat in the south to normal in the north at 27° S (Barazangi and Isacks, 1976; Cahill and Isacks, 1992; Gutscher et al., 2000; Ramos et al., 2002). Subducted slab angle variations during the Neogene produced migration of the magmatic arc, hydratation of the lower crust and subsequent thickening and uplift (Allmendinger et al., 1983; Isacks, 1988; Kay et al., 1991).

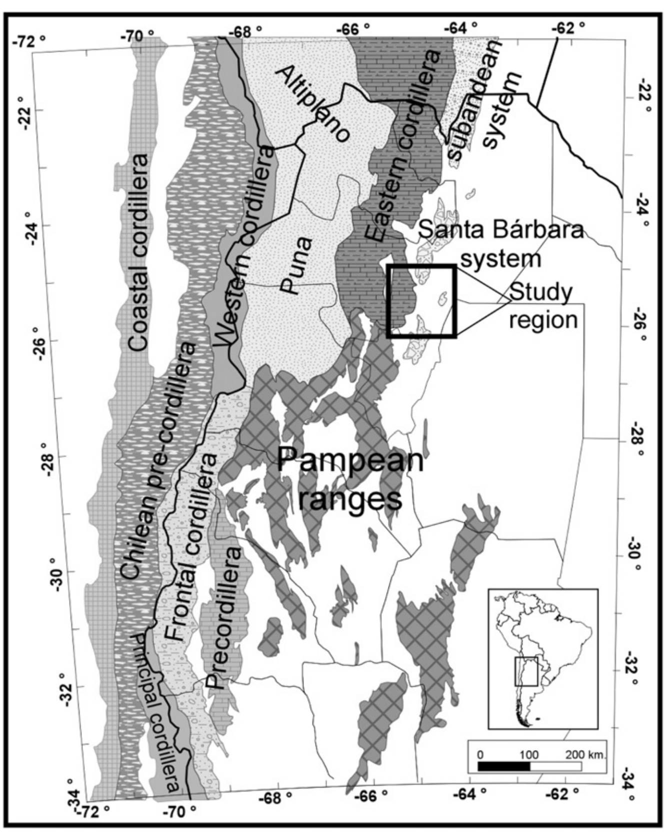

Fig. 1. Regional map of the central Andes in Argentina, Chile and Bolivia and location of the study area. Main geological provinces are displayed, modified from Ramos (1999a) and Hilley and Coutand (2009).

Along the study area the thrust front of the Central Andes is not a continuous and linear uplift. On the contrary, it consists of a series of stepped structures with related ranges that produce a significant compartmentalization of the adjacent Neogene foreland basin (Fig. 2). The present topography shows the intricate geometry of the foreland basin which consists of different interconnected subbasins with diffuse boundaries. In particular, the eastern boundary of the Metán Basin is made up of gentle and discontinuous structures which are still active.

The Andean thrust front has evolved since the Early Miocene. The present geometry does not necessarily reflect the foreland basin configuration of the early stages (Carrera and Muñoz, 2008). The first stage of the foreland basin infill is characterized by a constant thick succession of fine grained sediments, suggesting a continuous foreland basin across the studied area and further west into the Lerma and Calchaquíes valleys (Fig. 2). Coarsening upwards sequences and growth strata geometries of the late stages of the foreland basin infill furnish evidence of the activity of the frontal structures in the study area and the onset of compartmentalization as observed today (Strecker et al., 1989, 2007; Reynolds et al., 2000; Bossi et al., 2001; Carrapa et al., 2006; Carrera and Muñoz, 2008). The gradation from fine to coarse grained sediments is not synchronous in the whole area because it is related to the eastwards migration of the deformation and to the activity of local structures (Jordan et al., 1983; Coughlin et al., 1998; Kley and Monaldi, 2002; Carrera et al., 2006; Oncken et al., 2006).

One problem concerns the significance of such a complex structural grain and the influence of the foreland basin compartmentalization on its sedimentary infill. Another issue is the structure of the floor of these subbasins and their relationship with the emergent structures that surround them. All these points will be addressed in this paper making use of the available subsurface data and surface geology in the Metán Basin.

3. Stratigraphy

The sedimentary infill sequence of the foreland Metán Basin consists of Neogene to recent continental sediments. These units unconformably overlie either the Paleogene and Cretaceous rift rocks or the Precambrian to Palaeozoic rocks (Fig. 3). Thus from bottom to top, the following sequences can be encountered: prerift, synrift, postrift and foreland.

The prerift sequence is constituted by two units: the Precambrian basement and the Palaeozoic cover. The Precambrian basement outcrops are located to the west and to the southwest of the Metán Basin, in the Sierra de Metán and in the Sierra de la Candelaria, respectively (Fig. 2). The basement in the Sierra de Metán consists of strongly deformed slates and phyllites of the Precambrian to Early Cambrian Puncoviscana Formation (Turner, 1960; Aceñolaza, 1978; Rapela et al., 1998). The Palaeozoic cover lies discontinuously below the Metán Basin and crops out to the south and to the north. Cambrian to Ordovician siltstones and quartzarenites (Ricci and Villanueva García, 1969; Mon, 1971) crop out on the eastern slope of the Sierra del Campo (Mángano and Buatois, 1996), in the Sierra de la Candelaria to the south (Moreno Espelta et al., 1976), in the Sierra de San Antonio and in the Sierra de González to the north (Fig. 2). These rocks correspond to the southernmost deposits of a marine clastic platform developed mostly in Bolivia (Ramos, 2008). Moreover, Devonian pink and white quartzite crop out at Cerro Cantero to the southeast, and in the Sierra de San Antonio and in the Sierra de González to the north (Ruiz Huidobro, 1955). In addition to Devonian, Carboniferous deposits were drilled by exploratory wells farther east (Cristallini et al., 1997). Both Precambrian and Palaeozoic rocks have been reported in the Sierra de Mojotoro to the northwest (Ruiz Huidobro,

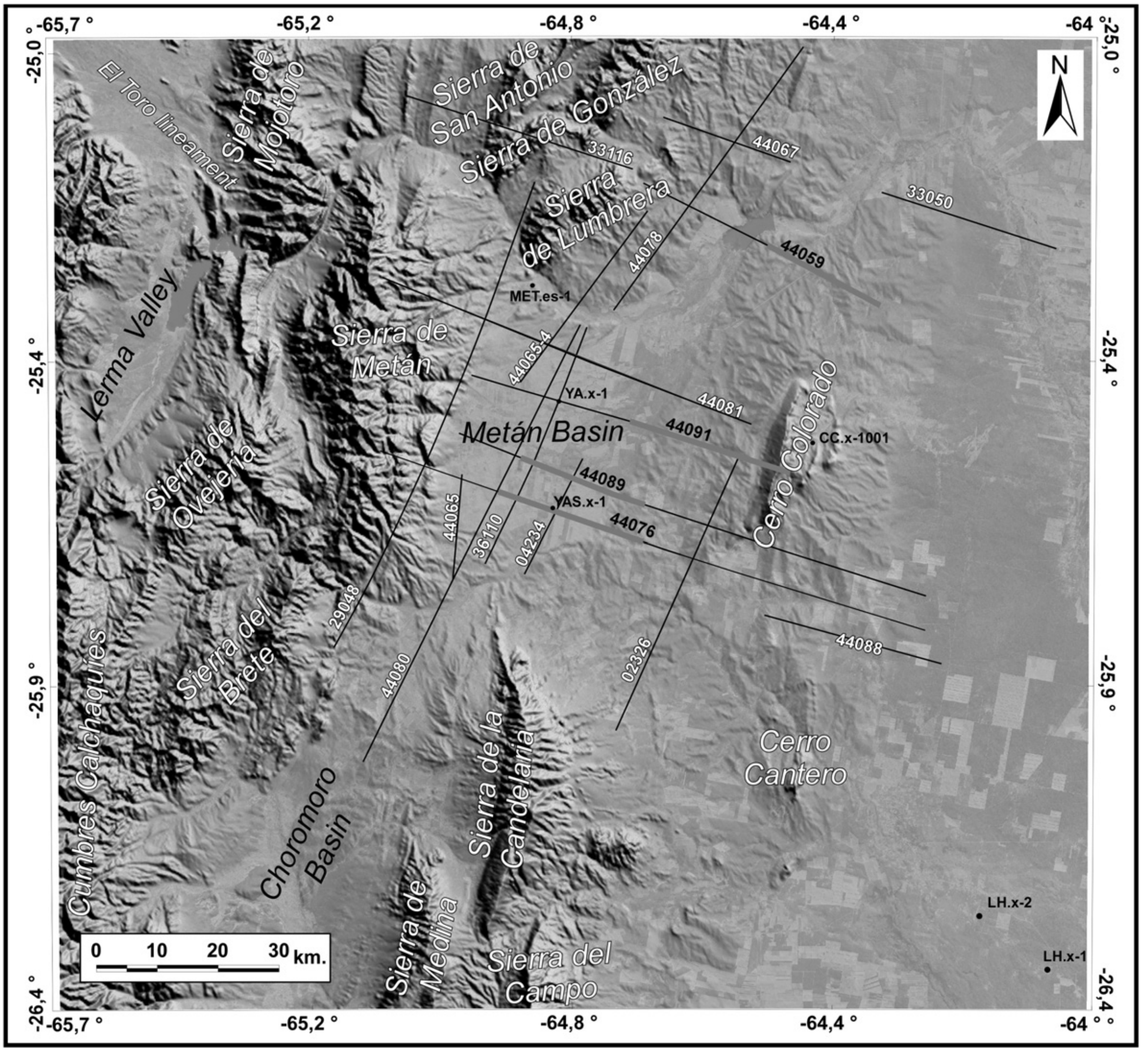

Fig. 2. Shaded relief map of the studied area with names of geographic features and location of wells and seismic lines.

1955; Moya, 1998). The contact between the Precambrian basement and the Palaeozoic cover is often due to an angular unconformity (Ramos, 1986; Mon and Hongn, 1991; Comínguez and Ramos, 1995; Mon and Salfity, 1995). To the east of the Tucumán Basin a seismic section describes a series of faults thrusting the basement over a Palaeozoic basin (Cristallini et al., 2004). Palaeozoic layers are not found stratigraphic above the Precambrian basement except in the Sierra de Mojotoro and in few small remnants of mainly Ordovician rocks (e.g. in the Sierra de la Candelaria).

The Precambrian basement and Palaeozoic cover are unconformably overlain by Cretaceous synrift rocks of the Pirgua subgroup, which is the basal unit of the Salta Group (Vilela, 1951) and was deposited in the Cretaceous to Paleogene Salta Rift Basin (Salfity and Marquillas, 1981, 1994). The Pirgua Subgroup is composed of red beds of conglomerates, breccias, sandstones and siltstones with strong lateral thickness variations. These rocks have been deposited in continental environments such as alluvial fans and fluvial plains (Ruiz Huidobro, 1955; Salfity and Marquillas, 1981; Monaldi et al., 2008). The sedimentation of the Pirgua Subgroup was controlled by the activity of extensional faults with the result that the layer thickness and granulometry increase towards the master fault of the half grabens (Salfity and Marquillas, 1981; Gómez Omil et al., 1989; Grier et al., 1991; Sabino, 2004; Kley et al., 2005; Carrera et al., 2006). Volcanic deposits are intercalated in the red beds (Salfity and Marquillas, 1981). Alkaline basalts have been documented and dated with ages between 128 and 76 Ma (Galliski and Viramonte, 1988).

The Balbuena and Santa Bárbara Subgroups correspond to the postrift stage that was deposited when the activity of the extensional faults ceased (Turner, 1960; Moreno, 1970). The postrift sequence extends beyond the synrift deposits and overlies the Precambrian basement and the Palaeozoic cover along the margins of the Salta Rift Basin. This sequence shows considerable lateral changes in thickness and thins out towards the borders of the basin. This geometry was attributed to the thermal cooling stage of the Salta rifting (Bianucci et al., 1981; Gómez Omil et al., 1989; Comínguez and Ramos, 1995; Cristallini et al., 1997). The Late Cretaceous, mainly Maastrichtian, Balbuena Subgroup overlies the Pirgua Subgroup and the basement of the basin margins (Moreno, 1970). It includes marine oolitic and stromatolitic limestones together with lacustrine greenish shales of the Yacoraite Formation (Turner, 1960; Gómez Omil et al., 1989; Salfity and Marquillas, 1994). This formation is a good stratigraphic reference level in the predominantly red rocks of the Mesozoic and Cenozoic succession (Marquillas et al., 2005; Monaldi et al., 2008). The Paleocene to Early Eocene Santa Bárbara Subgroup is more extensive and overlies the Balbuena Subgroup and the basement. It consists of red

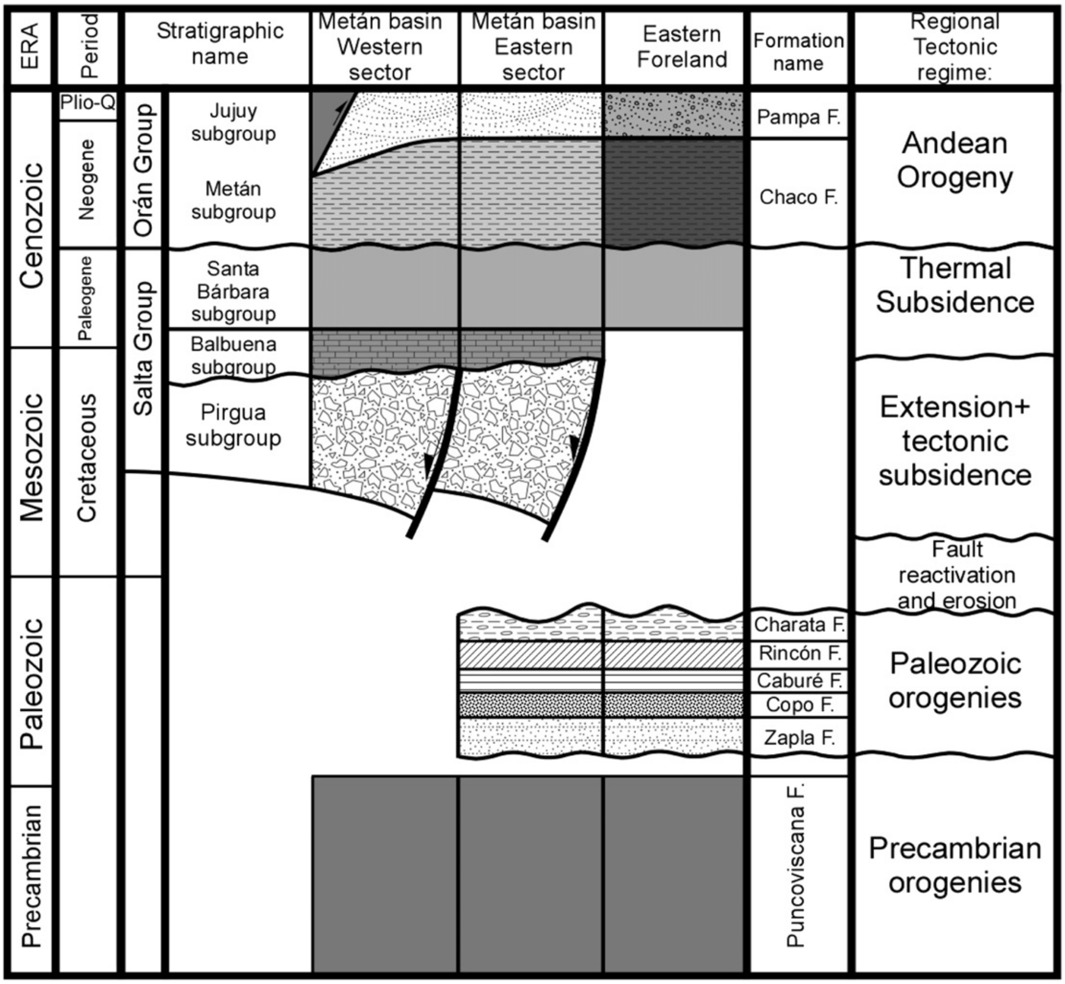

Fig. 3. Chronostratigraphic chart of the Metán Basin and the foreland to the east.

sandstones and shales with some greenish levels of fluvial to alluvial plain depositional environments.

In the Cordillera Oriental to the west of the Metán Basin but to the east of the Puna, the lower foreland sediments record the onset of the subsidence in the foreland and the denudation of the hinterland chains to the west of the Cordillera Oriental (Jordan et al., 1983; Reynolds et al., 2000; Carrera and Muñoz, 2008). A Late Paleogene age was assigned to these sediments of the Payogastilla Group (Galli et al., 1996; Ramos, 1999a; Carrera et al., 2006; Del Papa et al., 2010). In the foothills, the foreland sediments correspond to the Orán Group and are arranged in a thick Neogene succession unconformably overlying the postrift and the synrift sequences of the Salta Group (Gebhard et al., 1974; Russo and Serraiotto, 1979; Salfity and Marquillas, 1994). Two subgroups can be distinguished: the lower Metán and the upper Jujuy (Fig. 3). The Metán subgroup consists of mainly pelitic and sandy sediments with few evaporites of Miocene age. It has been attributed to a distal sedimentary supply and to the Paraná marine transgression (Ramos and Alonso, 1995). No significant structures were developed in the Metán Basin at the time of its deposition. The Jujuy Subgroup is Pliocene to Quaternary in age and is formed by a coarsening upwards succession of sandstones to conglomerates (Gebhard et al., 1974). These sequences developed during the significant uplift of ranges in the area (Gebhard et al., 1974; Mingramm et al., 1979; Galli et al., 1996). As a result of this uplifting, sedimentary units of this subgroup show several internal angular unconformities and growth strata geometries (Gebhard et al., 1974; Ramos, 1999b). Eastward of the Metán Basin, the foreland sediments are constituted by the Chaco and Pampa Formations (Fig. 3).

4. Basin description

4.1. Well stratigraphy

A number of petroleum exploratory wells were drilled in the Metán Basin. For this study, six wells have been analysed to construct a structural model (Fig. 4). Three wells are located in the middle of the Metán Basin (MET.es-1, YA.x-1 and YAS.x-1), one well is at Cerro Colorado on the eastern boundary of the basin (CC.x-10001) and the two others are located to the southeast of the Metán Basin (LH.x-2 and LH.x-1).

Fig. 4 is a summary of the stratigraphic columns interpreted from the aforementioned wells. The Yatasto (YA.x-1) and Yatasto Sur (YAS.x-1), the two deepest (3329 m and 3554 m, respectively) wells are located in the centre of the basin (Fig. 2). These wells were drilled into the Orán Group foreland sediments, reaching the Salta Group. Only the YAS.x-1 penetrated the synrift beds of the Pirgua Subgroup. Neither of these two wells reached as far as the Precambrian basement or the Palaeozoic cover.

Towards the NNW, the Metán well (MET.es-1) is located close to the northern boundary of the Metán Basin on a structural high (anticline). This well shows a column similar to those of the Ya.x-1 and Yas-es.1 wells, except for two features: 1) all units are slightly thinner except the foreland sediments of the Jujuy Subgroup which

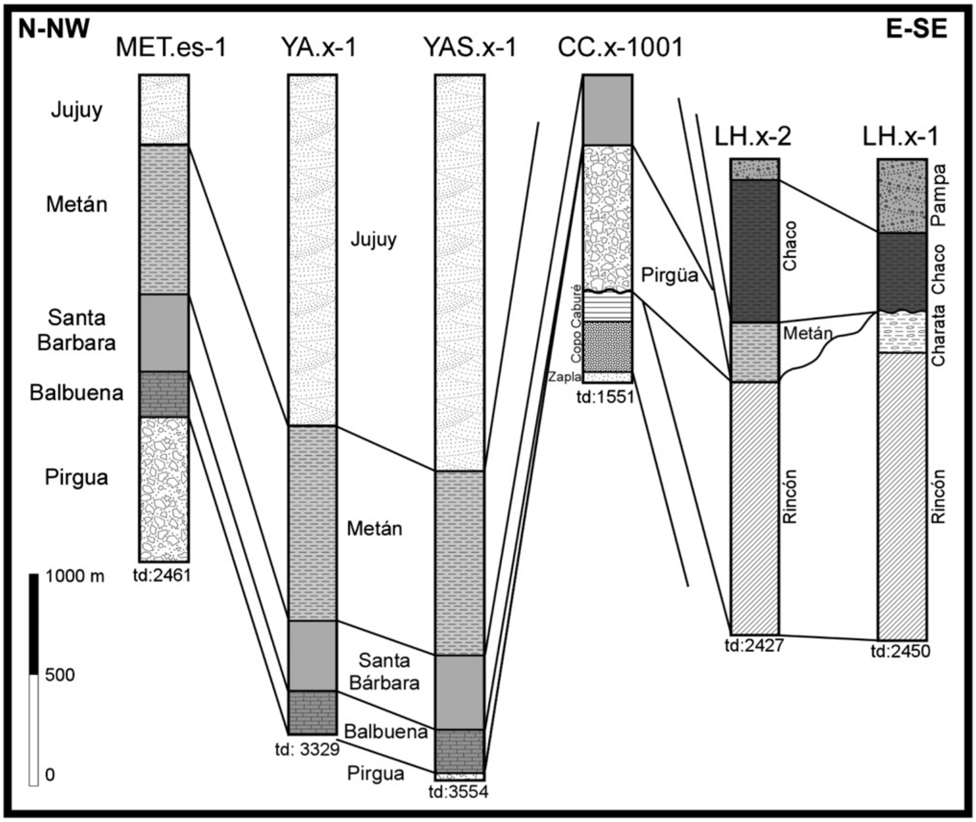

Fig. 4. Correlation of well stratigraphic columns that represent lithologies and thickness.

are much thinner (not deposited or eroded) and 2) the well penetrated several hundred metres into the Pirgua Subgroup (Fig. 4).

The Cerro Colorado Well (CC x-1001) is located on a structural high that corresponds to the eastern boundary of the Metán Basin (Fig. 2). This well shows a very different stratigraphic column with respect to the aforementioned ones. The postrift sequence is not complete owing to the absence of the Balbuena Subgroup. For this reason, it is not possible to use Yacoraite limestones as a reference level. The bottom part of the well is composed of Pirgua and Palaeozoic metasedimentary rocks.

The Los Horcones wells (LH x-2 and LH x-1) are located to the southeast of the Metán Basin (Fig. 2). The former well cuts 825 m into the Jujuy Subgroup, which overlies 300 m of the Metán Subgroup. The foreland sequence unconformably overlies the Palaeozoic cover, which consists of Devonian rocks. The LH x-1 well shows a similar stratigraphic column but with two differences: 1) The Metán Subgroup sediments are absent and 2) the foreland sediments unconformably overlie Early Carboniferous rocks that are not present in LH x-2.

The difference in the stratigraphic columns of these 6 wells should be noted. The wells in the Metán Basin show a thick foreland sequence and a complete Salta Group (rift and postrift sequences). By contrast, the Los Horcones wells, which are located in the foreland plain to the southeast of the Metán Basin show a thinner and less complete foreland sequence and provide no record of the Salta Group and do not reach the basement.

4.2. Seismic sections interpretation

This study was undertaken using analogue seismic data acquired by YPF (former national oil company of Argentina) during different campaigns between 1976 and 1997. Thirty-six seismic lines across the area were studied and 17 of them were used to construct 4 geological cross sections, and the structural map presented in this paper (Figs. 2, 6 and 7). Fig. 5 shows four selected parts of the seismic sections.

A number of seismic stratigraphic units can be distinguished in the Metán Basin. The upper package has poor to medium reflectivity with low frequency and poor lateral continuity (Fig. 5), and corresponds to the Jujuy Subgroup of the upper foreland sequence. One notable feature of this upper package is that locally some of the uppermost reflections occur in a fan like arrangement with onlapping layers that can be interpreted as growth strata (Fig. 5C). Below, the lower foreland Metán Subgroup shows good reflectivity with high frequency and good lateral continuity (Fig. 5A and B). The postrift sequence shows the strongest and more continuous reflections that can be identified and followed in all the area and used as a key reference. The lower package has poor reflectivity but locally a number of more or less continuous reflections show a fan like arrangement (Fig. 5D), giving rise to strong lateral changes in seismic facies and thickness. These fan like reflections can be assigned to the synrift Pirgua Subgroup. This interpretation is consistent with the correlation of the seismic sections and the wells through a synthetic seismogram computed by Cristallini et al. (1997) from sonic log information of the YAS x-1 well.

A number of different seismic facies can be observed below, strong but very short reflections and weak reflections with small to moderate lateral continuity. These two patterns can be regarded as the seismic basement that probably corresponds to the Precambrian basement or to the Palaeozoic cover. The fan geometry of the synrift reflections is very helpful in differentiating between the Pirgua subgroup and the basement (Cristallini et al., 1997).

In the eastern part of the study area, the seismic sequence differs from that in the Metán Basin as corroborated by the well logs

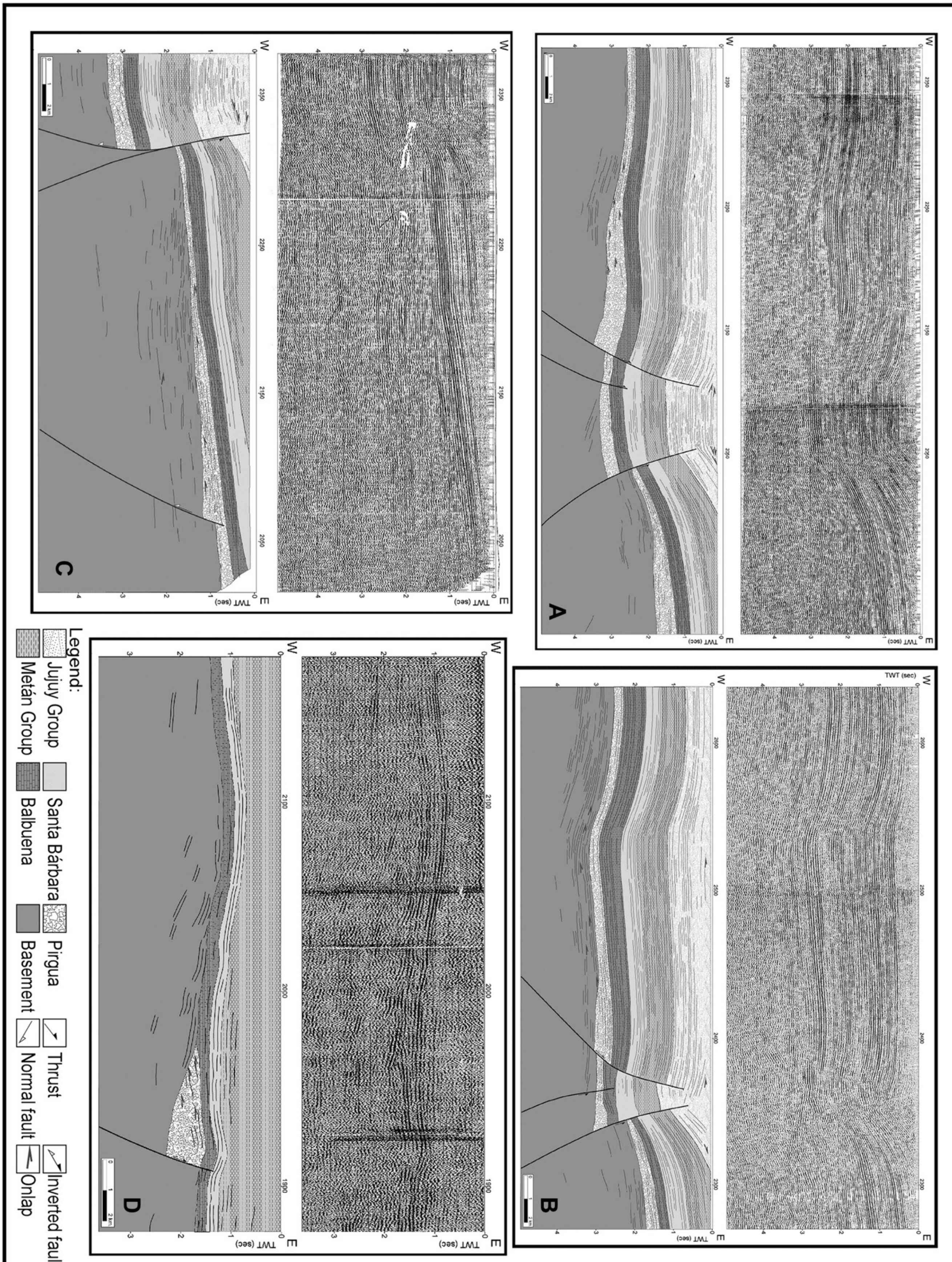

Fig. 5. Seismic sections segments A) section 44076. B) Profile 44089. C) Profile 44091-3. D) Profile 44059. Location of these segments in the cross sections is shown in Fig. 6.

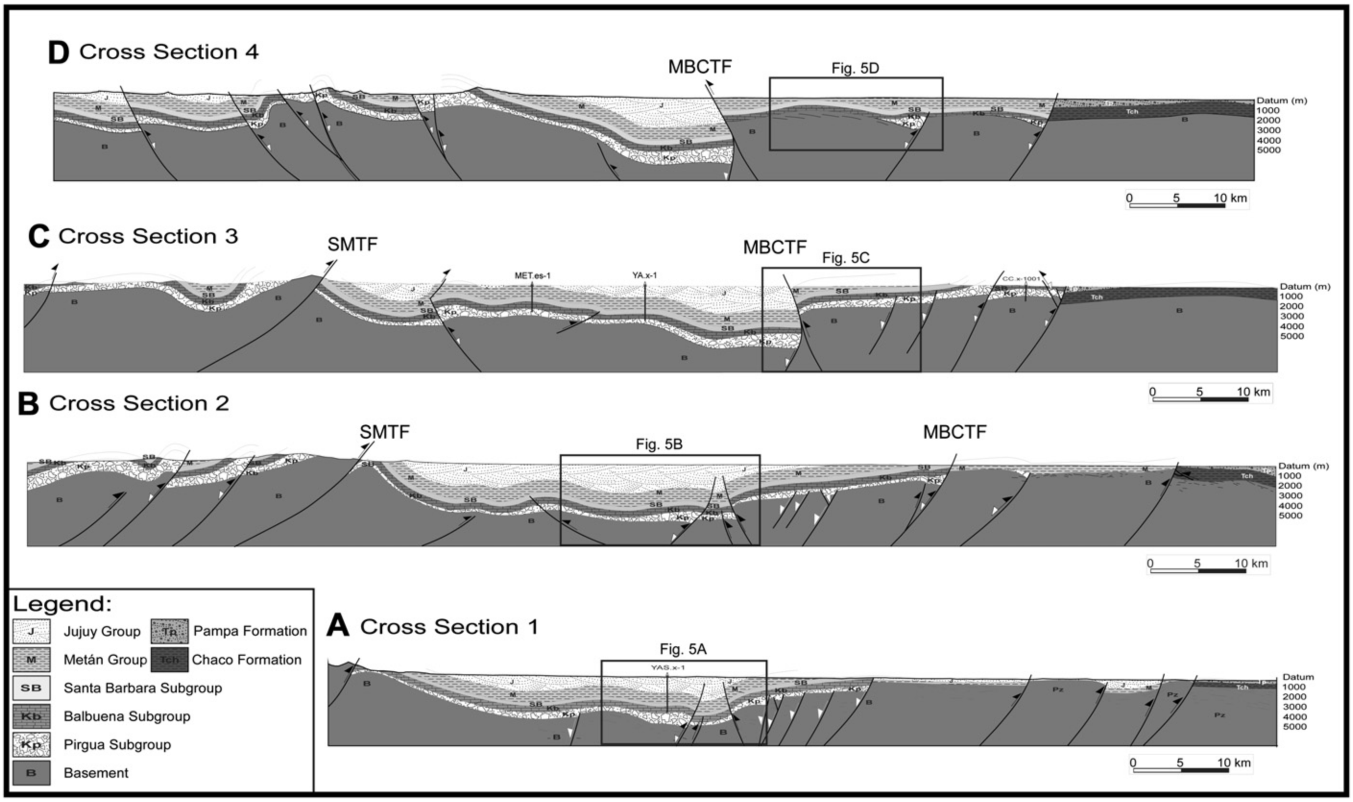

Fig. 6. Metán Basin cross sections. Datum is 700 m above sea level. Depths are below Datum. Horizontal and vertical scales are the same. Location of the cross sections in Fig. 7.

(Fig. 4). In this region, there is an upper package with strong but moderately continuous reflections (Fig. 5C). The lowest reflection of this set is the strongest and the most continuous in this area. This reflection is attributed to the bottom of the Neogene sediments of the foreland unit (Fig. 5C) and can be used as a key reference. Below this upper package, short and discontinuous reflections of low intensity are unconformably lying that correspond to the seismic basement, which in this area is the Palaeozoic cover.

5. Structural interpretation

5.1. Methodology

Successive steps were followed to construct a structural model of the Metán Basin integrating seismic and well data with the surface geology: 1) unification of the datum planes of the seismic lines, 2) interpretation and correlation of selected horizons in all the seismic sections, 3) construction of a structural contour map in time, including fault traces and fold axis, and 4) conversion of the map to depth and integration of the surface data.

Given that the seismic sections were obtained in different campaigns using different datums (ranging between 500 and 1300 m above sea level), it was necessary to unify the datums. A velocity of 1700 m/s was applied to transform the datums of all the seismic sections to 700 m above sea level.

The structural model, which is derived from the interpretation of the 17 seismic sections, is based on the construction of a contour map of the continuous and strong reflective seam corresponding to the base of the Santa Bárbara Subgroup (Figs. 2, 5–7). In the eastern part of the study area, which is devoid of Salta Group rocks and sediments, the contour lines in the structural map correspond to the top of the Palaeozoic cover.

The velocity law used to convert the time contour map to depth was obtained by tying the interpreted seismic sections with the four wells located inside the basin (Table 1). These velocities were significantly smaller than the Normal Move Out velocities used in the processing (Table 1). For this reason, the depths labelled in the structural map (Fig. 7) must be regarded as minimum values. These depths are also slightly smaller than the depths computed by Cristallini et al. (1997). Regardless of these uncertainties, the final structural map and the cross sections show structural features with the adequate relationships at depth (Figs. 6 and 7). Depth conversion using higher velocities would have resulted in an increase in the amplitude of the structures.

Surface geology was compiled from different geological maps and satellite image interpretation to represent lithologies and structures cropping out in the area (Figs. 2 and 7).

5.2. Main structures

The most striking feature of the Metán Basin is the variety of the structural trends. Several sets of major faults and folds are present in the Metán Basin. The strike of these sets is: N–S, NNE–SSW, NE–SW, ENE–WSW and NW–SE (Fig. 7). High-angle thrust faults of the Sierra de Metán and the Sierra de la Candelaria strike N–S. In the rest of the area, most of the faults strike NNE–SSW, NE–SW or ENE–WSW. Few faults strike NW–SE, such as the El Toro lineament, at the northern end of the Sierra de Metán. Another fault with this strike is located between the Sierra de la Candelaria and the Sierra de Metán (Figs. 2 and 7).

Deformation is stronger in the western part of the Metán Basin than in the eastern one. The boundary between these two domains is a long, high-angle thrust fault dipping to the east and striking NNE–SSW. The Metán Basin Central Thrust Fault is the most

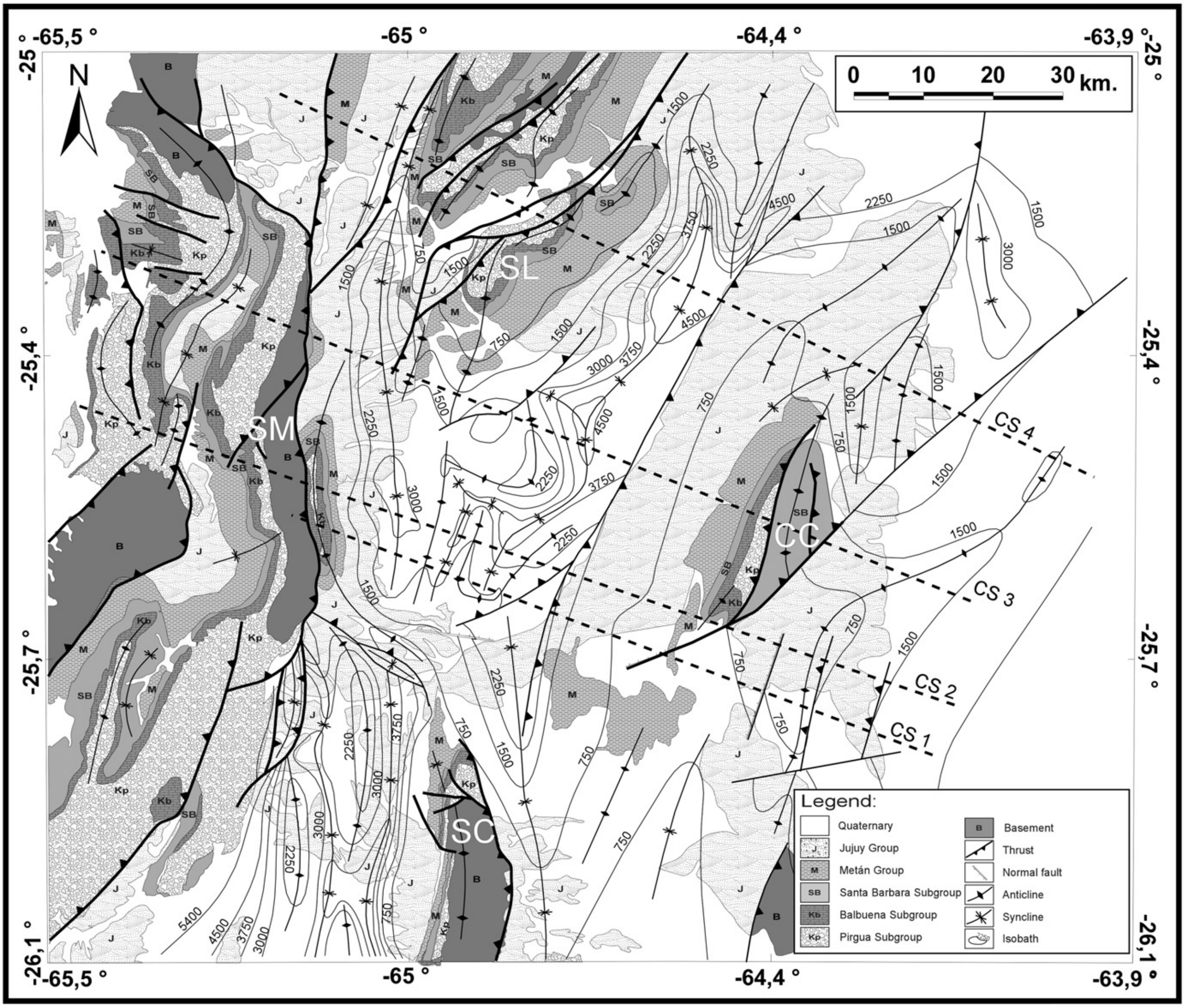

Fig. 7. Structural map of the Metán Basin with the main outcropping units. Contour lines of depth below the datum of the Santa Bárbara Subgroup basal reflections. Datum is 700 m above sea level. Thick line indicates outcropping faults and thin line buried faults. SM, Sierra de Metán; SL, Sierra de Lumbrera; SC, Sierra de la Candelaria; CC, Cerro Colorado.

important in the basin and its displacement attains values of thousands of metres (Figs. 6 and 7).

Maximum depths of the Metán Basin are located in the footwall adjacent to the Metán Basin Central Thrust Fault and outline a sinuous trough. The depth of the northern part of the Choromoro Basin located west of the Sierra de la Candelaria (Fig. 2) exceeds that of the Metán Basin (Fig. 7).

Folds in the western part of the Metán Basin have no preferential trend and the map view corresponds to an interference fold pattern (Fig. 7). Folds in the eastern part of the basin show a more regular trend and most of them strike NNE–SSW. The folds of the Sierra de Metán, the Sierra de la Candelaria and the Choromoro basin strike N–S and are subhorizontal. Moreover, the Sierra de Metán displays E–W trending folds interfering with the main N–S folds. These E–W folds are most prominent in the northwest (Mon et al., 2005b). By contrast, folds in the Sierra de San Antonio, the Sierra de González and the Sierra de Lumbrera show a sigmoidal map pattern and plunge SSW.

Most of the thrust faults are NW vergent in the Sierra de San Antonio, the Sierra de González and the Sierra de Lumbrera although some of the faults on the eastern and southeastern slopes of these Sierras are SE vergent. By contrast, the thrust faults of the Sierra de Metán and the Sierra de la Candelaria are E vergent (Fig. 7).

5.3. Cross sections

Four geological cross sections were constructed using the seismic sections and the structural map (Figs. 5–7).

Cross section 1 (Fig. 6A) is constrained by seismic sections 44076 and 44088 and the Yatasto Sur (YAS x-1) well (Figs. 2, 5A and 7). Two domains were differentiated: the Metán Basin and the foreland to the east. The Metán Basin appears as a huge synclinorium truncated in the central part by the west verging Metán Basin Central Thrust Fault (Fig. 6A). The western limb of the synclinorium shows two normal faults dipping to the west. These faults control the thickness of the Pirgua Subgroup but do not displace the postrift sequence, which is consistent with the formation of these faults during the Cretaceous extension. Immediately to the east of the well YAS.x-1 is a harpoon like structure that resulted from the inversion

Table 1
Velocities and depths versus time. The first column is Two Ways Time in milliseconds. The second column is NMO velocities used in the processing. The third column is the velocities used to convert to depth the structural map in Fig. 7. The fourth column is the depth obtained using the velocities of the previous column. The fifth column is depth obtained using NMO velocities. The sixth column is the depth used in Cristallini et al. (1997).

TWT (ms)	Average used in depth conversion according to NMO				Cristallini et al. (1997)	
	NMO vel. (m/s)	Velocity (m/s)	Depth (m)	Depth (m)	Depth (m)	TWT (ms)
200	2200	1700	170	220		
400	2500	1750	350	500	450	375
600	2600	1800	540	780		
800	2700	1875	750	1080		
1000	2800	2000	1000	1400	1121	900
1200	3000	2071	1243	1800		
1400	3100	2143	1500	2170	1999	1350
1600	3200	2230	1784	2560		
1800	3300	2293	2064	2970		
2000	3400	2356	2356	3400		
2200	3700	2420	2662	4070		
2400	3800	2500	3000	4560		
2600	3900	2580	3354	5070		
2800	4000	2679	3750	5600		
3000	4100	2750	4125	6150		
3200	4200	2817	4507	6720		
3400	4400	2892	4916	7480		
3600	4600	3000	5400	8280		

of a Cretaceous extensional fault during the Andean compression. The western end of the synclinorium culminates in an anticline located at the footwall of the thrust fault of the Sierra de Metán. This anticline is cut by the Metán fault as is evidenced by the geometrical relationship observed at the structural map (Fig. 7). In cross section such cross cutting relations could be ambiguous. However the different attitude between the thrust and the fold in map view (the first concave westwards and the second the opposite) and mostly the truncation of the southern part of the fold together with their related structures reinforces the out of sequence character of the Metán Basin Central Thrust Fault. The eastern limb of the Metán Basin synclinorium shows a stair step arrangement owing to the presence of some normal faults, most of which dip to the west. Further east of the Metán Basin, the Salta Group sediments are absent and the structure consists of uplifted and down-faulted blocks limited by west dipping faults that are both normal and high-angle thrust faults.

Cross section 2 (Fig. 6B) is constrained by seismic section 44089 (Figs. 2 and 5B) and surface data. The structure of the Metán Basin in this section is fairly similar to the one in cross section 1. A West vergent low angle thrust fault is present in the western limb of the synclinorium and normal faults dip to the west and east in the eastern limb. Two important features of the Sierra de Metán should be highlighted: 1) the fold wavelength exceeds that of the Metán Basin, suggesting a deeper detachment in the Sierra de Metán than in the Metán Basin (Figs. 6 and 7); and 2) the Pirgua Subgroup sediments are thicker in Sierra de Metán than in the Metán Basin. This last observation may be ascribed to the El Brete fault, which is the master fault of one of the extensional subbasins of the complex Salta Rift Basin.

Cross section 3 (Fig. 6C) is constrained by seismic section 44081, by wells MET.es-1, YA.x-1 and CC.x-1001 (Figs. 2 and 5C) and by surface data. This cross section resembles the previous ones except for a number of features that should be noted: 1) One of the W vergent high-angle thrusts of the Sierra de San Antonio, the Sierra de González and the Sierra de Lumbrera is visible to the west of the MET.es-1 well and branches to an E vergent fault defining a thrust wedge. 2) an E vergent low angle thrust fault is present east of MET.es-1 well; and 3) the Cerro Colorado structure consists of one anticline between two west dipping normal faults subsequently inverted to thrust faults.

Cross section 4 (Fig. 6D) is constrained by seismic sections 33116 and 44059 (Figs. 2 and 5D) and by surface data. A set of east dipping high-angle thrust faults is present in the W–NW half of the section. Most of these thrust faults control the thickness of the Pirgua Subgroup sediments and display a hanging wall anticline. These reverse faults belong to the Sierra de San Antonio, the Sierra de González, the Sierra de Lumbrera and to other similar structures to the west. In the ESE half of the section Pirgua Subgroup sediments are absent except in two small harpoon structures that correspond to inverted half grabens with a west dipping master fault.

6. Discussion

6.1. Folds

Several sets of faults and associated folds with different strikes were present in the study area. These resemble those encountered elsewhere in the Central Andes (Allmendinger et al., 1983; Marrett et al., 1994; Carrera et al., 2006). Most of the folds resulted from Andean shortening. Nevertheless, some of them were produced by interference of extensional roll-overs and compressional anticlines (Carrera et al., 2006), e.g. the fold drilled by YAS x-1 well (Fig. 6A). Moreover, the sigmoidal plunging folds trending SSW in the Sierras de San Antonio, the Sierra de González and the Sierra de Lumbrera can be ascribed to the influence of previous extensional faults on the Andean folds (Fig. 7).

Subhorizontal north trending folds in the Sierra de la Candelaria, the Sierra de Metán and the Choromoro Basin are due to regional E–W shortening (Marrett et al., 1994). E–W folds northwest of the Sierra de Metán are due to local N–S shortening related to a constrictional situation given that the hanging wall of the Metán thrust fault was transported eastwards between the NW–SE El Toro and the NE–SW El Brete oblique faults (Mon et al., 2005b). N–S and E–W folds in the Sierra de Metán form an interference fold pattern.

An interference fold pattern is also present in the western part of the Metán Basin (Fig. 7) as a result of a constrictional shortening. It was probably induced by the NW oblique boundary between the Metán and Choromoro Basins.

Folds trending NNE that could be consistent with a WNW to ESE shortening direction (Marrett et al., 1994; Oncken et al., 2006) are present in the eastern half of the Metán Basin and in the foreland plain further east.

The boundary between the areas that was shortened E–W and WNW–ESE adopts a zigzag line from north to south along the Mojotoro Sierra thrust fault, the El Toro Lineament, the Sierra de Metán thrust fault and the Sierra de la Candelaria thrust fault (Figs. 2 and 7).

Seismic sections show that growth strata related to Andean folding are restricted to the upper part of the foreland sequence (Fig. 5A and C). Furthermore, west facing folds related to thrust faults located west of the Sierra de San Antonio, the Sierra de González and the Sierra de Lumbrera involve Pleistocene conglomerates (González, 2000). Thus, in accordance with earlier studies (Mon, 1976; Reynolds et al., 2000; Hain et al., 2011), these structures are considered to be Pliocene and Quaternary in age.

6.2. Faults

The thickness distribution of the Pirgua Subgroup sediments allows us to identify the faults that were active during the Salta rifting in Cretaceous times. Syn sedimentary extensional faults are characterized by thicker synrift deposits in the hanging wall. The

NW dipping, NE–SW El Brete fault located between the Sierra del Brete and the Choromoro Basin (Figs. 2 and 7) was the master fault of the Cretaceous subbasin during Salta rifting. Further south (approximately 80 km S–SE) a similar but smaller NE–SW fault crops out at the southern end of the Sierra de Medina (Fig. 2). This range is an inverted half graben and represents the southernmost unit of the Santa Bárbara System (Iaffa et al., 2011). Moreover, in the Sierra de San Antonio, the Sierra de González, the Sierra de Lumbrera and further north, the thickness of the Pirgua Subgroup sediments were controlled by NNE–SSW to NE–SW faults, indicating that these thrust faults are inverted Cretaceous extensional faults (Kley and Monaldi, 2002; Monaldi et al., 2008). At Cerro Colorado, the interpretation is the same given that a sliver of Palaeozoic rocks is located along the NNE–SSW thrust fault. This fault is located west of CC x-1001 well (Fig. 6C) and places Pirgua sediments over those of Santa Bárbara.

By contrast, N–S striking thrust faults do not control the thickness of the Pirgua Subgroup sediments in the western part of the study area. It is therefore reasonable to assume that these N–S thrust faults were formed during the Andean orogeny.

Seismic sections (Fig. 5), geological cross sections (Fig. 6) and a geological map (Fig. 7) are helpful in determining the variations in the thickness of the Pirgua Subgroup sediments. The following conclusions may be drawn: 1) The Metán Basin Central Thrust Fault strikes N–NE to S–SW (Fig. 7) and must be a result of Andean compression since it does not control the thickness of the Pirgua Subgroup sediments. 2) By contrast, the fault located immediately west of the Metán Basin Central Fault that strikes N–NE to S–SW, NE–SW and is clearly an inverted extensional fault (Fig. 6B). 3) The long NE–SW thrust fault along the southeast boundary of the Cerro Colorado anticline (Fig. 7) is an inverted Cretaceous extensional fault because the Pirgua Subgroup sediments are only present in the hanging wall and not in the footwall (Fig. 6). Furthermore, a small harpoon like structure is present in this fault to the northeast of Cerro Colorado (Fig. 6D). 4) Low magnitude normal faults in the eastern limb of the Metán Basin synclinorium are not sufficiently long to be correlated in the adjacent seismic sections with the result that their strike cannot be determined.

To summarize, the N–S faults are Andean thrust faults; the NE–SW faults are Cretaceous extensional faults that were inverted

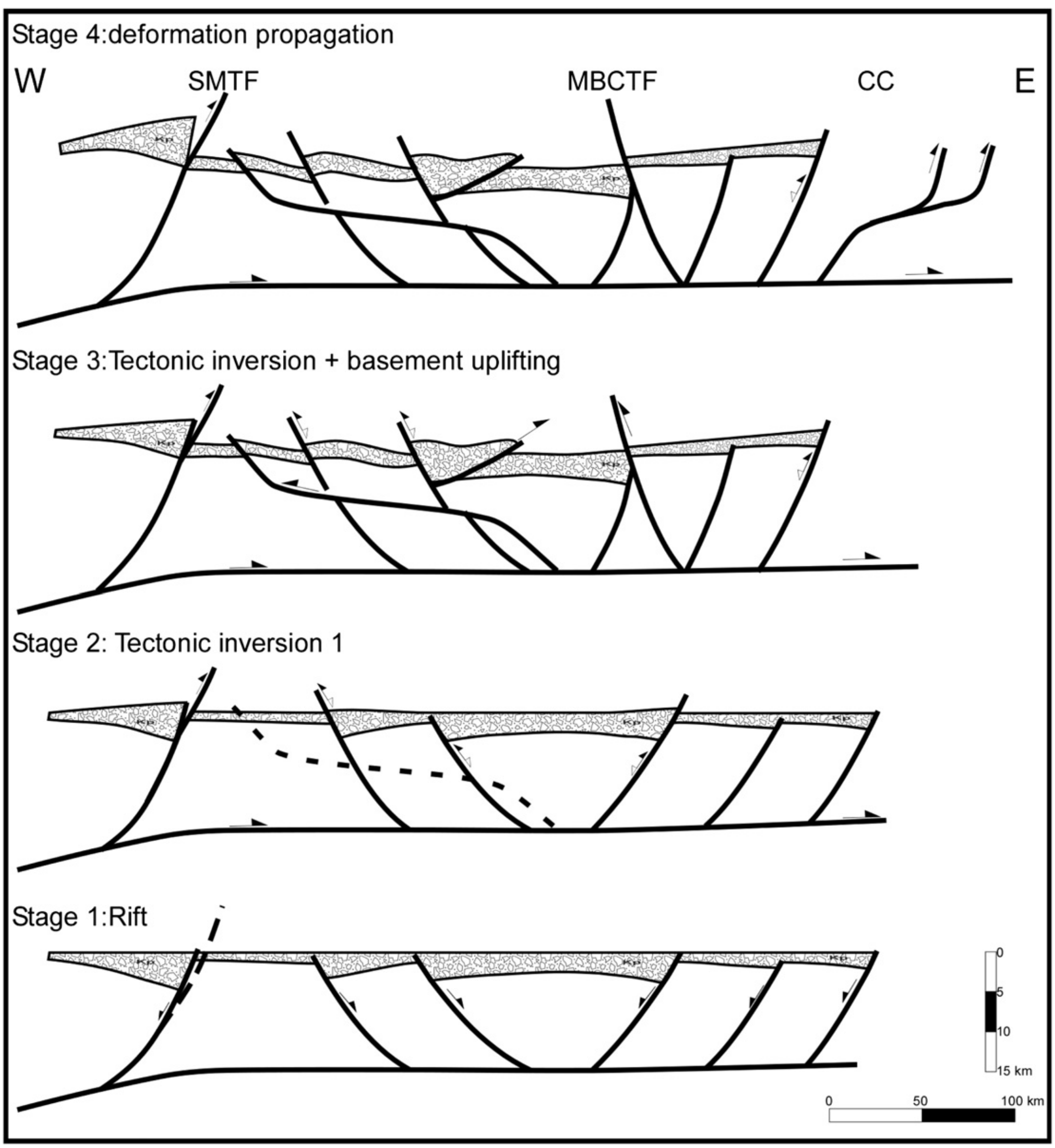

Fig. 8. Sketch showing kinematics of the structures in the study area. 1) Cretaceous Salta rifting time. 2), 3) and 4) sequential evolution during Andean compression. Only active displacements are indicated by arrows. SMTF, Sierra de Metán Thrust Fault; MBCTF, Metán Basin Central Thrust Fault; CC, Cerro Colorado.

during Andean deformation as the N–NE to S–SW could be as well. Moreover, during Andean deformation, the NE–SW faults could behave as oblique faults with a small dextral strike slip component in addition to the thrust fault displacement (Mon, 1976; Kley and Monaldi, 2002).

6.3. Depth to detachment

The depth of the contractional and the extensional detachments should be determined. Studying the location of earthquake hypocentres, Cahill et al. (1992) proposed that the basal detachment of the thrust system is 20 km deep in the northern part of the Santa Bárbara System. Using seismic data and balanced cross sections, Cristallini et al. (1997) and Kley and Monaldi (2002), respectively, consider that the Cretaceous extensional detachment was reactivated and acted as a contractional detachment during Andean deformation. Cristallini et al. (1997) proposed a gently east dipping detachment of 20 km depth for the Metán Basin. Kley and Monaldi (2002) estimated a detachment of 10–16 km depth for the Santa Bárbara System. These two results do not necessarily exclude each other; detachment can show step stair geometry and is probably located at more than one depth. This hypothesis is considered by the aforementioned authors and will be used below. Fold wavelength in the western half of the Metán Basin is smaller than in the rest of the study area (e.g. in the Sierra de Metán, Fig. 7). This observation lends support to the above hypothesis.

6.4. Kinematics

Seismic sections clearly show the presence of growth strata in the layers of the Jujuy Group, however seismic data are not good enough to extract timing information from the relations between structures and the foreland basin layers. Stratigraphic correlation cannot be done with the necessary accuracy to deduce the sequence of deformation. Nevertheless, the following should be emphasized: 1) Data presented in the previous sections are consistent with a general in-sequence, eastward migration of the deformation. 2) As explained before, the footwall anticline cut by the Sierra de Metán Thrust Fault (Fig. 7) gives support to a break-back deformation. In order to make compatible this apparent contradiction the following sequence of deformation is proposed (Fig. 8):

Stage 1) Several inherited basement discontinuities acted as master faults of half graben basins during the Cretaceous extension.

Stage 2) The oldest Andean compressive structures in the study area was probably the N–S Sierra de Metán Thrust Fault and its hanging wall anticline, and resulted from W–E shortening. Local N–S shortening in the Sierra de Metán gave rise to an interference fold pattern. Deformation was propagated eastwards above a 20 km deep detachment. NE–SW inherited faults were slightly reactivated until deformation reached the NNE–SSW west dipping extensional fault located in the middle of the Metán Basin. Its relative orientation to the shortening axis could be critical, at the same time it was partially inverted and gently folded. Carrera et al. (2006) reported west dipping Cretaceous extensional folds folded during Andean deformation in the Eastern Cordillera.

Stage 3) Eventually a new east dipping thrust fault, the Metán Basin Central Thrust Fault was formed. At the footwall of this east dipping thrust fault, deformation will migrate towards the west in a similar way as were described by Jordan et al. (1989) and Ramos et al. (2002). A shallow detachment around 10–16 km depth (Kley and Monaldi, 2002) is propagated westwards and all the small wavelength folds in the western part of the Metán Basin could have formed in front of the Sierra de Metán as a result of this shallower detachment.

Stage 4) Deformation continued to propagate to the east reaching first the Cerro Colorado and, then its present location further east.

7. Concluding remarks

The Metán Basin is a good example of how inherited structures, Cretaceous and older faults, exert a strong control over the foreland basin structure and evolution. During the Cretaceous, some of this crustal discontinuities were reactivated in an extensional context. As a result, a set of rift subbasins developed to form the Salta Rift Basin. At that time the main faults in the study area were striking NE–SW and ENE–WSW and the secondary faults were NW–SE.

After a period of quiescence, the area underwent the Andean compression since the Pliocene. This generated newly formed thrust faults and related folds, striking N–S to NNE–SSW in response to an E–W to WNW–ESW shortening, and reactivated as thrust faults a number of pre-existent rift faults. Most of the reactivated faults could have behaved as oblique thrust faults because they were not perpendicular to the regional shortening (e.g. the NE–SW faults). Interaction between these older reactivated faults and the newly generated ones gives rise to a complex pattern of fold interference, which is one of the main structural features of the Metán Basin. Other pre-existent rift faults could have an orientation unfavourable to reactivation and therefore act as a buttress. This buttressing effect together with the high synorogenic sedimentation rate would have favoured an inward migration of the deformation. Out of sequence thrusts would be synchronous to the frontal structures forward and produced a significant compartmentalization of the foreland basin adjacent to the mountain belt. The resulted geometries and structural styles, resemble the ones observed further west in the Cordillera Oriental.

Some specific conclusions are as follows:

1) A number of faults in the study area that acted as extensional faults during the Cretaceous Salta rifting were inverted during Andean compression. Most of the NE–SW extensional faults were inverted as reverse faults. Other extensional faults such as the NNE–SSW ones were slightly inverted or folded depending on their dip.
2) Most of the new thrust faults and folds generated during Andean compression strike N–S to NNE–SSW and are related to a W–E to WNW–ESE shortening.
3) The western part of the Metán Basin is strongly deformed between the eastwards advance of the Sierra de Metán Thrust Fault and the west vergent Metán Basin Central Thrust Fault. Moreover, a constrictional deformation was imposed by the different strike of inherited faults gave rise to an interference fold pattern.
4) Crustal discontinuities due to inherited faults prevented a steady propagation of the deformation in the foreland and deformation jumped from one inherited fault to another. In sequence, eastward migrating deformation could be interrupted by a backward jump.

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