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The role of inversion tectonics in the structure of the Cordillera Oriental (NW Argentinean Andes)

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Abstract

The Salta Basin of Cretaceous age in the Andes of NW Argentina was inverted during the development of the Cordillera Oriental between the Neogene and Recent. The different orientations of the extensional faults of the Salta Rift System and the subsequent W-E shortening resulted in a great variety of inversion structures. Extensional faults dipping NE to ESE were preferentially reactivated as contractional faults. The initial stepped geometry of these faults gave rise to a distinctive sigmoidal pattern of basement-involved thrusts and related folds. These contractional structures tended to run parallel to the extensional faults and acquired a N-S trend across the previous accommodation zones, resulting in folding interference patterns. Other interference patterns are attributed to the superposition of contractional folds on previous rollovers and to the constrictional deformation imposed by the reactivation of adjacent extensional faults with different orientations. The NNW to WSW dipping extensional faults show no evidence of reactivation despite the fact that some of them are folded. The inversion at crustal scale is limited owing to the presence of the Cretaceous Salta Rift across the different Andean structural units and foreland.

Keywords: Inversion tectonics; Argentina; Andes; Oblique inversion

1. Introduction

Along strike structural differences of the Andes have been mainly related to dip changes in the Nazca subduction plate and to the influence of inherited structures of the contractional and extensional events which affected the South American plate before the Cenozoic Andean tectonics (Jordan et al., 1983). Both flat-slab subduction and inversion of earlier structures gave rise to a thick-skinned tectonic style with the involvement of the basement. Conversely, thin-skinned structures developed in the over-riding plate above a steep subduction.

This paper seeks to evaluate the role played by inherited structures in the southern part of the Cordillera Oriental in the Andes of NW Argentina (Fig. 1). The study area is located in a transitional zone with respect to the dip of the subducted slab, northwards of the flat-slab area of Sierras Pampeanas and southwards of the steep-slab area of Sierras Subandinas (Isacks, 1988).

The main features of the southern Cordillera Oriental are the extensive outcrops of Precambrian basement rocks, the absence of the Paleozoic series and the irregular distribution of very thick (up to 12 km) Mesozoic and Cenozoic continental clastic sequences. This stratigraphic record is related to the tectonic events that have shaped the area. The Ordovician Ocloyic orogenic event was responsible for the exhumation

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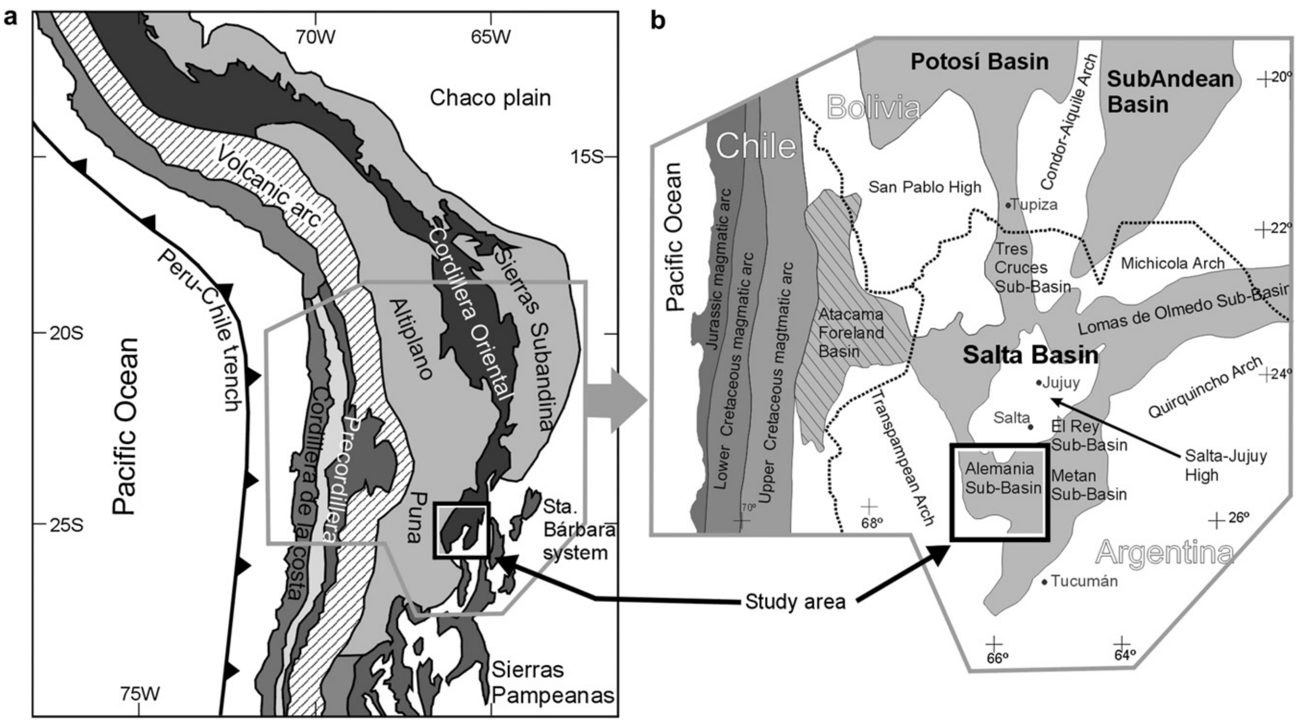


Fig. 1. (a) Distribution of the main structural units of the Central Andes with location of the study area (black square) and the sketch map of Fig. 1b (grey box). Modified from Coutand et al. (2001). (b) Location of the study area in sketch map showing the main sub-basins of the Cretaceous Salta Basin (synrift sediments are ornamented in light grey) as well as other Cretaceous features in the surrounding domains. Modified from Viramonte et al. (1999), and Salfity and Marquillas (1981).

of basement rocks and for the absence of lower Paleozoic sequences (Mon and Hongn, 1991; Mon, 1994). The Cretaceous rift event led to the development of the Salta Basin (Fig. 1b) (Salfity and Marquillas, 1981; Salfity, 1982). The Andean orogenic event led to development of an eastward migrating foreland basin which was progressively incorporated into the thrust system (Ramos, 1999).

The Salta Basin has been described as part of a rift system, which extended beyond the Andean Range from the central Andes of Peru and Bolivia to the southern Andean foreland (Uliana et al., 1989). The Salta rift has a complex geometry. Basins of different trends surround, and radiate from, a central uplifted area, the Salta-Jujuy high (Fig. 1b).

Inversion of the Salta Basin has been documented from surface data in the Cordillera Oriental (Grier at al., 1991; Kley et al., 2005) as well as from seismic data north of the study area (Kley et al., 2005) and eastwards in the Santa Bárbara system (Cristallini et al., 1997).

This paper provides detailed maps of selected areas, that coupled with original structural information made it possible to re-interpret the tectonic evolution of the Cordillera Oriental. New data supporting positive inversion of the Salta Basin are presented, and the structural style and geometries resulting from such inversion tectonics are described in detail. The paucity of seismic data to constrain the deep geometry of the study area is compensated by excellent exposures, that were investigated through geological mapping, integrated with satellite image interpretation.

2. Geological setting

2.1. Tectonostratigraphic units

The main stratigraphic units of the study area and their related tectonic events are schematized in the chronostratigraphic diagram of Fig. 2. The sedimentary record comprises a thick Mesozoic-Cenozoic sequence (3–12 km) of continental sediments, mostly red beds, unconformably overlying the Precambrian and Paleozoic basement.

The basement mainly consists of a monotonous succession of thinly bedded sandstones and shales of Precambrian-Lower Cambrian age (Puncoviscana Formation; Aceñolaza, 1979; Turner and Mon, 1979), and a few isolated Ordovician outcrops of reddish pelites. These rocks were metamorphosed and intruded by granites during the Cambrian and Ordovician. The effects of both magmatism and metamorphism increase in intensity and in number, respectively, south and west of the study area. During the Late Ordovician, the Ocloyic orogeny produced west-directed thrusts and folds; these were associated to development of a steeply east-dipping axial plane cleavage (Mon and Hongn, 1991).

The oldest rocks that unconformably overlie the basement belong to the Cretaceous to Lower Eocene Salta Group (Turner, 1959). The stratigraphic sequence of this Group is well known in NW Argentina and comprises three units that are, from bottom to top (Fig. 2): the Pirgua Subgroup, the Balbuena Subgroup and the Santa Bárbara Subgroup (Moreno,

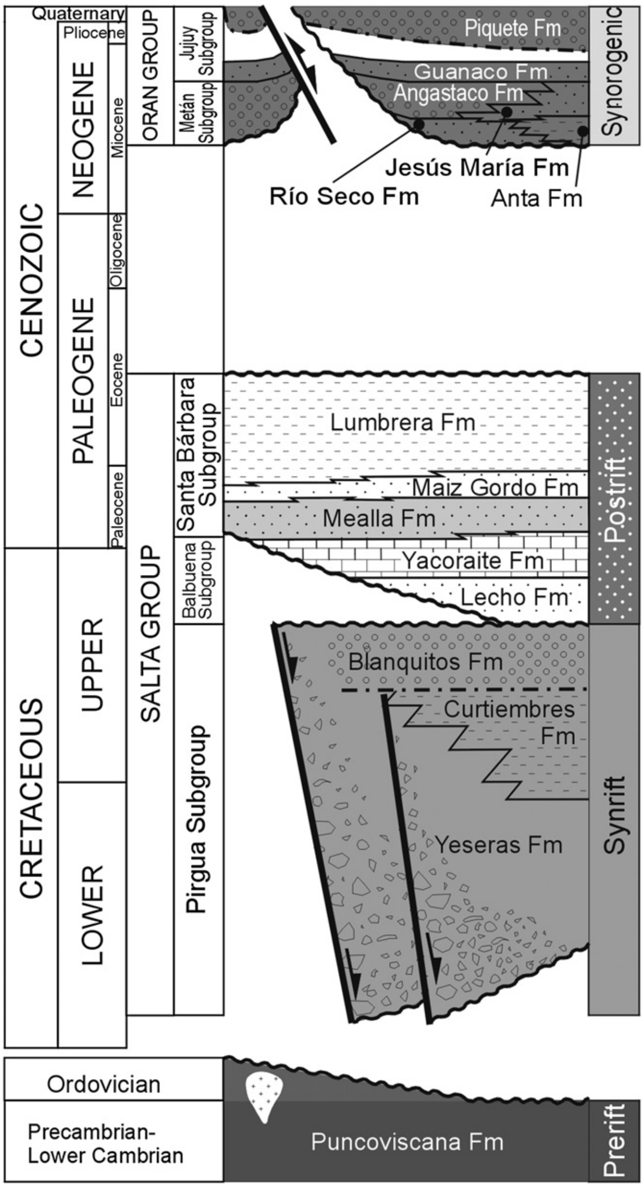


Fig. 2. Chronostratigraphic diagram showing the tectonostratigraphic units involved in the Andean structure of the study area, as well as the main tectonic events that controlled their deposition. The main formations outcropping in the area are shown. The major unconformities bounding the main units are outlined by wavy lines, whereas internal unconformities of minor importance are indicated by dash-dot lines.

1970; Reyes and Salfity, 1973; Salfity and Marquillas, 1981; Gomez Omil et al., 1989).

The Cretaceous Pirgua Subgroup belongs to the synrift units that were deposited during the formation of the Salta Basin (Fig. 2). It consists of alluvial and fluvial sediments made up of red breccias, conglomerates, sandstones and shales. The thickness and lithology of these deposits are strongly controlled by the extensional faults of the Salta Basin the maximum thickness is reached to the west (Pucará and Brealito-Molinos areas; Fig. 3) and south of the study area, where thick packages (up to 2 km) of breccias occur. Volcanic rocks with an alkaline signature are alternated with sediments of the Pirgua Subgroup (Galliski and Viramonte, 1988). K/Ar dating of these basaltic lava flows yield ages from 114 ± 5 Ma, in the lower part of the Pirgua Subgroup (Galliski and Viramonte, 1988; Viramonte et al., 1999), to 76.4 ± 3.5 Ma (Valencio et al., 1976) in the middle part. The Pirgua Subgroup sediments are exposed over a wide area in the southeast and are restricted to smaller domains in the west where basement outcrops predominate. They gradually thin northwards towards the Salta-Jujuy High (Fig. 1b). The Pirgua Subgroup has been subdivided into a number of formations (Reyes and Salfity, 1973) which are, from bottom to top: La Yesera (breccias), Las Curtiembres (lutites) and Los Blanquitos (sandstones and conglomerates). However, this succession is not observed along the extensional faults where breccias tend to predominate (Fig. 2).

The Balbuena and Santa Bárbara subgroups correspond to the post-rift sequence (Fig. 2). They overlie the basement rocks, extending beyond the margins of the Salta Basin. The Maastrichtian Balbuena Subgroup unconformably overlies both the Pirgua Subgroup and the basement of the basin margins, mostly to the north of the study area above the Salta-Jujuy High (i.e., Escoipe and Cerro Tintin areas; Fig. 3). In this unit, the yellowish stromatolitic limestones and the greenish shales of the Yacoraite Formation is distinguished. This is a good marker horizon in the dominantly red Mesozoic-Cenozoic succession. Above the Balbuena Subgroup, the Paleocene-Eocene Santa Bárbara Subgroup extensively crops out, overlying both the Yacoraite Formation and the basement (i.e., La Yesera and San Lucas areas; Figs. 3 and 4). This Subgroup is made up of red fluvial sandstones and shales with some greenish horizons (i.e., Maiz Gordo Formation).

Unconformably overlying the Salta Group and the basement, the Oran Group (Russo and Serraiotto, 1979) consists of a Neogene succession of fluvial and aeolian sediments up to 6 km thick (Fig. 2). This is a synorogenic sequence outcropping along the main valleys (i.e., Luracatao, Calchaqui, Amblayo, Lerma, Pampa Grande); it is characterised by several internal angular unconformities, as well as growth geometries adjacent to the Andean contractional structure.

2.2. Structural framework

The study area comprises the southernmost part of the Cordillera Oriental and its boundaries with the Sierras Pampeanas to the south and the Puna to the west (Fig. 1). The Andean structure of this segment of the Cordillera Oriental consists of a fold-and-thrust system that controls the areal distribution of all the previously described tectonostratigraphic units (Fig. 3). Thrusting was mainly west-directed, with development of associated, asymmetric thrust-related folds (Fig. 3). The tectonic style is dominated by tight asymmetric anticlines, cored by high-angle thrusts that truncate inverted stratigraphic sequences in their hanging-wall blocks (Fig. 3). These features and the simultaneous presence of footwall synclines adjacent to the thrust surfaces are indicative of limited amounts of displacement.

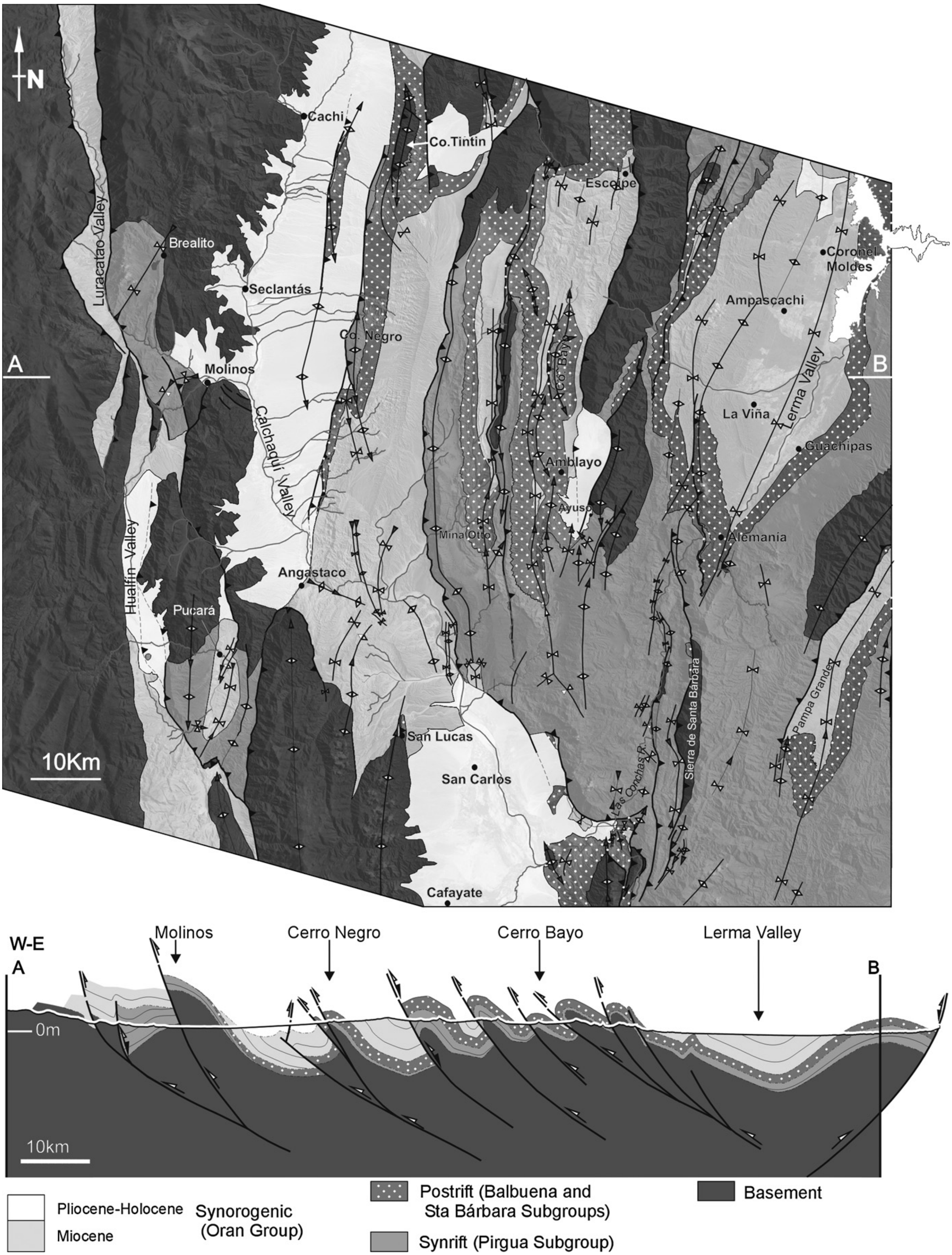


Fig. 3. Geological sketch of the Valles Calchaquies area with the main structures and tectonostratigraphic units and a cross-section of the study area showing the general tectonic style.

Contractional structures trend N-S, NNE-SSW NW-SE and E-W. N-S trending structures are present mainly in the central and western parts of the study area, west of the Amblayo Valley and the Sierra de Santa Bárbara (Fig. 3). These structures trend normal to the inferred local E-W Andean shortening direction (Hindle et al., 2002). The NNE-SSW trending structures predominate in the east, whereas in the southwest the main thrusts trend NW-SE.

These different trends of contractional structures result in complex interference fold patterns seen at different scales.

3. Inversion tectonic structures

In order to better evaluate the role of Cretaceous extensional structures during the Andean deformation, we focus on three areas where different types of inversion tectonic structures are recognised.

3.1. Quebrada de La Yesera- Las Conchas River

Overprinting relationships between the Andean contractional structures and the Cretaceous extensional faults are observed at the Quebrada de La Yesera (Fig. 4). Here the Pirgua synrift strata were thrust over syn-orogenic and post-rift sequences that unconformably overlie basement rocks. Detailed mapping of the area revealed structures and stratigraphic relationships that make it possible to reconstruct a history of positive inversion of the Pirgua extensional basins. Extensional faults affected all the Pirgua Subgroup from its lower to its upper parts (Figs. 4 and 5). Pirgua syn-rift sediments were thrust on top of post-rift sediments that unconformably overlie basement rocks. The association of both situations suggests a rift setting for all the Pirgua Subgroup.

The main fault, termed the El Zorrito-Las Chacras thrust is a west-directed thrust and marks the SW boundary of the Pirgua syn-rift sediments (Fig. 4). It shows along-strike differences in orientation, from NNW-SSE in the north, to E-W at the Las Conchas River and finally to N-S at the Quebrada de La Yesera (Fig. 4). In the last location, south of the mapped area, the hanging-wall of the El Zorrito-Las Chacras thrust shows a well preserved N-S trending extensional fault (La Yesera fault) (Fig. 4). Folded by a N-S anticline, this extensional fault is almost vertical in outcrop. This fault is decorated by volcanic dykes intruded along its plane (Fig. 4c). The fault footwall, to the west, consists of pelitic basement rocks of the Puncoviscana Formation (Fig. 4c) whereas the hanging-wall is constituted by pelitic basement-derived breccias of the Pirgua sequence that dips at high angles against the fault. The La Yesera fault and the basement rocks in its footwall are unconformably overlain by Pirgua conglomerates which differ markedly in colour and composition (granitic and quartz pebbles) from the lower Pirgua breccias (Fig. 4d). These relationships indicate that the El Zorrito-Las Chacras thrust propagated upwards defining a short-cut through the footwall of the pre-orogenic La Yesera normal fault (Figs. 4b,d).

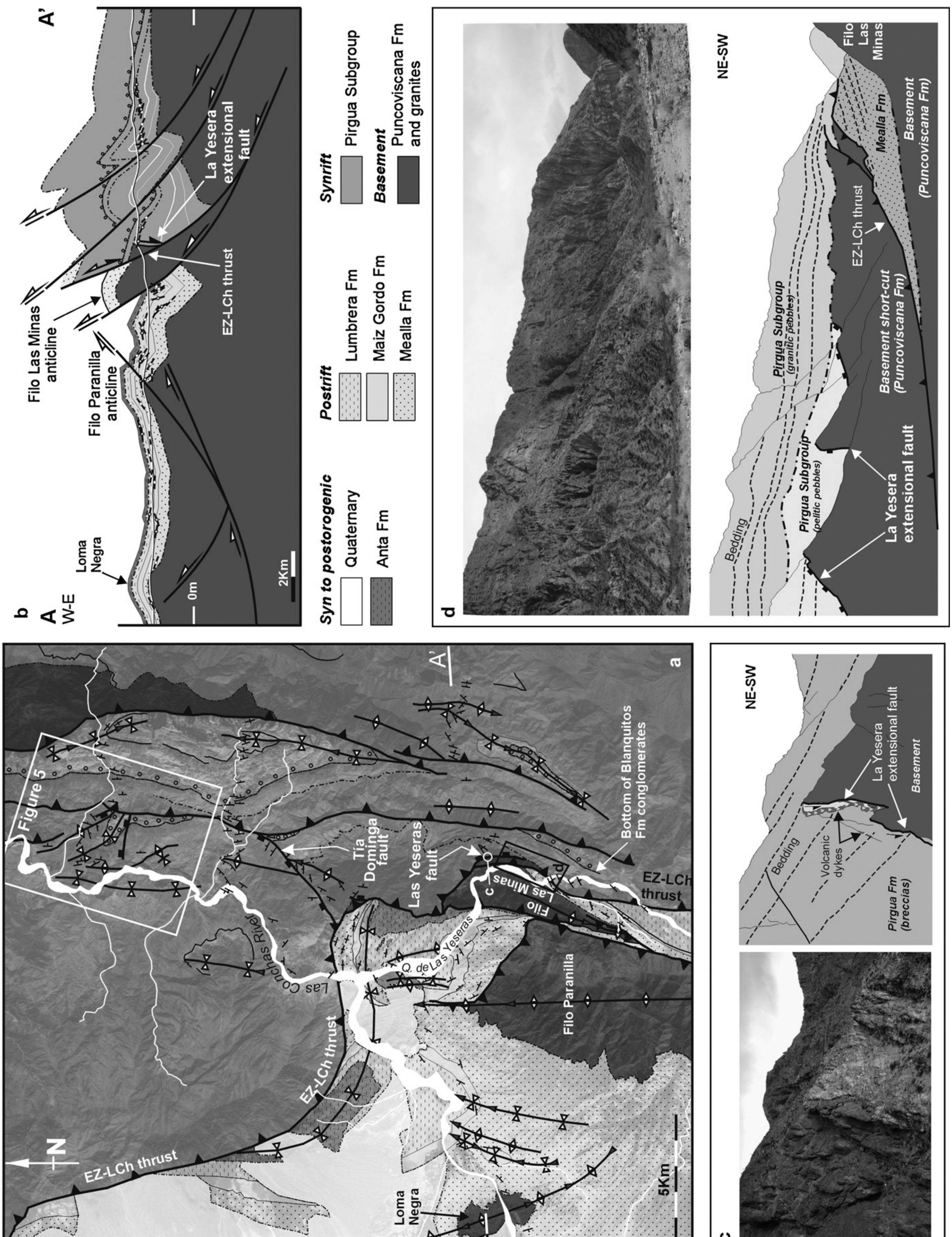
A similar structure is observed to the north, where a smaller outcrop of basement rocks is exposed in the core of an anticline close to the El Zorrito-Las Chacras thrust (EZ-LCh thrust) (Fig. 4a). This basement outcrop is bounded to the east by a N-S trending normal fault that also affects Pirgua sediments: these relationships led to interpret also this structure as a pre-orogenic normal fault decapitated by the upward thrust propagation, which define a short-cut. Further north, a major structure, the Tía Dominga fault is recognised. This structure trends NE-SW, and dips towards NW (Fig. 4). This extensional structure affects the granite-derived conglomerates that unconformably overlie La Yesera fault. This fault is folded by a N-S trending anticline and merges westwards with the EZ-LCh thrust at the corner of its reentrant (Fig. 4a). Reactivation of this extensional fault is documented to occur where the EZ-LCh thrust changes orientation into a W-E trending, oblique to lateral ramp.

Related to these major extensional faults, small-scale faults have also been observed in the hangingwall of the EZ-LCh thrust to the north and at a distance from the thrust front (Fig. 5). These faults with a E-W to NW-SE trend affect the thick sedimentary succession of the Pirgua Subgroup (Figs. 4a and 5). Adjacent folds and small thrusts trend parallel to these normal faults trends (Fig. 5). The overprinting relationships between contractional and extensional structures are clear eastwards, where the normal faults are truncated by a major N-S west-directed thrust that duplicates the Pirgua sequence deposits (Fig. 5).

The footwall of the EZ-LCh thrust consists of basement rocks unconformably overlain by the post-rift Santa Bárbara Subgroup and the syn-orogenic Oran Group. South of the mapped area, in front of the N-S segment of the EZ-LCh thrust, these rocks are affected by N-S trending folds and thrusts. The main folds are the Filo Las Minas and the Filo Paranilla anticlines. The Filo Las Minas Anticline, located close to the EZ-LCh thrust, affects metasedimentary rocks of the Puncoviscana Fm and is deformed by smaller N-S thrusts with opposite dip. The Filo Paranilla Anticline trends N-S, plunges to the north and is cored by granitic basement rocks; it is associated to an east-directed thrust (Fig. 4).

Further north, at the reentrant of the EZ-LCh thrust, a remarkable fold interference pattern is observed: this result from superposition of N-S folds and a major syncline running parallel to the E-W trace of the thrust. Westwards, this syncline and the EZ-LCh thrust show a gradual change in orientation from E-W to N-S.

The structural relationships described above indicate that the Andean structure of the Quebrada de La Yesera-Las Conchas River area result from positive inversion of the SW rift margin of the Salta Basin (see also Grier et al., 1991; Strecker and Marrett, 1999). The differences in thickness and facies recognised across the main thrust faults, i.e. comparing the sequences found in their hanging-wall and footwall blocks, are independent stratigraphic evidence that further support the hypothesis of a positive tectonic inversion episode (Fig. 4). Moreover, the inferred relationships also demonstrate that pre-orogenic normal faults were important controlling factors


a
Figure 5
Tía Dominga fault
Las Yeseras fault
Bottom of Blanquitos Fm conglomerates
EZ-LCh thrust
Filo Las Minas
Las Conchas River
Q. de Las Yeseras
Filo Paranilla
EZ-LCh thrust
EZ-LCh thrust
N
Loma Negra
5Km
A
A'
c
d
b
A
W-E
A'
Loma Negra
Filo Paranilla anticline
Filo Las Minas anticline
La Yesera extensional fault
EZ-LCh thrust
0m
2Km
Syn to postorogenic
Quaternary
Anta Fm
Postrift
Lumbrera Fm
Maiz Gordo Fm
Mealla Fm
Synrift
Pirgua Subgroup
Basement
Puncoviscana Fm and granites
c
NE-SW
Bedding
Volcanic dykes
La Yesera extensional fault
Basement
Pirgua Fm (breccias)
d
NE-SW
Filo Las Minas
Bedding
Pirgua Subgroup (granitic pebbles)
Pirgua Subgroup (pelitic pebbles)
La Yesera extensional fault
Basement short-cut (Puncoviscana Fm)
EZ-LCh thrust
Mealla Fm
Basement (Puncoviscana Fm)

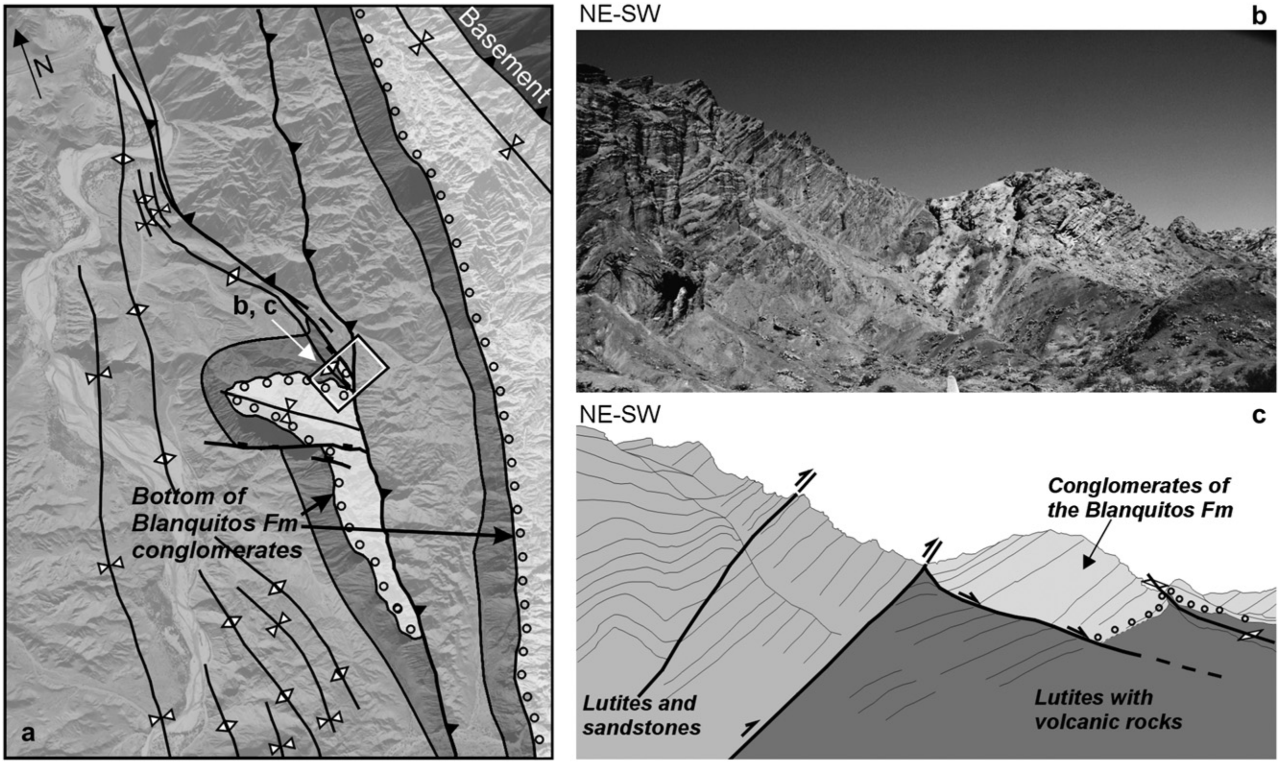


Fig. 5. (a) Structural sketch map north of Rio de las Conchas showing the location and change of orientation of folds and thrusts; these appear controlled by earlier, pre-orogenic extensional faults. (b) Panoramic view of a preserved extensional fault which is truncated by a thrust. This thrust controls the location and the orientation of the anticline in its hanging-wall. See Fig. 4 for location.

during the development and evolution of the Andean contractional structures. The orientation of lateral or oblique contractional structures is determined by the trend of earlier extensional faults. These developed during the pre-orogenic rift stage and were subsequently folded and truncated as deformation progressed during the Andean contractional events.

3.2. Brealito-Molinos

The west-directed thrust system along the Luracatao and Hualfín valleys marks the boundary between Cordillera Oriental and Puna in the study area (Fig. 3). The syn-rift Pirgua sediments crop out in two areas in the hanging-wall of this thrust system, namely at Brealito-Molinos and Pucará. These sediments are not found in the footwall of the thrust system, where the basement is directly overlain by post-rift and syn-orogenic sediments (Fig. 3). Thus, the development of this thrust system was clearly controlled by the tectonic inversion of Cretaceous rift basins.

In the Brealito-Molinos area, where the northernmost exposures of Pirgua Subgroup sediments occur, these rests unconformably over the basement, that crops out to the north and east. In this area, the Pirgua strata are bounded to the west by reverse faults that belong to an east-dipping thrust system. These contractional structures affect basement rocks, unconformably overlain by post-rift and syn-orogenic successions. The thrusts branch northwards into a single, major thrust (Fig. 6). The Pirgua sediments reach their maximum thickness (up to 3000 m) next to their western fault margin: here they consist of coarse breccias, with clasts up to tens of cm in size that vary in composition along the margin. Breccias grade into finer and thinner sediments to the east and progressively onlap the basement in the same direction (Fig. 6). The unconformity and the onlap relationships are well preserved along the eastern margin of the Brealito-Molinos Pirgua outcrop (Fig. 6).

South of the study area, the fault along the western margin of the Pirgua sediments acquires a NW-SE orientation. The southern part of this fault produces younger-on-older relationships, with the emplacement of the Pirgua beds on top of the basement. This feature as well as the distribution of facies discussed above indicates for this fault an extensional character (Fig. 6). However, careful examinations of the deformation fabrics within the oldest Cenozoic units

Fig. 4. Main structural features of Quebrada de La Yesera-Las Conchas River area. (a) Geological map showing the location of the cross-section (A-A′) and photographs as well as Fig. 5. (b) Cross-section of Quebrada de La Yesera. Note the stratigraphic differences on both sides of the El Zorrito-Las Chacras thrust (EZ-LCh thrust) as well as other structures resulting from the tectonic inversion of the Salta Basin. (c) Detail of the La Yesera extensional fault. This was tilted to vertical and even overturned by underthrusting. Subvolcanic dykes have intruded along the fault. (d) Panoramic view of the La Yesera extensional fault and its related shortcut in the hangingwall of the El Zorrito-Las Chacras thrust. Upper Pirgua sediments unconformably overlie the La Yesera fault. Postrift sediments (Mealla Formation) rest directly on top of the basement in the footwall of the El Zorrito-Las Chacras thrust.

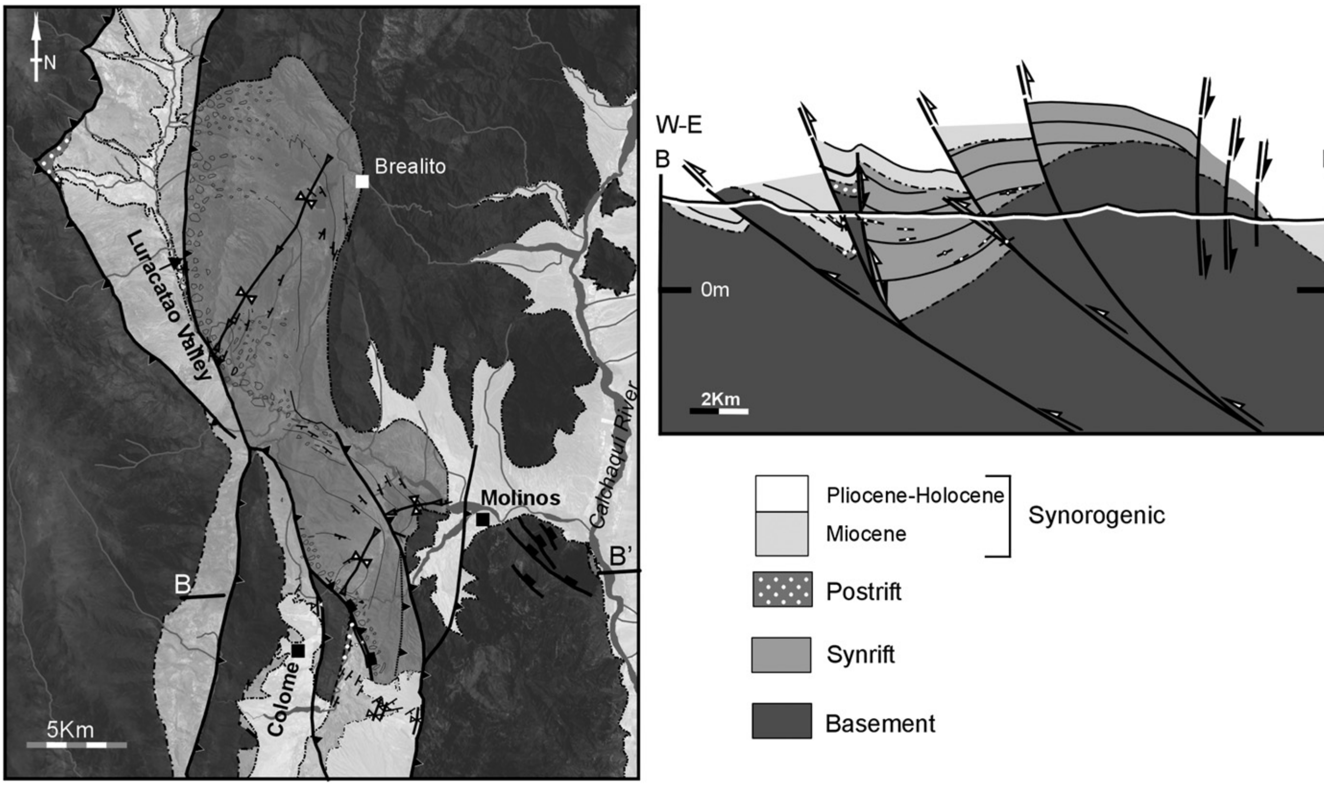


Fig. 6. Geological map and cross-section of Brealito-Molinos area. Evidence for inversion tectonics, such as thickness and facies changes, preserved extensional faults and thrusts propagating with short-cuts, is shown. Coarse grained breccias are observed adjacent to the main faults.

that unconformably overlie the basement in the footwall of this fault reveal reverse kinematics. Younger syn-orogenic units unconformably overlie the fault; these units are deformed by N-S trending folds, and are truncated by a N-S trending thrust further east (Fig. 6). This structure splays northwards into a NNW-SSE trending thrust and then into a N-S trending thrust near Molinos. Eastwards, Pirgua breccias in the Calchaquí River are exposed: these outcrops are controlled and preserved by NW-SE extensional faults (Fig. 6).

The structure observed in the Brealito-Molinos area indicates that the outcropping Pirgua sediments form part of an inverted half-graben that was bounded to the west by a NW-SE trending master fault with normal kinematics. The partially inverted portion of this extensional fault, which developed in the early stages of inversion, is preserved between younger thrusts, which produced short-cuts in its footwall, and bypass thrusts in its hanging-wall. These younger structures tend to a more N-S trend, a feature suggesting that they were less controlled by pre-existing, NW-SE extensional faults. The inferred relative chronology is further supported by the syn-orogenic sediments that unconformably overlie the partially reverse-reactivated normal fault. These sediments are truncated by younger N-S trending thrusts.

3.3. Amblayo-Ayuso

East of the Amblayo valley, folds and faults trend NNE-SSW (Fig. 3). A closer inspection of one of these faults, near Ayuso, SE of Amblayo (Figs. 3 and 7) reveals a preserved extensional geometry.

West of Ayuso, a N-S trending folds pair is very well expressed in aerial view because of the post-rift Yacoraite Formation (Fig. 7). Eastwards, the Pirgua sediments are folded by two stepped N-S trending anticlines that plunge in opposite directions, defining a WNW-ESE structural depression. The northern anticline, adjacent to Ayuso (Fig. 7), plunges south and affects the stratigraphic contact along which the basement is unconformably overlain by Pirgua beds. The attitude of bedding defines a fan geometry outlined by an eastwards expansion towards the NNE-SSW trending fault. In the same direction, the facies grade abruptly from fine-grained sediments into massive breccias (Fig. 7). To the north, the fault is almost vertical and the Pirgua beds are truncated at high angles. To the south, the fault dips progressively to the ESE, carrying basement rocks on top of Pirgua breccias: here a syncline is observed close to the fault trace. Both structures continue further south where they affect Pirgua sediments. To the east, a basement-cored anticline also runs parallel to the fault. A minor set of folds deforms the Pirgua beds in the area between these two basement-cored anticlines.

Based on the geometry and the facies distribution of the Pirgua sediments, we infer that the described structure was initially a west dipping extensional fault that was subsequently folded and partially reactivated (Fig. 7). The syncline parallel to this fault developed during, and probably due to its reactivation. The stepped geometry of anticlines and the change

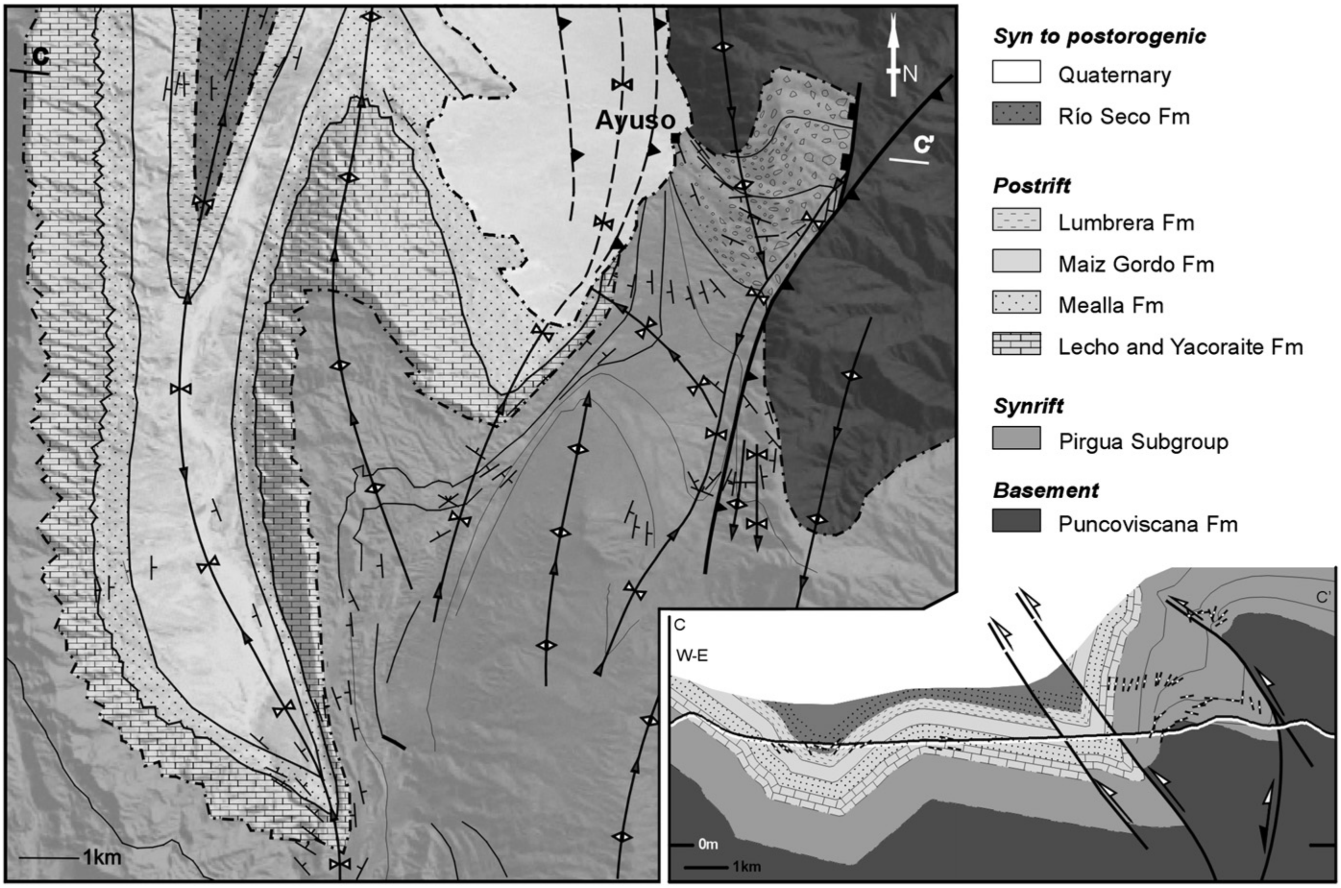


Fig. 7. Geological map and cross-section of Amblayo-Ayuso area. In this area, a roll-over anticline related to an originally W-dipping extensional fault is preserved. Pirgua deposits grade into fine-grained sediments away from the fault to the west. The extensional fault is folded and only moderately reactivated.

of the orientation of the fault trace suggest that the resulting fold interference pattern is the consequence of the inversion of an earlier relay of the extensional fault system. The structural depression between the anticlines plunging in opposite directions developed at the expense of this pre-orogenic relay ramp.

4. Discussion

The structural and stratigraphic relationships described in the above section make it possible to outline an episode of positive tectonic inversion, from pre-orogenic rifting to orogenic contraction in the Salta Basin, and to evaluate the role of pre-existing normal faults on thrusting.

Several sets of extensional faults shaped the area during rifting in Cretaceous times. These structures are responsible for the pronounced V-shaped geometry that is observed in map view in the southern part of the Salta Basin. The two branches of this V-shaped basin were separated by the Salta-Jujuy High (Figs. 1b and 8). The main normal faults that controlled the shape of the basin trend NW-SE in the western branch, and pass abruptly to a NNE-SSW trend in the eastern branch. The N-S extensional faults are the master faults in the south. The orientation of the faults and their stepped geometry may be inferred from the disconnected location and geometry of major Pirgua Subgroup depocentres (Fig. 8). This inference is supported by the orientation of the preserved extensional faults and of the parts of the thrusts that provide evidence for positive inversion.

The angular relationships between pre-orogenic normal faults and the subsequent ENE-WSW to E-W direction of Andean contraction were mainly responsible for different degrees of inversion, as well as for different structural patterns (Hindle et al., 2002). Most of the inverted faults dip NE to E (i.e., La Yesera fault; Figs. 3, 4 and 8). Conversely, extensional faults dipping WNW to WSW were either moderately reactivated or not reactivated; in this case they were mainly folded (i.e., Quebrada de La Yesera-Las Conchas River and Ayuso areas; Figs. 3, 4, 7 and 8). The tendency to fault reactivation depends on the attitude (strike and dip) of pre-existing fault surfaces. It seems likely that faults trending at a high angle with respect to the shortening direction are more prone to reverse reactivation. However, most of these west-dipping faults including those striking NNE-SSE and the ones striking NW-SE and N-S, in fact, were not reactivated. This feature is noteworthy given the location of these structures in the eastern part of the Andean orogen, where east directed thrusts are common. In this connection, it could be argued that W dipping extensional faults were steeper that E-dipping faults; these differences would result in the development of asymmetric basins in the

Fig. 8. Palinspastic sketch map showing the main extensional faults with their related depocentres, the main contractional structures and the basement lithologies found in the study area.

western margin of the Salta Rift. As a consequence of superposed contraction, however, the original extensional cut-off angles along normal faults were severely modified, and this does not make it possible to confirm the hypothesis of originally asymmetric graben.

The sinuous geometry of the main thrusts of the western part of the study area derives from the inversion of stepped extensional faults. Oblique NW-SE trending ramps of the thrust system result from the reactivation of the extensional faults, whereas the N-S frontal ramps developed across the extensional accommodation zones (Fig. 8).

A set of stepped and segmented folds and thrusts deform the post-rift sequences in the Amblayo Valley and exhibit an arcuate pattern with its concave part facing east. The NW-SE structures are longer in this arcuate pattern (Fig. 3). This geometry also suggests inversion of a left-stepping array of NW-SE extensional faults that affect the Pirgua sediments at depth (Fig. 8).

The oblique inversion resulted in three types of folding interference patterns in the hanging-wall and in the footwall blocks of the main thrusts. A first interference pattern is outlined by the sinuous geometry of folds that connect the stepped extensional faults. Partial reactivation of these faults would result in double plunging anticlines, with pronounced structural depressions in the pre-existing relay ramps (i.e., Amblayo-Ayuso area; Fig. 7). A second pattern results from constrictional deformation during inversion of extensional faults with different orientations; this is observed in the footwall of the EZ-LCh thrust in the Quebrada de La Yesera-Las Conchas River area (Figs. 4 and 8). A third interference pattern is due to the superimposition of contractional structures on earlier extensional fold geometries (such as roll-over anticline) as observed in Brealito-Molinos and Amblayo-Ayuso (Figs. 6 and 7).

Apart from the extensional faults of the Cretaceous Salta Basin, other inherited structures could have played a significant role during the Andean episode of positive inversion. Prior to the Cretaceous extensional event, the area was affected by the Cambro-Ordovician tectonometamorphic and magmatic processes, and by the Ocloyic orogeny, which resulted in the development of west-verging folds. These Ocloyic structures would have favoured the younger, superimposed western vergence of the Andean structures and the reactivation of the E-dipping Cretaceous extensional faults. Granites intruding the Puncoviscana Formation (pelites) mainly crop out in the footwall of major faults. The mechanical and rheological differences between these two fundamentally different basement lithologies would produce stain concentration along inherited structures during inversion, and probably also during extension. A good example of this would be the buttressing effect exerted by the Filo Paranilla granite during the reactivation of the La Yesera fault (Figs. 4 and 8).

Most Andean structures departing from the N-S regional trend result from reverse reactivation of earlier extensional faults. The chronological relationships suggest that oblique contractional structures developed in the early stages of inversion (Figs. 5 and 6). As deformation progressed, reactivation of the oblique extensional faults became less important, and N-S trending thrust and folds were dominant, connecting the stepped extensional array of faults through their relay ramps. In these stages, the thrusts propagating across pre-orogenic normal faults defining short-cuts and the bypass structures were the main inversion structures (i.e., Brealito-Molinos and Quebrada de La Yesera).

The results of this investigation, and the inferred controls of inherited normal faults on younger contractional structures, yield a relevant implication. All the oblique structures in the Salta Basin were preserved because of the generally mild to moderate tectonic inversion of the area. A stronger inversion would probably have obliterated most of the observed structural relationships. This should be taken into account in other inversion orogens, such as in the Alps and in the Pyrenees, where a significantly greater amount of inversion has been documented: here the occurrence of slight deflections from the general trends of folds and thrusts may ultimately reflect the location of early structures, oblique with respect to the general thrust direction (for the Alps see Butler, 1992; for the Pyrenees see Bond and McClay, 1995).

As for the Salta Basin, the syn-orogenic structures and the resulting interference patterns with pre-existing normal faults could be explained in the framework of one continuous episode of positive inversion. This hypothesis is consistent with the displacement and the shortening direction inferred by different methods (Hindle et al., 2002) but it is at odds with some structural interpretations derived from fault slip data alone (Marrett et al., 1994; Grier et al., 1991). This observation ultimately indicates that, in the study of inversion processes, interpretations based on structural data are best constrained by the integration of stratigraphic data, if available.

5. Conclusions

Detailed mapping of key locations in the studied area revealed considerable evidence for an episode of positive inversion during the Andean contractional event. This episode occurred at the expenses of pre-orogenic normal faults of the Cretaceous Salta Basin. A wide variety of inversion structures was observed, including short-cuts and complex buttressing folds: however, examples of pre-orogenic normal faults that were not reactivated but just folded by subsequent contractional deformations also occur. These structures demonstrate that the location and geometry of some of the Andean contractional structures of the Cordillera Oriental are determined by the architecture of the Salta Basin. Most inverted faults dip to the E and NE, whereas faults with different orientations show little or no evidence for reverse. The folded extensional faults dip to the W and NW. Sinuous patterns of thrusts and related folds resulted from inversion of stepped extensional faults trending NW to NNE.

These stepped faults were connected by contractional structures across the partially to non-overlapped pre-existing accommodation zones (Fig. 8). Other folding interference patterns resulted from constrictional deformation of adjacent extensional faults with different orientations (Figs. 4 and 8) and with the superposition of thrust related folds to earlier roll-over anticlines.

A tectonic inversion style is recognised within the Cordillera Oriental, but inversion was moderate, as suggested by the trends of Andean contractional structures, that obliquely truncate the differently oriented realms of the complex Salta Basin at regional scale. As a consequence, the Salta Basin is split into the main structural units of the Andes in NW Argentina, even in the foreland.

All the differently trending contractional structures that coexist and are well exposed in the southern Cordillera Oriental could have arisen from one single tectonic event of positive inversion superimposed onto a complex original architecture of the Salta Basin. The variability in orientation of Cordillera Oriental structures could thus result from a simple, continuous contraction with no significant changes in the average shortening direction, partitioned by a complex pre-orogenic architecture.

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