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Structural style of the Malargüe fold-and-thrust belt at the Diamante River area (34°30′–34°50′S) and its linkage with the Cordillera Frontal, Andes of central Argentina

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ABSTRACT

The Malargüe fold-and-thrust belt is a thick-skinned belt developed in Miocene-Pliocene times during the Andean orogeny, which together with the Cordillera Frontal constitutes the Andes of central Argentina in the Diamante River area. Detailed field mapping and construction of three regional balanced cross-sections, supported by seismic and well information, constrains the structural style of this Andean region as two basement uplifts in the western and eastern sectors surrounding a central region of thin-skinned deformation. In the west, large basement wedges related to thrust faults developed during Andean compression propagated along favourable horizons (commonly gypsum) into the sedimentary cover. These wedges transferred shortening to the cover rocks producing the thin-skinned structures. There is therefore a close spatial and temporal relationship between basement and cover deformation. In the thin-skinned region, the abundance of shales and salt horizons in the west facilitated the formation of fault-related folds while the more competent units in the east were deformed into duplex and imbricated thrusts. The basement uplift in the eastern sector represents the southern end of the Cordillera Frontal, where the Carrizalito fault placed pre-Jurassic rocks over tertiary synorogenic sediments in the northern area while in the southern region it remained as a blind thrust. A common feature is the development of backthrust systems related to the major east-vergent basement structures. The backthrusts therefore serve to locate basement uplifts where outcrops are absent. Three-dimensional integration of the cross-sections and a structural map at the top of the pre-Jurassic basement show that although the main structures change considerably along strike, the total shortening of each section shows little variation.

1. Introduction

The architecture of the central-west side of Argentina is the result of several tectonic, magmatic and accretionary processes occurred from Paleozoic to recent times (Ramos, 1988, 1999). At the end of the Paleozoic, a large magmatic activity that extended up to the Triassic is represented mainly by acid volcanic rocks included in the Choiyoi Group (Llambías et al., 1993). The best exposures of these rocks are in the Cordillera Frontal, to the north of the study area (Fig. 1). Generalized extension during the Mesozoic in a back-arc setting generated the Neuquén Basin, one of the most important hydrocarbon-producing sedimentary basins in Argentina. The Cenozoic Andean compression deformed all these materials (Paleozoic to Triassic basement rocks and Mesozoic sedimentary rocks) forming the Cordillera Principal geological province which is divided in several fold-and-thrust belts along the strike. The Malargüe fold-and-thrust belt (Koslowski et al., 1993) is a basement-involved orogenic belt developed during the Andean orogeny in Mendoza province, on western Argentina (Fig. 1a). The study area is located approximately 90 km to the north of Malargüe city, in the mountainous area of the Diamante River. This region is particularly interesting because it is the surficial boundary between the Cordillera Principal and Cordillera Frontal geological provinces and thus is an extraordinary place to observe basement and cover deformation.

The aim of this work is to comprehend the structural style that characterize this portion of the Malargüe fold-and-thrust belt and the Cordillera Frontal based on a detailed field mapping and three balanced structural cross-sections, supported by seismic and well information. In order to explain the structures observed in the Malargüe fold-and-thrust belt at the Diamante River area, a structural model that considers basement-involved low angle thrusts originated due to the Andean compression is proposed. In this model three basement wedges occur in the west and transmit the shortening to the east, assuming a normal sequence of faulting,

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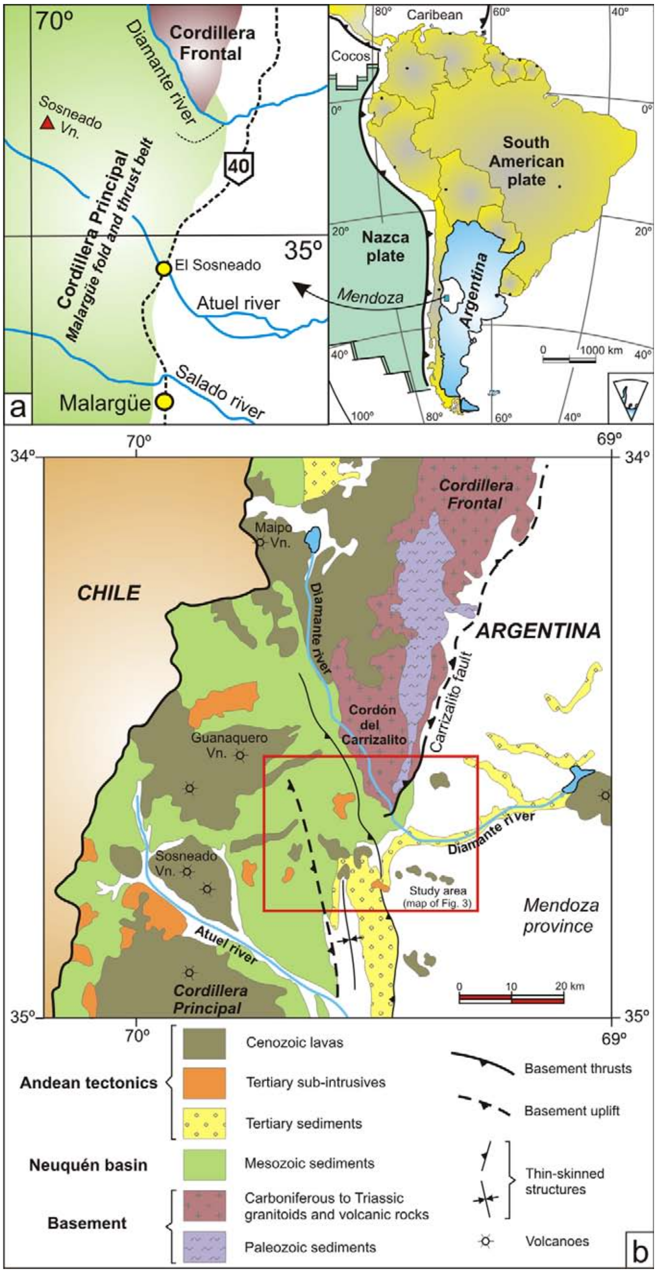

Fig. 1. (a) Location map of the studied region involving the Cordillera Principal and Cordillera Frontal geological provinces, in the Andes of central Argentina. (b) Regional map (modified from Sruoga et al., 2005) showing the main geological features in this part of the Andes between the Diamante and Atuel rivers.

producing directly the thin-skinned structures developed in the sedimentary cover. The three balanced cross-sections allow to calculate the basement and cover shortenings and its three-dimensional integration show the along-strike variations of the main thick and thin-skinned structures.

2. Geological setting

The actual configuration of this part of the Andes was produced by a complex tectonic evolution due to several accretionary processes during the Paleozoic and continuous subduction of the oceanic crust below the western side of the South American plate from the Mesozoic up to nowadays (Fig. 1a). As a consequence, very different types of rocks compose the geological record of this region (Fig. 1b). Paleozoic sediments and Permian–Triassic igneous rocks were grouped as pre-Jurassic basement, Mesozoic sediments filled the Neuquén basin and finally Tertiary synorogenic sediments were deposited together with sub-intrusive bodies and volcanic rocks during the Andean orogeny. The nomenclature, lithology, age and tectonic setting of all these materials are summarized in a stratigraphic column (Fig. 2) and they are briefly described below. More detailed information about the lithological characteristics, age and spatial distribution of these stratigraphic units can be found in the works of Groeber (1947), Volkheimer (1978) and Sruoga et al. (2005).

2.1. Pre-Jurassic basement

The older unit is composed of sedimentary and low-grade metamorphic rocks of the Las Lagunitas Formation (Volkheimer, 1978), probably of Late Ordovician age (Tickyj et al., 2009), which were intruded in the Carboniferous by the Carrizalito tonalite (334 Ma, Dessanti and Caminos, 1967). This igneous-metamorphic assemblage was intruded by granites and covered by basaltic to rhyolitic volcanic and phyroclastic rocks assigned to the Permian–Triassic Choiyoi cycle (Llambías et al., 1993). A strong angular unconformity exists between these volcanic rocks and the underlying Late Carboniferous–Early Permian strata folded by the Sanrafaelic orogenic phase, a Permian compressive event widely recognized in the Cordillera Frontal (Caminos, 1979; Ramos, 1988). There are not absolute ages data of the granites in the Diamante River area but they would be equivalents to the plutonic rocks observed in the other places of the Cordillera Frontal (Llambías et al., 1993) intruded from Permian to Early Triassic, after the Sanrafaelic orogeny. Outcrops of these basement units are restricted to the northeast of the study area (Fig. 3), in the Cordón del Carrizalito, and they are absent southward of the Diamante River. Exposures of the basement rocks have a strong structural control since they were thrust eastward over younger sediments during the Andean orogeny and represent the southern end of the Cordillera Frontal. Micro and mesoscale studies of the plutonic rocks along the Diamante River valley revealed a marked brittle behaviour for these basement rocks during the Cenozoic deformation coherently with a small overburden due to the thin sedimentary cover in this marginal portion of the Mesozoic basin (Turienzo et al., 2006).

2.2. Mesozoic sediments of the Neuquén basin

In the studied region, the infill of the Neuquén basin started with the deposition of the Early to Middle Jurassic Cuyo Group. This unit is composed of a fining upward sequence, which begins with coarse conglomerates of the El Freno Formation (Hettangiano) followed by sandstones (Puesto Araya Formation) and black shales (Tres Esquinas Formation) containing ammonites and others marine fossils (Bajocian). According to Manceda and Figueroa (1995) the rocks of Cuyo Group were deposited in isolated depocenters in the initial rift stage of the basin. Faults controlling the subsidence in these rift systems would be responsible of large changes of thickness in this unit (Manceda and Figueroa, 1995; Giambiagi et al., 2005a,b; Lanés, 2005; Lanés et al., 2008). On the other hand, Spalletti et al. (2005) mentioned a uniform thickness of approximately 300 m for the Cuyo Group in the Atuel River region, immediately to the south of the study area (Fig. 1b). Gypsum of the Tábanos Formation (Callovian) at the top of the Cuyo Group reveals an important shallowing of the marine environment. The sub-aerial and shallow water conditions continued during the Oxfordian with the deposition of eolian sandstones (Lotena Fm.), fossiliferous limestones (La Manga Fm.) and evaporites (Auquilco Fm.) which form the Lotena Group. A thick sequence of mainly fluvial red beds (Tordillo Fm., Kimmeridgian) indicates a progradation of continen-

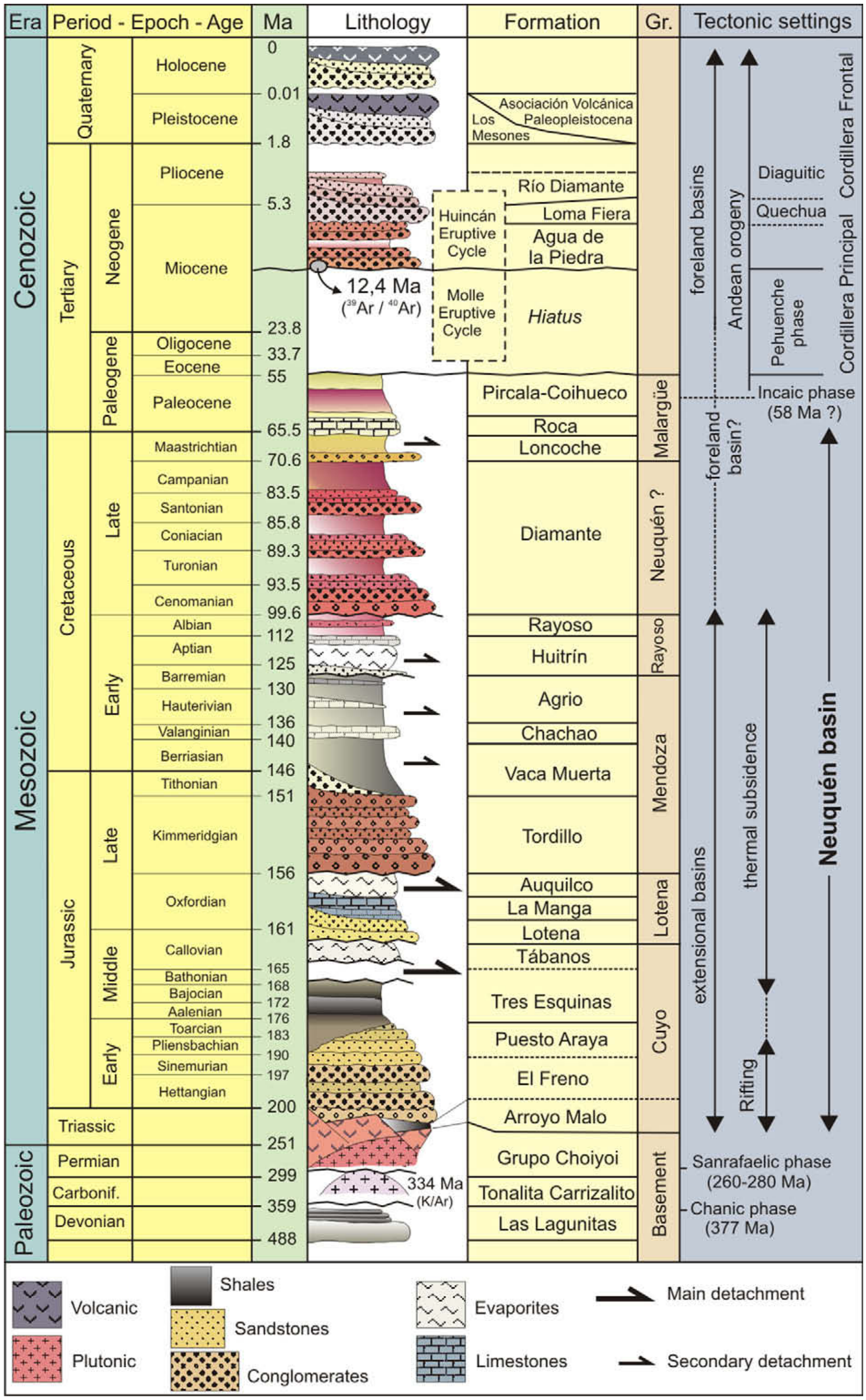

Fig. 2. Stratigraphic column including the nomenclature, lithology, age and tectonic setting of the units present in the studied area. Detachment levels within the cover are indicated.

tal facies over marine rocks. After that, a sudden marine inundation is registered by the black shales of the Vaca Muerta Formation (Tithonian), which represent the maximum oceanic development in the Neuquén basin and it is the most important source rock of this petroliferous province. As the study area is near to the north-east basin edge there is a marked facies change from marine shales in the west to sandstones and conglomerates to the east, which is observed in outcrops and also is registered by the oil wells located in the foreland. The ~30 meters-thick fossiliferous limestone of the Chachao Formation (Valanginian), widely exposed in the study area, represent a regional relative fall of the sea level and constitutes an excellent key bed to reconstruct the tectonic structures. Covering this horizon, deep-water black shales of the Agrio Formation (Late Valanginian-Early Barremian) represent the last marine inundation of the Neuquén basin. This sequence from Tordillo to Agrio Formations forms the Mendoza Group, which is covered by evaporites (in the west) and limestones (in the east) of the Huitrín Formation (Barremian-Aptian). The latter together with red beds of

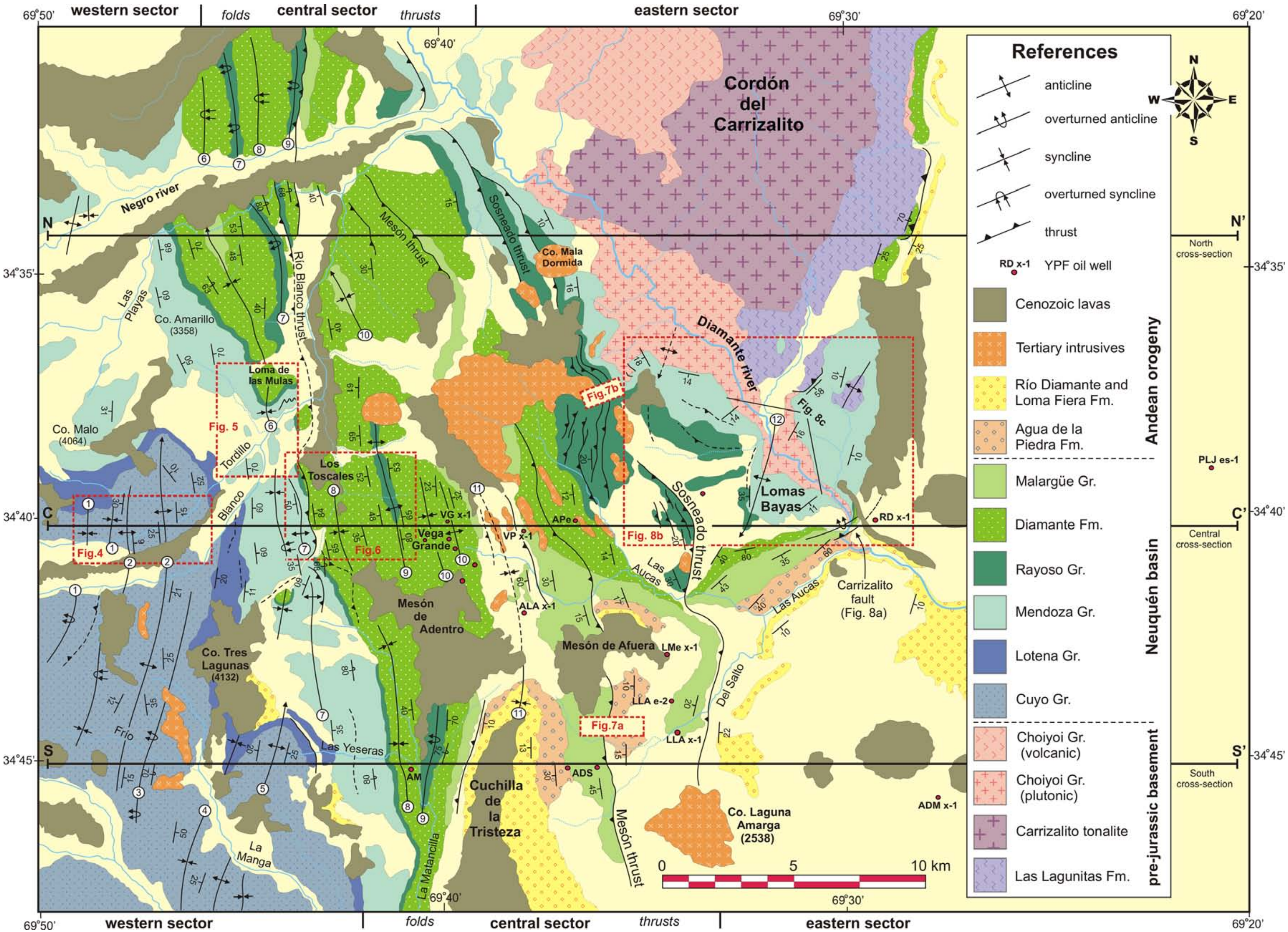

Fig. 3. Geological map of the Diamante River region (simplified from Turienzo, 2008), with the structural domains recognized for this portion of the Malargüe fold-and-thrust belt and the Cordillera Frontal. Numbers in white circles correspond to the main folds in the area. (1) Cerro Malo anticlines and synclines, (2) Arroyo Tordillo anticlines, (3) Arroyo Frio anticline, (4) Tres Lagunas syncline, (5) Las Yeseras anticline, (6) Loma de las Mulas syncline, (7) Rio Blanco anticline, (8) Los Toscales syncline, (9) Vega de los Patos anticline, (10) Vega Grande anticline and syncline, (11) Cuchilla de la Tristeza syncline, and (12) Lomas Bayas anticline.

the Rayoso Formation (Albian) constitutes the Rayoso Group, accumulated in a continental environment, indicating the end of the connection with the Pacific Ocean. Continental deposition continued during the Late Cretaceous with a thick succession of red conglomerates, sandstones and claystones of the Diamante Formation. Reddish and greenish fine grain sediments that compose the Malargüe Group were accumulated from Late Cretaceous to Early Tertiary, mainly in a fluvial-lacustrine environment. However, at the middle of this unit, calcareous rocks of the Roca Formation with fossils of Campanian–Maastrichtian age represent a shallow-marine transgression from the Atlantic Ocean.

2.3. Andean related Cenozoic rocks

In this portion of the Andes, an important hiatus took place after the deposition of the Paleocene Pircala-Coihueco Formations that forms the top of the Malargüe Group. Neogene volcanic activity was intense and in the study area is represented by Middle to Late Miocene subvolcanic andesitic bodies emplaced during the Huincán Eruptive Cycle (Nullo et al., 2002). After the hiatus, Tertiary sedimentation started with the accumulation of the "rodados lustrosos" (Groeber, 1947), a conglomeratic level with pebbles of volcanic rocks, at the base of the Agua de la Piedra Formation. The radiometric age of these pebbles is about 12 Ma (Baldauf et al., 1992) thus accumulation of the synorogenic strata of the Agua de la Piedra Formation, in an alluvial fan environment, begun after the Middle Miocene linked to the Pehuenche phase of the Andean orogeny (Combina and Nullo, 2005). Sandstones and conglomerates of the Loma Fiera Formation (Late Miocene) and the Río Diamante Formation (Pliocene) lie unconformably over the Agua de la Piedra Formation. Neogene to Quaternary igneous activity was characterized by basaltic-andesitic flows and locally ignimbritic levels, preserved as flat hills and in the valleys of the rivers, which cover the previously folded sedimentary rocks. Pleistocene-Holocene erosion of the mountain front produced coarse-grain sedimentation at the foothills.

3. Structure

Description of the structures based on a detailed field mapping is essential to begin the understanding of the structural style of this Andean region, where semiarid weather conditions created exceptional scenery to observe natural folds and thrusts. The geological map (Fig. 3) comprises an area of approximately 1500 km^2 (45 km × 35 km) and was constructed with the aid of aerial photographs (~1:50.000) and Landsat satellite images. From a regional point of view, the structure of this sector of the Andes involves two basement uplifts occurring at the western and eastern sectors

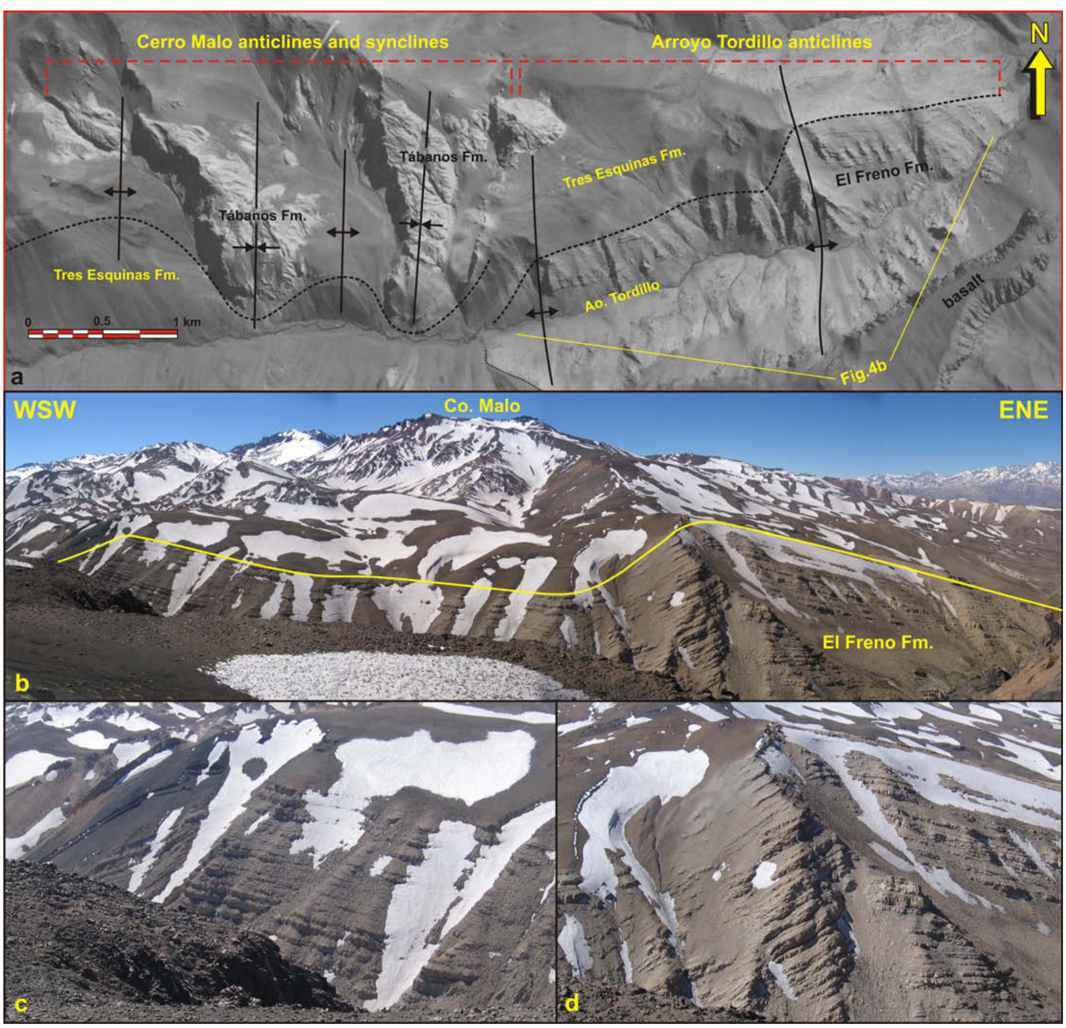

Fig. 4. (a) Aerial photograph of the Tordillo stream valley (see location on Fig. 3), which shows the structures affecting the Early Jurassic formations in the western sector. (b) Panoramic photograph of the Arroyo Tordillo anticlines characterized by long, gently-dipping backlimbs and short, steeply-dipping forelimbs, which depict the westward vergence of these folds related to backthrusts. (c and d) Detail of the angular hinges of the Arroyo Tordillo anticlines.

surrounding a central sector of thin-skinned deformation. The western thick-skinned and central thin-skinned sectors constitute the Malargüe fold-and-thrust belt while the basement-involved eastern sector corresponds to the southern part of the Cordillera Frontal. Although pre-Jurassic rocks are not outcropping in the western portion of the study area, an important elevation of the basement produced the exposure at high topographic levels of the Early-Middle Jurassic Cuyo Group (Fig. 3). Thick-skinned structures in the eastern sector are well exposed in the Cordón del Carrizalito and toward the south they are recognized from subsurface information. In the central sector, between these two large basement-involved regions, cover rocks were distinctly deformed according to their lithological changes related to the location into the basin. The abundance of shales and salt horizons at the west facilitated the formation of folds while the coarse-grain sediments and limestones located toward the east are more competent and thus they developed thrust, forming duplex structures and imbrications.

3.1. Western sector (thick-skinned zone of the Malargüe fold-and-thrust belt)

Jurassic sedimentary rocks in the western sector depict several N–S to NNE trending folds (Fig. 3). To the south of Cerro Malo, two anticline-syncline pairs involve the upper part of the Cuyo Group and particularly the gypsum of the Tábanos Formation is notably preserved in the core of the Cerro Malo synclines (Fig. 4a). Southward of the Blanco stream is possible to recognize only one of the Cerro Malo anticlines, with a steeply-dipping forelimb that indicates an east vergence. Immediately to the east are observed the Arroyo Tordillo anticlines, two westward-directed asymmetric anticlines with long, gently-dipping backlimbs (5–15°E) and short, steeply-dipping forelimbs (30–40°W) that involve the El Freno Formation (Fig. 4b). These folds have straight flanks and relatively angular hinges which define roughly a kink geometry (Figs. 4c and d). In the Frio stream area, along the line of the south cross-

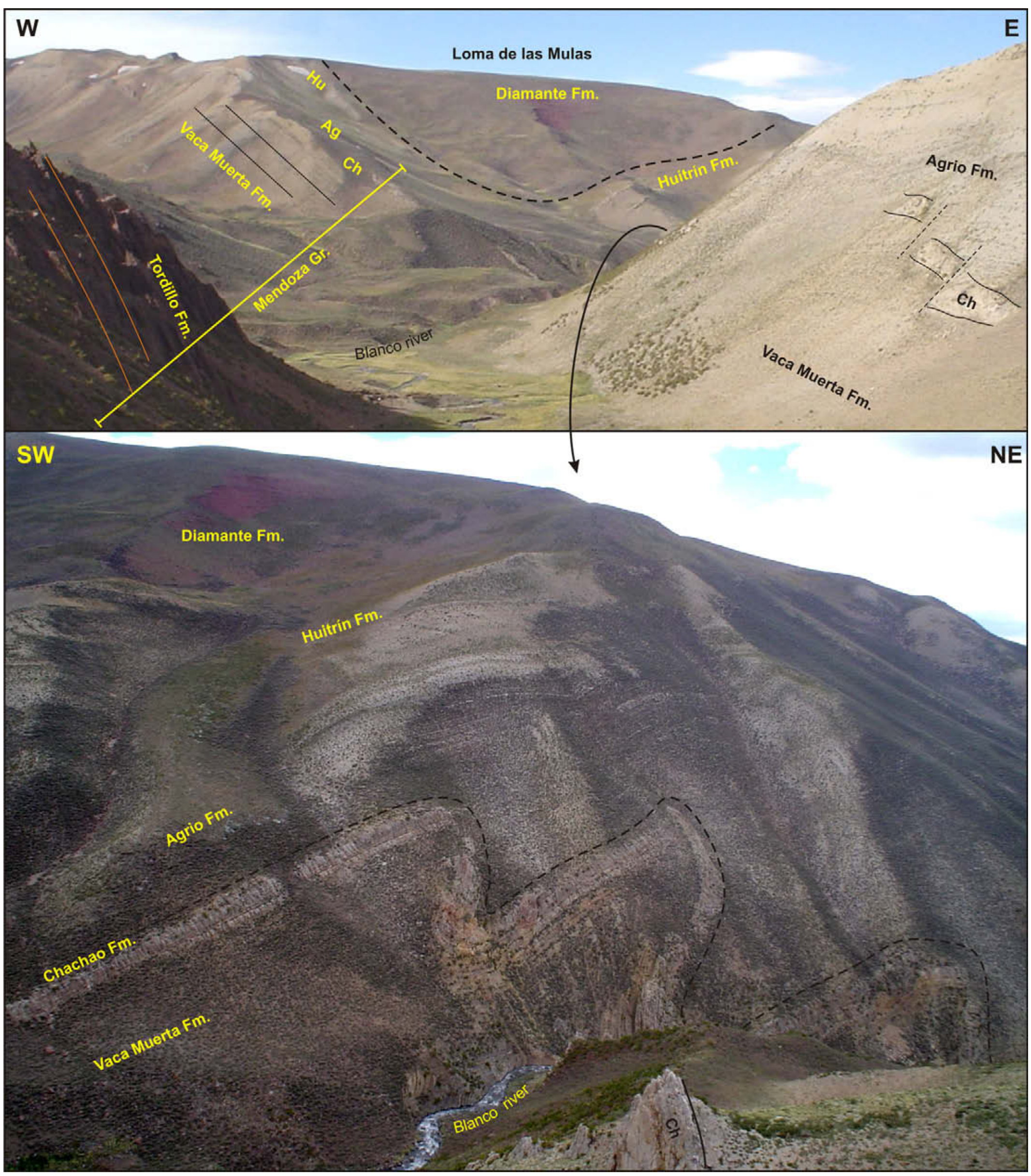

Fig. 5. (a) Panoramic view of the southern part of the Loma de las Mulas syncline (see Fig. 3 for location), which marks the boundary between the thick-skinned western sector and the folds zone in the central sector. (b) Disharmonic folding of the Chachao Formation limestones between the black shales of the Vaca Muerta and Agrio Formations in the eastern limb of the syncline.

section, only one of these westward-vergent anticlines was developed (Fig. 3). In the backlimb of this anticline, east dipping strata of the Cuyo Group abruptly become overturned forming the eastward-vergent Arroyo Frio anticline. Layers of the Cuyo Group to the south of Cerro Tres Lagunas form two open, northward-plunging folds, the Tres Lagunas syncline and Las Yeseras anticline (Fig. 3). All the described structures in the western sector plunge gently toward the north and thus outcrops of Early-Middle Jurassic rocks are absent in the Las Playas stream area, where the Late Jurassic to Early Cretaceous Mendoza Group is exposed.

3.2. Central sector (thin-skinned zone of the Malargüe fold-and-thrust belt)

3.2.1. Folds zone

The western region of this zone where folding structures prevail is marked by the notable Loma de las Mulas syncline, which extends from the Negro River in the north to the eastern slope of Cerro Tres Lagunas in the south (Fig. 3). Layers of Mendoza Group dipping 50–70°E constitute the western limb of this syncline, although the abundance of shales within this unit favoured locally intense folding with overturned beds. The axis of the syncline plunges to the north and in the Las Playas stream area, where this structure reaches a width of 5 km, it includes the Malargüe Group in its core (Fig. 3). There, the coarse-grain layers of the Diamante Formation that dip 80°E and 40–50°W in the western and eastern flanks respectively depict clearly this structure. In concordance with the northward plunge direction of the syncline, at Loma de las Mulas is possible to observe this structure involving layers from the Mendoza Group to the Diamante Formation (Fig. 5a). The deep valley of the Blanco River, formed after the confluence of the Tordillo and Blanco streams, allows to observe a spectacularly exposed disharmonic folding of the Chachao Formation limestones between the shales of the Vaca Muerta and Agrio Formations in the eastern limb of the syncline (Fig. 5b). This tight folding of the Mendoza Group layers, previously described by Volkheimer (1978), is also found in the sector between Los Toscales and Cerro Tres Lagunas where the syncline is overturned (Fig. 3).

To the east of the Loma de las Mulas syncline, several folds with different along-strike development are the more relevant structures in the sedimentary cover. These structures are completely exposed in the north side of the Negro River valley (Fig. 3) where is possible to recognize two eastward-vergent anticlines with an overturned syncline linking them, involving the Rayoso Group evaporites (Huitrin Formation) and the Diamante Formation red beds. The westernmost fold is the Rio Blanco anticline, which along the line of the north cross-section was thrust over the Los Toscales syncline and the Vega de los Patos anticline by means of the Rio Blanco thrust (Fig. 3). The fact that this fault placed the Rio Blanco anticline over the folds located to the east allow to interpret the Rio

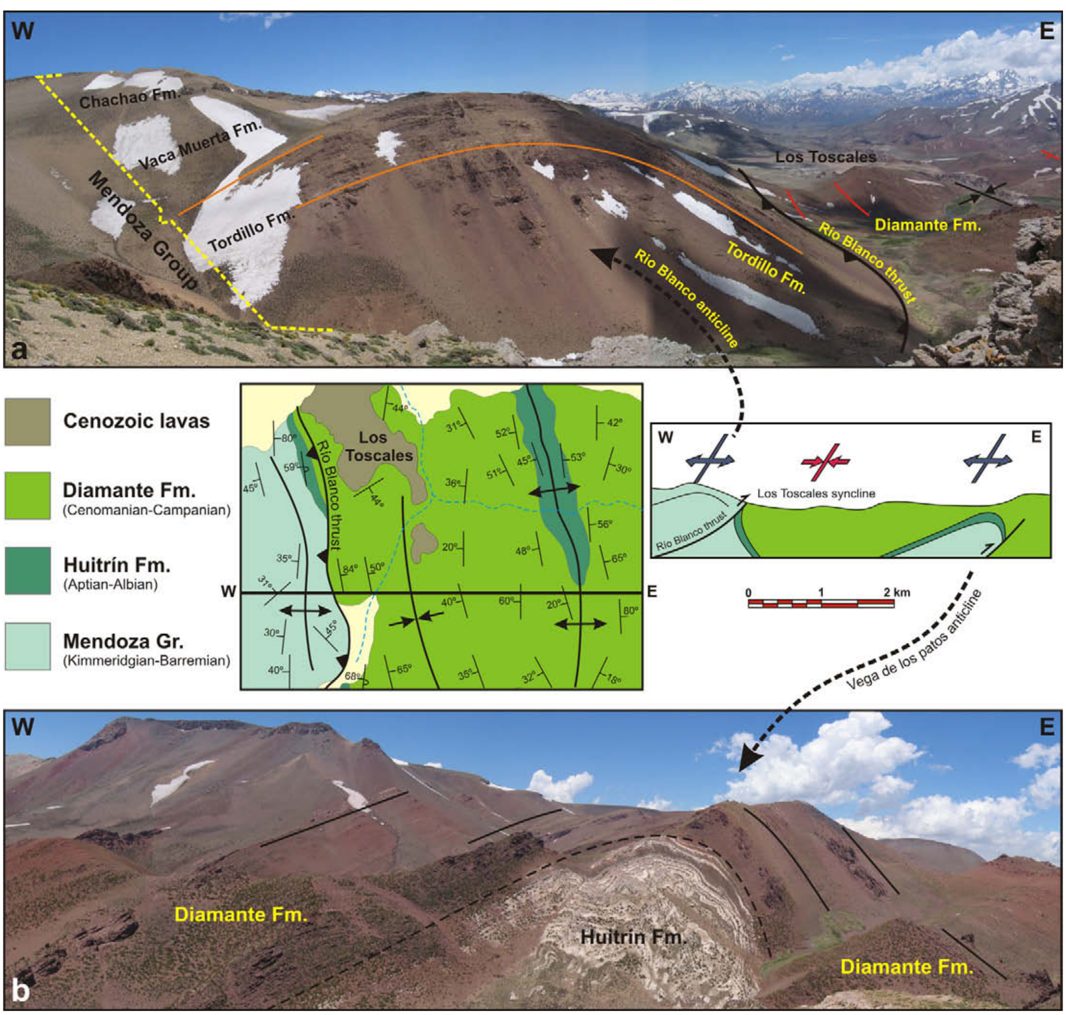

Fig. 6. Main folding structures in the folds zone of the thin-skinned central sector along the central cross-section (see location on Fig. 3). (a) The Rio Blanco anticline involving the Mendoza Group was thrust over the Diamante Formation, which forms the Los Toscales syncline, by means of the Rio Blanco thrust. (b) The Vega de los Patos anticline, wonderfully exposed due to the lithological contrast between the Huitrín Formation evaporites and the Diamante Formation red beds.

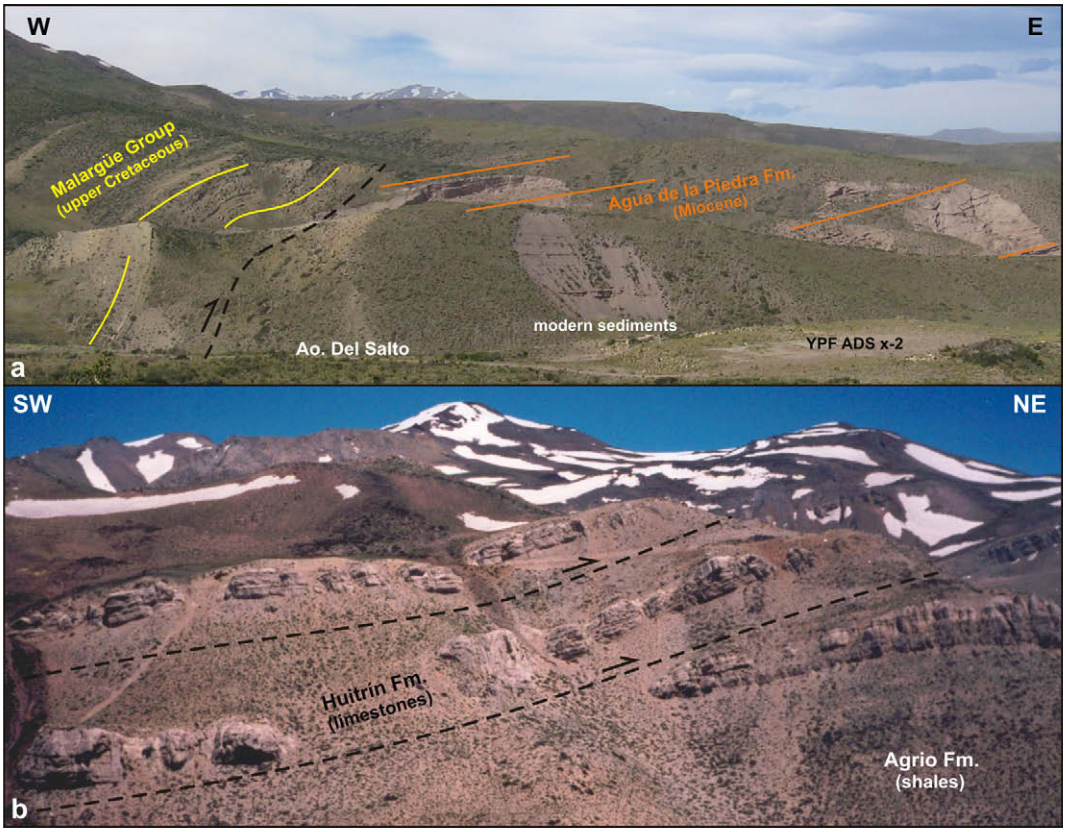

Fig. 7. Low angle faults affecting sedimentary layers in the thrusts zone of the thin-skinned central sector (see location on Fig. 3). (a) The Mesón thrust put the Late Cretaceous Malargüe Group over the Miocene syntectonic strata of the Agua de la Piedra Formation. (b) Duplex structures involving the limestones of the Huitrín Formation related to the Sosneado thrust.

Blanco thrust as an out-of-sequence thrust that broke through the forelimb of its related anticline. Toward the south, this thrust placed the Mendoza Group, which form the Rio Blanco anticline along the central cross-section, over the Diamante Formation beds in the Los Toscales syncline (Fig. 6a). This syncline, which is the same structure described at the north of the Negro River linking the anticlines, continues to the south up to the Las Yeseras stream area which emphasises the significance of this fold (Fig. 3). The Vega de los Patos anticline is beautifully exposed along a creek to the east of Los Toscales (Fig. 6b), involving the Huitrin and Diamante Formations. Strata of the Diamante Formation dipping 20–60°W in the backlimb and up to 80°E in the forelimb indicate an eastward vergence that is confirmed all along the axis, particularly to the south of Cerro Mesón de Adentro where the anticline is overturned. At the Negro River area, the Vega de los Patos anticline with gypsum in its core was thrust toward the east over the sediments of Malargüe Group that are dipping 40°W (Fig. 3).

3.2.2. Thrusts zone

To the east of the above described structural domain there is a region where the pinch out of the units that behave ductively (shales and evaporites), made difficult the development of folds and thus sedimentary layers were affected by thrusts that produced duplex and imbrications. The trend of these thrusts varies from N–S in the south area, near the Cerro Laguna Amarga, to NW–SE in the north area surrounding the Cerro Mala Dormida (Fig. 3). The westernmost structure correspond to the Mesón thrust (Kozloswki, 1984; Kozloswki et al., 1989), which to the south of Mesón de Afuera (Fig. 3) placed Late Cretaceous sediments of the Malargüe Group over Miocene syntectonic rocks of the Agua de la Piedra Formation (Fig. 7a). In the hangingwall of the Mesón thrust the Roca Formation dip ~45°W while in the footwall the Agua de la Piedra Formation has a general dip of 10–15°W resulting a reasonable cut-off angle of 30° for the thrust. Between the Mesón thrust and the Vega de los Patos anticline developed to the south of Mesón de Adentro there is a N–S trending hill known as Cuchilla de la Tristeza, which is an open syncline containing mainly syntectonic Tertiary sediments (Fig. 3). The Cuchilla de la Tristeza syncline (Gerth, 1931; Volkheimer, 1978; Kozloswki, 1984) has a maximum width of 5 km along the south cross-section and decreases toward the north where is recognized by scarce outcrops of the Malargüe Group nearby the Vega Grande oil field. Imbrications within the Diamante Formation, which only occasionally has been thrust over the Malargüe Group, represent the activity of the Mesón thrust in the northern area.

In the region of the Cerro Mala Dormida, along the north cross-section, the Sosneado thrust (Kozloswki, 1984; Nullo et al., 1987; Nullo and Stephens, 1993) produced repetitions that involve the carbonatic layers of the Agrio and Huitrín Formations (Fig. 3). Toward the south this faulting affected only limestone beds of the Huitrín Formation, with a thickness of approximately 15 m, which formed marvellously exposed duplex structures (Fig. 7b). The strata above the Sosneado thrust dip ~15°W, but they can reach 40° over the fault ramps. In the area of the Del Salto stream, near the south cross-section, this thrust uplifted the Malargüe Group that dips 20°W over the younger Tertiary strata, which are dipping 22°E (Fig. 3).

3.3. Eastern sector (Cordillera Frontal, basement outcrops)

One of the most important morphological features in the study area is the Cordón del Carrizalito, which represents the southern

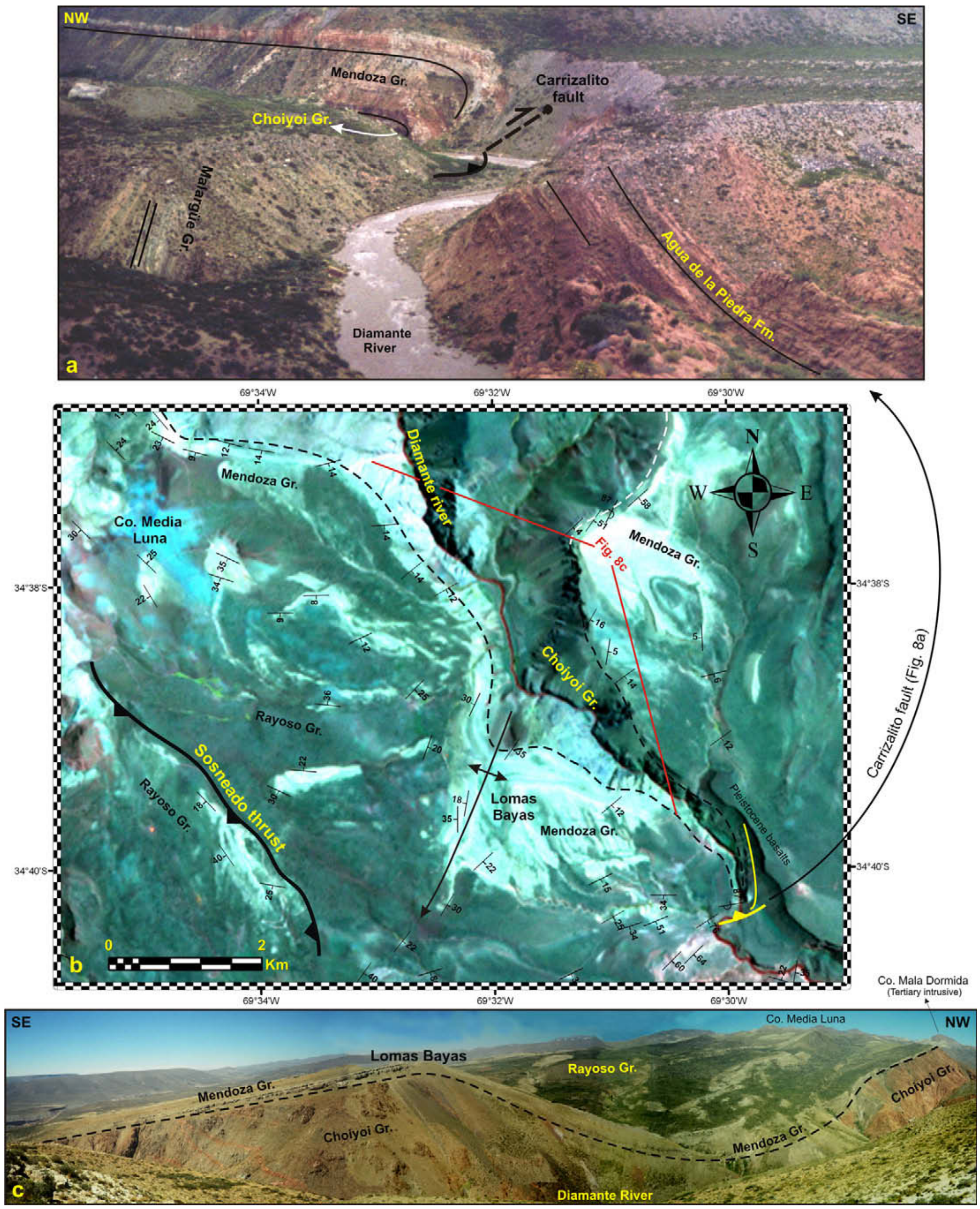

Fig. 8. Thick-skinned structures at the eastern sector (see location on Fig. 3). (a) Panoramic photograph of the Carrizalito fault in the Diamante River valley, which placed pre-Jurassic and Mesozoic rocks over Tertiary deposits of Agua de la Piedra Formation. (b) Landsat image of the Diamante River area showing the main structures in this sector, the structural data and the location of the panoramic photographs. (c) Panoramic view of the Lomas Bayas anticline, which involved basement rocks and has vergence to the west, associated to a backthrust that branches off from the Carrizalito fault.

end of the Cordillera Frontal geological province (Fig. 1b). This range is a huge anticlinorium that plunges to the south and disappears in the region of Lomas Bayas, cored by pre-Jurassic basement rocks (Fig. 3). The backlimb of the Cordón del Carrizalito anticlinorium in the studied region trends NW–SE, approximately parallel to the Diamante River valley in the area of the Cerro Mala Dormida, and toward the north it becomes N–S. The NNE trending eastern edge of the Cordillera Frontal is limited by reverse faults (Fig. 1b), which locally reached the surface and thus the basement rocks were thrust toward the foreland over the younger sedimentary rocks. In the study area, the main structure responsible of the Cordón del Carrizalito uplift was the Carrizalito fault (Baldi et al., 1984; Kozloswki et al., 1989; Nullo and Stephens, 1993). The Diamante Formation that lies unconformably over the basement in the line of the north cross-section, dip ~70°W and contain sedimentary structures indicating inverted layers. The Carrizalito fault placed these overturned Mesozoic beds over the Tertiary Río Diamante Formation that dips ~25°E (Fig. 3). A similar situation occurs close to the confluence of the Las Aucas stream with the Diamante River (line of central cross-section, Fig. 3), where the Carrizalito fault uplifted the pre-Jurassic basement and Mesozoic sediments over the Miocene deposits of the Agua de la Piedra Formation (Fig. 8a and b). In the hangingwall of the Carrizalito fault, cover rocks that overlie the basement and dip ~12°SE, suddenly become overturned (~87°NNW) and thinned near the fault (Fig. 8a). The ~ENE strike of the beds over the Carrizalito fault sug-

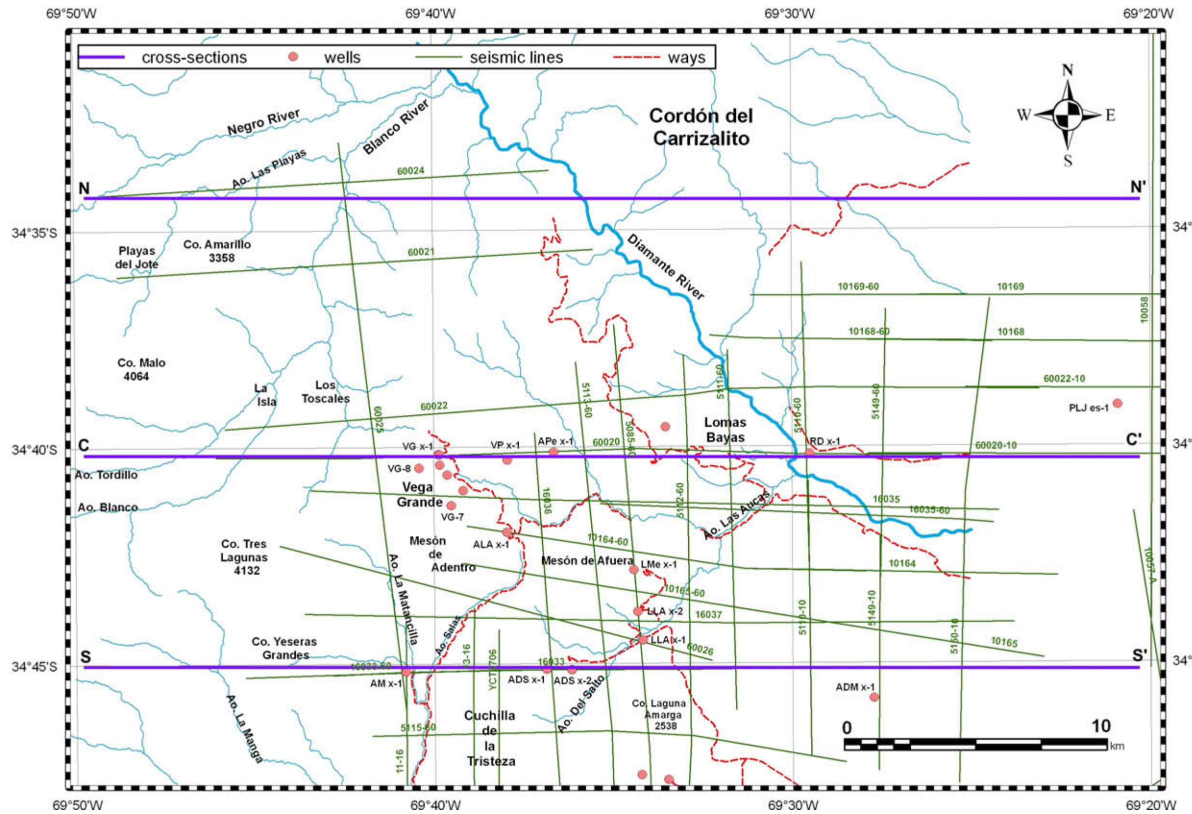

Fig. 9. Name and location of the seismic lines and oil wells considered for the construction of the balanced cross-sections.

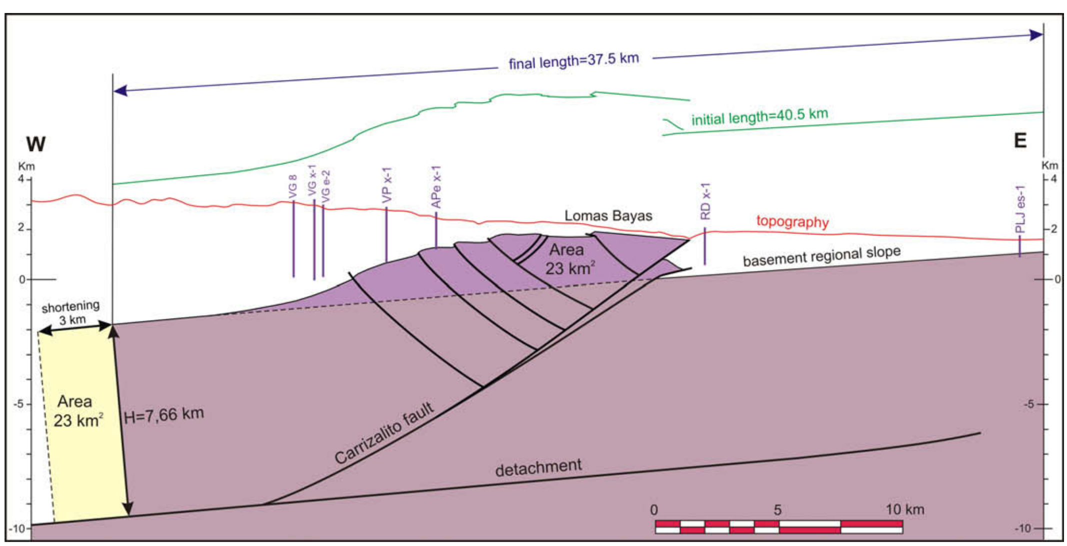

Fig. 10. Reconstruction of the basement-involved structures related to the Carrizalito fault in the central cross-section, which is very well constrained by both surface and subsurface data. The measured 23 km^2 of excess area and 3 km of shortening produced by these structures allow to calculate the depth to the regional detachment, which is located approximately 10 km below the sea level.

gest an ENE trend for this structure, corresponding to an oblique fault respect to the common NNE trend of this main fault in the Cordillera Frontal mountain front (Fig. 1b). In the footwall, layers of the Agua la Piedra Formation have a maximum dip of 64°SE that decrease considerably to the east of the fault.

Within the basement uplift that forms the Cordón del Carrizalito anticlinorium the most noticeable structure is the Lomas Bayas anticline, completely exposed in the southwest side of the Diamante River (Figs. 3 and 8b). It is an asymmetric anticline with a WNW vergence, which is related to a backthrust that branches off from the Carrizalito fault, and includes pre-Jurassic basement rocks in its core (Fig. 8c). Its forelimb is short and has an almost constant dip of 30–35°W, while the backlimb is longer and gently-dipping (~12°SE). The axis of the Lomas Bayas anticline plunges ~11° in a SSW direction, as was determined using stereographic methods with field data by Turienzo and Dimieri (2005a). Toward the northwest, the basement-cover contact along the Diamante River is inclined ~12–14°SE (Fig. 8b and c). It has been described elsewhere that anticlines related to backthrust systems involving basement rocks are characterized by long, gently-dipping backlimbs and shorter, steeply-dipping forelimbs (Erslev, 1993; Dimieri and Nullo, 1993; Turienzo and Dimieri, 2005a,b,c; Neely and Erslev, 2009) as is the case of the Arroyo Tordillo anticlines (Fig. 4b) and the Lomas Bayas anticline (Fig. 8c). Considering these features, the inclination of the basement-cover contact in the Diamante River was interpreted as the backlimb of a second westward-directed anticline (Turienzo and Dimieri, 2006).

4. Balanced cross-sections

In order to comprehend the structural style of this sector of the Andes, including the Malargüe fold-and-thrust belt and the Cordillera Frontal, three balanced cross-sections of 45 km each one and E–W orientation, normal to the main N–S trend of the Andean structures, were made. Detailed field mapping of the structures was essential to reconstruct the structural sections, which besides are supported by several 2D seismic lines and oil wells (Fig. 9). Despite of the poor quality of the seismic sections, reflectors corresponding to the main structures have been recognized and correlated with the units identified from well data. Time to depth conversion from the YPF.VG.x-1 well, located in the Vega Grande oil field (Fig. 9), was used to estimate the depth of the seismic horizons. The YPF.PLJ.es-1 well, situated near the eastern end of the central cross-section, indicates the depth of the basement-cover contact in the foreland. Based on this well, the top of the basement was extended to the west (into the basin) considering a regional slope of ∼4–5°, enough to explain the progressive onlap of the sedimentary units toward the foreland. The thickness of the units used in the balanced cross-sections were in general those mentioned by Volkheimer (1978), together with own observations and well data. The interpretation and restitution of the thin-skinned structures were made assuming bed-length conservation of the cover layers, with special attention in the location of the ramps and detachment levels. The geometry of the basement-involved structure related to the Carrizalito fault along the central cross-section (Fig. 10) is the best constrained by both subsurface information (seismic and wells from the Vega Grande oil field toward the east, Fig. 9) and field data (Fig. 3), particularly the excellent exposure of the basement-cover contact along the Diamante River (Fig. 8). Considering the excess area produced by this structure (∼23 km^2), which implies 3 km of shortening, was possible to calculate a depth to detachment of 7.66 km from the top of the basement, that is approximately 10 km below the sea level (Fig. 10). Applying this depth to the main detachment, the excess area was used to calculate the basement shortening related to the Carrizalito fault in the north and south cross-sections. A normal sequence of faulting, from west to east, was assumed for the structural reconstructions and only in particular cases break-through faults were interpreted cutting some of the folds that ambiguously could be interpreted as out-of-sequence faults.

4.1. Central cross-section

This section shows a complete development of all the structural domains recognized in this part of the Malargüe fold-and-thrust belt and the southern segment of the Cordillera Frontal, which are the western and eastern sectors with basement-involved structures and a central sector of thin-skinned deformation (Fig. 11). In the western sector, the Cerro Malo anticlines and synclines involving surficialy the Cuyo Group (Fig. 4a) were interpreted by Turi-

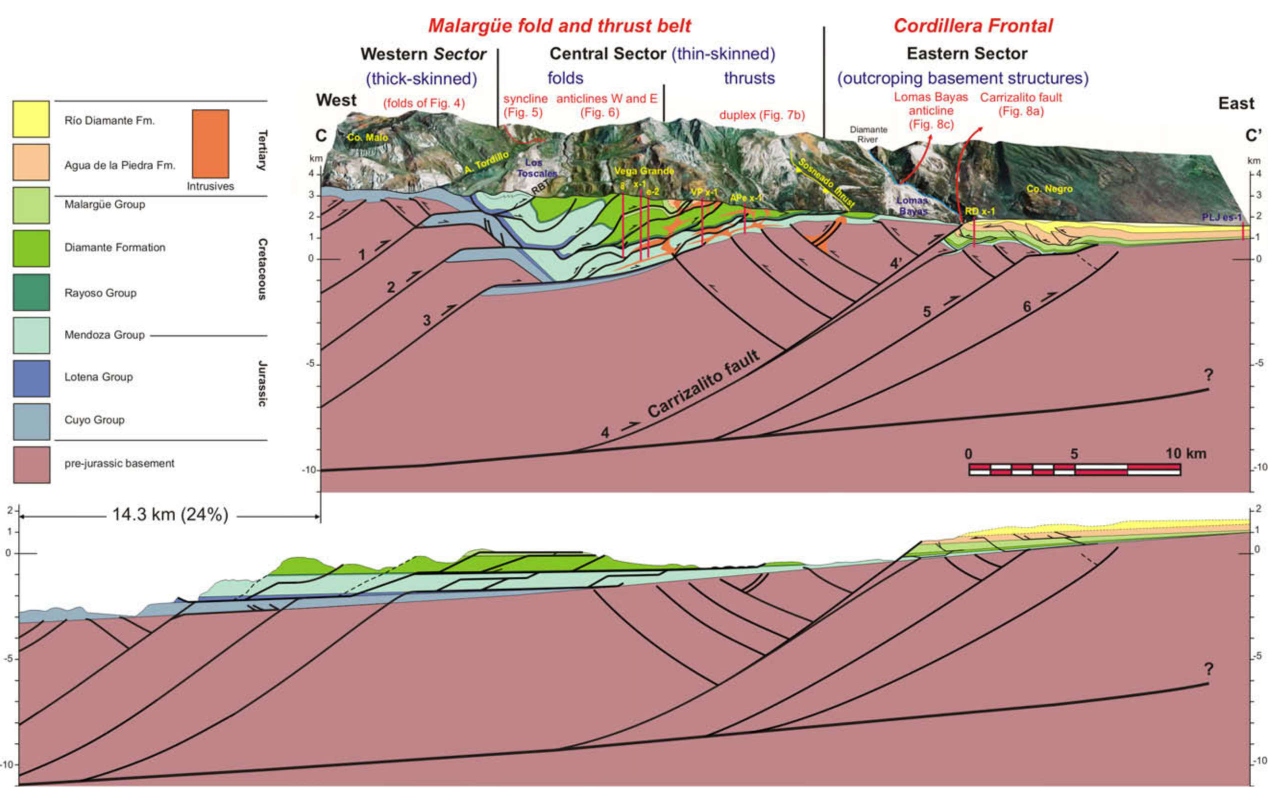

Fig. 11. Central balanced cross-section (C–C′), which is the most complete since it has well developed all the structural domains (western and eastern thick-skinned sectors and the central thin-skinned sector) recognized in this region of the Andes. In the western sector, a set of stacked basement wedges related to low angle thrusts formed during the Andean compression were responsible of the high structural relief (>5 km) and the exposure of Early Jurassic rocks. These wedges transmitted the shortening to the cover producing the folds and thrusts in the thin-skinned central sector. In the eastern sector, the lack of favourable detachment levels in the cover difficulted the development of large basement wedges as in the western sector and instead important back thrusting occurred. Due to further compression the Carrizalito fault cut up to the surface thrusting pre-Jurassic and Mesozoic over Tertiary rocks (see Fig. 8a).

enzo and Dimieri (2005c) considering both thin and thick-skinned deformation, resulting more suitable that reconstruction involving basement rocks. To the east of the Cerro Malo folds, the west-vergent Arroyo Tordillo anticlines (Fig. 4b) have a geometry similar to that of the Lomas Bayas anticline (Fig. 7c), which allows to interpret the Arroyo Tordillo structures as related to backthrusts involving basement rocks (Fig. 11). In this area, the outcrops of Early-Middle Jurassic rocks overlaying the basement are exposed higher than 3 km over the sea level and more than 5 km compared to the regional elevation of the same units in the footwall, below the Vega Grande oil field. In order to explain such basement elevations, a model including a set of stacked basement wedges related to low angle thrusts formed during the Andean compression is proposed (Fig. 11). These wedges have a lower detachment within the basement (~11 km) and an upper detachment along favourable levels in the cover (evaporites of the Tábanos and Auquilco Formations, Fig. 2), constituting basement-involved duplex structures that transmitted their shortenings to the sedimentary cover producing the structures in the central sector. This suggests a close spatial and temporal relationship between thick and thin-skinned deformations.

In the folds zone of the thin-skinned central sector, the Rio Blanco anticline (Fig. 6a) is interpreted as a fault-bend fold (Suppe, 1983) with a lower detachment in the Tábanos Formation (top of the Cuyo Group) and an upper detachment along the shales of the Vaca Muerta Formation, in the Mendoza Group (Fig. 11). The Rio Blanco thrust, responsible of the fault-bend anticline development, branched off from the ramp zone and broke through the forelimb of the anticline thrusting the Mendoza Group over the Diamante Formation that forms the Los Toscales syncline (Fig. 6). When the Rio Blanco thrust propagated toward the surface, the layers in front of the fault were folded and they can be interpreted locally as a trishear fault-propagation fold (Erslev, 1991; Allmendinger, 1998). As the Rio Blanco anticline, the Vega de los Patos anticline (Fig. 6c) can be reconstructed in two stages including an open fault-bend fold that duplicated the Mendoza Group, which afterwards was broken by the fault, increasing the forelimb dips and producing a tight fault-propagation anticline (Fig. 11). However, the same fold geometry was obtained with a kinematic reconstruction that considers a different sequence of events: an early fault-propagation fold that later was transported over an upper flat detachment (Turienzo, 2008). Beyond these interpretations, the important fact is that part of the displacement was transmitted along detachment horizons and produced other structures toward the foreland. Particularly in this region, duplication of the Mendoza Group transferred displacement to an upper detachment placed in the Rayoso Group evaporites, which was consumed by the duplex structures involving the Diamante Formation registered by all Vega Grande oil wells (Fig. 11). The antiformal stacking of these Diamante Formation slices is represented in the surface by the Vega Grande anticline (Fig. 3). The faults that repeated the Diamante Formation, which reached the surface near the YPF.VP.x-1 well affecting the Malargüe Group, were grouped in the Mesón thrust. Subsurface information allows to recognize structures involving the Mendoza Group below the Vega de los Patos anticline, where it is possible to observe the repetition of the Tordillo Formation that formed a duplex structure with lower detachment in the Auquilco Formation and upper detachment in the base of the Vaca Muerta Formation (Fig. 11). Displacement along the upper detachment produced the duplication of the roof of the Mendoza Group (Vaca Muerta, Chachao and Agrio Formations) verified in Vega Grande wells. The displacement linked to this duplication was then responsible of the imbrication affecting the Rayoso Group, detected in the YPF.Ape.x-1 well (Fig. 11), and the marvellously exposed duplex structures related to the Sosneado thrust (Fig. 7b).

The Mesozoic layers affected by thrusts in the central sector were tilted ~15–20° to the west due to the development of the Cordón del Carrizalito anticlinorium in the eastern sector, thus implying an overlap in depth between the sectors with thin and thick-skinned deformation (Fig. 11). Seismic sections and the YPF.VP.x-1 and YPF.APe.x-1 wells allow to interpret backthrusts with very small displacements, which accommodated the deformation in the hanging wall of the Carrizalito fault. The easternmost of these antithetic faults in the basement, formed the west-vergent

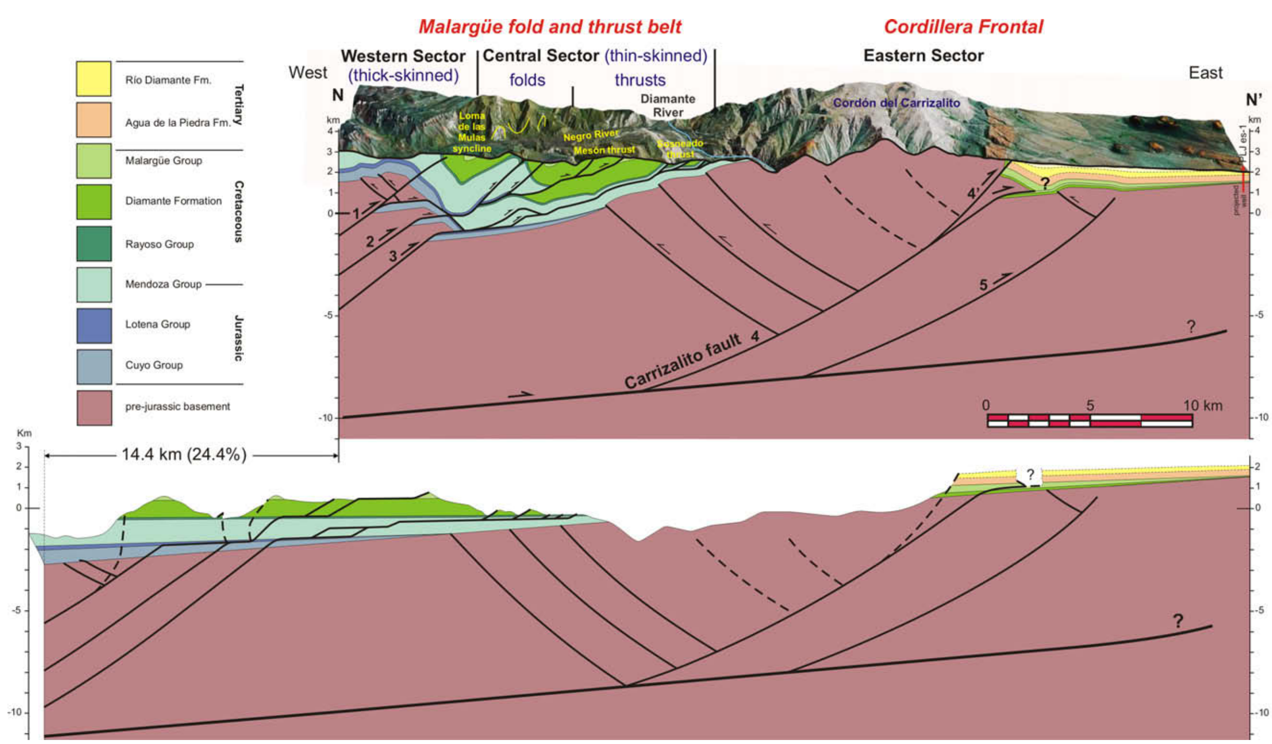

Fig. 12. North balanced cross-section (N–N′), which has the same structural domains than section B (explanation on the text).

Lomas Bayas anticline (Fig. 8c). Kinematics models have been developed (Turienzo and Dimieri, 2005a, 2006; Turienzo 2008) in order to explain the particular geometry of the basement-involved backthrust-related anticlines, which have long, gently-dipping backlimbs and shorter, steeply-dipping forelimbs (Fig. 4b and 8c). The lack of detachment horizons in the cover rocks at the eastern sector, due to its marginal position of the basin, difficulted the development of large basement wedges as in the western sector. On the contrary, deformation of the basement in the eastern sector took place initially by backthrusting. Furthermore, with the continuity of the compression, a branch of the Carrizalito fault cut towards the surface thrusting the basement over the tertiary strata (Fig. 11). The YPF.RD.x-1 well, which went through the basement-cover contact in the footwall of the Carrizalito fault, allows to estimate a vertical offset of ~900 m. The fold geometry observed in the sedimentary layers affected by the Carrizalito fault (Fig. 8a) was interpreted considering diverse models for basement-involved structures and it was concluded that this structure is more accurately explained as a trishear fault-propagation fold with a fault angle of ~40° (Turienzo and Dimieri, 2005b). Finally, if the basement-cover contact in the YPF.PLJ.es.1 is extended to the west with the regional slope, clearly results that the same contact in the YPF.RD.x-1 well it is in a higher position (Fig. 11). This step in the pre-Jurassic rocks, together with the seismic information, allows to interpret the incipient basement-involved structures developed to the east of the Carrizalito fault.

Manceda and Figueroa (1995) made a balanced cross-section of similar length to the central cross-section here introduced, from the west of Vega Grande to the Cerro Negro area, considering a tectonic inversion model that includes low-angle shortcut faults. Shortenings calculated from their Diamante River cross-section are ~18 km (33%) for the basement and 29 km (44%) for the cover. The central balanced cross-section (Fig. 11) allows to calculate a shortening of 14.3 km (24.1%) for both basement and cover rocks. This similar value of contraction is related to the link between thick and thin-skinned structures considered in the interpretation, where all the displacement associated to the basement thrusts that were inserted along sedimentary layers was consumed in the development of the folds and thrusts in the cover rocks.

4.2. North cross-section

This section depicts the continuation of the structural domains described for the central cross-section, although the most noticeable feature is the extraordinary development of the basement structures in the eastern sector (Fig. 12), which constitutes the southern end of the Cordillera Frontal geological province. Interpretation of the structures in this section was constrained by seismic information and field data (and comparison with the well developed structures in the central cross-section); unfortunately there is not well data in this region (Fig. 9). As in the central cross-section, the structure at the western sector is characterized by three stacked basement wedges related to low angle thrusts that were inserted in the sedimentary cover along the evaporites of the Cuyo and Lotena Groups, transmitting their displacement to the cover and thus producing the thin-skinned structures of the central sector (Fig. 12). The structural relief due to these basement wedges in the western sector of the north cross-section is smaller than in the central cross-section, which explains the plunge of the Early-Middle Jurassic Cuyo Group toward the north (Fig. 3). The displacement transferred from the upper and middle wedges to the top of the Cuyo Group generated the fold structures in the central sector (Rio Blanco anticline, Los Toscales syncline and Vega de los Patos anticline), which involved the overlying Mesozoic rocks (Fig. 12). The Loma de las Mulas syncline occurs between the fronts of the basement wedges in the western sector and the backlimb of the Rio Blanco anticline in the central sector. Afterwards, the out-of-sequence Rio Blanco thrust placed the Rio Blanco

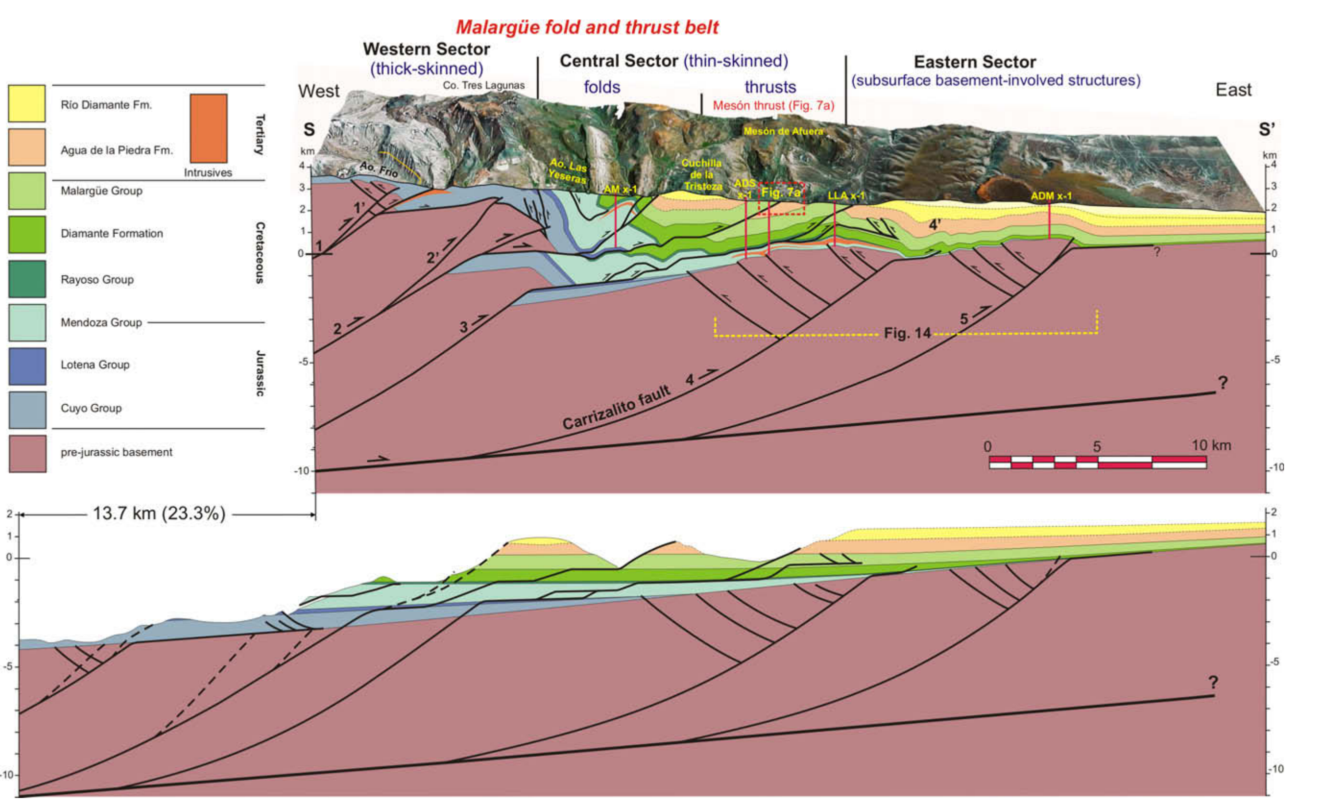

Fig. 13. South balanced cross-section (S–S′). In this section, the basement-involved structures in the eastern sector were interpreted from subsurface information (see Fig. 14).

anticline over the easternmost Vega de los Patos anticline. As it was explained before these anticlines can be considered as primary fault-bend folds, which then were affected by break-through faults that produced locally fault-propagation folding in the overlaying beds. The duplication of the Late Jurassic to Early Cretaceous units (Lotena, Mendoza and Rayoso Groups) transferred displacement to the base of the Late Cretaceous Diamante Formation. This displacement toward the east originated the Mesón thrust (Fig. 3), which produced the imbrication of the Late Cretaceous layers in the thrusts area of the central sector (Fig. 12). The lower basement wedge in the western sector employed the Auquilco Formation as detachment level in the cover and produced a duplex structure in the Tordillo Formation. This duplex structure has an upper detachment along the Vaca Muerta Formation, whose duplication transferred displacement to the east producing the imbrications related to the Sosneado thrust that affected the top of the Mendoza Group and the Rayoso Group nearby the Cerro Mala Dormida (Fig. 3). In the eastern sector, the seismic lines 60021 and 60024 (Fig. 9) show the backlimb of the Cordón del Carrizalito anticlinorium tilted ∼20° to the west, possibly affected by backthrusting as in the central cross-section. In the eastern flank of this range the Carrizalito fault caused the significant uplifts of the basement rocks, which were thrust over Tertiary sediments (Fig. 12).

Northward of the study area, Koslowski et al. (1993) made a regional cross-section covering the Malargüe fold-and-thrust belt and the Cordillera Frontal and they estimated a shortening of ∼20 km. In the region of Las Playas stream, Kim et al. (2005) constructed a balanced cross-section that includes the western and central sectors of the north cross-section presented here. These authors calculated a shortening of 9 km (44%) for the cover rocks and only 1.5 km for the basement. The restored north cross-section (Fig. 12) reveals a shortening of 14.4 km (24.4%) for both basement and cover rocks.

4.3. South cross-section

In this section the basement structures are notably well developed in the western sector while in the eastern sector structures related to the Carrizalito fault remains in the subsurface (Fig. 13), which constitutes the main difference with respect to the central and north cross-sections where pre-Jurassic rocks are outcropping (Figs. 11 and 12). At the west side of this section, the lower levels of the Cuyo Group were uplifted and affected by backthrusts related to an early basement structure (Fig. 13). Initially, a small basement wedge is interpreted moving toward the east along the basement-cover contact producing the imbricated backthrusts that affected the Cuyo and Lotena Groups near the Las Yeseras stream. A branch of the main thrust cut toward the surface folding the Cuyo Group layers and forming the overturned Arroyo Frio anticline (Fig. 3). Between the Frio and Las Yeseras streams, wide exposures of the Cuyo Group beds lie over a second basement wedge (Fig. 13). A branch of the main thrust cut upwards through the top of this second wedge and produced the open Las Yeseras anticline (Fig. 3). The movement of this wedge over the Tábanos Formation generated the duplication of the Mendoza Group (Fig. 13), which subsequently transferred displacement toward the east that was

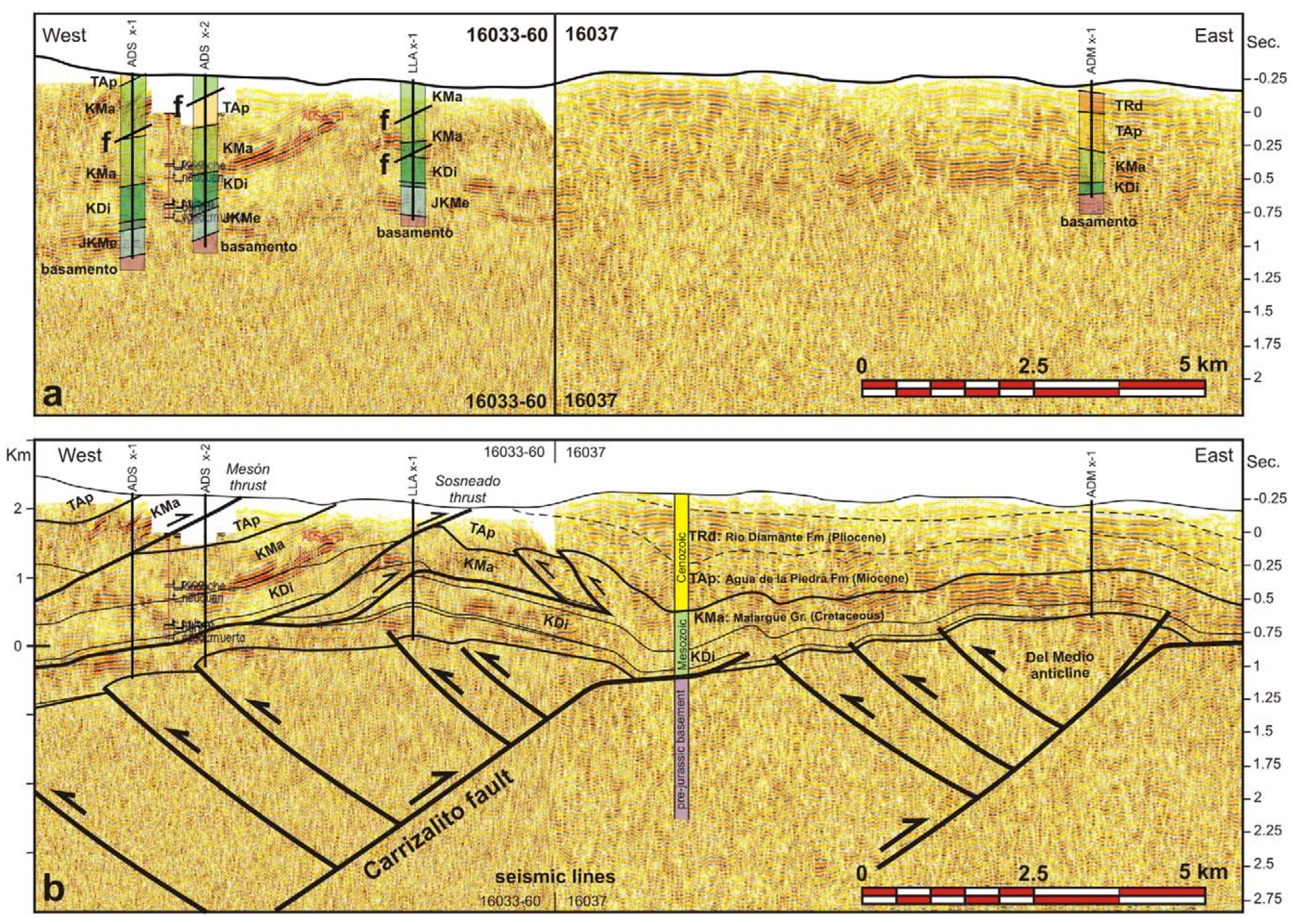

Fig. 14. (a) Un-interpreted seismic lines and oil wells located in the eastern portion of the south cross-section. (b) Interpreted structures from the subsurface data. Below the Mesón and Sosneado thrusts, which affected Mesozoic and Cenozoic rocks, the Carrizalito fault produced an incipient foreland-directed structure involving basement rocks with an important development of backthrusts. Toward the east, in the YPF.ADM.x-1 well, the basement-cover contact is higher than in the undeformed foreland due to the development of a new basement-involved structure named Del Medio anticline.

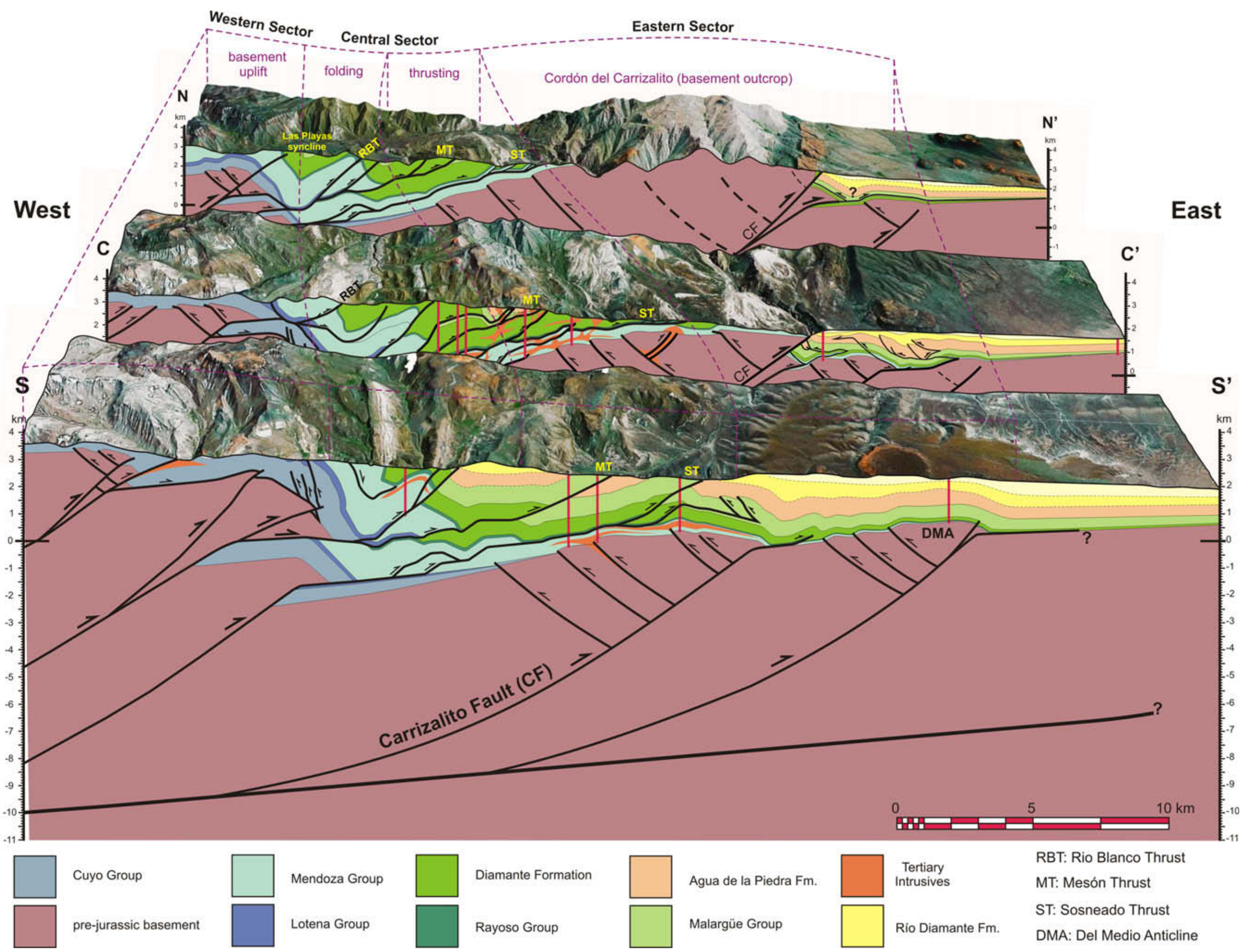

Fig. 15. Perspective view of the three structural cross-sections showing the structural style of this portion of the Andes at the Diamante River area and the along-strike variations of the main structures. The basement-involved structures in the western sector reach the maximum development in the south and decrease progressively to the north thus producing the plunge of the Early Jurassic rocks. The thin-skinned structures in the central sector show continuity from north to south although locally they are exposed affecting distinct sedimentary units due to the differential elevation produced by the thick-skinned structures in depth. In the eastern sector, the Carrizalito fault uplifted the basement rocks in the north and central cross-sections while it remained as a blind thrust in the south cross-section.

consumed by the Mesón thrust to uplift Late Cretaceous over Tertiary rocks (Fig. 7a). As was interpreted in the other cross-sections, an out-of-sequence fault affected the duplicated Mendoza Group producing a fault-propagation fold, the Vega de los Patos anticline, whose development in depth is constrained by the YPF.AM.x-1 well located westward of the Cuchilla de la Tristeza syncline (Fig. 13). A third basement wedge, placed over the Auquilco Formation, produced the duplex structure in the Tordillo Formation below the Vega de los Patos anticline and then the repetition of the Vaca Muerta and Agrio Formations under the Cuchilla de la Tristeza syncline. Following a flat-ramp-flat trajectory this displacement was transferred from the Mendoza to the Rayoso Group, therefore creating the imbrications that disturb the Late Cretaceous rocks (Sosneado thrust) observed in the YPF.LLA.x-1 well and in the seismic line 16033–60 (Fig. 14).

The basement-involved structures of the eastern sector in this cross-section were recognized exclusively by means of subsurface information, which allows to reconstruct the top of the basement affected by backthrusts below the thin-skinned structures associated to the Mesón and Sosneado thrusts (Fig. 14). Thus the different sectors separated in this work to highlight the existence of distinctive structural domains observed in the field, show some overlapping in depth since thick-skinned structures of the eastern sector are developed beneath the thin-skinned thrusts of the central sector (Fig. 13). The backthrust system is well developed despite the displacement along the Carrizalito fault in this section, which remained as a blind thrust, is smaller than in the central and north cross-sections. Several kilometres to the east of the Carrizalito fault, the seismic line 16037 and the YPF.ADM.x-1 oil well show a new basement-involved structure named Del Medio anticline (Fig. 14). The top of the basement in the YPF.ADM.x-1 well is higher than itself in the undeformed foreland, whose elevation is known from the YPF.EJ.es-1 well located to the east out of the study area.

The balance of the south cross-section (Fig. 13) results in a shortening of 13.7 km (23.3%) for both basement and cover rocks. This value agrees reasonably with the shortening at the region of the Atuel River, immediately to the south of the study area (Fig. 1b), estimated as 14.5 km (25%) by Giambiagi et al. (2008a) and as 18 km (24%) according to Fortunatti (2009).

5. Structural variations along strike

A three-dimensional view integrating the balanced cross-sections (Figs. 11–13) allows to compare the changes along strike of thick and thin-skinned structures in the study area (Fig. 15). In order to comprehend particularly the variations of the thick-skinned

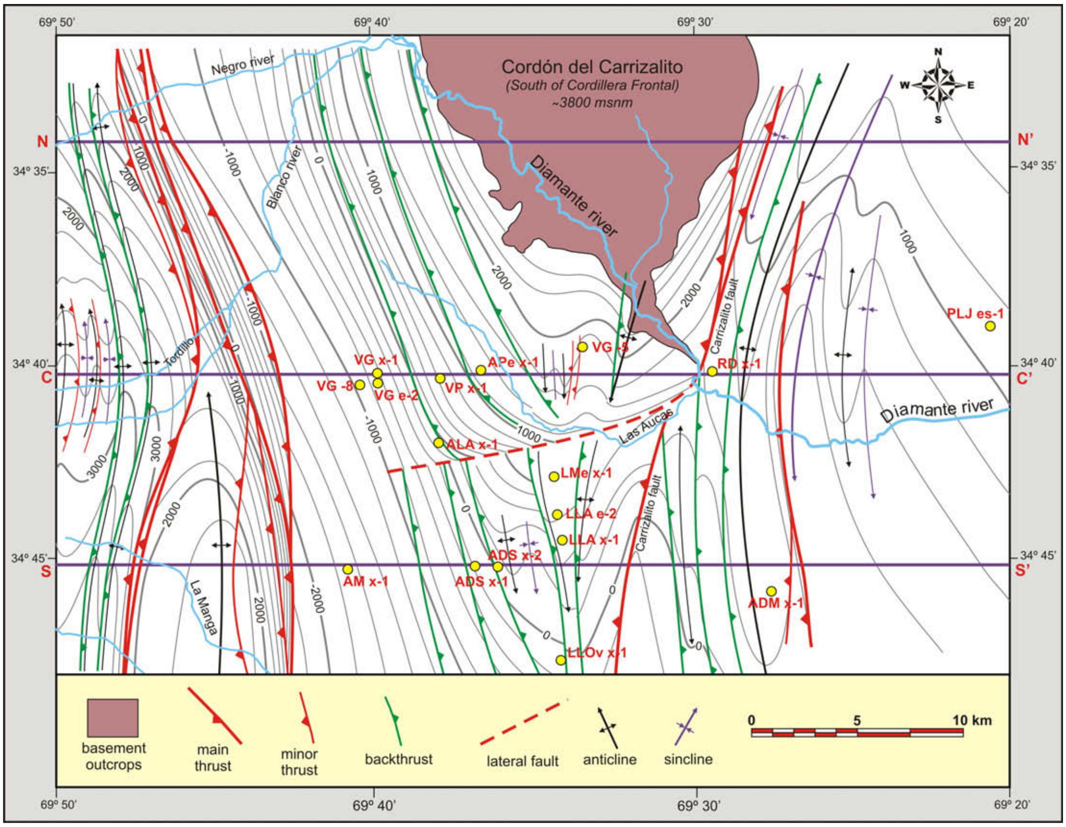

Fig. 16. Structural map constructed at the top of the pre-Jurassic basement, based on well data, seismic interpretation, and interpreted structural cross-sections. Contour interval is 200 m. The large structural relief caused by the stacking of basement wedges in the thick-skinned western sector varies from ~5.4 km in the south cross-section to ~3.1 km in the north cross-section. In the eastern sector, the structural reliefs associated to the Carrizalito fault are 2.7 km, 1.3 km and 0.6 km in the cross-sections north, central and south respectively. An oblique ramp was responsible of the different basement uplift linked to the Carrizalito fault between the central and south cross-sections. In the hanging wall of the Carrizalito fault, backthrust are very common structures in all cross-sections.

structures, a structural map showing the top of the basement was constructed (Fig. 16). This map is based on the depth to the basement from the oil wells in the region (Fig. 9) and it was completed with the aid of the interpreted cross-sections. At the western sector, three major thrusts produced basement wedges, which were inserted in the sedimentary cover along the less competent rocks of the Cuyo and Lotena Groups (Fig. 15). Stacking of these basement wedges was responsible of the large structural reliefs at the western region that vary from ~5.4 km (−2000 m to +3400 m) in the south cross-section to ~3.1 km (−1100 m to +2000 m) in the north cross-section (Fig. 16). The plunge toward the north of the Early-Middle Jurassic rocks and the structures affecting them is a direct consequence of this variation in structural relief associated to the basement wedges. As it was already mentioned the basement structures transferred the shortening to the cover producing the folds in the thin-skinned central sector, involving Late Jurassic and Cretaceous units (Fig. 15). The Rio Blanco anticline, linked to the Rio Blanco thrust, is differentially exposed along its strike. While in the north it was not affected by the basement wedges, in the south it was uplifted and eroded due to a higher and wider thick-skinned western sector. On the other hand, the Vega de los Patos anticline is observed in the surface invariably involving the Huitrín and Diamante Formations (Fig. 3 and 6b) because it was not affected by major basement-involved structures in depth. According to the field observations the Vega de los Patos anticline could be interpreted as a detachment fold above the Huitrin Formation evaporites, but the YPF.AM.x-1 oil well in its backlimb in the south cross-section records that the Mendoza Group is involved in this structure indicating a deeper detachment (Fig. 15). The structures of the folds area transmitted their displacements to the top of Mendoza Group generating fault systems that affected Cretaceous and Tertiary rocks in the thrusts area of the central sector. The most noticeable structures in the thrusts area are the Mesón and Sosneado thrusts, which in the southern region placed Cretaceous over Tertiary strata while in the north zone they are observed involving only Cretaceous units due to the large basement uplift produced by the Carrizalito fault (Fig. 15). The altitude of the basement rocks in the eastern sector varies considerably along strike since they are outcropping ~3800 m in the Cordón del Carrizalito and were found ~400 m in the YPF.LLA.x-1 well (Fig. 16). The structural relief associated to the Carrizalito fault, comparing it with the depth to the basement-cover contact in the footwall, is 2.7 km, 1.3 km and 0.6 km in the north, central and south cross-sections respectively. The N–S trending seismic lines 5110–60, 5111–60 and 5085–60, located between the central and south cross-sections (Fig. 9), show an important step in the top of the basement, which is higher in the north side of these lines. A ~ENE trending zone of faulting is defined connecting the points where this step was observed in the three seismic lines. This feature together with the NE to ENE strike of the beds southward of Lomas Bayas (Figs. 3 and 8b), allows to identify an oblique ramp of the Carrizalito fault that explains the differential basement uplift between the north and south regions (Fig. 16). Backthrusts affecting the basement rocks in the hanging wall of the Carrizalito fault are very common in all cross-sections (Figs. 15 and 16). The fact that these antithetic faults occur even in the south cross-section, where the Carrizalito fault remains as a blind thrust, suggests that the backthrusts were formed before the main displacement along the Carrizalito fault.

The basement and cover shortenings calculated from the balanced cross-sections decrease slightly from north to south

(14.4 km, 14.3 km and 13.7 km). This low variability in the magnitude of shortening indicates that, although the main thick-skinned structures vary considerably along the strike, a differential evolution of these structures in the western and eastern sectors results in a consistent amount of contraction (~14 km or 24%) for this region of the Andes.

6. Age of deformation

It is widely accepted that the Malargüe fold-and-thrust belt has evolved during Miocene-Pliocene times due to the main compressional phases of the Andean orogeny (Ramos, 1988, 1999; Baldauf, 1997; Combina and Nullo, 2005; Silvestro et al., 2005; Giambiagi et al., 2008a). Based on published information about the absolute ages of volcanic and subvolcanic rocks and syntectonic units, the evolution of the structures in the study area showed in the balanced cross-sections (Figs. 11–13) can be constrained approximately between 14.8 Ma and 2 Ma (Turienzo, 2008; Turienzo and Dimieri, 2009). In the region of the Atuel River, immediately to the south of the study area (Fig. 1b), a pre-tectonic subvolcanic rock dated in 14.87 Ma (Giambiagi et al., 2008a) may indicate the beginning of the deformation in the thick-skinned western sector. According to the structural model here proposed, the basement wedges of the western sector were inserted along favourable horizons in the sedimentary cover producing the thin-skinned structures in the central sector. Horizontal basaltic lavas of 9.1–10.8 Ma (Giambiagi et al., 2008a) covering the structures in the western sector indicates that these structures were formed previous to 10.8 Ma. In the central thin-skinned region, the fact that the Sosneado thrust does not cut the Laguna Amarga intrusive (10.5 Ma, Baldauf, 1997) supports the hypothesis that cover deformation is related to the western basement structures and both were completely developed at that time. It represents an important Middle Miocene compressive event since 10 km of strata were shortened in approximately 4 Ma (~2.5 mm/year, Turienzo and Dimieri, 2009). After the high structural relief was formed by basement wedges in the western sector, faulting progressed toward the foreland in agreement with the critical wedge theory (Davis et al., 1983) and a normal sequence of thrust propagation (Turienzo, 2008). Formation of basement-involved structures in the eastern sector, including the Carrizalito fault and its associated backthrusts, took place before the deposition of the horizontal basalts that cover the folded layers originated by the Carrizalito fault in the Diamante River (Figs. 3 and 8). These basalts were mapped as the Paleopleistocene Volcanic Association (Sruoga et al., 2005) and subsequently the deformation of the eastern sector was considered older than ~2 Ma (Turienzo and Dimieri, 2009), but recent studies about the Quaternary history of the Diamante River valley assigned these rocks to the Middle Pleistocene (~0.5 Ma, Barker et al., 2009). Thus, the ~4 km of shortening of the eastern sector between approximately 10.8 Ma and 0.5 Ma (rate of ~0.4 mm/year) suggests that Andean contraction diminished during the Late Miocene to Pliocene–Pleistocene times (Turienzo, 2008; Turienzo and Dimieri, 2009).

7. Discussion

Large exposures of basement rocks in many places of the Cordillera Principal allow to recognize a strong linkage between thick and thin-skinned deformation produced during the Andean orogeny. Different structural models have been proposed in order to explain the observed structures, being noticeable two idealized end members: inversion and non-inversion models. Inversion tectonic models imply that the structural configuration of this region was controlled by the Cenozoic reactivation of pre-existing Mesozoic normal faults (Manceda and Figueroa, 1995; Broens and Pereira, 2005; Giambiagi et al., 2005a, 2008a; Kim et al., 2005; Fuentes and Ramos, 2008). In the region of the Atuel River, southward of the study area (Fig. 1), the architecture and paleogeographical conditions of the Atuel depocenter was interpreted based on detailed stratigraphic studies of the Late Triassic–Early Jurassic sediments (Lanés 2005; Lanés et al., 2008). Structural analysis at regional scale (Manceda and Figueroa, 1995; Giambiagi et al., 2005b, 2008b) and mesoscale (Bechis et al., 2009), support extensional processes that explain the kinematic evolution of the Mesozoic rift in this sector of the Neuquén basin. Important thickness variations and studies of sediment provenience in the Tordillo Formation (Kimmeridgian) suggest extension and faulting even during the Late Jurassic (Mescua et al., 2008). As is expectable, all the Mesozoic normal faults constitute weakness zones able to be reactivated. An important question arise after this analysis: How much inversion of normal faults is possible? Numerous analogue studies examine the development of rift systems and the subsequent inversion under compressive stresses (McClay, 1989; Brun and Nalpas, 1996; Dubois et al., 2002; Yamada and McClay, 2004; Panien et al., 2005; Marques and Nogueira, 2008; Yagupsky et al., 2008). Contractional reactivation of extensional faults puts progressively older synrift strata into net contraction, and the point of change from net extension to net contraction is the null point (Williams et al., 1989). Most of these experimental works show that total inversion has occurred if the null point is at the base of the synrift sequence and the prerift layers have regained their pre-deformational regional elevation (Williams et al., 1989; Yamada and McClay, 2004). Larger movement along the pre-existing high-angle normal faults could occur if the friction on the fault surface is notably reduced (Marques and Nogueira, 2008) but commonly, with high values of shortening, low-angle shortcut faults develop in the footwall to accommodate the major horizontal displacements (McClay, 1989). One of the most important factors controlling the reactivation is the orientation of the previous normal faults that compose the rift respect to the compressive stress (Brun and Nalpas, 1996; Dubois et al., 2002; Panien et al., 2005; Yagupsky et al., 2008). Sandbox experiments were made to simulate the actual structural configuration in the southern part of the Malargüe fold-and-thrust, where the Late Triassic–Early Jurassic NW–SE trending rift is oblique to the ~W–E direction of the Andean shortening (Yagupsky et al., 2008). The results of these experiments show that, although in most cases the normal master faults are not reactivated, the contractional strain is initially accommodated by the reactivation of pre-existing half-graben segment closest to the deformation front while at some critical distance the deformation front departs from the half-graben control and becomes normal to the shortening direction (~N–S).

On the other hand, non-inversion models consider a structural configuration dominated by low-angle reverse faults (thrusts) formed during the Andean compression, where first order or basement structures transferred their shortenings along detachment horizons in the cover to produce second order structures (Gerth, 1931; Gorroño et al., 1984; Dimieri, 1992; Manceda et al., 1992; Dimieri and Nullo, 1993; Mingramm et al., 1993; Koslowski et al., 1993, 1996; Rojas and Radic, 2002; Turienzo and Dimieri, 2005c; Dicarlo and Cristallini, 2007; Turienzo, 2008; Fortunatti, 2009). Some of these first order basement-involved structures in several places of the Cordillera Principal have been interpreted as large basement wedges (Dimieri, 1992, 1997; Fortunatti and Dimieri, 2002, 2005; Dimieri et al., 2005; Turienzo and Dimieri, 2005c) or as large-scale fault-bend folds (Koslowski et al., 1996; Rojas and Radic, 2002). The N–S trending thrusts are in agreement with the Andean tectonic framework and these allow to produce significant amounts of horizontal shortenings subsequently generating most of the structures observed in the cover rocks. A simple trigonometric analysis illustrate that to produce shortenings as those registered in the Malargüe fold-and-thrust belt, the ~60° dipping normal faults are not as effective as the ~30° dipping thrusts, concluding that the inversion of normal faults should not be considered the main process contributing to the mountain building during the Andean orogeny (Dimieri et al., 1997).

From the precedent discussion is clear that both inversion of previous normal faults and new formed thrusts are mechanisms occurring in the development of the Malargüe fold-and-thrust belt (Manceda and Figueroa, 1995; Rojas and Radic, 2002; Giambiagi et al., 2008b; Giambiagi et al., 2008c; Yagupsky et al., 2008), although they contribute differentially to accommodate the Andean shortenings. An estimation based on regional balanced cross-sections from the southern part of the Malargüe fold-and-thrust belt suggests that ~30% of shortening took place by inversion while ~70% occurred along new low-angle faults (Giambiagi et al., 2008c). In the study carried out in this paper, despite of a partial reactivation of previous normal faults may have occurred in the western sector generating some of the folds affecting the Cuyo Group, clear evidences indicating tectonic inversion were not recognized. The large structural relief at the thick-skinned sector of the Malargüe fold-and-thrust belt, where the basement was uplifted several kilometres from its regional position (Figs. 15 and 16), is unlikely to be produced along inverted faults; on the contrary is more probably to consider it generated by new low-angle faults. In the interpretations here developed such elevation is attained by stacking of three thrust-related basement wedges, each one transmitting displacement to the cover to generate the structures in the thin-skinned sector. A similar model of stacked basement structures was proposed for the southern region of the Malargüe fold-and-thrust belt, out of the study area, where the YPF.BaB.x-1 oil well cuts trough several slices of the Choiyoi Group (Manceda et al., 1992). Since in the interpreted cross-sections all the structures developed in the cover are related to displacements transferred from the basement, the calculated shortenings are equivalent for the basement and cover (~24%). This value of contraction agrees reasonably with the shortenings of 24% (Dimieri, 1992), 25% (Giambiagi et al., 2008b), 24% (Fortunatti 2009), calculated from balanced cross-sections in other regions of the Malargüe fold-and-thrust belt.

8. Conclusions

The structural style of this portion of the Andes at the Diamante River region is characterized by thick-skinned deformation in the western and eastern sectors surrounding a central sector with thin-skinned deformation. The western thick-skinned and central thin-skinned sectors constitute the Malargüe fold-and-thrust belt while the basement-involved eastern sector corresponds to the southern part of the Cordillera Frontal. To the west, three basement wedges related to thrust faults developed during Andean compression were stacked producing a high structural relief that decreases progressively from south to north. These wedges have propagated into the sedimentary cover along favourable detachment horizons transferring the shortening to the cover rocks and producing the thin-skinned structures, therefore implying a close spatial and temporal relationship between basement and cover deformation. In the central thin-skinned sector, shales and evaporites prevail at the west facilitating the development of folds, while toward the east the units are more competent and formed duplex and imbrications. According to a normal sequence of thrust propagation, further compression generated the Carrizalito fault and other structures in the eastern thick-skinned sector. The lack of detachment levels in the cover of this sector made the development of large basement wedges more difficult than in the western sector and instead important backthrusting occurred. Afterwards, the Carrizalito fault broke through to the surface, as seen in the central and north cross-sections, uplifting pre-Jurassic and Mesozoic rocks over Tertiary synorogenic sediments while in the southern cross-section it remained a blind thrust. An oblique ramp of the Carrizalito fault located to the south of the central cross-section was responsible for the differential elevation of basement rocks in the northern region with respect to the south. Subsurface recognition of basement-involved structures in the eastern sector of the south cross-section demonstrates that the structures affecting the southern segment of the Cordillera Frontal near the Diamante river valley are also developed below the thin-skinned zone of the Malargüe fold-and-thrust belt. Thus, it is possible that the Malargüe fold-and-thrust belt and the Cordillera Frontal were structurally linked during the Andean orogeny constituting large basement uplifts with different developments along strike.

The structural development in this part of the Andes took place from Middle Miocene to Pliocene–Pleistocene, with an important Middle Miocene compressive event that generated the structures of the western and central sectors. The thrusts have propagated from basement to cover and within the cover from the fold zone to the thrust zone following a staircase trajectory. Thus the large displacements of the main faults were progressively consumed by several structures in the cover and the total basement and cover shortenings are equivalent. The calculated shortenings are 14.4 km (24.4%), 14.3 km (24.1%) and 13.7 km (23.3%) for the north, central and south cross-sections respectively, which indicate that, although the main thick-skinned structures varied considerably along the strike, the differential evolution of these structures in the western and eastern sectors resulted in a consistent amount of contraction for this sector of the Andes.

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