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The control of pre-existing extensional structures on the evolution of the southern sector of the Aconcagua fold and thrust belt, southern Andes

Laura B. Giambiagi[a,b,*], P. Pamela Alvarez[a,1], Estanislao Godoy[c,2], Victor A. Ramos[a,1]

[a] *Laboratorio de Tectónica Andina, Universidad de Buenos Aires, Ciudad Universitaria s/n, Pabellón II, 1428 Capital Federal, Argentina*
[b] *Centro Regional de Investigaciones Científicas y Tecnológicas, Parque San Martín s/n, 5500 Mendoza, Argentina*
[c] *Servicio Nacional de Geología y Minería. Casilla 10465, Santiago, Chile*

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Abstract

The Aconcagua fold and thrust belt, located in the Andean mountains at 32°30′ to 34°S, has been described as a classic model of a thin-skinned thrust belt. However, new structural data from its southern sector have shown that it has a complex structural framework reflected in multiple Mesozoic extensional phases, overprinted by structural inversion, as well as thin- and thick-skinned tectonics.

Two major superimposed extensional structural styles have been identified for the Mesozoic characterized by distinctly oriented stress fields. A key role in the evolution of this part of the fold and thrust belt was played by a Late Triassic to Early Jurassic depocentre and by Late Jurassic block faulting.

Shortening was accommodated by a combination of inversion of pre-existing normal faults, development of footwall short cuts and both thin and thick-skinned thrusting. Synrift and postrift sedimentary rocks were uplifted by reactivation of normal faults, with further shortening along newly formed thin-skinned thrust faults. The geometry of thin-skinned fault systems is controlled by the architecture of the rift basin, competent footwalls forming barriers to the lateral propagation of detachments.

Keywords: Andes; Structural evolution; Pre-existing structures; Jurassic rift system; Neogene compression

1. Introduction

The Andes shows a remarkable along-strike variation in the patterns of deformation controlled by paleogeographic setting and intracrustal inhomogeneities (Jordan et al., 1983; Mpodozis and Ramos, 1989; Kley et al., 1996). Not all studies, however, address the question of how the inherited structure has influenced Late Cenozoic structural evolution.

* Corresponding author. Centro Regional de Investigaciones Científicas y Tecnológicas, Parque San Martín s/n, 5500 Mendoza, Argentina. Fax: +54-11-45763329, +54-261-4287029.

E-mail addresses: lgiambia@lab.cricyt.edu.ar, andes@gl.fcen.uba.ar (L.B. Giambiagi), andes@gl.fcen.uba.ar (P.P. Alvarez), egodoy@sernageomin.cl (E. Godoy), andes@gl.fcen.uba.ar (V.A. Ramos).

[1] Fax: +54-11-45763329.

[2] Fax: +56-2-7380235.

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The Aconcagua fold and thrust belt, located between 32°30′ and 34°S, is a classic example of an Andean thin-skinned belt (Ramos, 1988; Kozlowski et al., 1993; Cegarra and Ramos, 1996; Ramos et al., 1996). Several authors point out that Middle to Upper Jurassic marine units were deposited on top of a Permo–Triassic volcanic unbroken peneplain and therefore an Early Jurassic rift system is excluded (Yrigoyen, 1972; Ramos, 1985; Cegarra et al., 1993; Lo Forte, 1996). However, in recent years, growing evidence has been found for the presence of Early Jurassic rift sequences (Alvarez et al., 1997; Alvarez and Ramos, 1999) and the control of pre-existing extensional structures in the development of the fold and thrust belt (Godoy, 1993, 1998; Giambiagi and Ramos, 2002).

In this contribution, we analyse the sector of the Andes comprised in the southern half of this belt, between 33°30′ and 33°45′S (Fig. 1), which includes the northernmost part of the Mesozoic Neuquén basin. The development of the fold and thrust belt is controlled by the pre-existing basin geometry. Based on the analysis of the architecture of both this basin and the Andean structures, the complex relationships between thin-skinned thrusting and basin inversion are evaluated. The paper will also attempt to relate the extensional feature and the geometric pattern of two successive and superposed no coaxial extensional

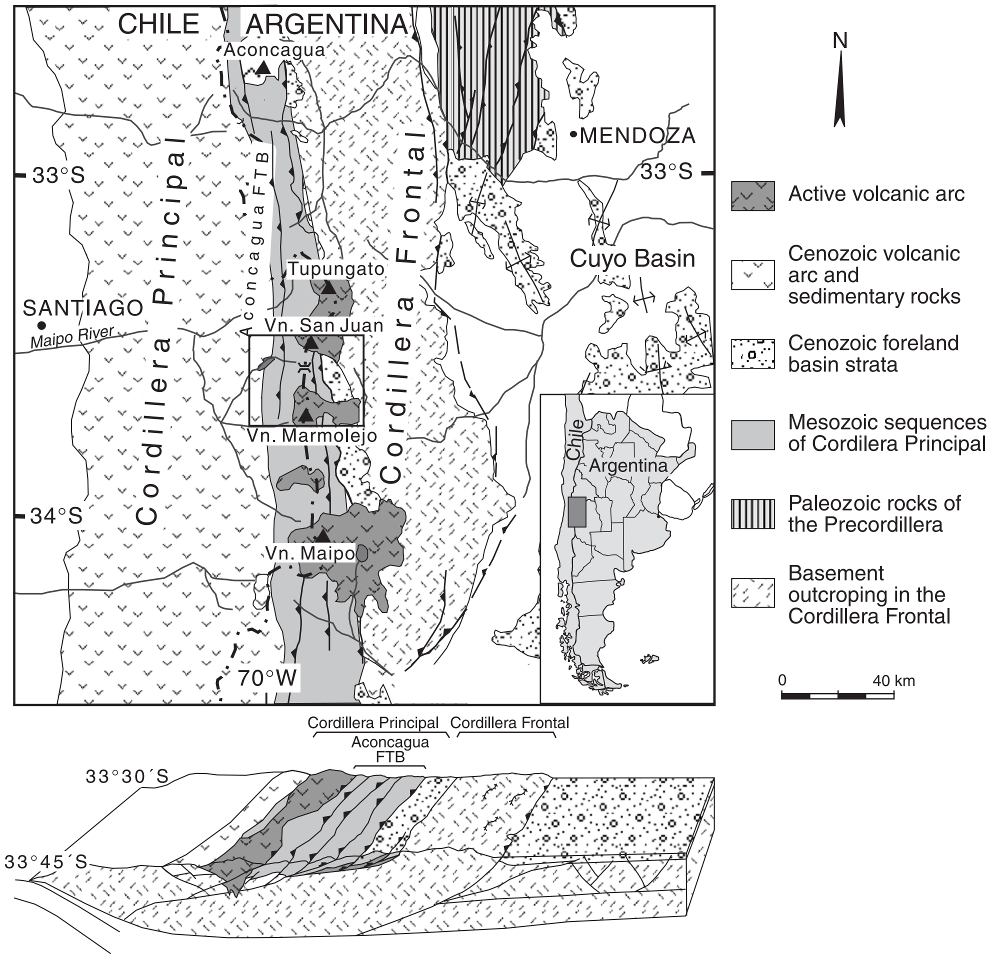

Fig. 1. Morphostructural map of the Andes between 32° and 35°S and 3D block between 33°30′ and 33°45′S (modified from Giambiagi and Ramos, 2002). Frame indicates location of the study area and Fig. 4.

systems and propose a model for the Mesozoic extension.

2. Geological setting

During the Mesozoic and Cenozoic, the subduction regime along the western margin of southern South America and the Mid-Atlantic spreading rates along its eastern margin provided the first-order controls on subsidence and uplift in the area, defining its tectonic evolution (Uliana and Biddle, 1988). During the Mesozoic, the western margin was marked by an active trench, a relatively narrow magmatic arc and a series of retro-arc extensional basins (Legarreta and Uliana, 1991). The most important of these basins is known as the Neuquén basin, characterized by NNW-trending depocentres implanted on pre-Jurassic continental crust. The northernmost exposures extend into the Mendoza province, up to 33°30′S, where the study area is located.

The Neuquén basin has a complex structural framework. It was first affected by NE–SW extension in the Triassic–Early Jurassic and later, according to Vergani et al. (1995), by NW–SE extension related to Late Jurassic–Cretaceous fragmentation of western Gondwana and opening of the Atlantic Ocean. In the northernmost part of this basin, two rifting episodes are recognized, one in the Late Triassic to Early Jurassic and the other in the Late Jurassic.

2.1. Pre-Jurassic basement

The Cordillera Frontal, east of the Cordillera Principal, exposes the basement of the Aconcagua fold and thrust belt (Fig. 1). Precambrian metamorphic rocks are unconformably covered by Upper Paleozoic marine black shales (Fig. 2). These units are intruded by Carboniferous and Permian granitoids (Polanski, 1964). In Late Permian–Early Triassic times, a widespread compressive event, locally known as the San Rafael orogeny (Caminos, 1979), deformed these units and generated a 500-km-wide orogenic belt (Llambias and Sato, 1990). Permian–Triassic intermediate and acid volcanic rocks of the Choiyoi Group unconformably overlie the previously deformed rocks. This group has been divided in two sections. The lower one was related to subduction and orogenesis, while the upper section associated with lower rates of subduction was dominated by crustal thickening followed by generalized collapse (Llambias and Sato, 1990; Mpodozis and Kay, 1990; Uliana and Legarreta, 1993).

2.2. Late Triassic–Early Jurassic synrift phase

In Late Triassic–Early Jurassic times, central western Argentina and eastern Chile underwent an extensional tectonic process (Digregorio et al., 1984; Legarreta and Uliana, 1991). The peripheral development of rift systems in southern South America was controlled by ancient major crustal boundaries among previously amalgamated terranes (Ramos et al., 1986; Ramos and Kay, 1991). The extensional basins have an overall NNW–SSE trend developed along pre-Triassic basement structures, linked by NE–SW trending accommodation zones. A series of rift systems were formed during this time along the western margin of Gondwana, with a strong tectonic control on deposition (Fig. 3) (Charrier, 1979; Uliana and Biddle, 1988).

In the Neuquén basin, the rift system began in the Late Triassic. Continental clastic rocks were deposited in isolated depressions throughout the Jurassic in what is now the Cordillera Principal (Gulisano, 1981; Uliana and Biddle, 1988; Legarreta and Gulisano, 1989). Examples of these depocentres are the Mercedario rift in the La Ramada basin (Alvarez and Ramos, 1999) and the La Valenciana–Río Atuel in the Neuquén basin (Fig. 3). In the Alvarado, Nieves Negras and Yeguas Muertas depocentres, located at the study latitude, rifting may have also begun in the Late Triassic, though field evidence is lacking (Alvarez et al., 2000). The paleogeographic reconstruction at the Early–Middle Jurassic shows that these basins were separated by an important topographic high named Alto del Tigre (Groeber, 1951) (Fig. 3).

2.3. Early?–Middle Jurassic postrift period

According to Gulisano and Gutierrez Pleimling (1994), a regional subsidence process began during the Bajocian in the Neuquén basin. This sag phase is reflected in the study area by the deposition of Early?–Middle Jurassic black shales outcropping in

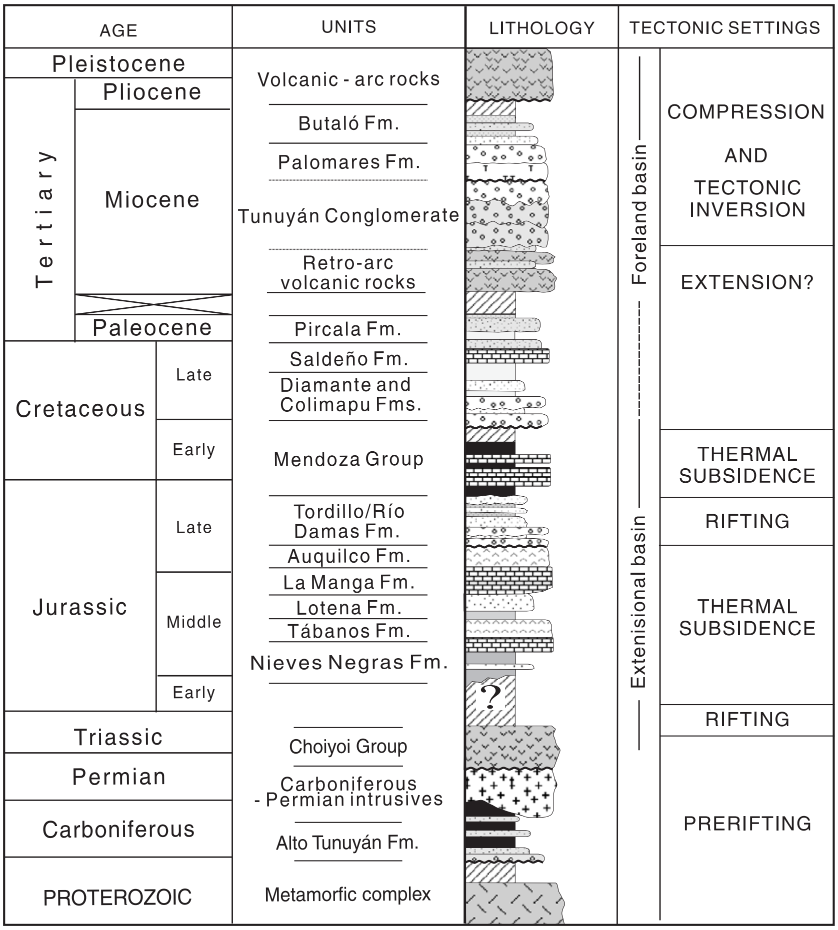

Fig. 2. Generalized stratigraphic column and tectonic settings of the outcropping units of the Cordillera Principal and Cordillera Frontal between 33°30′ and 33°45′S.

the western sector of the belt, in the Yeguas Muertas anticline: the Nieves Negras Formation (Figs. 4 and 5) (Alvarez et al., 1997). This unit is characterized by black shales, first interbedded with fine and medium sandstones and then with both thin and nodular mudstones. Because its base is not exposed, the total thickness is unknown, although its minimum thickness is 450 m. Late Bathonian to Early Callovian ammonite faunas corresponding to the Steinmanni Zone were found in these layers. Sedimentological characteristics of these beds together with the absence of benthonic fauna are indicative of a hostile turbiditic environment (Alvarez et al., 1997).

During the Middle and Late Callovian, the basin was completely desiccated due to a rapid relative sea level fall (Gulisano and Gutierrez Pleimling, 1994). Some tens of metres of evaporites, referred to as the Tábanos Formation, and red beds of the Lotena Formation (Fig. 5) were deposited. Locally, this cycle is interpreted as a minor extensional event in the High Andes (Alvarez et al., 1999).

The Oxfordian–Early Kimmeridgian is represented by marine platform limestones (La Manga Formation) and extensive evaporites (Auquilco Formation) (Alvarez et al., 1999).

2.4. Late Jurassic synrift period

During most of the Jurassic and Cretaceous, the tectonic development of the western side of this

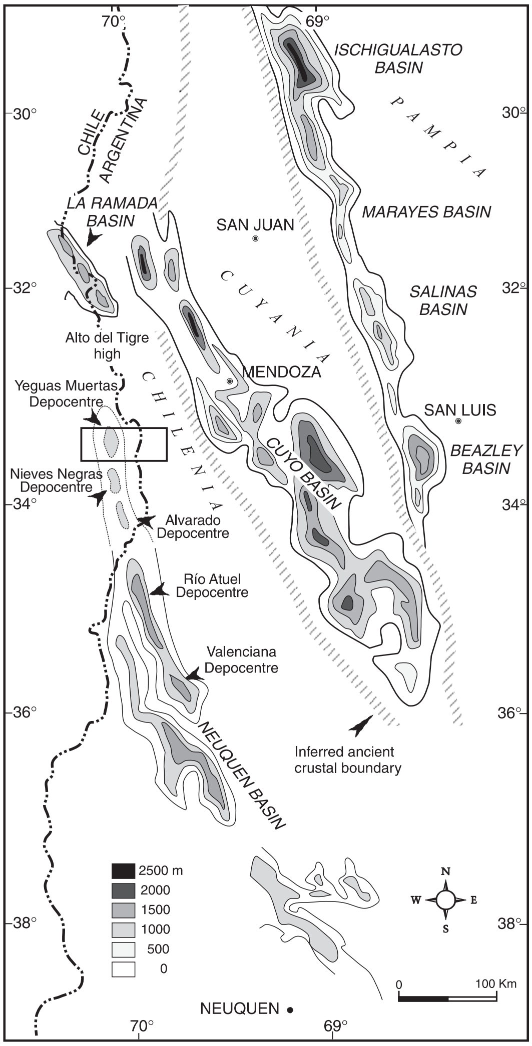

Fig. 3. Triassic–Jurassic rift systems, between 31°30′ and 38°30′S, showing the Yeguas Muertas, Nieves Negras, Alvarado and Río Atuel–La Valenciana depocentres of the Neuquén basin (modified from Alvarez and Ramos, 1999). Location of the study area is shown by frame.

portion of South America was controlled by a subduction regime along the Pacific margin and the opening of the South Atlantic Ocean, which created a major reorganization of the extensional stress field (Vergani et al., 1995). During the Jurassic, the magmatic arc along the Pacific margin is characterized by thick bimodal, submarine volcanics locally metamorphosed by syntectonically emplaced granitoids (Rivano and Sepúlveda, 1986; Rivano et al., 1993). This Late Jurassic magmatic arc co-existed with widespread extension (Charrier, 1984; Mpodozis, 1984).

Although it is generally argued that, from Late Jurassic onwards, the Neuquén basin sedimentary rocks are not associated with faulting in the northernmost extension of this basin, several lines of evidence suggest that thick sequences of red conglomerates, sandstones and shales of the Tordillo Formation were deposited in half-grabens (Figs. 6 and 7). Thickness of these continental sequences is highly variable, between 50 m to more than 1000 m in a 2-km-long area, well shown in a reconstruction of the rift geometry. In the Chilean slope, this unit has been correlated with the Río Damas Formation, composed by thick coarse sediments and lavas (Klohn, 1960; Thiele, 1980). As stated before, Late Jurassic sedimentation and volcanism are widespread toward the west, implying an expanded Early Jurassic extensional framework.

2.5. Late Jurassic–Early Cretaceous postrift period

In the High Andes of Argentina and Chile, especially south of the Aconcagua peak, after deposition of the Tordillo Formation, the Mendoza Group represents flooding of the basin related to a new thermal subsidence during the Early Tithonian–Neocomian. This subsidence is also reflected in northward crustal attenuation during the Neocomian, as recorded by the geochemical signature of retro-arc basaltic andesites of that age along the western margin of the Valenciana depocentre (Vergara and Nyström, 1996). The Mendoza Group consists of three lithostratigraphic units: fetid black shales bearing levels of calcareous nodules with abundant nektonic fauna, mostly ammonites, fishes, marine reptiles and lacking benthonic organisms: the Vaca Muerta Formation, corresponding to offshore-basinal environment. This unit is followed by bioturbated packstones of big oysters, first interbedded with wackestones and then forming amalgamated, up to 4 m thick beds: the Chachao and Agrio Formations. These sequences represent a shallow platform environment (Aguirre-Urreta, 1996; Aguirre-Urreta and Alvarez, 1998).

2.6. Compressional period

Another major plate tectonic reorganization took place by the end of the Early Cretaceous (Somoza,

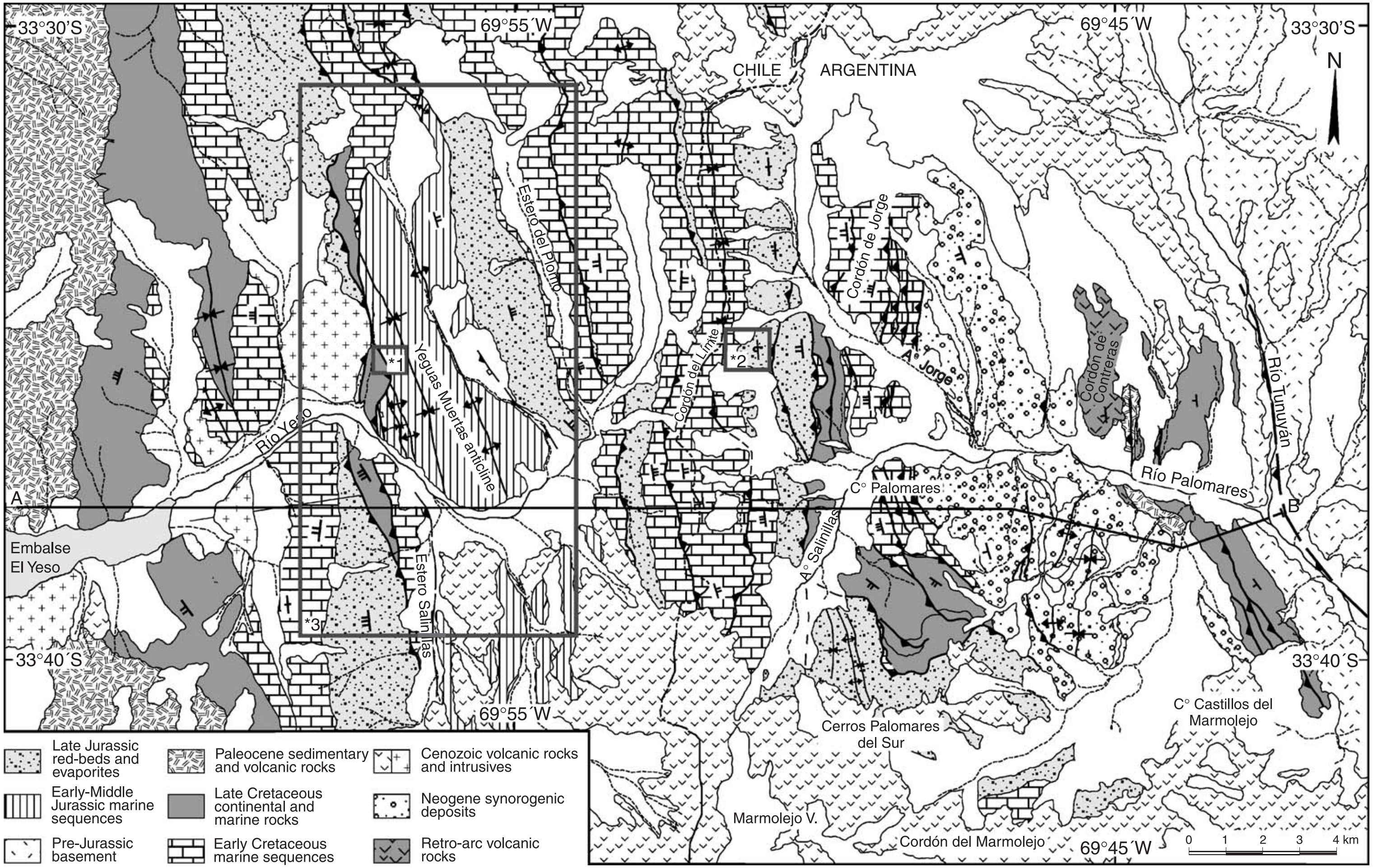

Fig. 4. Generalized geological map of the Aconcagua fold and thrust belt in the Yeso and Palomares rivers area. For section A–B see Fig. 7. (*1) Location of Fig. 5. (*2) Location of Fig. 6. (*3) Location of Fig. 8.

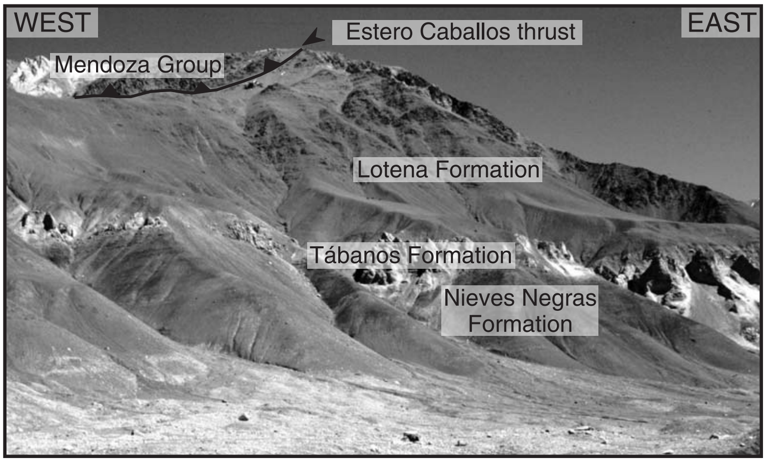

Fig. 5. Northward view of the Middle Jurassic units in the western limb of the Yeguas Muertas Anticline area. See Fig. 4 for location. Note the younger-over-older relationship of the Estero Caballos thrust putting the Cretaceous Mendoza Group over the Middle Jurassic strata.

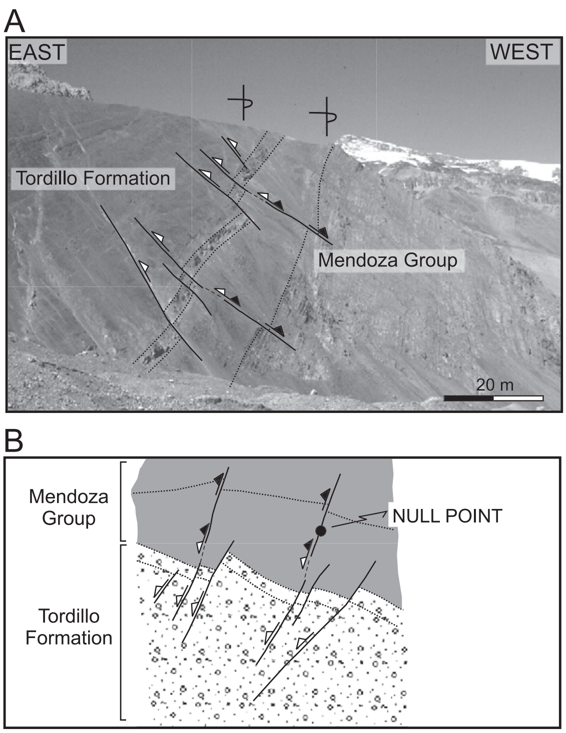

Fig. 6. (A) Overturned Tordillo Formation red beds and Mendoza Group limestones in the Cordón del Límite (international boundary). See Fig. 4 for location. (B) Restoration and interpretation of the view A: normal faults controlled the sedimentation of the red beds, and two of them are inverted with a null point along the fault profile in which there is no net offset of beds.

1998), as a consequence of which the extensional regime of the marine intra-arc and retro-arc basins ended (Mpodozis and Ramos, 1989). Red beds and volcanics of the Early to Late Cretaceous Colimapu and Diamante Formations, which overlie the Mendoza Group, were followed by siltstones and carbonates deposited during the Late Cretaceous first Atlantic ingression (Saldeño Formation) (Tunik, 2001), and by continental sediments of the Paleocene Pircala Formation (Fig. 2).

Compressive tectonics along segments of the Andean belt started in the Late Cretaceous (Mpodozis and Ramos, 1989). There is, however, no evidence of this early compression in the study area; where shortening started during the Early to Middle Miocene. This age is supported by: (1) the retro-arc geochemical signature of the Early Miocene Contreras Formation, located at the base of the synorogenic deposits, which suggests magma generation prior to crustal thickening (Ramos et al., 1996) and the beginning of thrusting in the Cordillera Principal at these latitudes (Giambiagi and Ramos, 2002); (2) the onset of higher exhumation rates in the magmatic arc, as recorded in the La Obra Pluton (Kurtz et al., 1997); and (3) the Late Miocene age of the youngest rocks involved in inversion of an Oligocene to Early Miocene intra-arc extensional basin (Godoy et al., 1999).

Synorogenic sediments filling a foreland basin located eastward from the fold and thrust belt (Fig. 4) are represented by three Middle to Late Miocene units, which record the uplift and eastern migration of the Andean thrust front (Giambiagi, 1999; Giambiagi et al., 2001). Pliocene to Quaternary volcanic rocks from the Marmolejo and San Juan volcanic complexes, on the other hand, unconformably overlie the Miocene synorogenic deposits.

3. Structure

Cenozoic compressional deformation and its relation to the pre-existing extensional structures were studied by detailed structural mapping of the area. A structural cross-section (A–B, Fig. 7) was constructed across the Andes to enable the study of the kinematic history of the belt and illustrate the combination of deformational styles across strike.

The southern sector of the Aconcagua fold and thrust belt has been divided into three structural domains (Fig. 7). In the eastern domain, a dense array of imbricate thin-skinned thrust units overlie decollements located in Upper Jurassic evaporites of the Auquilco Formation or in Vaca Muerta Formation black-shales (base of the Mendoza Group). The dip of the basement-cover interface is 20°W as the result of later tilting of the Cordillera Frontal block. Toward the west, in the Cordón del Límite and Yeguas Muertas Anticline areas (Fig. 4), surface data document thick and thin-skinned structural interactions. The area was interpreted as a frontal basement wedge because of the presence of a broad anticline and associated back-thrusts, and constitutes a basement-involved thrust complex. This intermediate area is dominated by thin as well as thick-skinned east- and west-verging structures, which according to our model are superimposed on a Mesozoic extensional tectonic framework. The western domain is represented by a series of thin-skinned out-of-sequences thrusts; such as Chacayal and Esteros Caballos thrusts which cut the previously developed Yeguas Muertas anticline.

Four contrasting styles of deformation are recognized to have developed in this sector of the Aconcagua belt since the Early Mesozoic: (1) extensional deformation, (2) thin-skinned contractional deformation, (3) tectonic inversion and (4) basement-involved contractional deformation without inversion.

3.1. Extensional deformation

The Mesozoic extensional system of the Neuquén basin has experienced two main phases of rifting and consists of several groups of linked faults with different orientations (Manceda and Figueroa, 1995; Vergani et al., 1995). In the study area, the northernmost depocentre of this basin, the Yeguas Muertas depocentre (Fig. 3) (Alvarez et al., 2000), accounts for the tectonic inheritance of the Late Triassic–Early Jurassic extensional structures.

The Late Jurassic rifting event is believed to overprint and to some extent reactivate earlier rift structures. A NNW–SSE Late Triassic–Early Jurassic trend and a N–S Late Jurassic trend are observed for the Mesozoic extensional events. Although little can be known about the Late Triassic–Early Jurassic rift system because no subsurface data exist and exposures are few, rift stratigraphy, specially thickness variations in strata of this age and their structural relationships, provides evidence for normal faulting. At depth, six major high-angle faults have been assumed (Fig. 7). We propose that faults numbered 1 to 3 are related to the Late Triassic–Early Jurassic rift system; while faults 4 to 6 are developed during the Late Jurassic. The first three faults define a narrow depression running diagonally (NNW–SSE) across the Andes. Fault 1 is now an antithetic east-dipping structure preserved at the surface in the western flank of the Yeguas Muertas anticline near the Yeso River (Fig. 8). South and north of this point, the fault is cut by the thin-skinned out-of-sequence Estero Caballos thrust. The difference in thickness of the Upper Jurassic beds between the Yeguas Muertas anticline and the adjacent zone toward the east amounts at least 200 m. This variation can be explained by a NNW-trending pre-thrusting normal fault (Fault 2). This normal fault also accounts for the location of a frontal ramp of the Piuquenes thrust (Fig. 7). Fault 3 is inferred by the thickness variation of the Upper Jurassic strata.

The thickness of the Upper Jurassic strata changes abruptly from 450 m in the sheet uplifted by the Morado thrust to less than 50 m in the eastern thrust sheets. This indicates the presence of Fault 4. The westernmost thrust of the study area, the Chacayal thrust, places the thickest sheet of the Tordillo For-

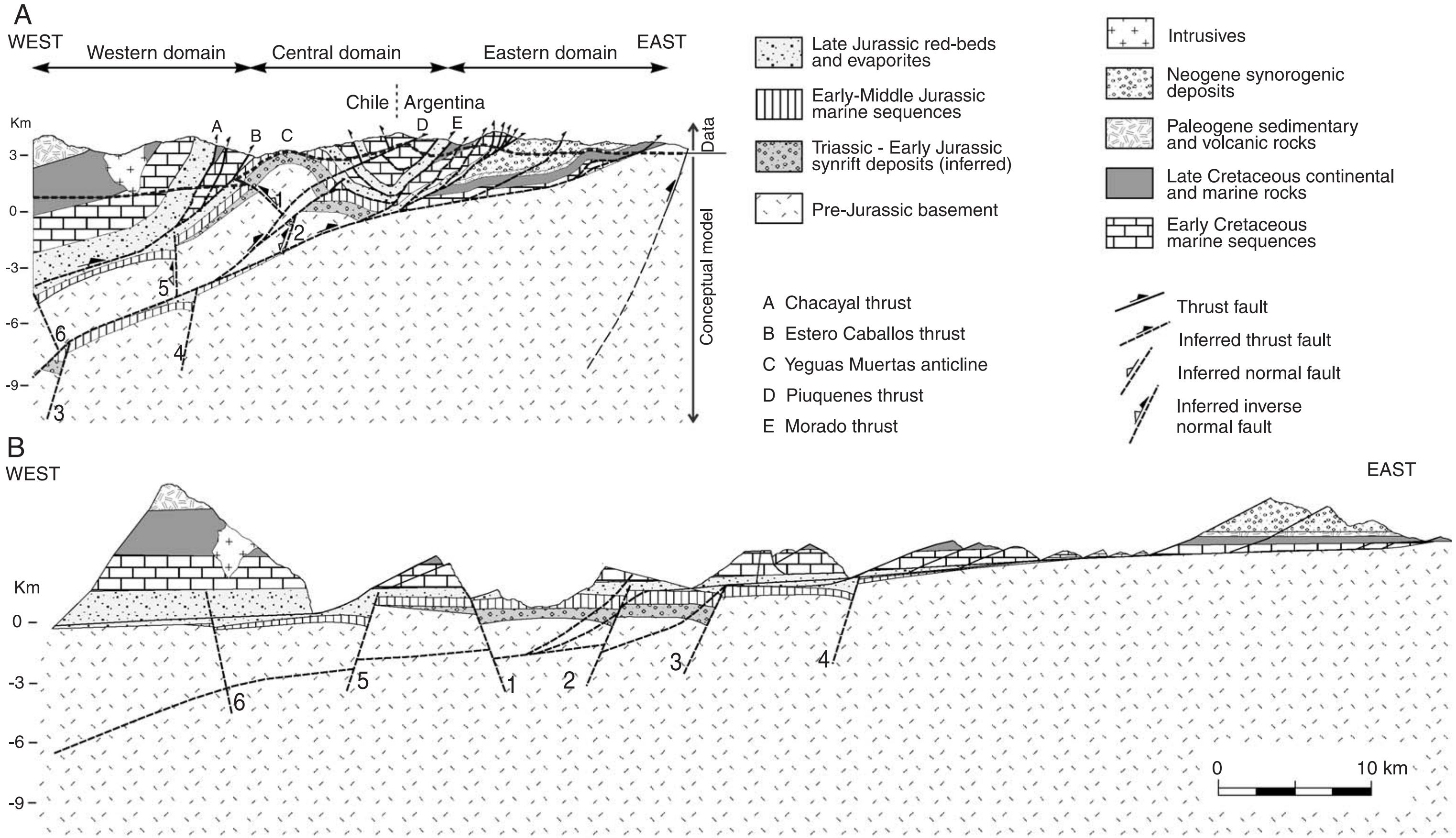

Fig. 7. (A) Balanced structural cross-section of the Aconcagua fold and thrust at approximately 33°40′S. See Fig. 4 for location (modified from Giambiagi and Ramos, 2002). The dashed black line represents the boundary between data and conceptual model. The different structural domains are indicated. Letters identify structures discussed in text. (B) Restoration of the cross-section. Numbers identify normal faults discussed in text.

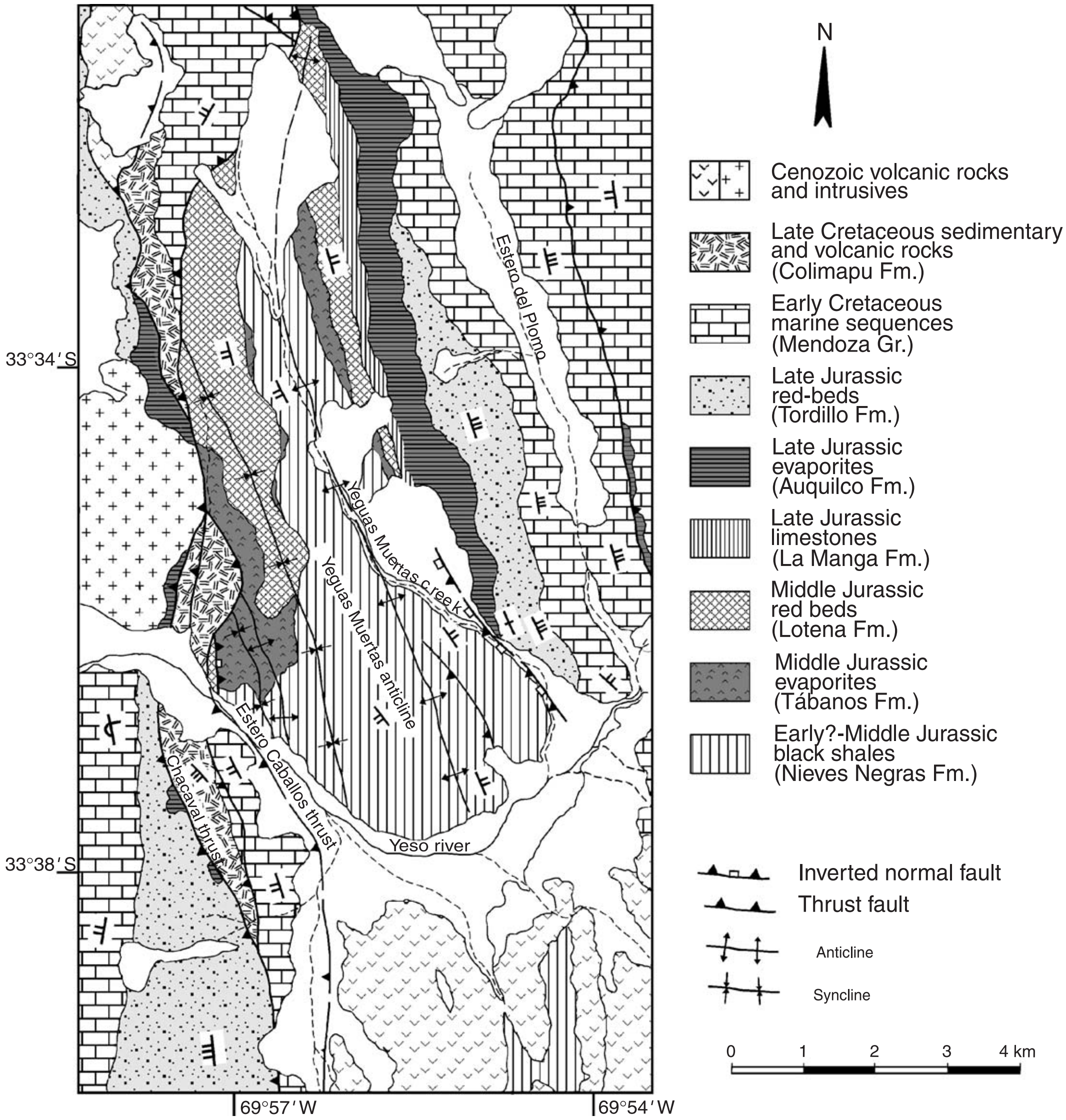

Fig. 8. Detailed geological map of the Yeguas Muertas anticline area. See Fig. 4 for location. Note the presence of Fault 1 in the northern side of the Yeso River, and the inferred Fault 2 in the Yeguas Muertas creek.

mation over the Cretaceous section. West of this thrust, the Upper Jurassic thickness in the hanging wall varies between 2000 and 1500 m, while immediately eastward, the thickness is 400 m. This arrangement is best explained by sitting a west-dipping north-trending normal Fault 5 as a boundary to a graben filled by the Tordillo Formation red beds. The westward-increasing thickness of the Upper Jurassic sediments suggests the presence of normal faults in the Chilean side of the Andes, such as Fault 6 whose existence will be discussed later.

As a result of the above analysis, the Late Triassic–Early Jurassic rift system implies an extensional system with west and east-dipping NNW-trending normal faults. On the contrary, the bulk of Upper Jurassic sediments was accumulated in the hanging wall of a set of widely distributed north-trending extensional faults.

3.2. Thin-skinned contractional deformation

The eastern structural domain is composed of several east-verging low-angle thrusts which form an imbricate fan involving the limestones and mudstones of the Mendoza Group and Upper Cretaceous to Miocene strata (Figs. 4 and 7). These thrusts present steep dips as a result of subsequent rotation during eastward migration of the thrust front. Toward the west, a set of out-of-sequence thrusts truncates the imbricate fan and uplifts the Upper Cretaceous red-beds of the Diamante Formation over the previously deformed sheets of the Mendoza Group.

There is no evidence for the presence of pre-existing extensional structures in the eastern sector of the belt, and geometry constraints point to thin-skinned deformation. Thin-skinned thrusting was facilitated where Upper Jurassic evaporites of the Auquilco Formation were present over the basement-cover interface. Evaporites disappear towards the east, where the Lower Cretaceous Vaca Muerta Formation black shales act as a decollement level (Fig. 7).

In the western structural domain, deformation is characterized by thin-skinned mostly north trending, east-vergent thrusts. They are out-of-sequence thrusts because they override the Yeguas Muertas anticline structure cutting the limb of the fold and inducing a younger-over-older relationship.

3.3. Tectonic inversion

Inversion structures are formed by compressional reactivation of pre-existing extensional faults. For Coulomb materials, the capability of a normal fault to reactivate depends on its orientation to the principal compressive stress, as well as the difference in friction coefficients and cohesion (Sibson, 1985). Both systems of pre-existing normal faults were favourably oriented for the N–S trending compressional reactivation during the Andean orogeny, indicating that they were probably reactivated as inverse faults.

Field evidence shows that structural inversion of the Mesozoic basin is an important controlling factor in the development of the central structural domain of the belt. Although it is very difficult to identify the inversion of structures in a zone of important compression, several features may be considered as indicators of structural inversion in this sector of the belt:

(1) Abrupt changes of stratigraphy correlate with major tectonic boundaries, suggesting that pre-existing extensional faults have been reactivated during Andean compression. Structural inversion is conspicuous in the Yeguas Muertas anticline area (Fig. 9A), which has been interpreted as a pop-up structure, resulting from inversion of two opposite-vergent faults (Faults 1 and 2, Fig. 7).

(2) A common feature developed in an inversion tectonic environment is a bypass fault (McClay and Buchanan, 1992), usually produced in order to generate a more gently inclined fault trajectory, favourable to rupture by sub-horizontal compressional stress (Hayward and Graham, 1989). The Piuquenes out-of-sequence thrust has been interpreted as a hanging wall bypass thrust which cuts the syn- and postrift deposits. It merges in the Argentine side of the Cordón del Límite range (Fig. 4), putting an eastward dipping sheet composed of limestones of the Mendoza Group on top of a westward-dipping sheet of the same unit (Fig. 9B).

(3) Another common feature associated with inversion tectonics is the presence of inverted normal faults cut by thrust faults. The Morado out-of-sequence thrust cuts the previously inverted half-graben associated with the inferred Fault 4 (Fig. 9C) in the Cerros Palomares del Sur area (Fig. 4).

(4) The Chacayal out-of-sequence thrust, emplaced in the western domain, uplifted a thick sheet of the Tordillo Formation, associated to the inferred extensional Fault 6 (Fig. 7). Although a detailed study is still lacking, the Upper Jurassic strata show fanning wedge geometries that suggest a syntectonic sedimentation (Fig. 9D).

(5) The emplacement of stratigraphically younger rocks onto older rocks with the apparent omission of rock sequences is a good evidence for reactivation of pre-existing extensional faults. The Estero Caballos thrust shows younger over

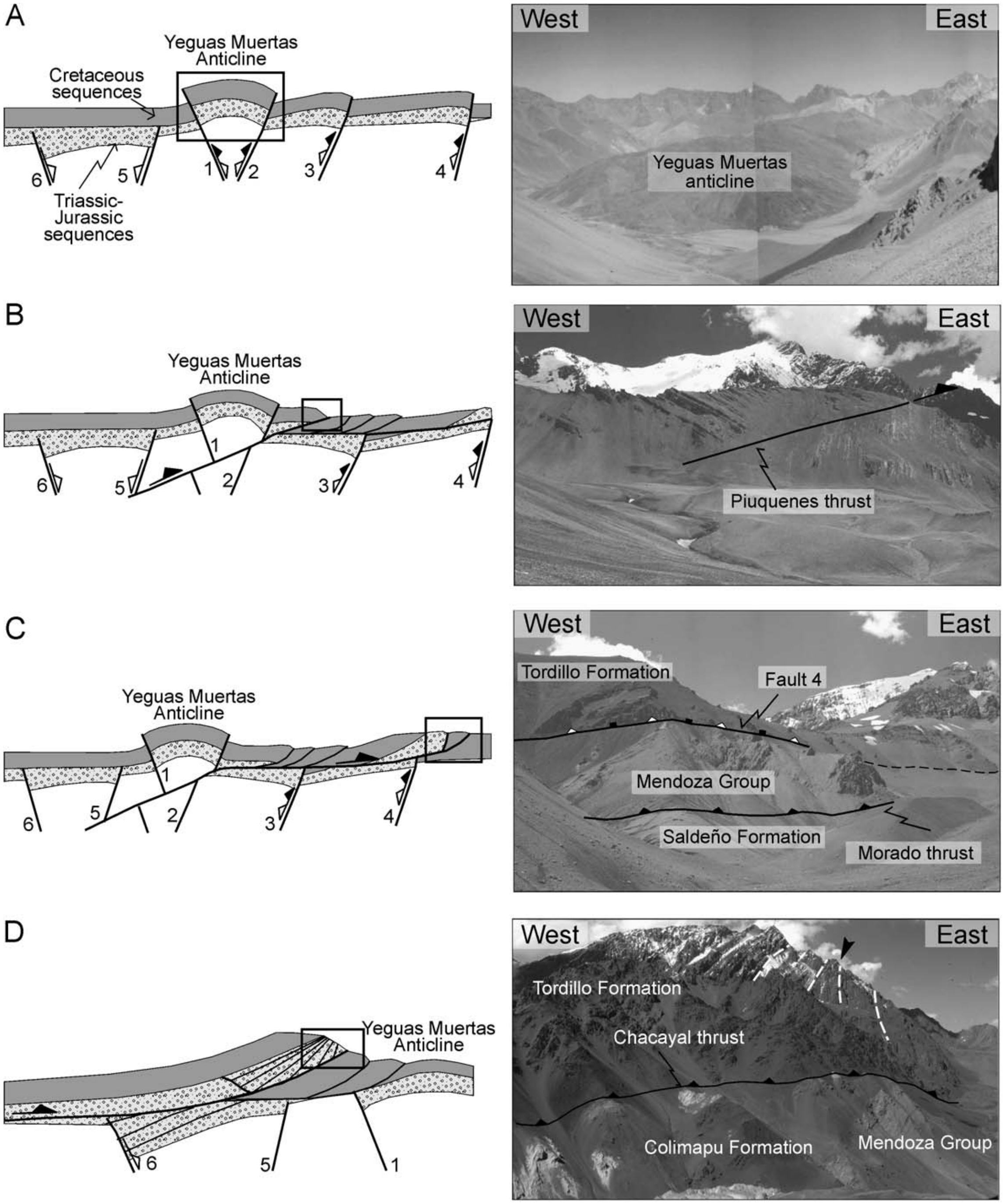

Fig. 9. Field evidence of structural inversion. (A) Pop-up geometry of two opposite-vergent faults in the Yeguas Muertas anticline. (B) The Piuquenes out-of-sequence thrust in the Cordón del Límite range, related to a bypass fault in the basement. (C) The Morado out-of-sequence thrust cutting an inverted normal fault. (D) The Chacayal thrust uplifting a Late Jurassic fanning wedge.

older relationships, indicating the presence of pre-existing structures. It places Lower Cretaceous limestones (Mendoza Group) over the Middle Jurassic Lotena and La Manga Formations, omitting the Late Jurassic Tordillo Formation (Figs. 5, 8 and 10).

3.4. Basement-involved contractional deformation

Steep faults are highly efficient to produce structural relief but achieve only a small amount of shortening. Thus, the highly compressional deformation registered in the southern sector of the Aconcagua fold and thrust belt, which achieves 57% of shortening (Giambiagi and Ramos, 2002), may not be entirely explained in terms of inversion of the Mesozoic basin. Surface data show a change in style of deformation in the central zone of the belt and point to thick and thin-skinned structural interactions in this zone. This area is dominated by east-verging basement-involving structures, represented by the Yeguas Muertas anticline and a set of back-thrusts (Figs. 4 and 7). These structures define a frontal basement wedge where basement deformation was synchronous with foreland thin-skinned deformation of the cover rocks. We propose that this wedge depicts a low-angle detachment at basement levels, unrelated to the inversion of previous structures (Fig. 7). The principal constraint for this interpretation was the need to match shortening of the cover with that of the basement.

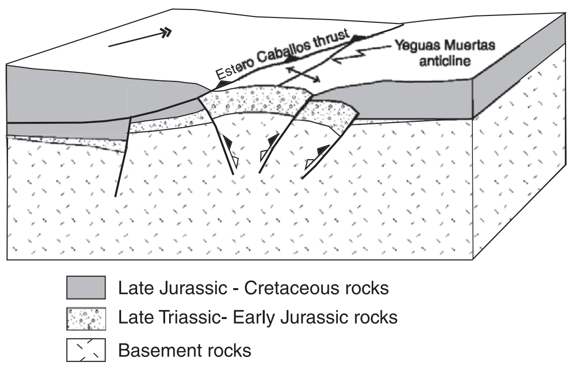

Fig. 10. Schematic block diagram of the emplacement of Early Cretaceous rocks onto Middle Jurassic sequences with omission of Late Jurassic strata. Note the N–S strike of the Estero Caballos thrust and the NNW-trending Yeguas Muertas anticline.

4. Discussion

4.1. Structural style and paleostresses of the Mesozoic extension

From stratigraphical and structural studies of three NNW–SSE trending depocentres, Yeguas Muertas, Nieves Negras and Alvarado, located in the Cordillera Principal (Alvarez et al., 2000) (Fig. 3), we distinguish at least two successive episodes of rifting during the Mesozoic:

(1) The first episode developed during the Late Triassic–Early Jurassic, causing emplacement of west and east dipping, roughly NNW–SSE-trending faults. Their consistent trend and the narrowness of the associated troughs support the idea that the least principal paleostress (σ_3) was perpendicular to the basin axis, the troughs being the product of ENE–WSW extension. This paleostress orientation is also valid at a regional scale, as was pointed out by Vergani et al. (1995) for the Neuquén basin; and it was related to ENE extensional collapse of the Late Permian–Early Triassic orogenic belt. Although regional structural inhomogeneities within the crust may control the orientation of rifting, it is unlikely that the NE–SW to NNE–SSW structural grain of the Late Paleozoic basement (Polanski, 1964) in the study area had a strong influence during Late Triassic–Early Jurassic extension.

(2) The second rifting episode developed during the Late Jurassic and its faults were localized close to the pre-existing rift system, which was oriented obliquely to the new system. Although Vergani et al. (1995) and Tankard et al. (1995) proposed a NW–SE regional paleostress orientation for the Neuquén basin during this stage, in the study area, the east- and west-dipping faults generated asymmetric N–S-trending grabens and half-grabens. Fault development may not have occurred exclusively along the mechanically expected directions, but was rather influenced by the inherited structural lineations of the previous extensional stage. As the new extensional direction became oblique to the previous rift axis, there probably was a strike-slip movement along reactivated normal faults. Some

previously generated faults were reactivated by the new extensional process, but others remained unreactivated. Sinistral transfer faults, responsible for the fragmentation of the Late Triassic–Early Jurassic troughs, are thought to have developed during this stage.

4.2. Numerical and analogue modeling for oblique rift zones

In extensional environments with oblique rifting processes, the geometry and kinematics of fault patterns suggest that extension is not perpendicular to the boundaries of the deforming domain (Tron and Brun, 1991). The 3D-trishear numerical model of Cristallini et al. (2003) has been used to simulate instantaneous extension axes oriented oblique to rift zones, comparable to those observed in the Aconcagua fold and thrust belt. 3D-trishear modeling provides a kinematic description of a deforming triangular shear zone and allows an analysis of the three principal strain directions, which in turn can be used to predict fracture orientations (Fig. 11). It is used here to produce multistage deforming models to demonstrate the influence of an earlier normal fault in subsequent extensional deformation and to point out the difficulties

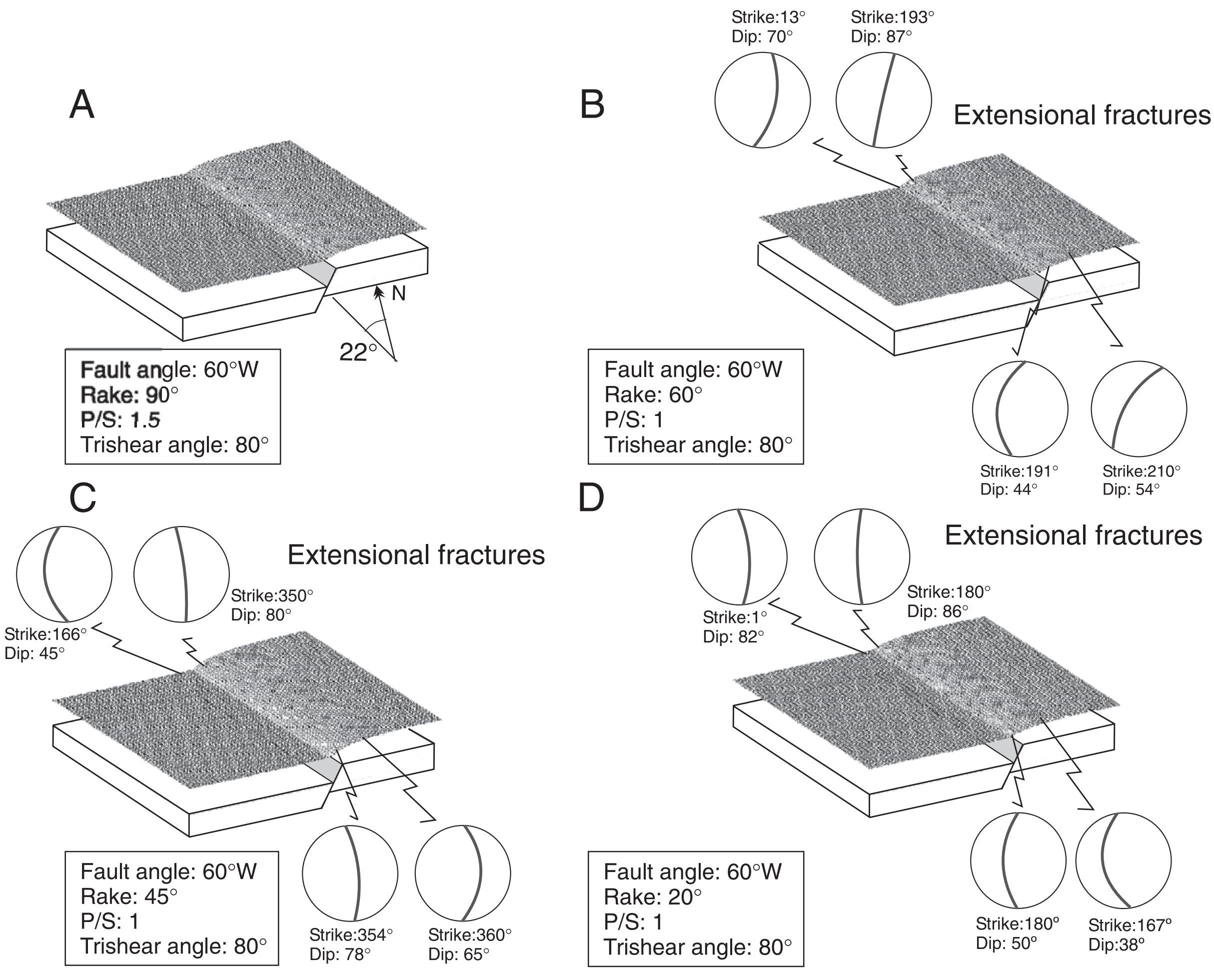

Fig. 11. 3D-Trishear numerical models for fault orientations resulting from oblique rift systems. Generation of a 60° normal fault NNE-trending which simulates the first extension (A). Reactivation in a strike-slip mode of the previous fault with an extensional stress axis oriented E–W (B), ENE–WSW (C) and NE–SW (D).

involved in deriving paleostress orientations from structural trends.

The first stage of deformation was a pure dip–slip displacement above a 60° west-dipping NNW-trending fault, which simulates Fault 3 (Fig. 7). For this stage, a 1.5 P/S ratio, which determines how rapidly the tip line propagates relative to the slip on the fault itself, was used (Fig. 11A). For the Late Jurassic extension, three models, with rakes varying between 60°, 45° and 20°, were performed in order to simulate W–E, WNW–ESE and NW–SE extensions (Fig. 11B, C and D).

Although the model does not allow for synrift deposits and the amount of displacement as well as the angle of the trishear zone are uncertain, the extensional fractures achieved by the numerical model compare well with the Late Jurassic normal fault trends. The model suggests that during the second extensional stage, faults located near the previous rift margin are slightly oblique to the rift trend. This is due to the presence of a secondary stress system that forms at the rift margins. In case of the Yeguas Muertas depocentre, this type of oblique rift model is attractive because it explains the generation of new N–S trending normal faults at an angle of 20–30° to the pre-existing normal fault with least paleostress direction varying from W–E to NW–SE (Fig. 12). This is consistent with the analogue models presented by Tron and Brun (1991) and Clifton et al. (2000). These numerical and analogue models suggest that in an area with a complex history of deformation, the paleostress axes are not necessarily perpendicular to the main structural trends, but are rather controlled by previous structures.

During regional extension, ductile layers at the basement-cover interface may help detach the cover sequence from the underlying oblique basement faults. Unless the cover is fully decoupled, basement faults may, however, still influence the cover faulting (Higgins and Harris, 1997). The presence of two thick evaporite formations in the Aconcagua fold and thrust belt may have favoured the development of an oblique-rifting system. Deformation would be dispersed through those ductile layers and faulting associated with the Tordillo Formation would not entirely be geometrically related to the basement faults. Instead, faulting may have been influenced by both the extension direction and reactivation of basement faults.

4.3. The rift model

Structural and paleostress studies show that the area has undergone a polyphase history characterized by two successive rift episodes. During the first stage, a basin was created due to a subhorizontal maximum extensional direction (σ_3) oriented ENE–WSW. In contrast, there was a single Late Jurassic basin whose development is related to a subhorizontal maximum extensional direction (σ_3) oriented between E–W and NW–SE.

Numerical and analogue models suggest that the initial thickness and heat-flow environments strongly control the style of deformation during the first episode of rifting (Buck, 1991; Bassi et al., 1993; Benes and Davy, 1996; Gartrell, 2000). Thick crust with high heat flow is the special condition for the development of low-angle detachment faults; while narrow rifts are likely when the lithosphere is rela-

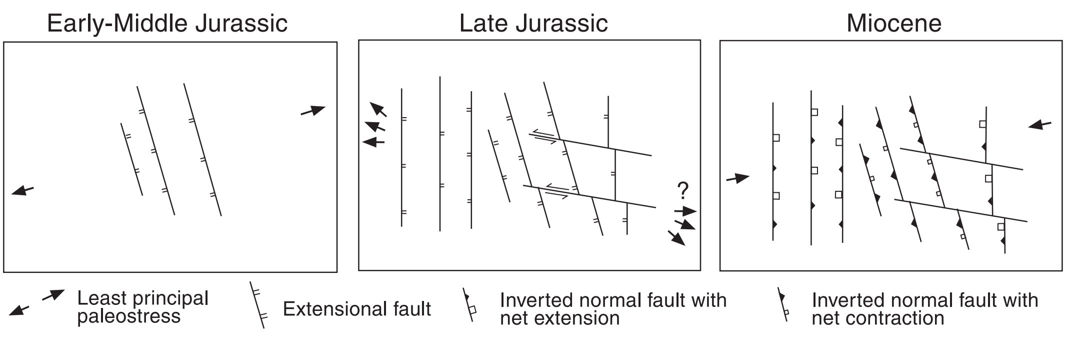

Fig. 12. Diagrams of the Late Triassic–Early Jurassic and Late Jurassic rift systems showing two distinct trends as a result of different stress regimes. Miocene compression favoured the reactivation of pre-existing structures.

tively cool and the crust is thin (Gartrell, 2000). For the Triassic–Early Jurassic period, a tectonic setting of abnormal hot continental crust has been documented (Kay et al., 1989; Llambias and Sato, 1990). We propose a rift model for the Late Triassic–Early Jurassic system with an extensional ramp-flat detachment geometry, crestal collapse graben faults (Faults 1 and 2) and an extensional roll-over structure associated with Fault 3 (Fig. 13). The model predicts that hanging wall deformation is accommodated by extension localized at the crest of a rollover anticline whereas the head of the hanging wall rotates but remains underformed (McClay, 1989). Major along strike changes occur in the area interpreted as an en echelon transfer system related to the extensional period (Fig. 12). For the Late Jurassic extension, the model assumes a graben fault system which cuts the pre-existing normal faults.

4.4. The relationships between tectonic inversion and thick- and thin-skinned thrusting

The restored cross-section (Fig. 7) suggests that the actual structural zonation of the fold and thrust belt coincides with pre-existing structures. While thin-skinned deformation occurred in the postrift Mesozoic sequences of the Cordillera Principal in Argentina, additional deformation by the reactivation of synrift normal faults has resulted in a hybrid thick and thin-skinned style of deformation in the Cordillera Principal of Chile. The thin-skinned nature of the eastern domain may reflect the location of subhorizontal cover strata above a relatively flat basement and favourable lithologies for decollement transfer. In contrast, in the central and western domains, shortening was accommodated by a combination of inversion of pre-existing normal faults, development of a low-angle basement thrust and thin-skinned fault systems controlled by the architecture of the rift basin. Unlike the simple flat basement-cover interface of the eastern domain, in the central domain that surface is complicated by the presence of normal faults.

The relationships previously described suggest that during the contractional cycle, the eastern margin of the Late Triassic–Early Jurassic basin was markedly reactivated. In contrast, the western margin of the Late Jurassic basin probably underwent only a small amount of reactivation because the contraction was partly accommodated along a newly developed basement-involved low-angle fault. This can be due to several factors, including the steeply dipping Late Jurassic faults, as well as the overburden of these faults by the volcanic deposits.

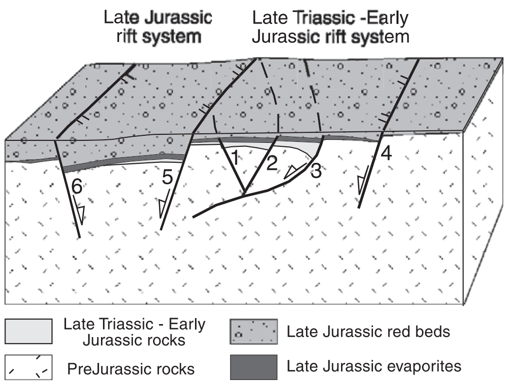

Fig. 13. Schematic model of the paleogeography and pre-existing faults of the extensional basin. The Late Jurassic rift system (Faults 4, 5 and 6) cuts the pre-existing normal faults (Faults 1, 2 and 3).

4.5. Implications for structural development of the Andes

Recognition of the different styles of deformation within the Aconcagua fold and thrust belt has important implications regarding the tectonic significance of the Andes. As discussed above, the evolution of the Andes at these latitudes is partly controlled by the pre-existing Neuquén basin geometry. The low angle detachment inferred beneath the Chilean–Argentine border is not predicted by a simple reactivation model. Although the role of pre-existing extensional basin faults in controlling the structural style of the Andes is important, it cannot account for the high levels of shortening within this belt. The model presented here postulates that a first stage contractional deformation generated the inversion of pre-existing normal faults in the Yeguas Muertas anticline area. Afterwards, as deformation involved a much higher amount of shortening, it incorporated the inverted structures into the thrust sheets of the low-angle basement detachment fold and thrust belt. The superficial western Estero Caballos out-of-sequence thrust, on the other hand, may be related to early stages of inversion of the Oligocene intra-arc basin located further to the west

(Godoy et al., 1999). Basement fault inversion has played a significant role in the evolution of the fold and thrust belt mainly because the synrift faults were approximately perpendicular to the direction of thrust propagation.

Available data suggest a direction of Andean shortening oriented roughly N80°, sub-parallel to both rift-phase extension directions, which generated the reactivation of the principal NNW–SSE and N–S trending normal faults as thrust faults. This direction almost coincides with the present convergence (N76°) (Somoza, 1998), which indicates only minor variations in the subduction vector in Late Cenozoic times.

5. Conclusions

The relationships discussed in this paper show that the structural evolution of the southern part of the Aconcagua fold and thrust belt cannot be explained solely by a thin-skinned deformational model. On the contrary, the structural analysis has revealed the complex variations in structural style of this mountain belt during the compressional cycle. The variability in structural style between thin-skinned, basement involved and inversion tectonics appears to be strongly controlled by the pre-existing geometry of the northernmost part of the Neuquén basin, particularly the position of Mesozoic normal faults, and the relationship between the orientation of the Late Triassic–Early Jurassic and Late Jurassic basin structures and the displacement vector. Although compressional faults have been controlled to some degree by the pre-existing extensional structures, reactivation of these normal faults has been local.

According to our tectonic model for the Mesozoic, the region experienced at least two stages of rifting. The first stage was active during the Late Triassic–Early Jurassic with an extension close to ENE–WSW direction. During the second Late Jurassic stage, the regional stress field changed. Because of the influence of pre-existing structures, its direction cannot be inferred from structural trends alone, it may be assumed to vary from W–E to NW–SE. A rift inversion model in which the Andean shortening direction is sub-parallel to the direction of rift extension is used to generate the present-day structural geometries.

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