Cenozoic deformation and tectonic style of the Andes, between 33° and 34° south latitude

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[1] The Andes of Argentina and Chile between latitudes 33° and 34°S are composed from west to east of an Oligocene to Miocene volcanic arcs and the Neogene east-vergent Aconcagua fold and thrust belt of the Cordillera Principal, and the basement-block faulted Cordillera Frontal. A regional cross section suggests that shortening across the Andes was achieved by thrusting along detachments at several levels in the crust. While thin-skinned deformation along newly formed thrusts occurred in Mesozoic sequences of the eastern Cordillera Principal, reactivation of preexisting Jurassic and Oligocene normal faults has resulted in additional hybrid thick- and thin-skinned structures in the western Cordillera Principal. Five major thrusting events are recognized in this part of the Andes: (1) Early to Middle Miocene tectonic inversion of the extensional faults in the western Cordillera Principal, (2) Middle to Late Miocene development of the Aconcagua fold and thrust belt, (3) Late Miocene uplift of Cordillera Frontal, (4) Late Miocene–Early Pliocene out-of-sequence thrusting in the Cordillera Principal, and (5) Pliocene to present deformation of the foreland. *INDEX TERMS:* 9604 Information Related to Geologic Time: Cenozoic; 9360 Information Related to Geographic Region: South America; 8015 Structural Geology: Local crustal structure; 8102 Tectonophysics: Continental contractional orogenic belts; *KEYWORDS:* central Andes, Cenozoic deformation, Aconcagua fold, thrust belt. **Citation:** Giambiagi, L. B., V. A. Ramos, E. Godoy, P. P. Alvarez, and S. Orts, Cenozoic deformation and tectonic style of the Andes, between 33° and 34° south latitude, *Tectonics*, *22*(4), 1041, doi:10.1029/2001TC001354, 2003.

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1. Introduction

[2] It is generally accepted that compression of the active margin between the Nazca and South American plates controls the development of the Andean orogenic belt. Timing of the onset of Andean deformation and the different structural phases remain, however, uncertain. From 33° to 34°S, the present-day structure of the chain is characterized from west to east by the Cordillera Principal and Cordillera Frontal (Figure 1). The Oligocene to Miocene volcanic arcs and the Neogene Aconcagua fold and thrust belt make up the western and eastern Cordillera Principal respectively. The foreland, in the east, is marked by the inversion of Triassic extensional faults of the Cuyo basin and middle dipping basement faults.

[3] This paper integrates previous data with new structural data to analyze the style, distribution and timing of deformation of the Andes between 33° and 34°S. The sedimentological and provenance data from the synorogenic units are considered within the context of a new regional cross section. Because indirect evidence across the Aconcagua fold and thrust belt suggests the influence of older extensional fault systems on Late Cenozoic deformation, particular attention has been given to the structural geometry and evolution of the different Mesozoic and Cenozoic extensional systems developed across strike.

2. Plate Tectonic Setting

[4] At 33°–34°S the Nazca plate is subducting beneath the South American plate at a relative velocity of 10 cm/yr [*Pardo-Casas and Molnar*, 1987]. The downgoing slab is segmented into a zone of subhorizontal subduction north of 33°S, and a zone of normal subduction south of 34°S (Figure 1) [*Stauder*, 1975; *Barazangi and Isacks*, 1976; *Cahill and Isacks*, 1992]. Changes in large-scale tectonic features of the Andean orogenic system, such as volcanism and distribution of morphostructural belts, correlate with these geometries [*Jordan et al.*, 1983]. North of 33°S the flat subduction segment lacking arc magmatism underlies the Cordillera Principal, Cordillera Frontal, Precordillera

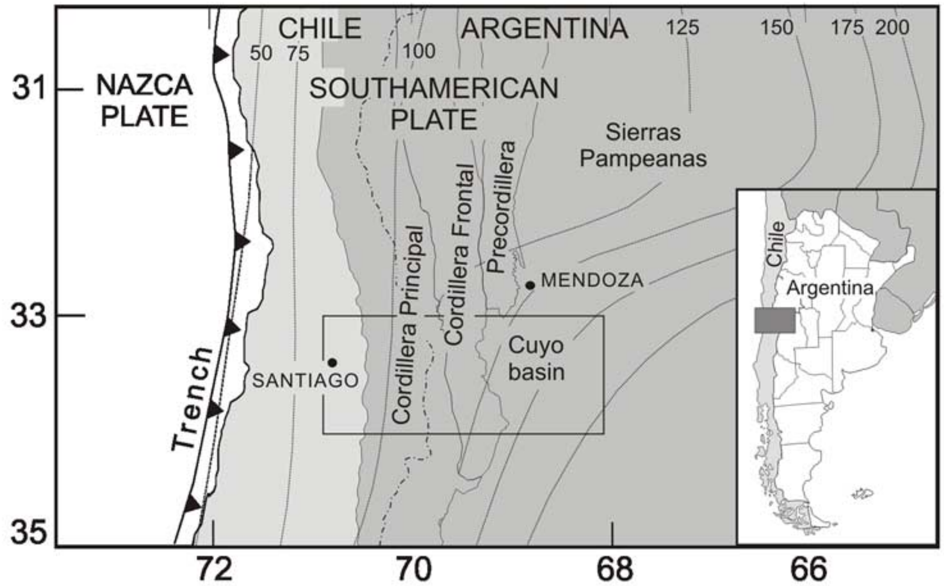


Figure 1. Regional location map. Shape of the subducted Nazca plate is shown via contours to depth of the Wadati-Benioff zone, according to *Cahill and Isacks* [1992]. The box indicates location of the study area and Figure 3.

and Sierras Pampeanas structural provinces since Miocene times. South of 34°S the normally dipping slab segment with arc magmatism underlies the Cordillera Principal and Cordillera Frontal. Neither the Precordillera nor Sierras Pampeanas were developed in this segment. Between the flat and normal subduction segments there is a transition zone (33°–34°S) where the study area is located.

3. Stratigraphy

[5] A deformed belt of Mesozoic and Cenozoic sedimentary and volcanic rocks that unconformably overlie Proterozoic to Early Triassic basement rocks characterizes the study area. The stratigraphy, examined in previous studies by *Polanski* [1964], *Thiele* [1980], and V. A. Ramos et al. (Descripción de la Hoja Geológica Cerro Tupungato, scale 1:250,000, unpublished map, 2000, available from Subsecretaría de Minería de la Nación, Dirección Nacional del Servicio Geológico), has been divided into six main sequences (Figure 2): (1) Proterozoic to Lower Triassic rocks composing the basement; (2) Triassic and Jurassic rift sequences; (3) Cretaceous to Paleogene marine and non marine sedimentary rocks; (4) Oligocene to Lower Miocene volcanic rocks; (5) Upper Cenozoic foreland basin deposits; and (6) Upper Cenozoic intrusives and volcanic-arc rocks.

3.1. Basement Rocks

[6] The oldest rocks correspond to Proterozoic metamorphic rocks cropping out on the southeastern side of the Cordón del Plata and Cordón del Portillo ranges, in the Cordillera Frontal (Figure 3). They are unconformably overlain by Upper Paleozoic marine black shales and sandstones and are intruded by Carboniferous and Permian granitoids [*Polanski*, 1964].

[7] In Permian times a widespread compressive event, known as San Rafael orogeny, deformed these units generating a wide orogenic belt and important crustal thickening [*Llambias and Sato*, 1990]. This event was the responsible for the generation of the La Carrera and others fault systems in the Cordillera Frontal. The deformed rocks are unconformably overlie by Permian-Triassic intermediate and acid volcanic rocks. These lithologies generated a rigid rheological behavior of this basement during the Andean deformation.

3.2. Triassic and Jurassic Rift Sequences

[8] During Triassic-Jurassic times a series of rift systems, with overall NNW trend, were formed along the western margin of Gondwana [*Charrier*, 1979; *Uliana et al.*, 1989]. Two successive phases of rifting during the Mesozoic have been distinguished by stratigraphical and structural studies in the Andes at these latitudes; during Triassic to Early Jurassic and during Late Jurassic [*Giambiagi et al.*, 2003], each followed by an associated phase of thermal subsidence, in the Middle Jurassic and Early Cretaceous respectively. The oldest extensional structures are related to ENE extensional directions in the Cuyo and Neuquén basin (Figure 4). In the Cuyo basin, Triassic continental sequences were unconformably deposited in isolated fault-control depressions on the Paleozoic substratum of the Andean foreland and lie beneath 2,000–3,000 m thick of Cenozoic foreland deposits (Figures 2 and 3) [*Kokogian and Mancilla*, 1989].

[9] The Mesozoic extensional system of the Neuquén basin is represented in the study area by the Yeguas Muertas

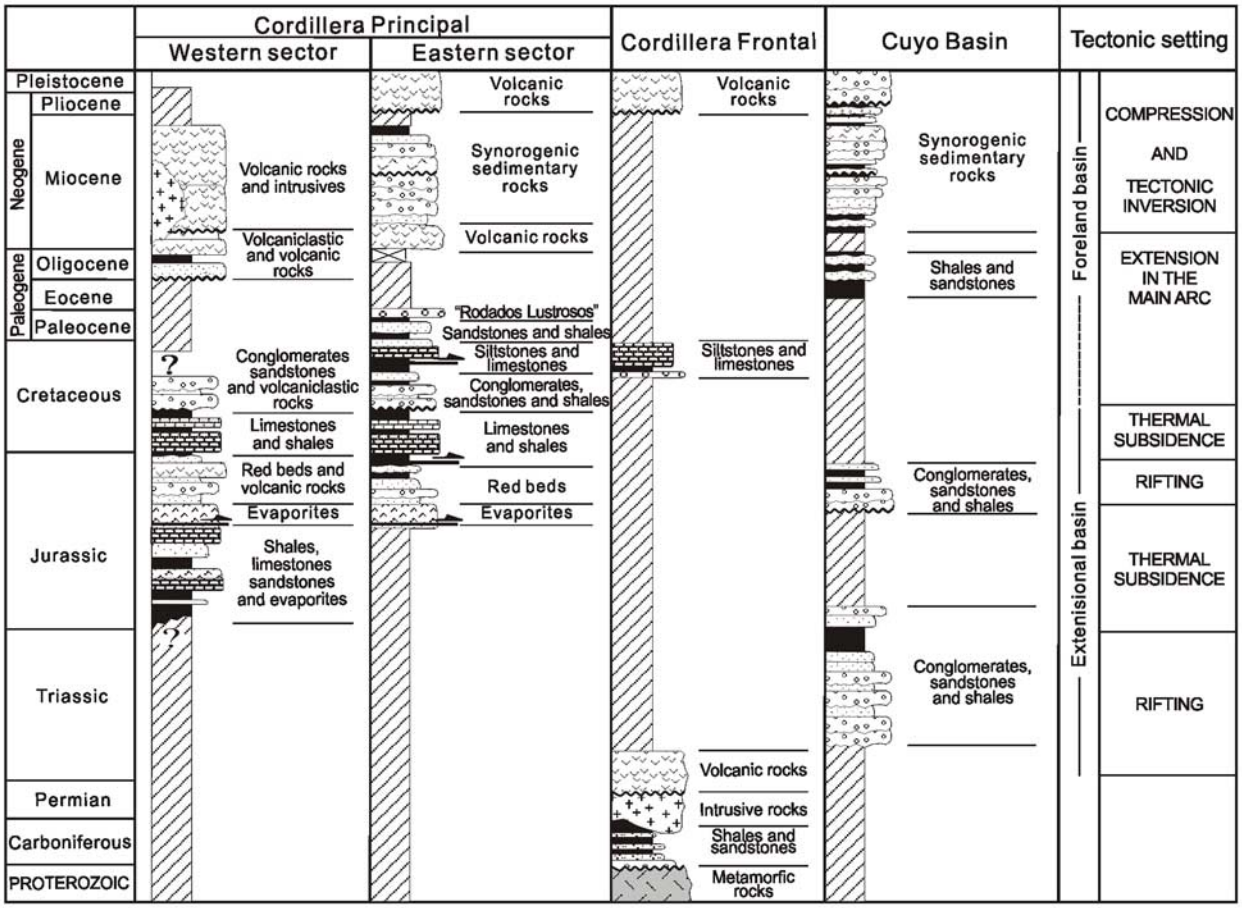


Figure 2. Generalized stratigraphic columns of the units outcropping in western and eastern Cordillera Principal, Cordillera Frontal and Cuyo basin, between 33° and 34°S, (compiled from references in the text). Black arrows indicate detachment horizons.

and Nieves Negras depocenters (Figure 4) [*Alvarez et al.*, 2000b]. The rift sequences are made up of Lower to Middle Jurassic black shales, evaporites and red beds, and Middle to Upper Jurassic marine platform limestones [*Alvarez et al.*, 1999]. Overlain these rocks there is a thick layer of Upper Jurassic evaporites that constitute the detachment level of many faults in the Aconcagua fold and thrust belt (Figure 2). The bulk of Upper Jurassic sedimentary rocks, composed of up to 2,000 m of continental sandstones and conglomerates with volcanic flow interbedded, was accumulated in the hanging-wall of a set of predominantly east-dipping north-trending extensional faults localized close to the preexisting rift system situated in the Cordillera Principal. This is indicated by thickening of the red beds toward the west, and abrupt cross-strike variation in facies and thickness of these units [*Thiele and Nasi*, 1982; *Cegarra and Ramos*, 1996; *Lo Forte*, 1996; *Giambiagi and Ramos*, 2002; *Giambiagi et al.*, 2003].

3.3. Cretaceous to Paleogene Platform Rocks

[10] The Jurassic units in the Cordillera Principal are overlain by black shales, mudstones, limestones and sandstones, deposited as a stable platform succession during Titho-Neocomian thermal subsidence [*Polanski*, 1964; *Aguirre-Urreta*, 1996]. The Upper Cretaceous rocks, which are separated from the Lower Cretaceous units by an erosional unconformity, consist of conglomerate and sandstone beds and volcaniclastic rocks. The presence of continuous Maastrichtian to Danian siltstones and limestones deposited during the last Atlantic ingression in the eastern Cordillera Principal and the southwestern sector of the Cordillera Frontal [*Tunik*, 2001] indicate a subdued relief close to sea level for this region. Paleocene fine-grained sedimentary rocks follow, which are conformably covered by a 2 m thick bed of conglomerate with desert varnish indicating a long period of weathering, named the "Rodados Lustrosos."

[11] In the Cuyo basin, sandstones and mudstones interbedded with evaporites of Late Eocene to Early Miocene age unconformably overlay the Triassic rocks [*Kokogian and Mancilla*, 1989].

3.4. Oligocene–Lower Miocene Volcanic Rocks

[12] During the Oligocene–Early Miocene, volcanic activity confined to the western Cordillera Principal con-

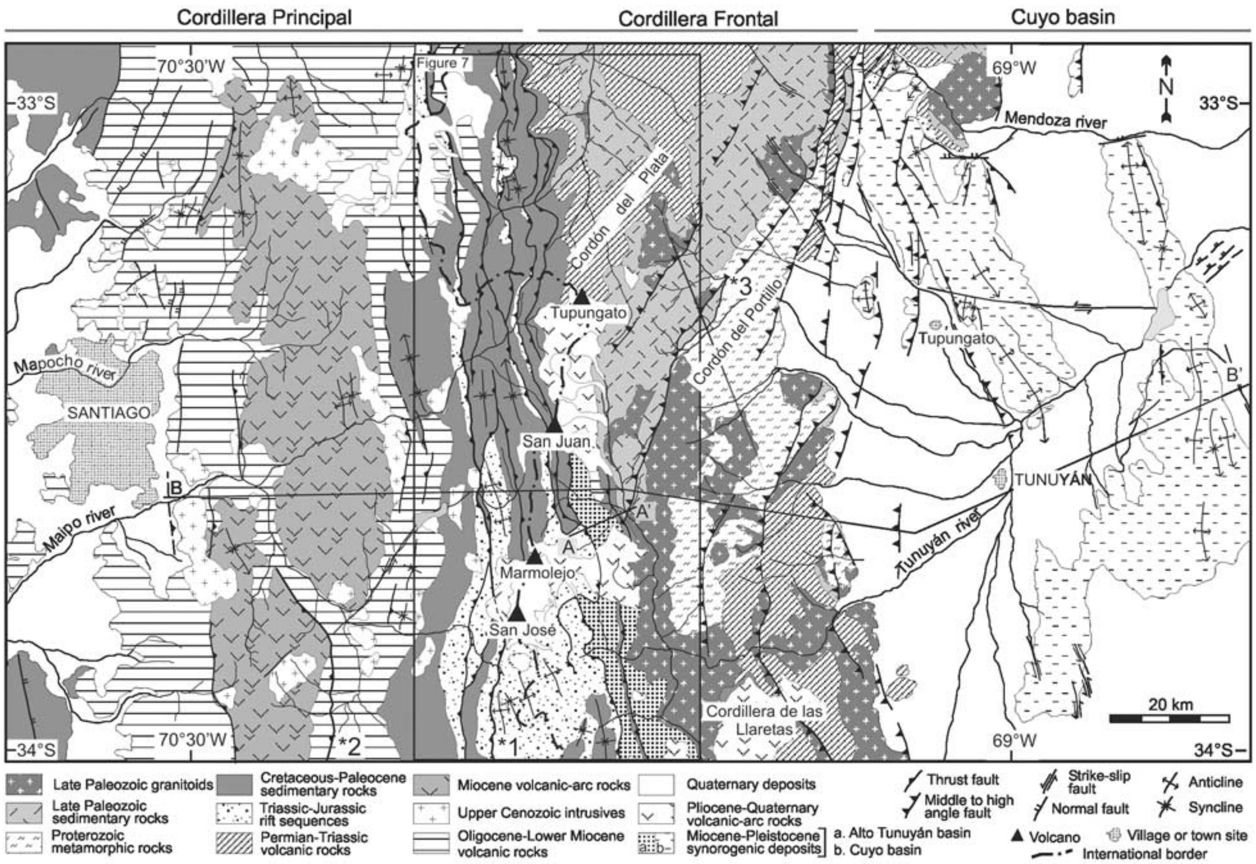


Figure 3. Simplified geological map of the Andes between 33° and 34°S, showing major structural features and location of cross sections in Figures 5 (AA') and 6 (BB'). Minor structures have been omitted. Area of Figure 7 is indicated by a box. Starred numbers 1 and 2 refer to Chacayal and Fierro thrusts respectively; starred number 3 refers to the Cerro Arenal fault. Compiled from references in the text and our data.

siderably increased, after at least 10 Mys. of quiescent activity [*Godoy et al.*, 1996; *Charrier et al.*, 1997]. These volcanic rocks correspond to the Abanico and Coya Machalí Formations [*Klohn*, 1960] of Late Eocene to late Early Miocene age [*Wyss et al.*, 1990; *Flynn et al.*, 1995; *Gana and Wall*, 1997; *Vergara et al.*, 1999; *Charrier et al.*, 2002]. These units crop out in two north-trending belts (Figure 3) and are at least 2,000 m thick. The western belt consists of intermediate tuffaceous, pyroclastic and volcanic rocks, and the eastern belt of a thick sequence of basic lavas, tuffs and intermediate pyroclastic rocks, interbedded with sedimentary rocks [*Nyström et al.*, 1993; *Vergara et al.*, 1999]. The volcanic rocks have a primitive isotopic signature related to crustal thinning with a high paleothermal gradient [*Vergara et al.*, 1999]. This accumulation is interpreted to correspond to a volcano-tectonic extensional basin [*Charrier et al.*, 1997, 2002] with a probable transtensional component [*Godoy et al.*, 1999].

[13] The Contreras Formation, the oldest Cenozoic volcanic unit in the eastern Cordillera Principal, is located at the base of the Neogene synorogenic deposits and consists of basaltic lava flows and breccias. A sample in the middle sector of this unit yielded a K/Ar whole rock age of 18.3 Ma [*Giambiagi et al.*, 2001]. Its geochemistry suggests a retro-arc setting in an unthickened crust during its extrusion [*Ramos et al.*, 1996b].

3.5. Upper Cenozoic Synorogenic Deposits

[14] Upper Cenozoic clastic deposits occur in the basin located between the Cordillera Principal and Cordillera Frontal (Alto Tunuyán basin) and in the Cuyo basin (Figure 3). The foreland basin has been broken by the uplift of the Cordillera Frontal, separating the proximal deposits cropping out in the Alto Tunuyán basin from the distal deposits of the Cuyo basin.

3.5.1. Proximal Deposits

[15] Synorogenic sedimentary rocks filling the Alto Tunuyán basin are represented by three Miocene units. The oldest unit, the Tunuyán Conglomerate, consists of up to 1,400 m of conglomerates and sandstones deposited in an alluvial-fan setting. The vertical variation in clast composition and paleocurrent data reflects the progressive erosion and unroofing of the Aconcagua fold and thrust

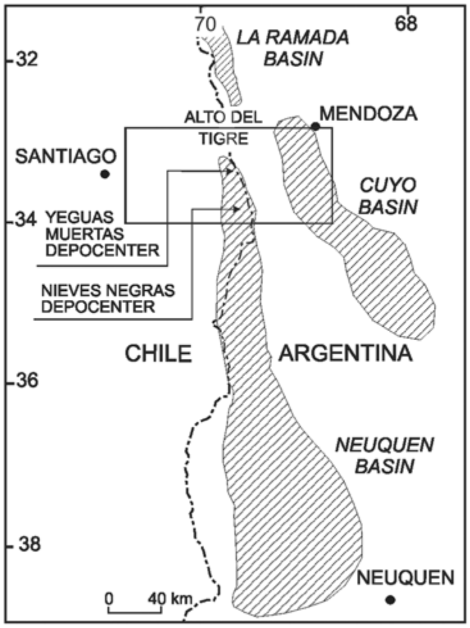


Figure 4. Triassic to Jurassic rift systems in the Andes, between 31°30′ and 38°30′S, as shown by the early reconstruction of *Charrier* [1979] and *Uliana et al.* [1989]. Note the Yeguas Muertas and Nieves Negras depocenters in the Cordillera Principal and the Cuyo basin (modified from *Giambiagi et al.* [2003]). Locations of Santiago, Mendoza and Neuquén cities are given for reference.

belt [*Giambiagi*, 1999]. The synchronism of deposition of the upper 400 m of this unit with the emplacement of thrusts within the basin is documented by syntectonic unconformities [*Giambiagi et al.*, 2001].

[16] The Palomares Formation fills a slight paleorelief in the Tunuyán Conglomerate. It consists of 200 m of volcaniclastic and clastic sediments deposited in an alluvial-fan setting. The Cordillera Frontal was the main source area of this unit, as indicated by clast composition, paleocurrent measurements and syntectonic geometries [*Giambiagi et al.*, 2001]. The Butaló Formation records the final infilling of the intermontane trough between the Cordillera Principal and Cordillera Frontal. It reaches a thickness of more than 300 m, and is made up of fluvial and lacustrine deposits.

[17] In the northern sector of the Alto Tunuyán basin, between the San Juan and Marmolejo volcanoes, the Palomares and Butaló Formations display a wedge-shaped geometry thinning eastward and decreasing in dip upward, and have been interpreted as growth strata. These strata indicate progressive basement tilting related to the uplift of Cordillera Frontal during sedimentation (Figure 5a) [*Giambiagi et al.*, 2001].

3.5.2. Distal Deposits

[18] Between 3000 and 4000 m of synorogenic deposits unconformably overlay the Triassic and Paleogene rocks in the Cuyo basin. The oldest unit, the Mariño Formation, comprises more than 1,000 m of conglomerate derived from the Cordillera Principal and sandstone beds [*Yrigoyen*, 1993]. The La Pilona Formation unconformably overlies the Mariño Formation and consists of 800 m of sandstones and conglomerates. A regionally extensive ash-rich unit within the synorogenic deposits (Tobas Angostura Formation) unconformably overlies La Pilona Formation north of 33°30′S and consists of tuffs, sandstones and conglomerates [*Irigoyen et al.*, 2002]. This unit is overlaid by the Río de los Pozos Formation, which consists of mudstones, sandstones and conglomerates. Provenance studies indicate the Cordón del Plata as a source area for this unit [*Irigoyen*, 1997; *Chiaramonte et al.*, 2000].

[19] The Pliocene-Pleistocene Mogotes Formation consists of boulder conglomerates interbedded with mudstones, sandstones and tuffaceous horizons, representing proximal alluvial-fan facies. The source area of this unit corresponds to both Cordillera Frontal and Precordillera.

3.6. Cenozoic Volcanic-Arc Rocks and Intrusives

[20] East of Santiago, the Andean range is built by Miocene (20 Ma to 7 Ma, southward younging) calc-alkaline andesitic lava and pyroclastic flows that overlie rhyolitic caldera complexes [*Rivano et al.*, 1990] (Figure 3). These rocks correspond to the Farellones Formation, which either overlies or is thrusted on top of a mainly Oligocene Abanico Formation. Several 10 to 5 Ma granitoid and subvolcanic dacitic intrusives, some of them porphyry-copper bearing, where emplaced in this Miocene volcanics.

[21] Pliocene-Quaternary volcanism is represented by the Tupungato, San Juan, Marmolejo and San José volcanic complexes (Figure 3). They represent the eastward shifted volcanic-arc rocks separated from the Miocene synorogenic deposits by an angular unconformity.

4. Structure

[22] Between 33° and 34°S, two geological provinces, the Cordillera Principal and Cordillera Frontal, compose the Andes, and the foreland is represented by the Cuyo basin (Figure 1). In order to study their kinematics, we have constructed a regional cross section across the Andes at 33°40′ (Figure 6). The tectonic structure in the upper crust was constrained by combining information from field work; geologic maps from the Chilean and Argentine Geological Surveys [*Polanski*, 1964, 1972; *Thiele*, 1980; *Rivano et al.*, 1993; *Wall et al.*, 1999; *Ramos et al.*, 2000]; and published information [*Caminos*, 1965; *Godoy*, 1993; *Cegarra and Ramos*, 1996; *Alvarez et al.*, 2000a; *Giambiagi and Ramos*, 2002]. A complete balancing of the section has not been possible because of the lack of subsurface data, the impossibility of defining a regional decollement level within the crust and the reactivation of Late Paleozoic structures. The regional cross section is therefore only an approximation that aims to illustrate the structural evolution of the region.

4.1. Cordillera Principal

[23] The Cordillera Principal can be subdivided into: a western sector, which comprises the Oligocene to Miocene

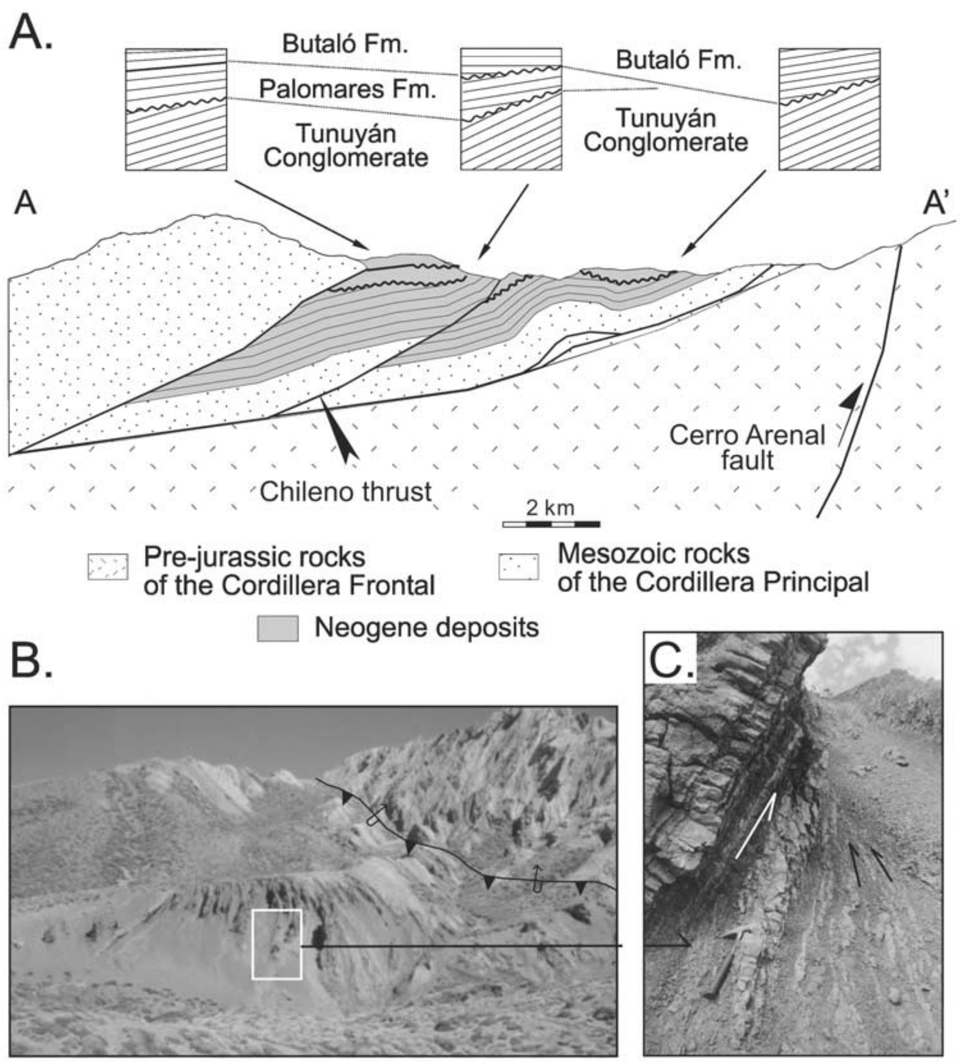


Figure 5. (a) Cross section through the northern part of the Alto Tunuyán foreland basin showing the angular unconformity between the Tunuyán Conglomerate and Palomares Formation and the progressive unconformity between Palomares and Butaló Formations (simplified from *Giambiagi* [1999]; see Figure 3 for location). The genesis of these growth strata is thought to be related to the uplift of the western part of the Cordón del Portillo by the movement of the Cerro Arenal fault during sedimentation. (b) Photograph looking north of the Conglomerado Tunuyán uplifted on top of the Butaló Formation beds by the overturned Chileno thrust. (c) Detail of the syntectonic unconformities indicated by arrows within the upper part of the Tunuyán Conglomerate. Black arrows indicate the offlapping relationships between overturned conglomerate beds and the white arrow shows onlapping relationship.

volcanic arcs, and an eastern sector corresponding to the Aconcagua fold and thrust belt.

4.1.1. Western Sector

[24] The structure of the western Cordillera Principal is dominated by the inversion of the Late Eocene-Early Miocene Abanico-Coya Machalí extensional basin in a bivergent sense. The style of deformation of the Abanico Formation corresponds to inclined folds with hectometric to kilometric wavelengths [*Rivano et al.*, 1990]. The Farellones Formation is generally gently folded with dips not exceeding 15° [*Vergara et al.*, 1988]. The western margin of this inverted basin is marked by the westward detachment of the Farellones Formation along its basal ignimbrite interbedded with sedimentary rocks [*Godoy et al.*, 1996]. The easternmost extension of the basin corresponds to the Chacayal thrust (Figure 3), which marks the border between the western and eastern sectors. This thrust, which uplifts the thickest sheet of Upper Jurassic rocks, runs from the Las Cuevas river (32°50′S) to the Maipo river (34°10′S) for more than 150 km along strike. West of this thrust the Upper Jurassic thickness in the hanging-wall varies between 2,000 and 1,500 m, while in the footwall the thickness is 400 m.

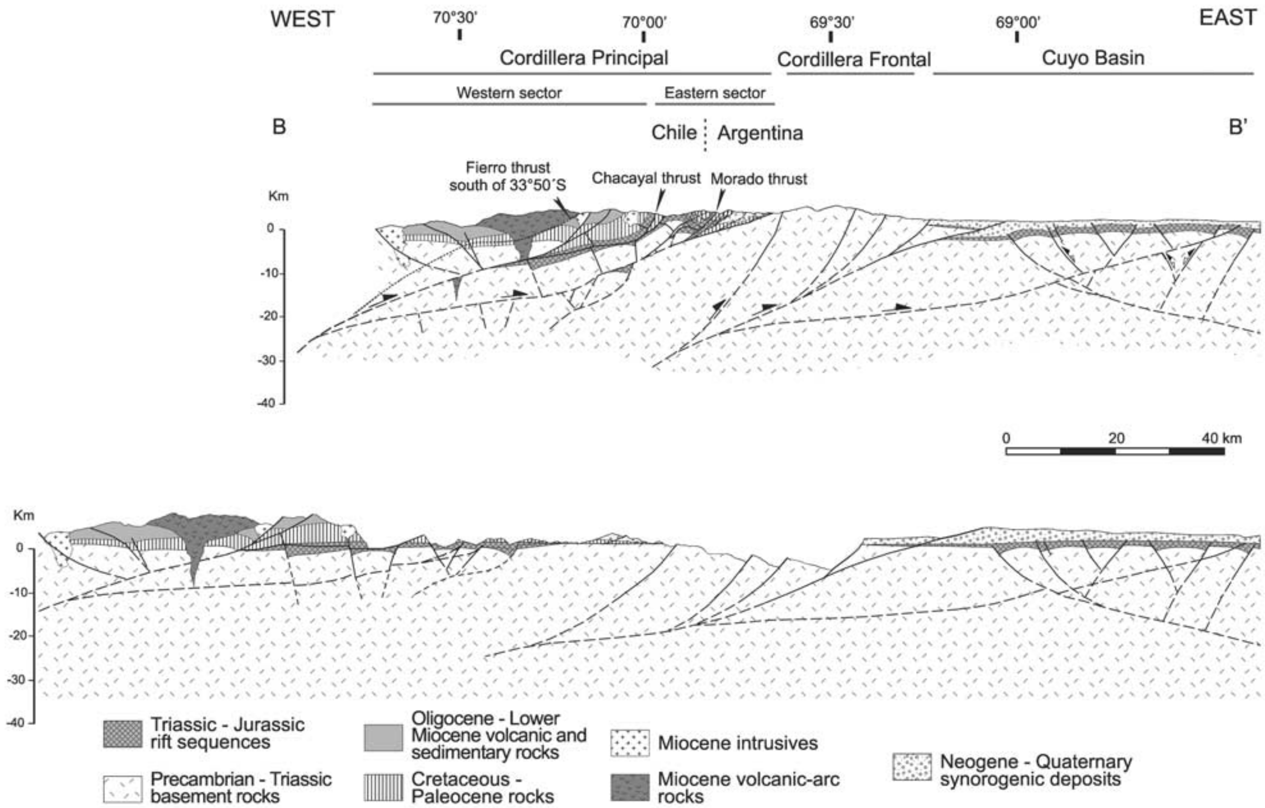


Figure 6. Generalized cross and restored sections through the southern central Andes, at 33°40′S. Minor faults have been omitted. The Aconcagua fold and thrust belt has been balanced and restored. Location is indicated in Figure 3.

This abrupt change in the thickness of the strata suggests that preexisting Late Jurassic normal faults influenced the generation of the Chacayal thrust (Figure 6). This thrust cuts the western flanks of a series of anticlines located in the fold and thrust belt with emplacement of stratigraphically younger rocks onto older rocks with the apparent omission of rock sequences.

[25] The Fierro thrust, a feature recognized for at least 200 km, juxtaposes Miocene arc rocks on top of the Abanico Formation and is interpreted as an out-of-sequence thrust [*Godoy and Palma*, 1990; *Godoy et al.*, 1999] (Figure 3). Seismic and gravimetric studies carried out by *Godoy et al.* [1999] indicate a 2.5 km deep detachment level for this structure.

[26] On a regional scale, the western sector of the Cordillera Principal is characterized by faults that are steep to moderate steep at the surface with inferred listric geometric at depth. We propose that compressional deformation is accommodated by a shallow and a deep detachment. The deep detachment is probably localized along the midcrustal thermally weakened brittle-ductile transition, between 8 and 12 km, while the shallow detachment is related to a ductile decollement horizon at the base of the sedimentary cover.

4.1.2. Eastern Sector

[27] The Aconcagua fold and thrust belt is located in the eastern sector of the Cordillera Principal, between 32°30′ and 34°S. It has traditionally been considered an example of thin-skinned tectonics with complete detachment of a deformed sedimentary cover from a gently west-dipping basement slope [*Ramos*, 1988; *Cegarra and Ramos*, 1996; *Pángaro et al.*, 1996; *Ramos et al.*, 1996a]. However, abrupt changes of stratigraphy, footwall shortcutting, buttressing, and the interference of structures with different strikes argue in favor of a hybrid thick- and thin-skinned tectonic style.

[28] In this paper the belt has been divided in three major domains: the eastern, central and western domains (Figure 7). The eastern domain, where Neogene synorogenic units crop out, comprises the Alto Tunuyán foreland basin. It runs from 33°30′ to 34°S and consists of thin-skinned fold-thrust sheets above a decollement developed in Upper Cretaceous siltstones. Within this zone there are faults, such as the Chileno thrust, related to syntectonic unconformities registered in the upper part of the Tunuyán Conglomerate, indicating sedimentation above an active thrust (Figures 5b and 5c) [*Giambiagi et al.*, 2001]. Other faults indicate activity after deposition of the Neogene units. In this domain the basement-cover contact dips between 15° and 22°W due to the uplift of the Cordillera Frontal blocks (Figure 6).

[29] The central domain is broad in the north and thins toward the south until it disappears south of Volcán Marmolejo (Figure 7), where it is cut by the Morado thrust. This domain is characterized by a dense array of imbricate low-angle thrusts and exhibits flat and ramp geometries, with flats corresponding to decollement levels located in the

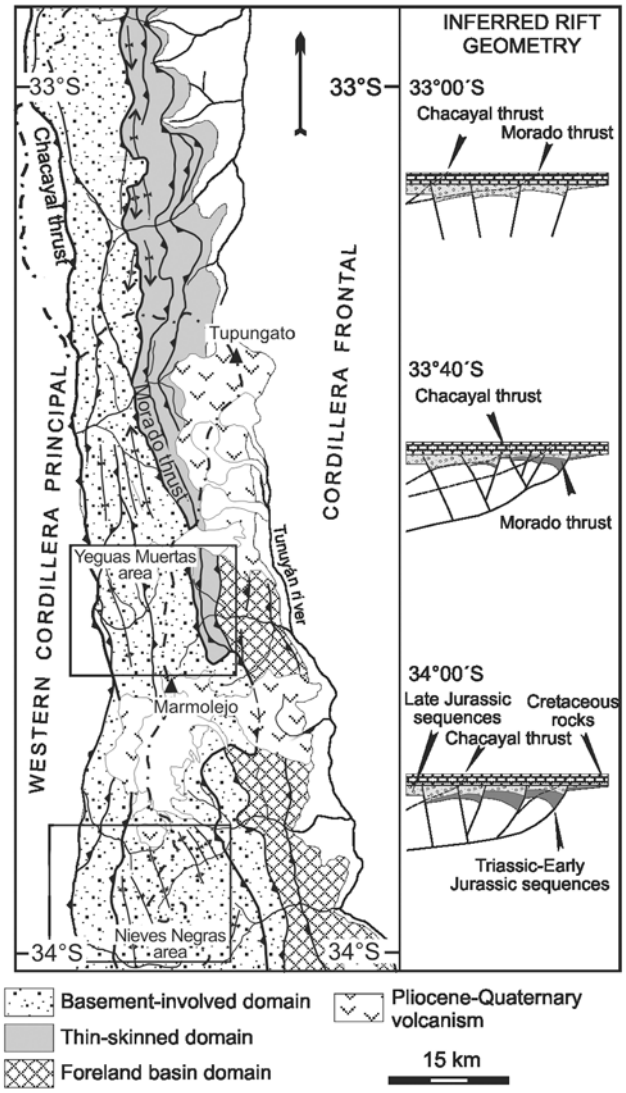


Figure 7. Simplified structural map of the different domains in the Aconcagua fold and thrust belt (eastern Cordillera Principal); and comparison (not to scale) of the inferred rift geometries at 33°00′, 33°40′ and 34°00′S. Boxes are locations of Figures 8a and 8b. Note the absence of the Triassic-Early Jurassic rift sequences in the northern part of the belt.

Upper Jurassic evaporites and Lower Cretaceous shales. These structural features point to a thin-skinned deformational style. The domain corresponds to the Alto del Tigre structural high [*Lo Forte*, 1996], related to the absence of Triassic–Early Jurassic preexisting structures (Figure 4). Although the majority of the structures are younger toward the east, it is common to observe thrusts cutting previously developed structures, some of them inducing younger-over-older relationships. This is the reason why this sector of the belt is interpreted as evolved by a forward propagating thrust sequence with constant periods of out-of-sequence thrust emplacement.

[30] The western domain is dominated by open NNW–SSE trending folds and N–S thrust faults. The majority of these thrusts are cutting the previously developed fold structures and show an eastward vergence, with the exception of a belt of west-verging back-thrusts at the border between Argentina and Chile (Figure 8a). Although the basement does not crop out, its involvement is deduced from the geometry of the structures, rift stratigraphy and significant thickness variations of the deformed Mesozoic succession exposed. The Yeguas Muertas and Nieves Negras zones are made up of open folded and thrusted Middle Jurassic strata [*Godoy*, 1993; *Alvarez et al.*, 1999] and show the influence of preexisting normal faulting in the Andean structural development (Figure 7). Figure 8 shows geological maps of both depocenters and cross section s illustrating the structural style. In the Yeguas Muertas area, *Giambiagi and Ramos* [2002] proposed the generation of a low angle basement thrust after the tectonic inversion to match shortening of the cover with that of the basement. Two ramps of this thrust led to the formation of the basement-involved system in western Aconcagua fold and thrust belt. In front of these ramps a thin-skinned thrust belt developed in eastern Cordillera Principal with back-thrusts above an advancing wedge (Figures 8a and 9a). The Nieves Negras structures have been interpreted as inverted roll over anticlines (Figures 8b and 9b). The faults present in the immediate footwall of the inverted faults may be interpreted as footwall short-cut faults. These folds are cut both in the western and eastern flanks by out-of-sequence thrusts indicating that they are the oldest structures of the area. Both Yeguas Muertas and Nieves Negras areas are narrow belts of folding and intense deformation interpreted to be the product of buttressing against preexisting normal faults controlling primary sedimentary thickness variation.

[31] The Morado thrust, identified from 33° to 34°S, outlines the border between thin and thick-skinned zones (Figure 7). This thrust defines a major tectonic feature, which emplaces the eastern sheet of Upper Jurassic red beds on top of the Cretaceous sequences. It is an outstanding out-of-sequence thrust because it decapitates the underlying folds in the Tupungato and Yeguas Muertas areas and cuts the thin-skinned structures of the central domain.

[32] The rift model proposed here corresponds to listric fault systems in which the NNW-trending faults nucleated above a major detachment (Figures 6 and 7). Because synrift deposits do not crop out and subsurface data are lacking, only assumptions about the polarity of the master detachment can be made. A westward polarity has been assumed to account for the inversion of the crestal collapse graben faults in the Yeguas Muertas depocenter and the inversion of rollover structures in the Nieves Negras depocenter.

4.2. Cordillera Frontal

[33] The Cordillera Frontal consists of several basement blocks uplifted toward the east of the Aconcagua fold and thrust belt. During Late Cenozoic compression this morphostructural unit behaved as a rigid block disrupted by medium to high angle faults. At the study latitudes it is composed, from north to south, by the Cordón del Plata,

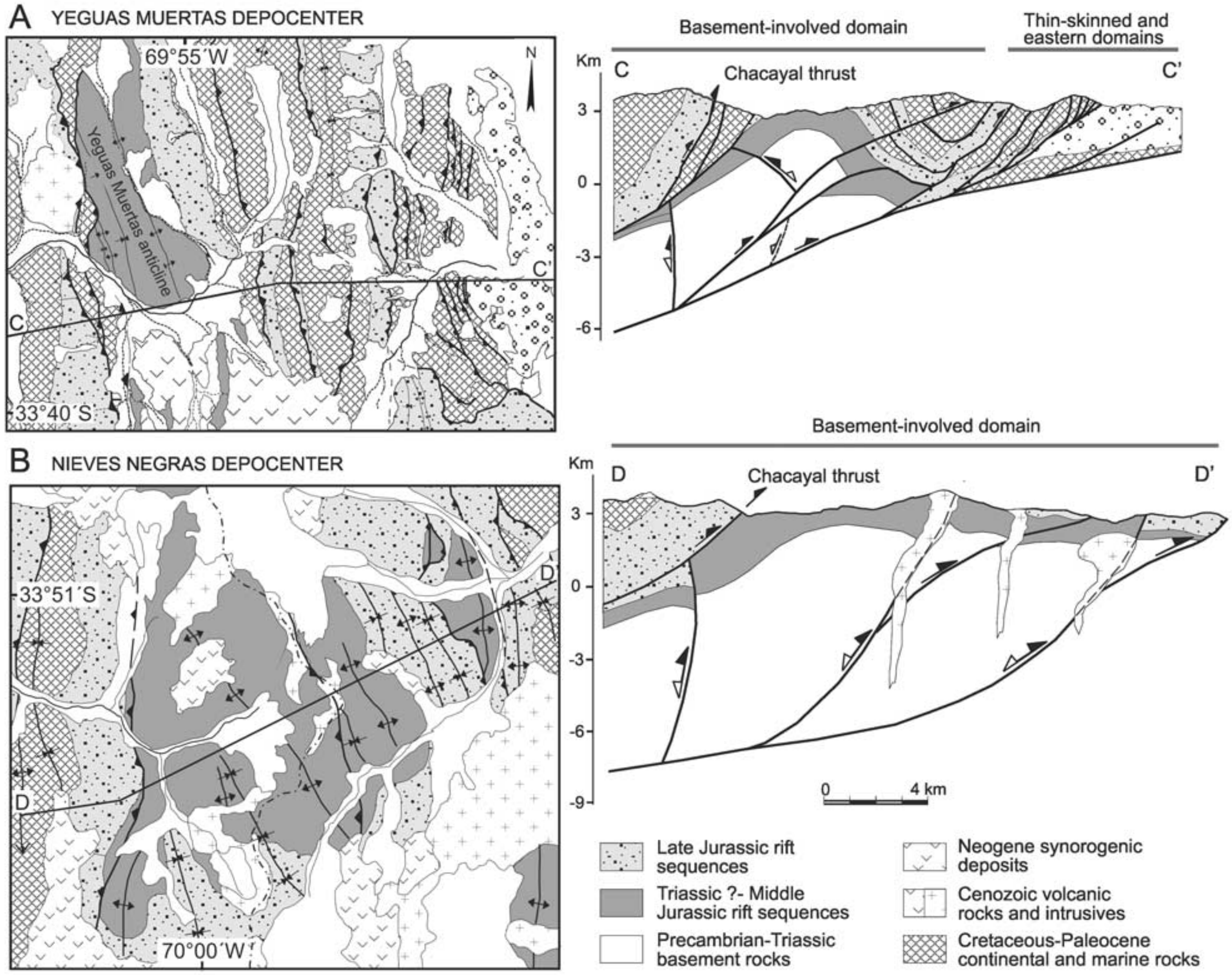


Figure 8. Geological maps and structural cross sections of (a) Yeguas Muertas depocenter and (b) Nieves Negras depocenter. Locations are indicated in Figure 7. Note the interaction between thin and thick-skinned structures in the north and the different amount of shortening between the Yeguas Muertas and Nieves Negras sectors.

Cordón del Portillo and Cordillera de las Llaretas ranges (Figure 3). The Cordón del Plata is uplifted by the La Carrera fault system [*Caminos*, 1965] consisting of four N to NNE-trending high-angle faults crossing by sinistral strike-slip faults with NW orientation and great continuity. The Late Paleozoic age of each structure can be well deciphered in areas where the angular unconformity separating the Permian-Triassic volcanics from the underlying rocks is present [*Folguera and Giambiagi*, 2002]. This unconformity was generated during the Late Paleozoic compression (San Rafael orogeny). Toward the southeast, the system involves other faults that have not yet become fully emergent in the alluvial cover of the Andean piedmont (Figure 3).

[34] In the Cordón del Portillo two trends of regional structures exist: NNE-trending faults in the northern region and N to NNW-trending faults in the southern half, related to Late Paleozoic structures (Figure 3). The range was also affected by the westernmost and easternmost faults of the La Carrera system. One of this structure, the Cerro Arenal fault, uplifts the Cordón del Plata and is responsible for the tilting of the basement of the Aconcagua fold and thrust belt. The Cordillera de las Llaretas was uplifted along two NNW-trending high angle faults which juxtaposed the Late Paleozoic granitoids to the Permian-Triassic volcanic rocks.

[35] A crustal detachment is required for propagating shortening within the Cordillera Frontal. This detachment can be related to a brittle-ductile transition or a weak zone inherited from a previous midcrustal flat detachment. Since the structures in the deformational front of the Cordillera Frontal are related to previously developed faults, these favorably oriented preexisting basement discontinuities constitute weakness zones available for reactivation.

4.3. Cuyo Basin

[36] The Triassic–Neogene Cuyo basin, located in the Andean foreland, is characterized by a series of spaced

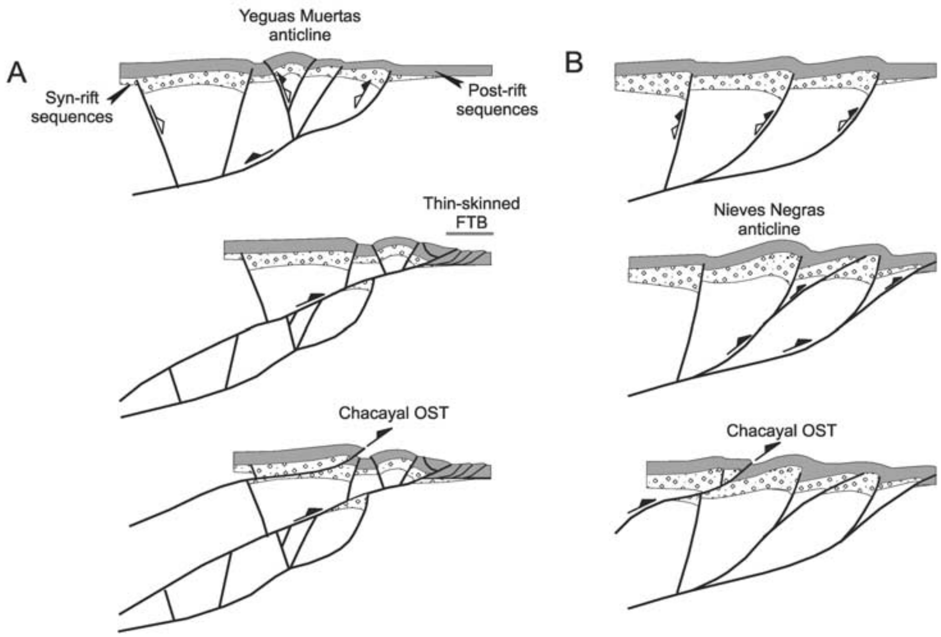


Figure 9. Three-stage schematic models (not to scale) illustrating two scenarios for tectonic inversion of the Triassic-Jurassic rift structures. (a) In the north, the generation of a bypass fault is interpreted after the reactivation of the crestal collapse graben faults [*Giambiagi and Ramos*, 2002]. (b) In the south, a phase of tectonic inversion was followed by the generation of shortcut faults in the footwall of the previously reactivated extensional faults. Note the Chacayal thrust cutting the previously folded Triassic-Jurassic strata.

elongate folds, locally broken by reverse faults displaying eastward or westward vergence [*Dellapé and Hegedus*, 1995]. These structures are aligned along two NNW-striking structural trends (Figure 3). This lineal development is thought to be reflecting the regional extension nucleated on a major crustal discontinuity along the Chilenia and Precordillera terrane boundary [*Ramos and Kay*, 1991].

[37] The basin was marginally uplifted and subjected to moderate structural inversion of the Triassic half-grabens and its related relay transfer faults bounded during Late Cenozoic compression [*Legarreta et al.*, 1992]. Several authors have postulated the tectonic inversion of previous normal faults [*Legarreta et al.*, 1992; *Dellapé and Hegedus*, 1995]; however, new seismic reflection studies combined with focal mechanisms of recent earthquakes show that normal faults were not significantly reactivated and middle to gently dipping basement faults with vergence toward the east (Figure 6) were responsible for the deformation of the basin [*Chiaramonte et al.*, 2000].

5. Timing and Style of Deformation

5.1. Correlations Between Distal and Proximal Synorogenic Units

[38] The Tunuyán Conglomerate represents the western proximal and coarser facies linked to coeval distal deposits of the Mariño Formation (Figure 10). Magnetostratigraphy carried out by *Irigoyen et al.* [2002], in the area between 33°00′ and 33°20′S, calibrated by $^{40}Ar/^{39}Ar$ dating of interbedded air-fall deposits, indicates an age of 15.7 Ma for the base of the Mariño Formation and 12.2 Ma for the top. Based on these data and the diachroneity between deposition in proximal and distal foreland basin, it has been proposed that deposition of the Tunuyán Conglomerate started around 18 to 17 Ma, and continued to ~10 Ma [*Giambiagi et al.*, 2001]. Deposition of the La Pilona Formation started at or slightly before 11.7 Ma and continued to 9 Ma in the Cacheuta-Tupungato area (33° to 33°20′S) [*Irigoyen et al.*, 2002]. In the same area, these authors dated the deposition of the Tobas Angostura Formation between 8.9 and 8.7 Ma and deposition of the Río de los Pozos Formation between 8.7 and 5.8 Ma. The volcanic material of the lower member of the Palomares Formation has been interpreted to proceed from the Tobas Angostura Formation; while the upper member has been assumed to be coeval with the sedimentation of the lower part of the Río de los Pozos Formation [*Giambiagi et al.*, 2001]. According to this interpretation the deposition of the Palomares Formation is considered to have occurred between 8.5 and 7 Ma. Because of the diachroneity in the uplift of the Cordillera Frontal, to be discussed later, the La Pilona Formation is thought to be diachronic along strike from 33° to 34°S, being younger toward the south.

[39] The Butaló Formation is unconformably overlaid by andesitic volcanic rocks dated as 5.9 Ma (whole rock K/Ar age) [*Ramos et al.*, 2000]. Therefore the age of this unit ranges from 7 to 6 Ma and indicates its deposition was

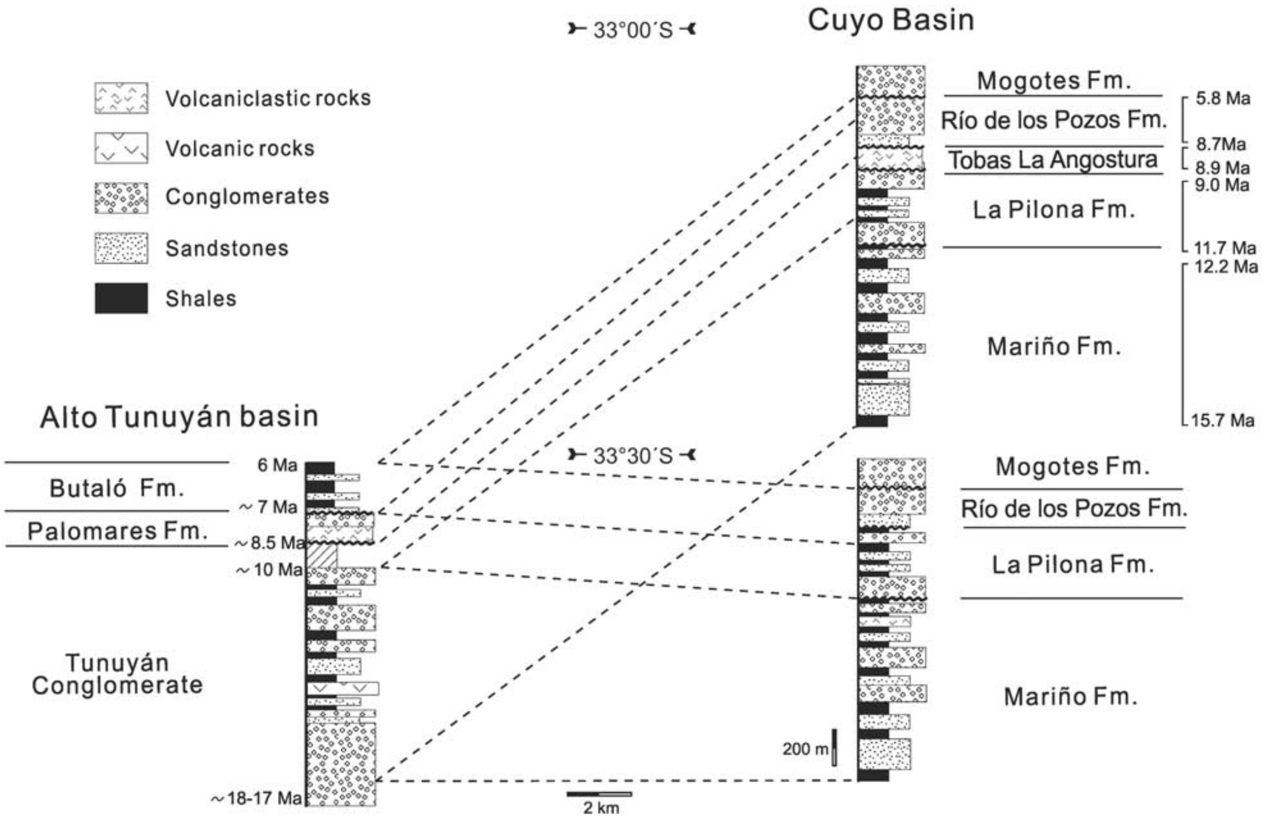


Figure 10. Representative lithological sections showing time correlations between the Neogene synorogenic units cropping out in the Alto Tunuyán and Cuyo basins [*Irigoyen*, 1997; this work]. Note the inferred diachroneity of the deposits north and south in the Cuyo basin. Age of the synorogenic deposits at 33°00′S has been magnetostratigraphically constrained by *Irigoyen et al.* [2000].

coeval with that of the upper part of the Río de los Pozos Formation.

5.2. Compressional Phases

[40] Based on accurate recording of the relationships between structures and synorogenic strata we identified five main local phases of compressional deformation (Figure 11). The clasts of the lower part of the Tunuyán Conglomerate and Mariño Formation were derived from the volcanic arc, indicating an earlier deformation phase (D1) of the Cenozoic extensional system and its superimposed volcanic arc. At 15 Ma, there was an abrupt change in clast composition of the synorogenic units, from volcanic clasts to the first appearance of Upper Mesozoic sedimentary clasts [*Irigoyen*, 1997; *Giambiagi*, 1999]. This is interpreted to be related to the second phase of deformation (D2), which accommodated shortening in eastern Cordillera Principal. The migration of deformation toward the foreland was documented by growth structures in the upper 400 m of the Tunuyán Conglomerate (Figures 5b and 5c).

[41] The unconformity that separates the Palomares and La Pilona Formations from the underlying strata, the changes in paleocurrent directions for both units, and the presence of locally derived conglomerates, provide evidence for the beginning of the phase D3 and the uplift of the Cordillera Frontal (Figure 11). After the deposition of the Palomares and La Pilona Formations sediments, interpreted as a sedimentary wedge system related to uplift of the Cordillera Frontal, the next phase (D4) is marked by the emplacement of out-of-sequence thrusts in the western and eastern Cordillera Principal and in-sequence thrusts in the Alto Tunuyán basin.

[42] A stock dated in 3.4 Ma [*Ramos et al.*, 1997] in the Paso Colinas area (34°S) slightly postdates the generation of the youngest structures of the region. Therefore, the main deformation event in the Cordillera Principal must have occurred before Early Pliocene (Figure 11).

[43] The last phase of deformation (D5) accommodates shortening concentrated in the Cuyo basin and in the La Carrera thrust system in the Cordillera Frontal. Earthquake focal mechanisms and neotectonic activity indicate that the eastern border of the Precordillera and the Cuyo basin are still active [*Cortés et al.*, 1999; *Chiaramonte et al.*, 2000].

5.3. Variation in Deformation Along Strike

[44] The first phases of deformation involve shortening across the Cordillera Principal with along strike variations

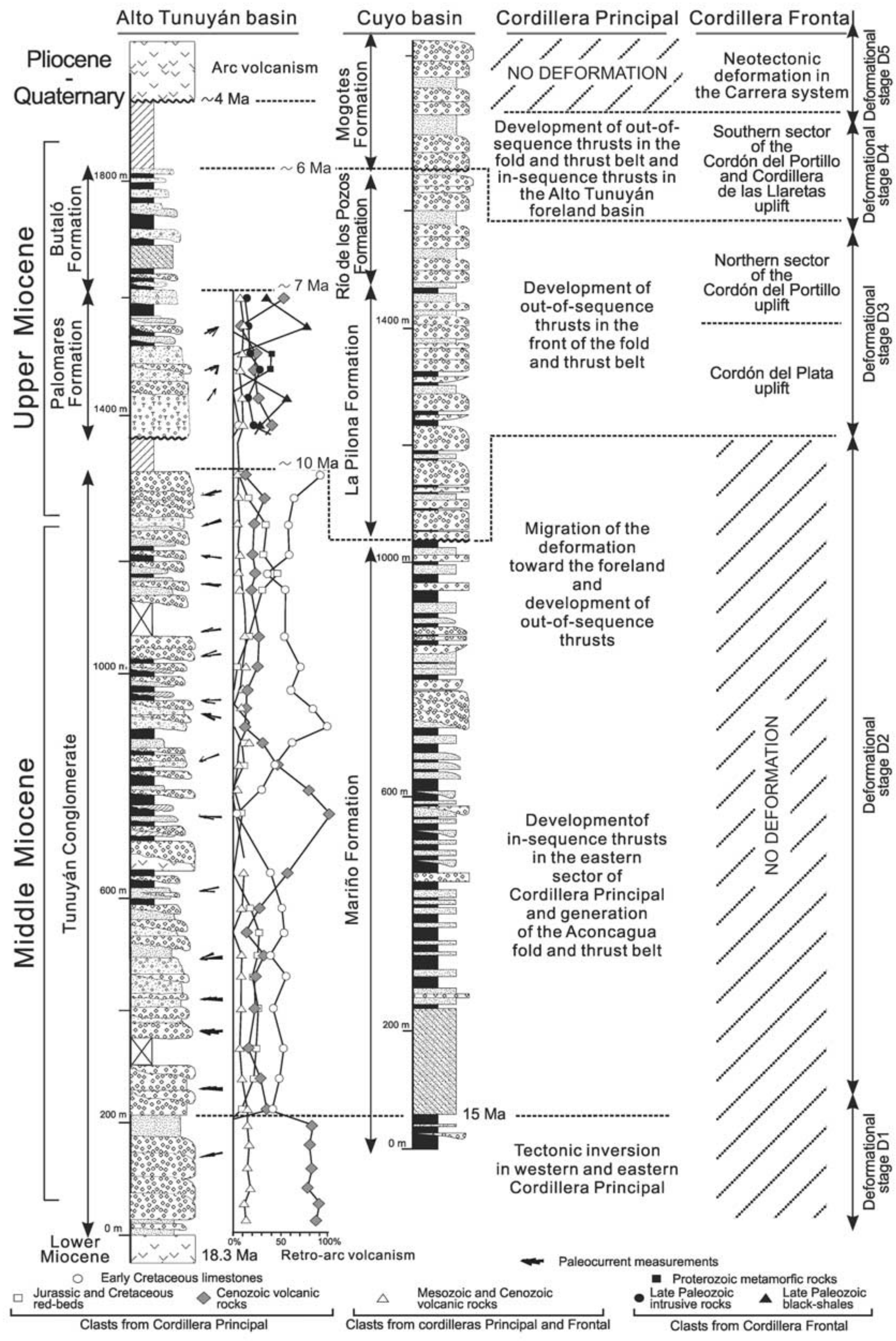


Figure 11. Representative vertical sedimentary sections of the Neogene synorogenic deposits of the Alto Tunuyán and Cuyo basins, and the main tectonic events in the Cordillera Principal and Cordillera Frontal between 33° and 34°S. Clast provenance and paleocurrent measurements of the Conglomerado Tunuyán and the Palomares Formation are indicated.

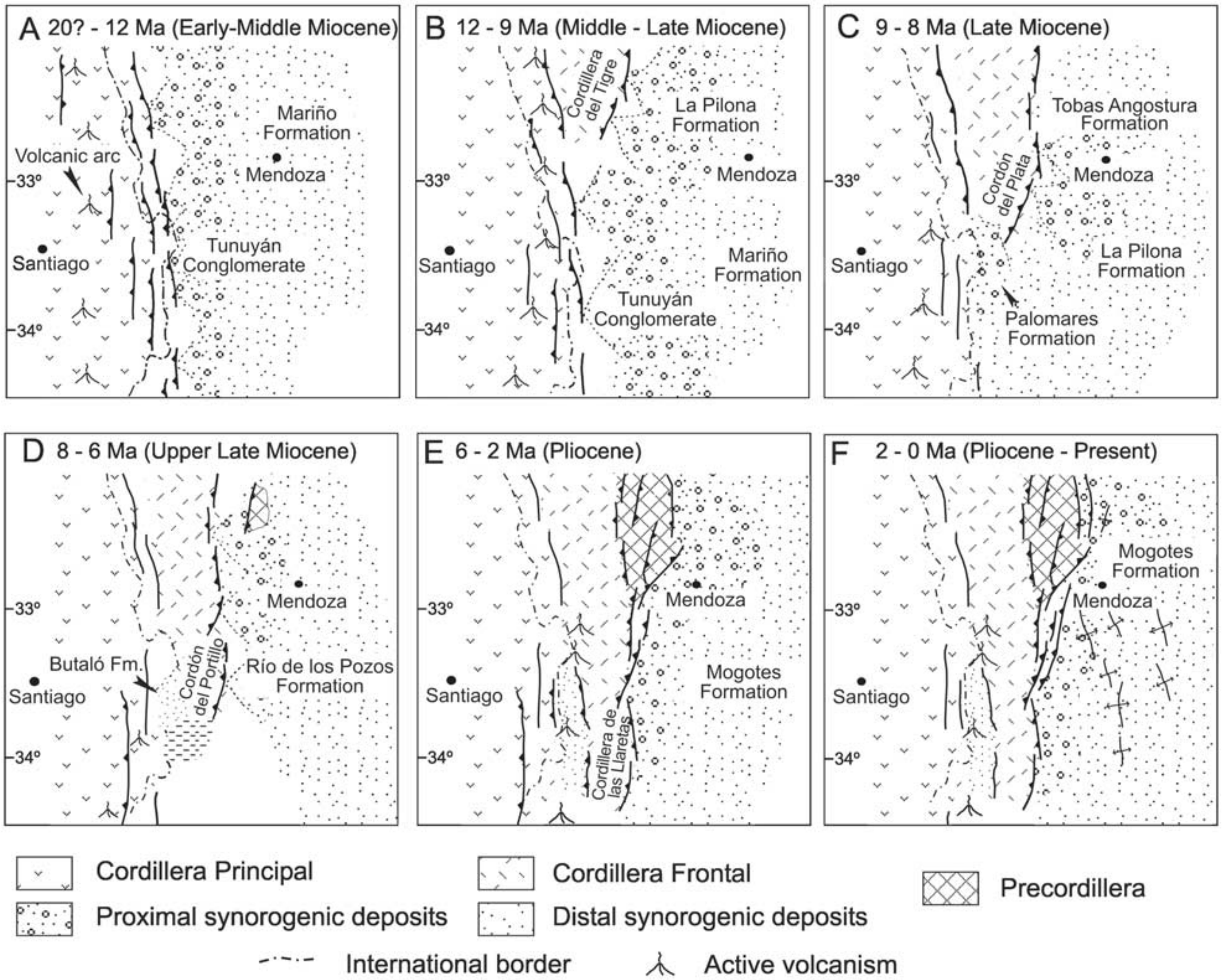


Figure 12. Series of interpretative maps summarizing along strike variations in the evolution of the Andes, from 32° to 34°S, based on structural relationships, sediment thicknesses, facies distribution, paleotransport data and clast composition. The cities of Mendoza and Santiago and the international border are given for reference. (a) Deformation and uplift of the Cordillera Principal and generation of a foreland basin. The volcanic arc is active in the present Chilean side. (b) Migration of the deformation toward the Cordillera del Tigre (Cordillera Frontal) north of 33°S. (c) The former uniform sedimentation area has been subdivided by uplift of the crystalline basement block of Cordón del Plata. This range constituted the source area for the La Pilona and Palomares Formations. North of 33°S the arc volcanism ceased. (d) Migration of the deformation of the Cordillera Frontal towards the south led to the basement uplift of the Cordón del Portillo and segmentation of the foreland basin. (e) Uplift of the southern range of the Cordillera Frontal, Cordillera de las Llaretas, and migration of the volcanic arc to its present-day position in the border between Argentina and Chile. (f) Deformation of the Cuyo basin and the Precordillera.

in the tectonic style due to basement structural control, but with apparently no significant along strike variation in timing of deformation (Figure 12a). The only variation in deformation registered occurred in western Cordillera Principal where, north of the Maipo river, the uplift and cooling of the intrusives occurred slowly during the Early Miocene (20–16 Ma), while south of this river the uplift of volcanics and plutons have been rapidly uplifted during Late Miocene [*Godoy et al.*, 1999].

[45] Neogene synorogenic deposits indicate regional along-strike change in style and timing of deformation. North of 33°S significant deformation has occurred between 12 to 9 Ma with the uplift of the Cordillera del Tigre, as indicated by paleocurrent data from the La Pilona Formation [*Irigoyen*, 1997] (Figure 12b). South of 33°30′S the foreland basin continued to receive sediments from the Cordillera Principal.

[46] Paleocurrent data from the lower and upper parts of the Palomares Formation show that the source area was the

southern part of the Cordón del Plata and the north-western part of the Cordón del Portillo respectively (Figure 12c). Therefore, it is suggested here that the Cordillera del Tigre was uplifted first and then the Cordón del Plata and Cordón del Portillo followed between 9 and 6 Ma (Figures 12c and 12d). The last ranges to be uplifted were the southern part of the Cordón del Portillo, the Cordillera de las Llaretas and Precordillera, as registered by clast provenance of the Río de los Pozos and Mogotes Formations (Figures 12d, 12e, and 12f).

[47] This along strike variation in timing of the deformation of the Cordillera Frontal is consistent with the southward propagation in the flat slab configuration [*Yáñez et al.*, 2001], indicating a relationship between this deformation and the subduction geometry change.

6. Discussion: Onset of Deformation

[48] The reorganization of plate motion in the South Pacific during the Late Oligocene [*Tebbens and Cande*, 1997] generated an increase in the rate of convergence between Nazca and South American plates [*Pilger*, 1984; *Pardo-Casas and Molnar*, 1987]. Prior to 28 Ma, the convergence rate was notable slow and the obliquity relative to the plate margin high at these latitudes. Between 28 and 26 Ma, the convergence rate roughly tripled in speed and obliquity dropped to approximately 10° [*Pardo-Casas and Molnar*, 1987; *Somoza*, 1998]. Traditional models link high rates of convergence to strong compressional coupling between overriding and subducting plates [e.g., *Uyeda and Kanamori*, 1979; *Cross and Pilger*, 1982]. However, there are several lines of evidence supporting the hypothesis that compressional deformation started only around 20 to 18 Ma at the study latitudes: (1) the first indication of tectonism and uplift of the Cordillera Principal represented by deposition of the synorogenic strata of the Tunuyán Conglomerate and Mariño Formation in the Early-Middle Miocene (~18 Ma); (2) the slow uplift and cooling of intrusives emplaced in the Abanico Formation during the Early Miocene (20–16 Ma) [*Kurtz et al.*, 1995, 1997]; (3) the presence of an extensional basin in western Cordillera Principal during Oligocene–Early Miocene times; and (4) the existence of the retro-arc geochemical signature of the Contreras volcanism in eastern Cordillera Principal which indicates an unthickened crust until ~18 Ma.

[49] The evidence described above suggests that there was a time lag of 8 to 10 Mys between the change in convergence rate and obliquity and the onset of compressional deformation. This conclusion meets those obtained by *Muñoz et al.* [2000] and *Jordan et al.* [2001] who remarked that the time of initiation of Oligocene–Early Miocene extensional basins correlate well with the time of plate convergence change.

[50] Confusion regarding the onset of deformation at these latitudes is attributed mainly to the presence of a residual conglomerate known as the "Rodados Lustrosos," wrongly correlated with the basal part of the Mariño Formation [*Gorroño et al.*, 1979; *Yrigoyen*, 1993]; as well as uncertainties about the age of the synorogenic strata. *Sempere et al.* [1994] proposed that deformation started in the volcanic arc and in the fold and thrust belt near the Early Oligocene-Late Oligocene boundary (~27 Ma) because they correlated the base of the synorogenic units with the "Rodados Lustrosos." In the Alto Tunuyán basin, the "Rodados Lustrosos" bed overlies a Paleocene unit and is unconformably overlain by the Early Miocene Contreras Formation. Stratigraphical relations thus suggest that the unconformity at the base of the Middle to Upper Miocene strata records the onset of tectonic loading in the fold and thrust belt, and not the base of the "Rodados Lustrosos" as previously pointed out by *Sempere et al.* [1994].

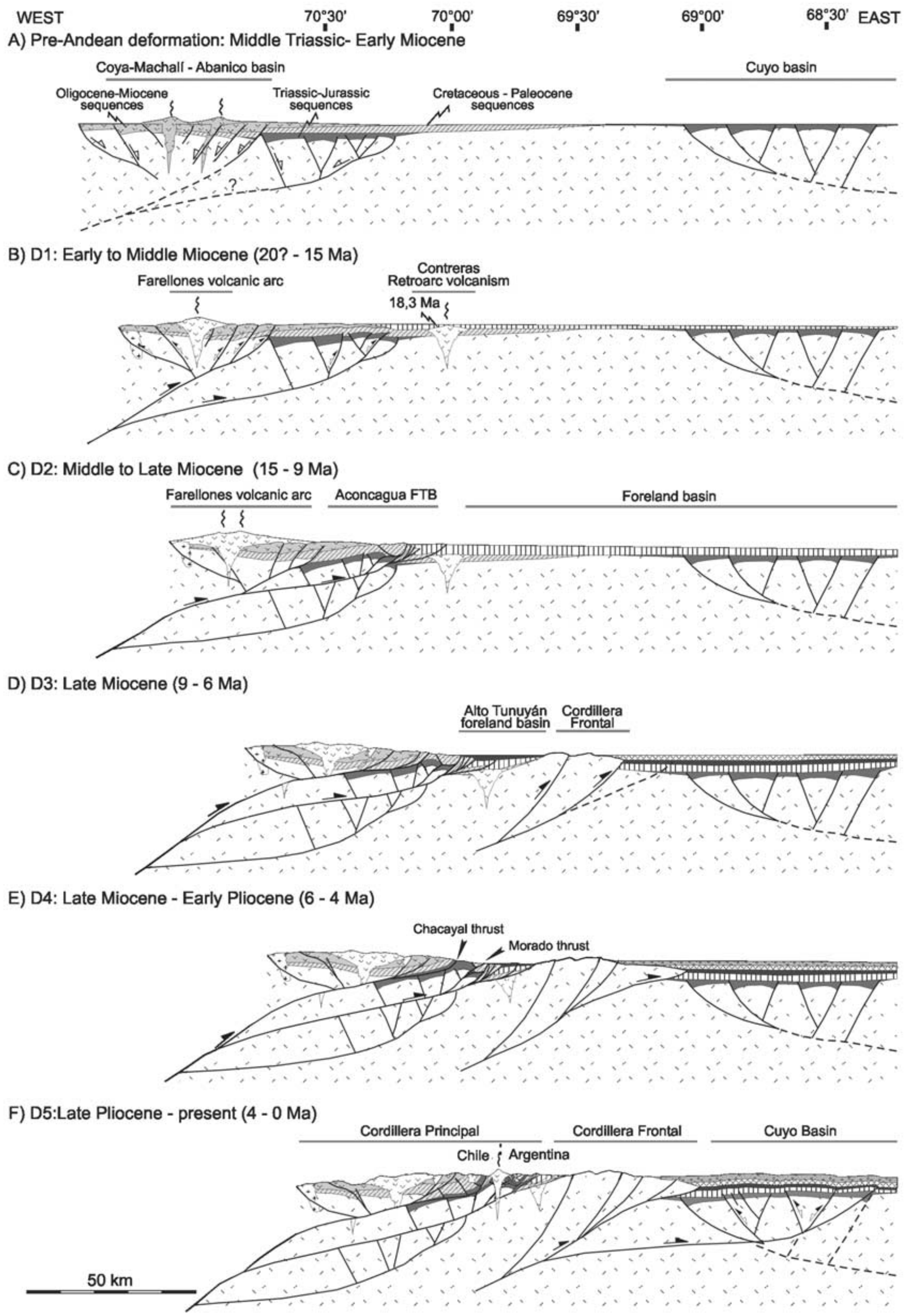
7. Evolutionary Model

[51] Structural and sedimentological data have been integrated to show the progressive development of the Andes at the latitudes between 33° and 34°S during Cenozoic times (Figure 13).

7.1. Pre-Andean Deformation

[52] During Mesozoic and Early Cenozoic times, a series of rift systems developed along the western margin of the continent at these latitudes. We believe that the westward shift of the rift systems from Late Triassic to Oligocene times in the Cordillera Principal is best explained by an intracrustal detachment model related to simple shear extension (Figure 13a), although we have no direct evidence

Figure 13. (opposite) Schematic sequence of cross section s summarizing the interpreted evolution (in stages) of the Andean deformation at 33°40′S, since Early Miocene time. (a) Configuration of basement-cover strata prior to Andean deformation. Possible intracrustal detachment rift systems for the Cordillera Principal. (b) Inversion of previously developed normal faults of western and eastern Cordillera Principal and presence of retro-arc volcanism in the foreland. Depositon of the lower part of the Tunuyán Conglomerate and the Mariño Formation synorogenic sediments. (c) Generation of a main thrust in the basement and in-sequence foreland-propagating fold-thrust evolution in the Aconcagua belt. Deposition of the upper part of the Tunuyán Conglomerate and the Mariño Formation sediments. (d) Uplift of the Cordón del Portillo. Deposition of the sedimentary wedge represented by the Palomares and Butaló Formations in the Alto Tunuyán basin, and the La Pilona and Río de los Pozos Formations in the Cuyo basin. (e) Out-of-sequence thrusting in the Cordillera Principal and active faulting of the easternmost Cordón del Portillo. Deposition of the Mogotes Formation sediments. (f) Migration of the magmatic arc toward its present position and deformation of the Cuyo basin. The position of the Chilean-Argentine border is shown for reference.


WEST
70°30'
70°00'
69°30'
69°00'
68°30'
EAST
A) Pre-Andean deformation: Middle Triassic- Early Miocene
Coya-Machalí - Abanico basin
Cuyo basin
Oligocene-Miocene sequences
Triassic-Jurassic sequences
Cretaceous - Paleocene sequences
B) D1: Early to Middle Miocene (20? - 15 Ma)
Farellones volcanic arc
Contreras Retroarc volcanism
18,3 Ma
C) D2: Middle to Late Miocene (15 - 9 Ma)
Farellones volcanic arc
Aconcagua FTB
Foreland basin
D) D3: Late Miocene (9 - 6 Ma)
Alto Tunuyán foreland basin
Cordillera Frontal
E) D4: Late Miocene - Early Pliocene (6 - 4 Ma)
Chacayal thrust
Morado thrust
F) D5:Late Pliocene - present (4 - 0 Ma)
Cordillera Principal
Cordillera Frontal
Cuyo Basin
Chile
Argentina
50 km

for such a detachment. For the Cuyo basin, normal faulting is thought to be linked to the reactivation of preexisting basement anisotropies.

7.2. Deformational Stage D1: Early to Middle Miocene (20?–15 Ma)

[53] During the Early Miocene, between 20? and 15 Ma, E–W and ESE–WNW shortening across the western and central sector of the Cordillera Principal was accommodated by tectonic inversion of the Mesozoic and Early Cenozoic extensional systems and its superimposed volcanic arc. The model presented here postulates that at the beginning of the contractional deformation the basement decollement reused the basal rift structure and generated the inversion of preexisting normal faults (Figure 13b). This is prone to occur immediately after the extensional process because the attenuated lithosphere has not thermally re-equilibrated [*Ziegler*, 1989]. During the first 1 or 2 Ma the uplift was concentrated in the Oligocene extensional basin of western Cordillera Principal. At around 18 Ma, inversion of the Mesozoic extensional basin located in the eastern Cordillera Principal took place after the extrusion of the Contreras retro-arc volcanic rocks.

7.3. Deformational Stage D2: Middle to Late Miocene (15–9 Ma)

[54] The main phase of deformation of the Aconcagua fold and thrust belt occurred during this stage. A basement thrust transported the inverted structures of the western Cordillera Principal, forming a hybrid thin and thick-skinned belt. Overprinting relationships indicate that the fold and thrust belt evolved by a forward propagating thrust sequence with constant periods of out-of-sequence thrusts emplacement. During this stage uplifting of the Cordillera Frontal was confined north of 33°S to the Cordillera del Tigre (Figure 11).

7.4. Deformational Stage D3: Late Miocene (9–6 Ma)

[55] The third phase of deformation was recorded by regional influx of thick coarse conglomerates, in both proximal and distal foreland basins, related to the uplift of Cordillera Frontal. During this stage, the deformation of the Cordillera Frontal progressed southward, uplifting the Cordón del Plata and then the northern part of the Cordón del Portillo (Figure 11). This event was responsible for the generation of a broken foreland basin and the development of a cumulative wedge represented by the proximal synorogenic deposits of the Palomares and Butaló Formations. During this time the emplacement of out-of-sequence thrusts took place in western Cordillera Principal (Figure 13d).

7.5. Deformational Stage D4: Late Miocene–Early Pliocene (6–4 Ma)

[56] The next phase (D4) is marked by the emplacement of out-of-sequence thrusts in the western and eastern Cordillera Principal and in-sequence thrusts in the Alto Tunuyán foreland basin (Figure 13e). During this phase, basin inversion and contemporaneous volcanic arc building in the western Cordillera Principal south of 33°30′S reached a climax due to the emplacement of the Fierro out-of-sequence thrust constrained between 9 and 3.5 Ma [*Godoy et al.*, 1999]. The basement uplift of the Cordillera Frontal prevented the propagation of the thrust belt towards the foreland. As a result, a series of out-of-sequence thrusts, such as the Morado and Chacayal thrusts, developed in the eastern Cordillera Principal and the Alto Tunuyán foreland basin was partially cannibalized. This phase terminated the sedimentation in this basin, while the Cuyo basin continued to be a site of sedimentation up to recent times.

[57] Deformation of the Cordillera Frontal continued during this time with the uplift of the southern sector of the Cordón del Portillo and Cordillera de las Llaretas (Figure 11). The Cordón del Plata continued uplifting by the emplacement of the easternmost faults of the La Carrera fault system.

7.6. Deformational Stage D5: Early Pliocene–Present (4–0 Ma)

[58] After the emplacement of fast cooling granitoids with isotopic signatures indicating generation in a thickened crust in the western Cordillera Principal [*Godoy et al.*, 1999], magmatism shifted eastward to its present position in the eastern Cordillera Principal (Figure 13f). The Lower Pliocene - Pleistocene volcanic rocks unconformably cover the deformed belt. Thrusting along the Cordillera Principal had terminated by ~4 Ma and subsequently, the deformation front migrated to the Precordillera foothills, north of 33°S, and to the Cuyo basin and Cordillera Frontal foothills, south of 33°S (Figure 11). At this time the basal decollement of the Cuyo basin began to move, reactivating preexisting normal faults and generating new thrust faults. Motion on the folds of the Cuyo basin started after the beginning of deposition of the Mogotes Formation at ~3.0 Ma [*Yrigoyen*, 1993]. The presence of growth strata in the Barrancas anticline suggests that deformation has been synchronous with deposition in that area [*Chiaramonte et al.*, 2000]. Active tectonics by reactivation of the La Carrera fault system has recently been documented by fault piedmont scarps and rock-avalanches triggered by seismic shakes [*Fauqué et al.*, 2000].

8. Conclusions

[59] Our study has compiled previous data with new structural data of the Andes between 33° and 34°S, which bear on the progressive development of the orogen during Cenozoic times. In this paper we have shown that the deformation has migrated over time from the Cordillera Principal across the Cordillera Frontal and finally into the sub-Andean zone in five major thrusting events: (1) Early to Middle Miocene phase of compression which produced tectonic inversion of the Triassic-Jurassic extensional systems located in the eastern Cordillera

Principal and the Oligocene-Early Miocene extensional basin located in the western Cordillera Principal, (2) Middle to Late Miocene development of the Aconcagua fold and thrust belt in the eastern Cordillera Principal with the basement involved in low-angle thrusting resulting in hybrid thick- and thin-skinned structures, (3) Late Miocene uplift of the Cordillera Frontal, (4) Late Miocene–Early Pliocene out-of-sequence thrusting in the Cordillera Principal, and (5) Pliocene to present deformation of the foreland by inversion of Triassic rift structures and subsequent development of medium angle faults cutting previously inverted structures.

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References

Aguirre-Urreta, M. B., El tithoniano marino en la vertiente Argentina del paso de Piuquenes, paper presented at XIII Congreso Geológico Argentino, Asoc. Geol. Argent., Buenos Aires, 1996.

Alvarez, P. P., E. Godoy, and L. B. Giambiagi, Estratigrafía de la Alta Cordillera de Chile Central a la latitud del paso Piuquenes (33°35′LS), paper presented at XIV Congreso Geológico Argentino, Univ. Nac. de Salta, Salta, Argentina, 1999.

Alvarez, P. P., E. Godoy, and D. Sellés, Geología de la región del río Colorado, Andes Principales de Chile (33°25′S), paper presented at IX Congreso Geológico Chileno, Univ. de Santiago, Puerto Varas, Chile, 2000a.

Alvarez, P. P., V. A. Ramos, L. B. Giambiagi, and E. Godoy, Relationships between different depocenters of Triassic-Jurassic rift systems in the main Andes of Argentina and Chile, paper presented at the XXIII Geological International Congress, Río de Janeiro, 2000b.

Barazangi, B. A., and B. L. Isacks, Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America, *Geology*, *4*, –692, 1976.

Cahill, T., and B. L. Isacks, Seismicity and shape of the subducted Nazca plate, *J. Geophys. Res.*, *97*, 17,503–17,529, 1992.

Caminos, R., Geología de la vertiente oriental del Cordón del Plata, cordillera frontal de Mendoza, *Rev. Asoc. Geol. Argent.*, *20*, 351–392, 1965.

Cegarra, M., and V. A. Ramos, La faja plegada y corrida del Aconcagua, in *Geología de la Región del Aconcagua, Provincias de San Juan y Mendoza*, an. 24, edited by V. A. Ramos, pp. 387–422, Subsecr. de Min. de la Nac., Dir. Nac. del Serv. Geol., Buenos Aires, 1996.

Charrier, R., El Triásico de Chile y regiones adyacentes de Argentina: Una reconstrucción paleogeográfica y paleoclimática, *Comunicaciones*, *26*, 1–37, 1979.

Charrier, R., J. J. Flynn, A. R. Wyss, F. Zapatta, and C. C. Swisher, Antecedentes bio y cronoestratigráficos de la Formación Coya Machalí–Abanico, entre los Ríos Maipo y Teno (33°55′ y 35°10′S), cordillera principal, Chile central, paper presented at VIII Congreso Geológico Chileno, Univ. Católica del Norte, Antofagasta, Chile, 1997.

Charrier, R., O. Baeza, S. Elgueta, J. J. Flynn, P. Gans, S. M. Kay, N. Muñoz, A. R. Wyss, and E. Zurita, Evidence for Cenozoic extensional basin development and tectonic inversion south of the flat-slab segment, southern central Andes, Chile (33°–36°S.L.), *J. S. Am. Earth Sci.*, *15*, 117–139, 2002.

Chiaramonte, L., V. A. Ramos, and M. Araujo, Estructura y sismotectónica del anticlinal Barrancas, Cuenca Cuyana, provincia de Mendoza, *Rev. Asoc. Geol. Argent.*, *55*, 309–336, 2000.

Cortés, J. M., P. Vinciguerra, M. Yamín, and M. M. Pasini, Tectónica cuaternaria de la region Andina del Nuevo Cuyo (28°–38°LS), in *Geología Argentina*, an. 29, edited by R. Caminos, pp. 760–778778, Subsecr. de Min. de la Nac., Serv. Geol. Min. Argent., Buenos Aires, 1999.

Cross, T. A., and R. H. Pilger, Controls of subduction geometry, location of magmatic arcs, and tectonics of arc and back-arc regions, *Geol. Soc. Am. Bull.*, *93*, 545–562, 1982.

Dellapé, D., and A. Hegedus, Structural inversion and oil occurrence in the Cuyo basin of Argentina, in *Petroleum Basins of South America*, edited by A. J. Tankard, R. Suárez, and H. J. WELSINK, *AAPG Mem.*, *62*, 359–367, 1995.

Fauqué, L., J. M. Cortés, A. Folguera, and M. Etcheverría, Avalanchas de rocas asociadas a neotectónica en el valle del río Mendoza, al sur de Uspallata, *Rev. Asoc. Geol. Argent.*, *55*, 419–423, 2000.

Flynn, J. J., A. R. Wyss, R. Charrier, and C. C. Swisher, An early anthropoid skull from the Chilean Andes, *Nature*, *373*, 603–607, 1995.

Folguera, A., and L. B. Giambiagi, Estructura de la Precordillera Mendocina y sector oriental del Cordón del Plata, entre Potrerillos y Uspallata, 32°20′ a 33°00′S., paper presented at XV Congreso Geológico Argentino, Prov. de Santa Cruz, Calafate, Argentina, 2002.

Gana, P., and R. Wall, Geocronología Ar/Ar y K/Ar del límite Cretácico-Terciario en el borde oriental de la cuenca de Santiago, Chile Central (33°–33°30′), paper presented at VII Congreso Geológico Chileno, Univ. Católica del Norte, Antofagasta, Chile, 1997.

Giambiagi, L. B., Interpretación tectónica de los depósitos neógenos de la cuenca de antepaís del Alto Tunuyán, en la región del Río Palomares, cordillera principal de Mendoza, *Rev. Asoc. Geol. Argent.*, *54*, 361–374, 1999.

Giambiagi, L. B., and V. A. Ramos, Structural evolution of the Andes between 33°30′ and 33°45′ S, above the transition zone between the flat and normal subduction segment, Argentina and Chile, *J. S. Am. Earth Sci.*, *15*, 99–114, 2002.

Giambiagi, L. B., M. Tunik, and M. Ghiglione, Cenozoic tectonic evolution of the Alto Tunuyán foreland basin above the transition zone between the flat and normal subduction segment (33°30′–34°S), western Argentina, *J. S. Am. Earth Sci.*, *14*, 707–724, 2001.

Giambiagi, L. B., P. P. Alvarez, E. Godoy, and V. A. Ramos, The control of pre-existing extensional structures in the evolution of the southern sector of the Aconcagua fold and thrust belt, *Tectonophysics*, *369*, 1–19, 2003.

Godoy, E., El Caloviano del Estero Yeguas Muertas, Río Yeso del Maipo, Chile: Implicancias tectónicas y paleogeográficas, paper presented at XII Congreso Geológico Argentino and II Congreso de Exploración de Hidrocarburos, Asoc. Geol. Argent., Mendoza, Argentina, 1993.

Godoy, E., and W. Palma, El corrimiento del Fierro y su propagación como plegamiento en el Alto Río Maipo, Andes de Chile Central, paper presented at II Simposio sobre el Terciario de Chile, Univ. de Santiago, Santiago, Chile, 1990.

Godoy, E., G. Yáñez and E. Vera, Late Miocene volcanic arc thickening in the Chilean central Andes: Seismic and gravity constraints, paper presented at Third International Symposium on Andean Geodynamics, OSTROM éditions, Paris, 1996.

Godoy, E., G. Yáñez, and E. Vera, Inversion of an Oligocene volcano-tectonic basin and uplift of its superimposed Miocene magmatic arc, Chilean central Andes: First seismic and gravity evidence, *Tectonophysics*, *306*, 217–326, 1999.

Gorroño, P., R. Pascual, and R. Pombo, Hallazgo de mamíferos eogenos en el sur de Mendoza, Su implicancia en las dataciones de los ‘‘Rodados Lustrosos’’ y del primer episodio orogénico del terciario en esa region, paper presented at VII Congreso Geológico Argentino, Asoc. Geol. Argent., Buenos Aires, 1979.

Irigoyen, M. V., Magnetic polarity stratigraphy and geochronological constraints on the sequence of thrusting in the principal and frontal cordillera and the precordillera of the Argentine central Andes (33°S latitude), Ph.D. thesis, 392 pp., Carleton Univ., Ottawa, Ont., Canada, 1997.

Irigoyen, M. V., K. L. Buchan, and R. L. Brown, Magnetostratigraphy of Neogene Andean foreland-basin strata, lat 33°S, Mendoza Province, Argentina, *Geol. Soc. Am. Bull.*, *112*, 803–816, 2000.

Irigoyen, M. V., K. L. Buchan, M. E. Villeneuve, and R. L. Brown, Cronología y significado tectónico de los estratos sinorogénicos neógenos alforantes en la region de Cacheuta-Tupungato, Provincia de Mendoza, *Rev. Asoc. Geol. Argent.*, *57*, 3–18, 2002.

Jordan, T. E., B. L. Isacks, R. W. Allmendinger, J. A. Brewer, V. A. Ramos, and C. J. Ando, Andean tectonics related to geometry of subducted Nazca plate, *Geol. Soc. Am. Bull.*, *94*, 341–361, 1983.

Jordan, T. E., W. M. Burns, R. Veiga, F. Pángaro, P. Copeland, S. Kelley, and C. Mpodozis, Extension and basin formation in the Southern Andes caused by increased convergence rate: A Mid-Cenozoic trigger for the Andes, *Tectonics*, *20*, 308–324, 2001.

Klohn, C., Geología de la Cordillera de los Andes de Chile central, provincia de Santiago, O'Higgins, Colchagua y Curicó, *Inst. Invest. Geol.*, *8*, 1–95, 1960.

Kokogian, D. A., and O. H. Mancilla, Análisis estratigráfico secuencial de la Cuenca Cuyana, in *Cuencas Sedimentarias Argentinas, Correl. Geol. Ser.*, vol. 6, edited by G. Chebli and L. Spalletti, pp. 169–201, Fac. de Cienc. Nat., Univ. Nac. de Tucumán, Tucumán, Argentina, 1989.

Kurtz, A., S. Kay, A. Tittler, C. Mpodozis, and E. Godoy, Neogene magmatism in the Andean Cordillera (26°S to 34°S): Evidence for spatial and temporal changes in crustal thickness (abstract), *Eos Trans. AGU*, *76*(17), Spring Meet. Suppl., S272, 1995.

Kurtz, A., S. Kay, R. Charrier, and E. Farrar, Geochronology of Miocene plutons and exhumation history of the El Teniente region, central Chile (34°35°S), *Rev. Geol. Chile*, *24*, 73–90, 1997.

Legarreta, L., D. A. Kokogian, and D. A. Dellapé, Estructuración terciaria de la Cuenca Cuyana: ¿Cuánto de inversión tectónica?, *Rev. Asoc. Geol. Argent.*, *47*, 83–86, 1992.

Llambias, E. J., and A. M. Sato, El batolito de Colangüil (28° – 31°S), cordillera frontal de Argentina: Estructura y marco tectónico, *Rev. Geol. Chile*, *17*, 89 – 108, 1990.

Lo Forte, G., Los depósitos jurásicos de la Alta Cordillera de Mendoza, in *Geología de la Región del Aconcagua, Provincias de San Juan y Mendoza*, an. 24, edited by V. Ramos et al., pp. 139 – 178, Subsecr. de Min. de la Nac., Dir. Nac. del Serv. Geol., Buenos Aires, 1996.

Muñoz, J., R. Troncoso, P. Duhart, P. Crignola, L. Farmer, and Ch. R. Stern, The relation of the mid-Tertiary coastal magmatic belt in south-central Chile to the late Oligocene increase in plate convergence rate, *Rev. Geol. Chile*, *27*, 177 – 203, 2000.

Nyström, J. O., M. A. Parada, and M. Vergara, Sr-Nd isotope composition of Cretaceous to Miocene volcanic rocks in central Chile: A trend towards an MORB signature and a reversal with time, paper presented at Third International Symposium on Andean Geodynamics, OSTROM éditions, Paris, 1993.

Pángaro, F., E. Godoy, and V. V. A. Ramos, La faja plegada y corrida de la cordillera principal de Argentina y Chile a la latitud del cerro Palomares (33°35′S), paper presented at XIII Congreso Geológico Argentino and III Congreso Exploración de Hidrocarburos, Asoc. Geol. Argent., Mendoza, Argentina, 1996.

Pardo-Casas, F., and P. Molnar, Relative motion of the Nazca (Farallon) and South American plates since Late Cretaceous time, *Tectonics*, *6*, 233 – 248, 1987.

Pilger, R. H., Cenozoic plate kinematics, subduction, and magmatism: South American Andes, *J. Geol. Soc. London*, *141*, 793 – 802, 1984.

Polanski, J., Descripción geológica de la hoja 25 a-b-Volcán de San José, provincia de Mendoza, *Bol. 98*, pp. 1 – 92, Dir. Nac. de Geol. y Min., Buenos Aires, 1964.

Polanski, J., Descripción geológica de la Hoja 24 a-b-Cerro Tupungato, provincia de Mendoza, *Bol. 128*, pp. 1 – 110, Dir., Nac. de Geol. y Min., Buenos Aires, 1972.

Ramos, V. A., The tectonics of the central Andes (30° – 33°S latitude), in *Proceses in Continental Lithospheric Deformation*, edited by S. Clark, D. Burchfiel, and D. Suppe, *Spec. Pap. Geol. Soc. Am.*, *218*, 31 – 54, 1988.

Ramos, V. A., and S. M. Kay, Triassic rifting and associated basalts in the Cuyo basin, central Argentina, in *Andean Magmatism and Its Tectonic Setting*, edited by R. S. Harmon and C. W. Rapela, *Spec. Pap. Geol. Soc. Am.*, *265*, 79 – 91, 1991.

Ramos, V. A., M. I. Cegarra, and E. Cristallini, Cenozoic Tectonic of the High Andes of west – central Argentina (30 – 36 S Latitude), *Tectonophysics*, *259*, 185 – 200, 1996a.

Ramos, V. A., E. Godoy, V. Godoy, and F. Pángaro, Evolución tectónica de la cordillera principal Argentino-Chilena a la latitud del Paso de Piuquenes (33°30′S), paper presented at XIII Congreso Geológico Argentino and III Congreso Exploración de Hidrocarburos, Asoc. Geol. Argent., Mendoza, 1996b.

Ramos, V. A., P. P. Alvarez, M. B. Aguirre Urreta, E. Godoy, La cordillera principal a la latitud del paso Nieves Negras (33°50′S), Chile-Argentina, paper presented at VIII Congreso Geológico Chileno, Univ. Católica del Norte, Antofagasta, 1997.

Ramos, V. A., M. B. Aguirre Urreta, P. P. Alvarez, A. Coluccia, L. B. Giambiagi, D. Pérez, M. Tunik, and G. Vujovich, Descripción de la Hoja Geológica Cerro Tupungato, 1:250.000, Subsecr. de Min. de la Nac. Dir. Nac. del Serv. Geol., Buenos Aires, 2000.

Rivano, S., E. Godoy, M. Vergara, and R. Villaroel, Redefinición de la Formación Farellones en la Cordillera de los Andes de Chile central (32° – 34°S), *Rev. Geol. Chile*, *17*, 205 – 214, 1990.

Rivano, S., P. Sepúlveda, R. Boric, and D. Espiñeira, Hojas Quillota y Portillo, 1:250,000, *Carta Geol.*, *73*, 1993.

Sempere, T., L. G. Marshall, S. Rivano, and E. Godoy, Late Oligocene – Early Miocene compressional tectosedimentary episode and associated land-mammal faunas in the Andes of central Chile and adjacent Argentina (32 – 37°S), *Tectonophysics*, *229*, 251 – 264, 1994.

Somoza, R., Updated Nazca (Farallon) – South America relative motions during the last 40 My: Implications for mountain building in the central Andean region, *J. S. Am. Earth Sci.*, *11*, 211 – 215, 1998.

Stauder, W., Subduction of the Nazca plate under Peru as evidenced by focal mechanism and by seismicity, *J. Geophys. Res.*, *80*, 1053 – 1064, 1975.

Tebbens, S. F., and S. C. Cande, Southeast Pacific tectonic evolution from early Oligocene to present, *J. Geophys. Res.*, *102*, 12,061 – 12,084, 1997.

Thiele, R., Hoja Santiago, IIG, *Carta Geol. Chile*, *39*, 51 pp., 1980.

Thiele, R., and R. Nasi, Evolución tectónica de los Andes a la latitud de 33° y 34° Sur (Chile Central) durante el Mesozoico, *V. Congr. Latinoam. Geol.*, *3*, 403 – 426, 1982.

Tunik, M., Análisis sedimentológico y tectónico de la primera ingresión Atlántica en la Alta Cordillera de Mendoza, Ph.D. thesis, 258 pp., Univ. de Buenos Aires, Buenos Aires, 2001.

Uliana, M. A., K. Biddle, and J. Cerdán, Mesozoic extension and the formation of Argentine sedimentary basins, in *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*, edited by A. Tankard and H. R. Balkwill, *AAPG Mem.*, *46*, 599 – 614, 1989.

Uyeda, S., and H. Kanamori, Back-arc opening and the mode of subduction, *J. Geophys. Res.*, *84*, 1049 – 1061, 1979.

Vergara, M., R. Charrier, F. Munizaga, S. Rivano, P. Sepúlveda, R. Thiele, and R. E. Drake, Miocene vulcanism in the central Chilean Andes (31°30′S – 34°35′S), *J. S. Am. Earth Sci.*, *1*, 199 – 209, 1988.

Vergara, M., D. Morata, R. Villarroel, J. Nyström, and L. Aguirre, Ar/Ar ages, very low-grade metamorphism and geochemistry of the volcanic rocks from "Cerro El Abanico," Santiago Andean Cordillera (33°30′S – 70°30′ – 70°25′W), paper presented at Fourth International Symposium on Andean Geodynamics, OSTROM éditions, 1999.

Wall, R. R., and P. F. Gana, Hoja Tiltil-Santiago, map, scale 1:100,000 scale 1:100,000, Serv. Nac. de Geol. y Min., Subdirec. Nac. de Min., Santiago, 1999.

Wyss, A. R., M. A. Norell, J. J. Flynn, M. J. Novacek, R. Charrier, M. C. McKenna, D. Frassinetti, P. Salinas, and J. Meng, A new Early Tertiary mammal fauna from central Chile: Implications for stratigraphy and tectonics, *J. Vertebr. Paleontol.*, *10*, 518 – 522, 1990.

Yáñez, G. A., C. R. Ranero, R. Von Huene, and J. Díaz, Magnetic anomaly interpretation across the southern central Andes (32° – 34°S): The role of the Juan Fernández Ridge in the Late Tertiary evolution of the margin, *J. Geophys. Res.*, *106*, 6325 – 6345, 2001.

Yrigoyen, M. R., Los depósitos sinorogénicos terciarios, in *Geología y Recursos Naturales de la Provincia de Mendoza*, edited by V. A. Ramos, *Congr. Geol. Argent. Rela., 12th*, 123 – 148, 1993.

Ziegler, P. A., Geodynamic model for alpine intra-plate compressional deformation in western and central Europe, in *Inversion Tectonics*, edited by M. A. Cooper and G. D. Williams, Geol. Soc. Spec. Publ., *44*, 63 – 85, 1989.

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