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Overview of the tectonic evolution of the southern Central Andes of Mendoza and Neuquén (35°–39°S latitude)

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ABSTRACT

The southern Central Andes of Argentina between 35° and 39°S latitude can be divided into two sectors with contrasting geological histories. The boundary between the sectors coincides with the Cortaderas lineament. North of the Cortaderas lineament, the Andes record a foreland expansion of arc magmatism that is associated with contractional deformation in the Malargüe fold-and-thrust belt, and subsidence of the Río Grande foreland basin between 15 and 5 Ma. The peak expansion of deformation into the foreland occurred as late Miocene magmatic arc rocks erupted more than 500 km east of the trench and the San Rafael basement block was uplifted in central Mendoza. This stage was followed by the collapse of the basement uplift by normal faulting, the retreat of the magmatic arc, and the eruption of widespread late Pliocene to early Pleistocene within-plate lava flows in the Payenia region. Extensive Quaternary calderas and rhyolitic domes along the axis of the main Andes reflect crustal melting associated with basaltic underplating. In contrast, the structural evolution of the sector south of the Cortaderas lineament is dominated by the Late Cretaceous development of the Agrio fold-and-thrust belt, which underwent minor reactivations in the Eocene and the late Miocene. The post-Miocene Guañacos fold-and-thrust belt that has since developed along the axis of the main Andes concentrates neotectonic contraction. Arc magmatism in this sector is largely restricted to the axial area of the Andes. Both the sectors north and south of the Cortaderas lineament show evidence of an important episode of extension during the Oligocene to early Miocene, and for renewed extension in the Pliocene and the Pleistocene. The contrasting geological histories north and south of the Cortaderas lineament reflect differences in the geometry of the subducting plate, variations in crustal rheologies inherited from a more restricted distribution of Mesozoic rifts in the northern than the southern segment, and variations in the trench roll-back velocity through time.

Keywords: Andes, Neuquén, Malargüe, Agrio, Payenia, flat-subduction, extension.

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INTRODUCTION

The various papers in this volume show that the segment of the Andean Cordillera between 35° and 39°S has distinctive characteristics when compared with other parts of the Argentine-Chilean Andes. Most of the Andean chain is under compression, and the present orogenic front is located between a retroarc fold-and-thrust belt and an undeformed foreland region. Magmatic rocks are generally concentrated along an active magmatic arc, except in areas of shallow subduction where volcanism is absent (e.g., Jordan et al., 1983; Kay et al., 1988). In contrast, the segment discussed here (Fig. 1) has some peculiarities, including: (1) a large amount of late Cenozoic magmatic activity in the foreland region (Bermúdez et al., 1993); (2) an active thrust front located west of an inactive Late Cretaceous to Miocene fold-and-thrust belt (Folguera et al., 2004; Ramos and Folguera, 2005); and (3) widespread Pliocene and Pleistocene extension (Polanski, 1963; González Díaz, 1964; Kozlowski et al., 1993; Folguera and Ramos, 2000, 2001, 2002).

The objective of this contribution is to present a synthesis of the tectonic evolution of the Neuquén and southern Mendoza segments of the Andes between 35° and 39°S based on information in recent publications and in the chapters in this volume. This synthesis shows that geologic observations in the northern part of the region fit with steepening of the subduction zone following a short period of flat-slab subduction during the Miocene as proposed by Kay (2001a, 2001b, 2002; Kay et al., this volume, chapter 2) and that those in the southern part fit with an oscillatory behavior of the subduction zone.

MAIN GEOLOGICAL FEATURES

The Andes between 35° and 39°S can be divided into two regions with distinctive evolutionary characteristics. These regions are bounded by a northwest-trending structural feature that was first described by Groeber (1938) and is referred to as the Cortaderas lineament (Ramos, 1981; Ramos and Barbieri, 1989). The Cortaderas lineament is defined by northwest-trending faults that can be traced to the Southern Volcanic Zone arc front where they control the recent craters of the Chillán volcano. The lineament was interpreted as a basement boundary that was reactivated during Andean deformation by Ramos (1981). Other authors consider the Cortaderas lineament to be a reactivated Paleogene north-verging thrust system (Cobbold and Rossello, 2003). Another important observation associated with the Cortaderas lineament is the concentration of Cenozoic magmatic activity to the north and the near absence of Cenozoic volcanism to the south (Ramos and Barbieri, 1989). Kay (2001a, 2001b; Kay et al., this volume, chapter 2) argued that the Cortaderas lineament marks the southern limit of a Miocene shallow subduction zone.

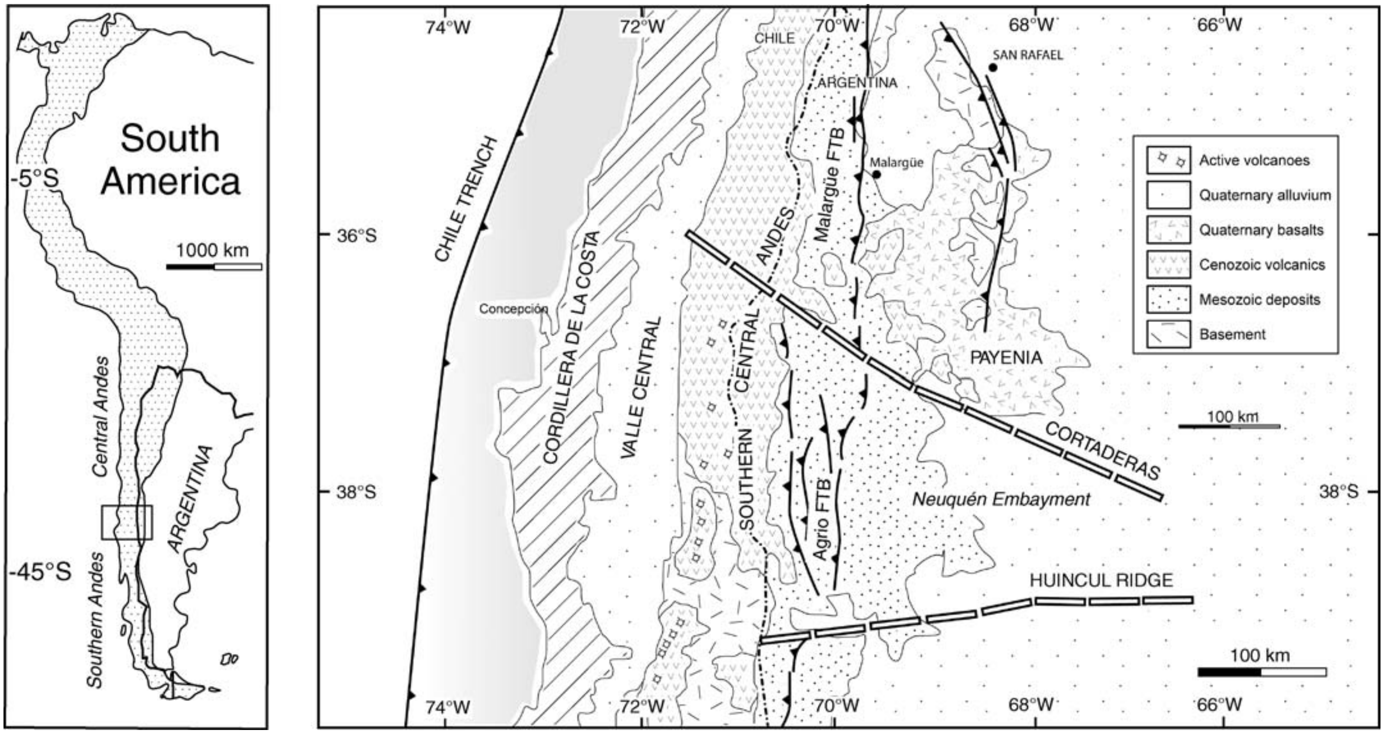


Figure 1. Map from the trench to the backarc showing the main geological provinces and structural features of the south-central Andes between 34°and 40°S. Differences in the regions north and south of the Cortaderas lineament are discussed in the text. Position of the Cortaderas lineament is based on Ramos and Barbieri (1989). FTB—fold-and-thrust belt.

The major geologic features of the regions north and south of the Cortaderas lineament are illustrated in the figures and summarized herein.

Region North of the Cortaderas Lineament

The major geologic features in the region between 37°S and 34°S, to the north of the Cortaderas lineament, are illustrated in Figures 2 and 3. The general characteristics of the area just north of the Cortaderas lineament are described in this volume by Kay and Copeland (chapter 9), Kay et al. (chapters 2 and 10), and Folguera et al. (chapters 11 and 12). The discussion herein integrates these features with those farther north in the province of Mendoza. From west to east, the main morphotectonic elements of the region include the main Andean range (Principal Cordillera), the Río Grande foreland basin, the San Rafael basement block, and the widespread Pliocene to Quaternary Payenia backarc volcanic field.

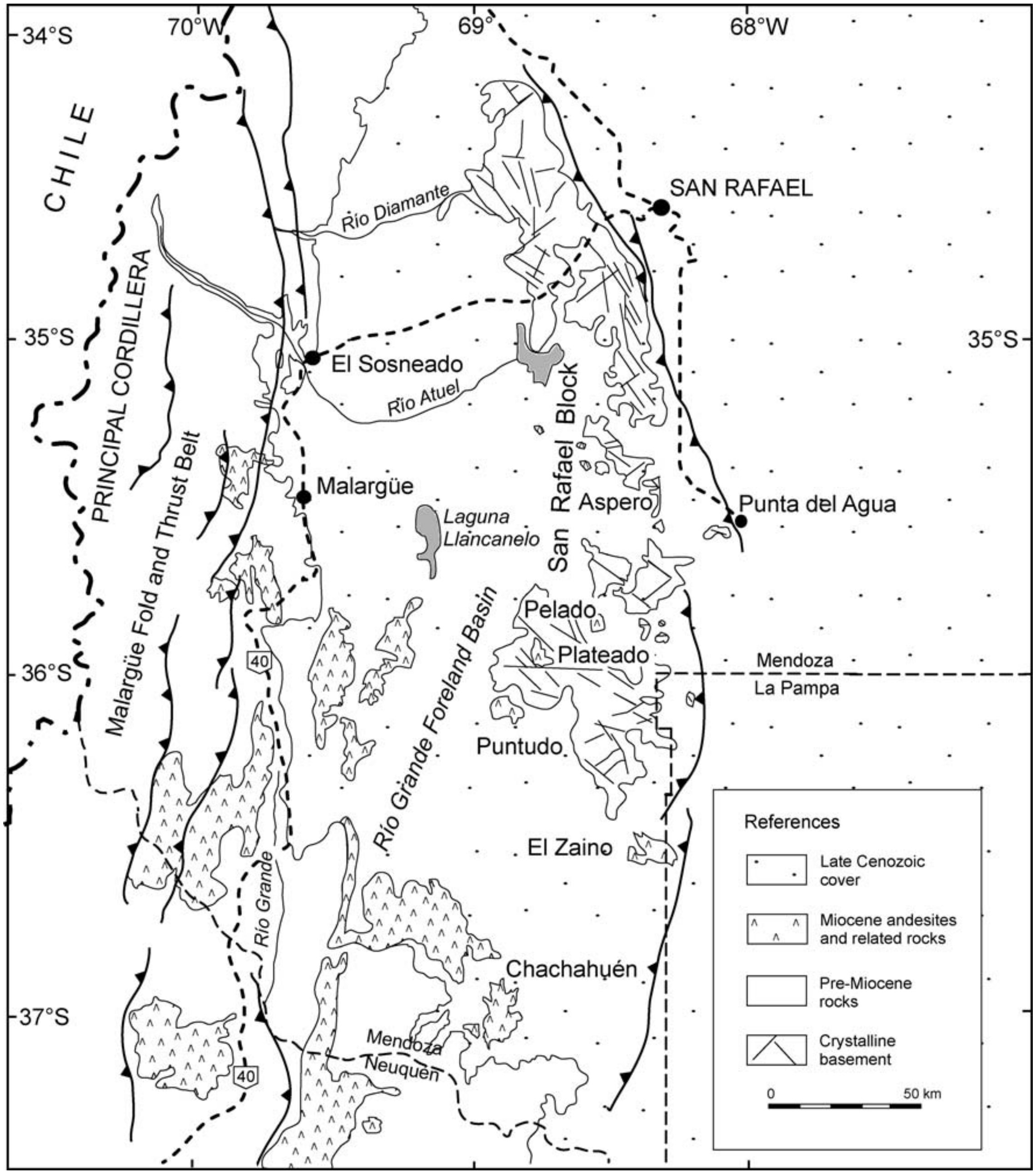


Figure 2. Generalized geological map of parts of the provinces of Mendoza, Neuquén, and La Pampa in Argentina showing the Miocene geologic features of the region north of the Cortaderas lineament discussed in the text. Post-Miocene structures and volcanic rocks in the foreland are shown in Figure 3. Bold dashed lines are principal highways.

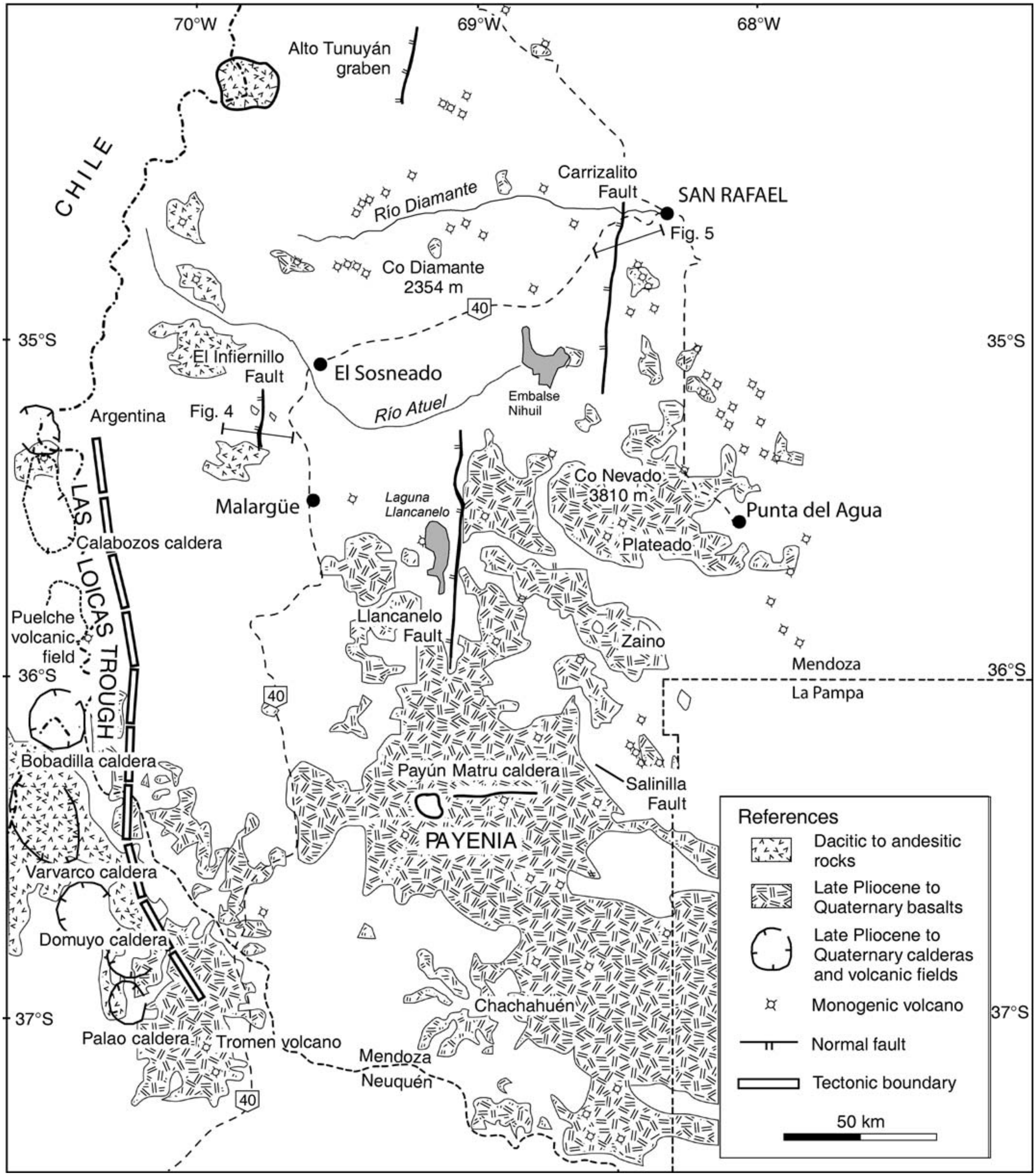


Figure 3. Map of the same region as in Figure 2 showing the principal Pliocene and younger structures and volcanic rocks. Lines show locations of cross sections shown in Figures 4 and 5. Short dashed lines are boundaries between the Argentine provinces of Mendoza, Neuquén, and La Pampa. Longer dashed lines are principal highways (symbol is for Highway 40).

Principal Cordillera

The Principal Cordillera straddles the Chilean-Argentine border zone (Figs. 1 and 2) and includes the active Andean Southern Volcanic Zone arc front, which at these latitudes (35°–39°S) is located on the Chilean side of the range. Generally, the Southern Volcanic Zone has been divided into three segments based on petrologic and geologic studies (e.g., López Escobar, 1984; Hildreth and Moorbath, 1988; Dungan et al., 2001). These segments are known as the northern Southern Volcanic Zone (Tupungato to Maipo, 33.5°–34.5°S latitude), the transitional Southern Volcanic Zone (Palomo to Tatara–San Pedro, 35°–36°S), and the southern Southern Volcanic Zone (Longaví to Hudson, 36°–46°S). Among other differences, crustal thicknesses are considered to decrease from 65–60 km in the northern Southern Volcanic Zone to ~42–35 km in the southern Southern Volcanic Zone (e.g., Hildreth and Moorbath 1988; Ramos et al., 2004). Recent studies have demonstrated a complex history of forearc subduction erosion and consequent late Cenozoic migration of the magmatic arc toward the foreland in the segment north of 36°S (Kay et al., 2005).

North of the Cortaderas lineament, the eastern slope of the Principal Cordillera coincides with the Las Loicas trough (named by Folguera et al., this volume, chapter 12). The Las Loicas trough is a Pliocene to Quaternary volcano-tectonic basin located east of the active Southern Volcanic Zone arc that is controlled by extensional north-northwest–trending faults and filled with thick sequences of Quaternary ignimbrites, lavas, and ash-fall deposits derived from large silicic volcanic centers like the Bobadilla, Varvarco, and Domuyo calderas (Fig. 3; see Hildreth et al., 1999; Folguera et al., this volume, chapter 12).

East of the Las Loicas trough lies the thick-skinned Malargüe fold-and-thrust belt (Fig. 2), which deforms Mesozoic marine and continental sequences (e.g., Kozlowski et al., 1993). The structure of this belt is dominated by large double-plunging anticlines that are cored by the Choiyoi Group (Permian-Triassic) volcanic and plutonic rocks, which constitute the exposed basement of the region. The Mesozoic strata in the belt are separated by an angular unconformity from pre–late Miocene Tertiary volcanics and granitoids, which are in turn unconformably overlain by thick sequences of late Miocene to Pliocene volcanics (Gerth, 1931; Ramos and Nullo, 1993).

Tertiary synorogenic conglomerates and sandstones occur in the Principal Cordillera as remnants of the western part of a foreland basin. Cobbold and Rossello (2003) discussed the evolution of the Paleogene deposits. The volume of the Paleogene deposits is relatively minor compared to that of Neogene sequences that are widely preserved in the eastern foothills of the Principal Cordillera from the Río Diamante valley in the north to the Río Grande valley in the south (Fig. 2). The Neogene sequences are interpreted as synorogenic deposits associated with the Miocene uplift and shortening of the main Andean range. According to Kraemer et al. (2000), an older sequence that is constrained between 15.1 Ma at the base and 6.7 Ma at the top by K/Ar ages on interbedded volcanic layers is separated by an angular unconformity from a younger sequence, the age of which, at the base, is constrained to be between 6.7 Ma and 5.4 Ma. Undeformed late Pliocene to Quaternary sequences, which include andesitic and basaltic lava flows, unconformably overlie the Miocene deposits.

Neogene normal faults are found along the eastern foothills of the Principal Cordillera. One of these is the Infiernillo fault (Kozlowski et al., 1993; Dajczgewand, 2002) that intersects the Río Salado valley (Figs. 3 and 4). As shown in Figure 4, the Infiernillo fault is a west-dipping normal fault that separates late Miocene deposits from Mesozoic sedimentary strata. Evidence for activity on this fault in Quaternary times comes from distinct pulses of basaltic lavas that have erupted along the fault (Fig. 4).

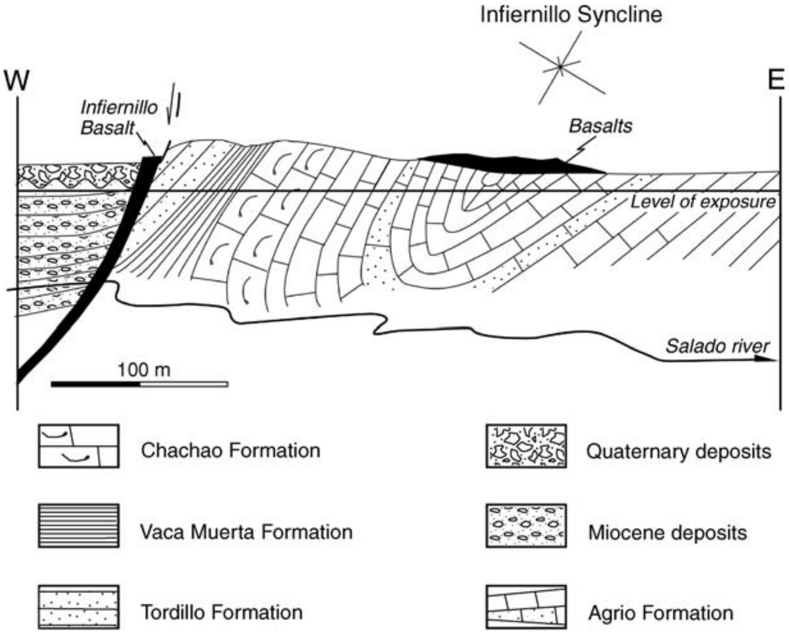


Figure 4. Cross section across the El Infiernillo normal fault along the Río Salado valley (modified from Dajczgewand, 2002). Location of section is shown in Figure 3.

Río Grande Foreland Basin

East of the Principal Cordillera, synorogenic deposits have accumulated in the large Río Grande foreland basin, which extends from the Río Diamante valley in the north to the southern limit of Mendoza province (Fig. 2). The basin fill includes more than 2000 m of synorogenic deposits that accumulated in two distinct depocenters located north and south of the Río Atuel (Yrigoyen, 1993). The Castillos de Pincheira outcrops, a few kilometers west of the city of Malargüe, expose both Paleogene and Neogene synorogenic sequences. Facies analyses of the Paleogene unit indicate a western provenance. Facies analyses of the Miocene deposits show that they constitute a coarsening-upward sequence with both an eastern and western provenance. The thick coarse deposits at the top of the sequence have a dominantly eastern provenance (Kraemer and Zulliger, 1994) and contain basement clasts that record the uplift of the San Rafael block (Fig. 2, see following). These sequences are unconformably covered by thick late Pliocene to Quaternary deposits.

Subsidence associated with extension has affected the region of the Río Grande basin in recent times. Active subsidence is presently occurring in the Laguna Llancanelo depression (Fig. 3) on the eastern side of the basin. This depression is bounded on the east by a normal fault (Manceda in Kozlowski et al., 1993). To the north is the Alto Tunuyán depression, which is interpreted as a half-graben (Fig. 3) that is filled by Quaternary clastic sediments. As recognized by Polanski (1963), the eastern side of the Alto Tunuyán depression is bounded by north-south–trending normal faults that affect Pliocene deposits and that can have throws of more than 700 m. One of these is the Cerro Negro de Capiz fault that affects late Pliocene deposits (Yrigoyen, 1993). The Extenso del Campo Bajo valley occurs in the region between the Alto Tunuyán depression and the Laguna Llancanelo.

San Rafael Basement Block

Further east is the San Rafael basement block (Fig. 2). This block consists of Middle Proterozoic metamorphic rocks and tightly folded Paleozoic deposits (Moreno Peral and Salvarredi, 1984) that are cut and unconformably overlain by Permian to Triassic granitoids and volcanic rocks of the Choiyoi Group (e.g., Kay et al., 1989). The presence of an old peneplain carved on these basement rocks was first noted by Polanski (1954). The time of uplift and exposure of the erosional surface is constrained by synorogenic deposits of the Río Grande foreland basin that form a bajada of low-energy clastic deposits, which were derived from the Andean foothills. The time of deposition of the sediments is constrained by the presence of mammalian fossils (Soria, 1984) with a middle Miocene Colloncurense age (15–12 Ma; Pascual et al., 2002) and the K/Ar ages of 15.1 Ma and 6.7 Ma in the tuffs in the sequences dated by Kraemer et al. (2000). A rapid period of uplift at 5 Ma is indicated by Pliocene synorogenic deposits with an eastern provenance from the Río Grande basin. This uplifted peneplain was subsequently cut by Pliocene and Quaternary normal faults described by Narciso et al. (2001). Among these normal faults is the west-dipping El Carrizalito fault (Figs. 3 and 5), which indicates activity in the late Pliocene to early Pleistocene recognized by González Díaz (1964). Another is the Llancanelo fault that bounds the western margin of the block further to the south.

The eastern margin of the San Rafael block is still actively shortening, as indicated by recent seismic activity as exemplified by the large Malvinas earthquake in the vicinity in 1929 (Bastías et al., 1993). The thrust front, which does not show a surface rupture, is expressed by a frontal monocline developed in Pleistocene basalts (Costa et al., 2004).

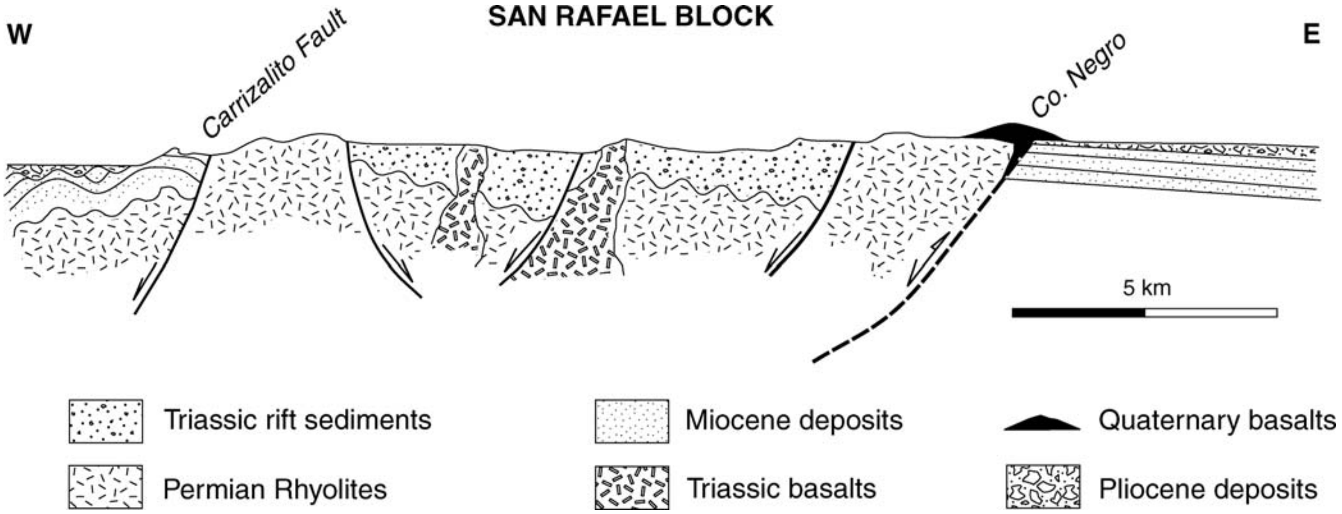


Figure 5. Cross section across the San Rafael block showing the Carrizalito fault and the late Miocene peneplain, which is broken by normal faults. One of these faults controls the position of the late Pleistocene basalts that erupted from the Cerro Negro volcano. The late Miocene thrust on the eastern side is inactive. Location of section is shown in Figure 3.

Retroarc Volcanic Field

The large retroarc volcanic province named Payenia by Polanski (1954) covers vast regions of the foreland between 35° and 37°S (Fig. 3). The maximum volumes of volcanic rocks erupted in the region between the Volcán Nevado and the Payún Matru caldera. These volcanic rocks pinch out to the north where they partially cover the San Rafael block. Regional studies by González Díaz (1972a, 1972b) and Bermúdez et al. (1993) indicate that these late Miocene to Quaternary volcanic rocks erupted in two distinct volcanic episodes.

The first episode produced the hornblende-bearing mafic andesites to rhyodacites found in the Cerro Plateado (35°40′S) and Sierra de Chachahuén (37°05′S) volcanic fields, which are located some 500 km east of the modern trench (Fig. 2). The andesitic to rhyolitic volcanic rocks in the Cerro Plateado field are considered to be late Miocene in age (Bermúdez, 1991). Volcanic rocks in the Sierra de Chachahuén field farther south have an arc-like magmatic chemistry and range in age from ca. 7.2 to 4.8 Ma (Kay, 2001a, 2001b; Kay et al., this volume, chapter 9). Younger volcanic rocks from the Volcán Nevado (3810 m) in the region of the Plateado field (Fig. 3) are dominantly composed of trachyandesite and are considered to be Pliocene in age (Bermúdez, 1991).

The second episode produced the extensive late Pliocene to Quaternary Payenia volcanic field that is temporally associated with the Cerro Diamante (2354 m), Cerro Payún (3680 m), Payún Matru caldera, and Auca Mahuida volcanic complexes (Figs. 3 and 6; see Bermúdez et al. 1993). Basaltic flows in these fields can reach lengths of over 200 km. The volcanic rocks of this episode generally have an alkaline within-plate chemical signature and are considered to be associated with an extensional regime (Muñoz et al., 1989; Bermúdez et al., 1993; Kay, 2001a, m2001b; Kay et al., this volume, chapter 2).

Region South of the Cortaderas Lineament

The major geologic features of the region south of the Cortaderas Lineament are illustrated in Figures 1 and 6. In striking contrast with the region north of the Cortaderas lineament, the retroarc east of the Loncopué trough is essentially devoid of Neogene volcanic rocks and synorogenic deposits (Fig. 6). Many of the general characteristics of this region are described in the papers in this volume by Mosquera and Ramos (chapter 5), Zamora Valcarce et al. (chapter 6), and Folguera et al. (chapters 11 and 12). From west to east, the main morphotectonic elements of the region are the Principal Cordillera, the Loncopué trough, the Agrio fold-and-thrust belt, the Chihuidos high, the Añelo basin, and the Neuquén Embayment.

Principal Cordillera

The Principal Cordillera south of the Cortaderas lineament is located within the southern segment of the Southern Volcanic Zone arc. Quaternary to Holocene arc volcanic complexes in this region include the centers at Chillán, Antuco, Copahue, Lonquimay, and Llaima (Fig. 6), which were assigned to the Lonquimay volcanic chain by Burckhardt (1900). These centers overlie Mesozoic marine sediments, Cretaceous plutonic rocks, and Oligocene to Miocene sedimentary and volcanic rocks that are unconformably covered by early Pliocene Cola de Zorro Formation volcanic rocks (e.g., Vergara and Muñoz, 1982; Burns et al., this volume, chapter 8). The Lonquimay chain is flanked to the east by the series of late Pliocene to early Quaternary volcanoes that Burckhardt (1900) assigned to the Pino Hachado chain. Most of the eastern flank of the Principal Cordillera north of the Copahue volcano is affected by the contractional deformation that created the late Miocene to Quaternary Guañacos fold-and-thrust belt (Folguera et al., 2004, this volume, chapter 11).

Loncopué Trough

The Loncopué trough, which is immediately east of the Principal Cordillera (Fig. 6), is an extensional basin associated with a thick cover of Pleistocene basaltic lavas and late Pleistocene–Holocene monogenic volcanic cones (Ramos, 1978; García Morabito, 2005; Folguera et al., this volume, chapter 12). The volcanic rocks have subdued-arc geochemical signatures (Muñoz and Stern, 1988). The Loncopué trough coincides with an important region of crustal attenuation that is discussed by Yuan et al. (this volume, chapter 3).

Agrio Fold-and-Thrust Belt

The next major feature to the east is the Agrio fold-and-thrust belt (Figs. 1 and 6), which was divided into two sectors by Ramos (1998). The western sector is composed of Jurassic and Early Cretaceous marine deposits that were deformed in a thick-skinned belt, which was produced by the inversion of Early Jurassic half-grabens (Vergani et al., 1995; Folguera et al., 2002) during the Late Cretaceous. These sequences are intruded and overlain by Late Cretaceous to Eocene magmatic rocks (Franchini et al., 2003; Zamora Valcarce et al., this volume, chapter 6). The eastern sector of the Agrio belt consists of Early Cretaceous marine sedimentary rocks that were deformed in a Late Cretaceous thin-skinned belt that detached in Late Jurassic evaporite deposits. Both parts of the Agrio belt were tectonically reactivated and last deformed in the middle to late Miocene (Zapata and Folguera, 2005).

Chihuidos High

Farther east, the Chihuidos high is a basement arch that is largely covered by Late Cretaceous red bed sequences, which are synorogenic foreland basin deposits associated with the Agrio fold-and-thrust belt. The age of the lower part of the synorogenic sequence is constrained by zircon fission-track ages of 88 ± 3.9 Ma in the Huincul Formation on the southern margin of the basin at Cerro Policía in the province of Río Negro (Corbella et al., 2004). These ages imply that deformation in the Agrio fold-and-thrust belt had started by the Late Cretaceous (before Turonian-Santonian times). According to Mosquera and

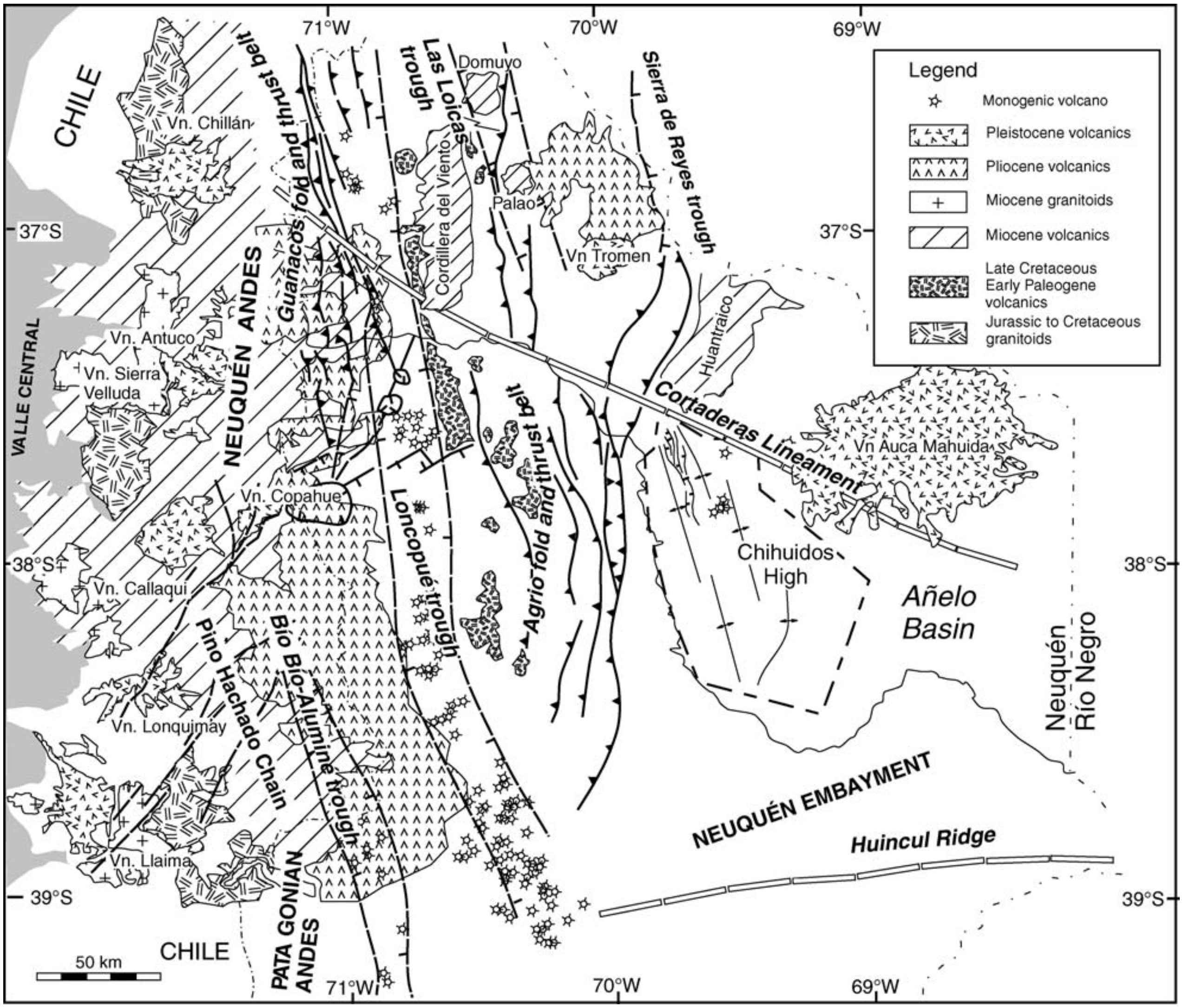


Figure 6. Generalized geological map of the northern part of Neuquén province in Argentina showing the geologic features along and south of the Cortaderas lineament discussed in the text.

Ramos (this volume, chapter 5), the presence of deformed middle Miocene synorogenic deposits on the Chihuidos high shows that the block was uplifted by tectonic inversion of normal faults during the late Miocene. Small post-tectonic basaltic cones with ages of 4.5 ± 0.5 Ma (Ramos and Barbieri, 1989) and an intraplate alkaline chemistry (Kay et al., 2004) occur near the northern boundary of the Chihuidos high (Fig. 6).

Añelo Basin

The sediments in the Añelo basin (Fig. 6) to the east record the Miocene uplift of the Chihuidos high. This basin represents a foredeep with a fill of a few hundred meters of late Miocene to Pliocene synorogenic deposits (Mosquera and Ramos, this volume, chapter 5), which include the strata exposed at Barranca del Palo and in the Sierra Blanca (Uliana, 1978). Most of the synorogenic sediments that formed in the Miocene bypassed the Añelo basin and Neuquén Embayment and ended up as far east as the continental margin (Folguera et al., 2005).

Neuquén Embayment

East of the Agrio fold-and-thrust belt and south of the Añelo basin, Mesozoic sedimentary rocks associated with the Neuquén Embayment are preserved (Fig. 6). These sequences include a large expanse of marine sediments that were deposited and subsequently covered by Late Cretaceous synorogenic deposits. Thin sequences of continental and shallow marine strata of Maastrichtian to Paleogene age represent the first transgression derived from the Atlantic Ocean after the Early Cretaceous opening of the South Atlantic. The more northern part of the embayment is partially covered by Neogene alkaline basaltic lavas associated with volcanic centers north of the Cortaderas lineament.

MAGMATIC AND DEFORMATIONAL HISTORY

Important differences in the regions north and south of the Cortaderas lineament are evident in the sequential episodes of contractional and extensional deformational events that affected this region of the Andes. These differences are discussed in the following within the general context of the tectonic cycles first proposed by Groeber (1953, and references therein).

Early Jurassic–Early Cretaceous Extensional Stage

Most of the Early Jurassic to Early Cretaceous Andean margin at these latitudes was associated with negative trench roll-back velocity of the subduction zone (see Mpodozis and Ramos, 1989; Ramos, 1999). Normal faults were dominant along the main Andean chain, and volcanic rocks were widespread on both slopes of the Main Andean Cordillera. During this time, deep marine depocenters accumulated thick deposits that interfingered with basaltic and andesitic rocks erupted in an extensional-type magmatic arc.

The main difference between the regions north and south of the Cortaderas lineament is that rift systems are more aerially restricted to the north. In detail, widespread grabens and half-grabens found in the foreland in the south are abruptly replaced by a much narrower zone of rift-related structures in the north. The faulting in these rifts, which started in the Triassic and continued into the Early Jurassic, preceded the inception of subduction along the Pacific margin.

The wider zone of rifts in the south coincides with a distinctive basement fabric. An important feature of this basement fabric is the N70°E-trending Huincul fault system that corresponds with the Huincul Ridge (Figs. 1 and 6) and marks a major crustal boundary. Mosquera and Ramos (this volume, chapter 5) interpret this boundary as a Paleozoic suture marking the collision between an allochthonous Patagonian terrane to the south and the Gondwana continent to the north. Evidence that the Huincul Ridge parallels the suture comes from aeromagnetic (Chernicoff and Zappettini, 2004), gravity (Kostadinoff et al., 2005), and seismic (Mosquera and Ramos, this volume, chapter 5) data.

Late Cretaceous Contractional Stage

Important changes in magmatism and deformation occurred near the end of the Early Cretaceous. One of these changes was the shutdown of the elongated magmatic belt that produced the 93–72 Ma granitoids exposed along the Chilean side of the Principal Cordillera (see Ramos and Folguera, 2005). South of the Cortaderas lineament, the end of this magmatic stage coincided with the eastward migration of the Late Cretaceous magmatic arc and its reestablishment in the western part of the Agrio fold-and-thrust belt. A contemporaneous migration of the frontal arc front did not occur in the northern sector. Another major development at this time was that the deformational regime became contractional throughout the region, with the most intense deformation occurring in the southern sector. The more extensive previous rifting in the southern region likely left an extended broken basement that was more susceptible to deformation.

Support for major Late Cretaceous contractional deformation south of the Cortaderas lineament comes from several lines of reasoning. First, ^{40}Ar/^{39}Ar ages obtained by Zamora Valcarce et al. (this volume, chapter 6) on pyroclastic breccias and andesitic lavas unconformably overlying deformed Early Cretaceous marine rocks show that deformation had begun by 77 Ma in the western Agrio fold-and-thrust belt. Second, ^{40}Ar/^{39}Ar ages obtained by Zamora Valcarce et al. (this volume, chapter 6) on east-west–trending andesitic dikes suggest that compression along the western margin of the Neuquén Embayment had begun by 100 Ma. Third, zircon fission-track ages in Neuquén Group strata reported by Corbella et al. (2004) show that foreland basin sedimentation had begun by 88 Ma. Finally, fossils in Neuquén Group rocks indicate the development of a deep, eastward-thinning, Late Cretaceous foreland basin related to contractional deformation in the Agrio fold-and-thrust belt.

Evidence for Late Cretaceous contractional deformation north of the Cortaderas lineament comes from the observation that andesitic volcanic rocks south of Cerro Domuyo and east of the Cordillera del Viento (Fig. 6) with K/Ar ages of 71.5 ± 5 Ma postdate deformed Cretaceous deposits (Llambías et al., 1979). Other evidence comes from a 69.09 ± 0.13 Ma ^{40}Ar/^{39}Ar biotite cooling age from the Varvarco pluton, which Kay (2001b) and Kay et al. (this volume, chapter 2) interpret as an uplift age for the Cordillera del Viento. Burns (2002) argued from fission-track data on zircons that the uplift of the Cordillera del Viento had begun by 70 Ma, and possibly before 80 Ma.

Paleogene Compressional Stage

There are still uncertainties concerning the distribution of magmatic rocks and the extent of contractional deformation that took place during the Paleogene. Well-preserved Eocene volcanic rocks occur along the Chilean Central Valley in the northern sector, but as noted by López-Escobar and Vergara (1997), similar-age volcanic rocks have not been found in Chile between 36° and 37°30′S. Paleogene volcanic rocks are present at these latitudes in Argentina (Franchini et al., 2003; Ramos and Folguera, 2005). Kay et al. (this volume, chapter 2) argue for a small eastward shift of the volcanic front in the Paleogene based on the age, chemistry, and distribution of volcanic rocks in northern Neuquén.

The scarcity of Paleogene synorogenic deposits across the region is linked to the question of the importance of Paleogene contractional deformation. Volumes of these deposits are low north of the Cortaderas lineament and even more limited to the south. A notable exception is in the Pampa del Agua Amarga region in the southern Agrio fold-and-thrust belt, where late Paleocene to early Eocene pyroclastic and tuffaceous deposits in the Puesto Burgos Formation unconformably overlie sediments of the Late Cretaceous Neuquén Group (Leanza and Hugo, 2001). The age of these tuffs is constrained by plant fossils. Overall, it is apparent that large parts of the Agrio fold-and-thrust belt and the adjacent Chihuidos high were positive areas during the Paleogene and that some synorogenic sediments accumulated in a foreland basin in the north.

Cobbold et al. (1999) and Cobbold and Rossello (2003) appealed to transpression to reconcile the relatively small amounts of synorogenic deposits found for this time with the important episode of Eocene contractional deformation that they proposed. Their argument for Eocene deformation was largely based on the orientation of bitumen veins in the Agrio fold-and-thrust belt east of the Cordillera del Viento. Farther south, evidence for Eocene uplift along the Cordillera Principal south of 38°S comes from apatite fission-track ages of 40.6 ± 4.5 Ma (Gräfe et al., 2002).

Oligocene to Early Miocene Extensional Stage

During the Oligocene to early Miocene, the Neuquén Andes were characterized by generalized extension in the forearc (e.g., Cisternas and Frutos, 1994; Stern et al., 2000), arc (e.g., Vergara et al., 1997; Burns et al., this volume, chapter 8), and retroarc (e.g., Folguera et al., 2003). The eruption of early Miocene alkaline basaltic volcanic rocks at distances up to 500 km from the modern trench has been used as evidence that crustal attenuation in an extensional regime extended far into the foreland (Ramos and Barbieri, 1989; Kay, 2001b; Kay and Copeland, this volume, chapter 9). This period has been associated with a period of negative trench roll-back by Kay and Copeland (this volume).

Middle to Late Miocene Contractional Stage

The middle to late Miocene was a time of contractional deformation across the region. Important differences occur north and south of the Cortaderas lineament. To the north, magmatism was widespread, the Malargüe fold-and-thrust belt propagated eastward, and synorogenic deposits were widely distributed. To the south, magmatism was confined to the region near the arc axis, and contractional deformation was restricted to inversion of the Cura Mallín basin in the Principal Cordillera and to minor reactivation of the Agrio fold-and-thrust belt.

The most dramatic changes occurred in the northern segment. Beginning in the region of the Principal Cordillera, the eastward broadening of the magmatic arc at the latitude of central and southern Mendoza was initially recognized by Gerth (1931). This eastward expansion of magmatism occurred at the time of important crustal shortening and uplift in the Malargüe fold-and-thrust belt, and the subsidence that led to the accumulation of the thick Neogene synorogenic deposits in the Río Grande basin. The eastward propagating sequence culminated in the contractional uplift of the San Rafael block by the end of the Miocene and the eruption of the Cerro Plateado and associated volcanic centers far to the east of the trench (Delpino and Bermúdez, 1985). Bermúdez (1991) pointed out that the late Miocene arc in central Mendoza was over 200 km wide. The eastward expansion of the Miocene volcanic arc across southernmost Mendoza and northern Neuquén that culminated in the eruption and uplift of the Sierra de Chachahuén between 7.8 and 4.8 Ma is discussed by Kay (2001a, 2001b) and Kay et al. (this volume, chapters 2 and 10).

The presence of sparse synorogenic deposits in the foreland south of the Cortaderas lineament is interpreted as indicating renewed contraction in this region. Among these deposits are those at Rincón Bayo that unconformably overlie Paleogene sediments in the Chihuidos high (Zapata et al., 2003) and conglomerates and sandstones containing middle Miocene mammal fossils (Repol et al., 2002). Based on the small volume of Miocene compared to Cretaceous synorogenic deposits, Miocene contraction in this region is considered to have been less important than in the Cretaceous (Ramos, 1998; Mosquera and Ramos, 2005, this volume, chapter 5).

Pliocene Extensional Stage

Differences across the northern and southern sectors are again striking in the Pliocene. The northern sector is characterized by important retroarc basaltic magmatism with a subdued arc to intraplate chemical character (Muñoz et al., 1989; Bermúdez et al., 1993; Kay, 2001b; Kay et al., 2004, and this volume, chapter 2). Large volumes of alkaline magmas erupted from fissures and important volcanic centers like the late Pliocene Payún Matru caldera. Magmatic activity was accompanied by generalized extension in the retroarc and adjacent areas, and the collapse of previously uplifted foreland areas like the San Rafael block (González Díaz, 1964; Bermúdez et al., 1993). Extension propagated from the foreland to the foothills of the Principal Cordillera as retroarc volcanoes, such as those in the Tromen region, erupted between the Principal Cordillera and the eastern foreland (Kay, 2001b; Kay et al., this volume, chapter 2). South of the Cortaderas lineament, extension was limited to the arc and western retroarc (Folguera et al., 2003, and this volume, chapter 11). The magmatic arc expanded toward the retroarc with stratovolcanoes erupting along the Pino Hachado chain (e.g., Muñoz and Stern, 1988; Lara and Folguera, this volume, chapter 14). Basaltic volcanism occurred only as far east as the Loncopué trough (Fig. 6).

Pleistocene to Holocene Stage

During the Pleistocene, extension propagated to the main axis of the Principal Cordillera. Large volumes of rhyolite erupted from a series of calderas and volcanic domes north of the Cortaderas lineament, including the Planchón, Calabozos, Bobadilla, Varvarco, Domuyito, and Domuyo centers (Fig. 3).

The rhyolitic magmas are considered to have been generated by crustal melting associated with basaltic underplating (Hildreth et al., 1999). The volcanic and pyroclastic deposits produced by these eruptions filled the fault-bounded Las Loicas trough (Fig. 3; see Folguera et al., this volume, chapter 12). Volcanic activity also took place in the retroarc in stratovolcanoes like Tromen and in alkaline monogenic basaltic and alkaline complexes like Payún Matrú and Auca Mahuida (see Holmberg, 1964; Llambías, 1966; González Díaz, 1972b; Bermúdez et al., 1993; Kay, 2001b; Kay et al., 2004, and this volume, chapter 2). During the same period, contractional deformation in the Guañacos fold-and-thrust belt straddled the western part of the Cortaderas lineament in the Principal Cordillera (Fig. 6) as the Pliocene-Pleistocene volcanic arc was thrust over Pleistocene bajadas (Folguera et al., this volume, chapter 11). Contractional deformation also occurred along the eastern margin of the San Rafael block, where thrust faults involve Quaternary lavas and the large 1929 Las Malvinas earthquake is interpreted to have had a compressional mechanism (Costa et al., 2004).

Farther south, the main Pleistocene to Holocene arc volcanic activity was largely focused along the Lonquimay chain on the western slope of the Andes, where active volcanism continues in the southern sector of the Southern Volcanic Zone today. Mafic volcanism and normal faulting was largely restricted to the Loncopué trough, and evidence for Quaternary shortening is absent (see Folguera et al., this volume, chapter 12)

TECTONIC EVOLUTION OF THE ANDES NORTH AND SOUTH OF THE CORTADERAS LINEAMENT

The geologic history and features discussed in the previous sections are utilized in the following to propose a model for the contrasting evolution of the regions north and south of the Cortaderas lineament. Important factors in explaining the differences between these sectors are discrete crustal rheologies inherited from Paleozoic and Mesozoic events and differences in underlying subducting plate geometry. Conceptual cartoons in Figure 7, not drawn to scale, emphasize the difference in the various stages of this evolution. A more detailed discussion of the Miocene development of the region just north of the Cortaderas lineament is presented by Kay (2001a, 2001b, 2002) and Kay et al. (this volume, chapters 2 and 10).

Early Rifting (Triassic to Early Jurassic)

The Mesozoic evolution of the region is shown to begin in Figure 7A with the generalized extension and rifting related to the early breakup of the Pangean supercontinent. This rifting was concentrated north of the Huincul Ridge (Fig. 1), which is interpreted by Mosquera and Ramos (this volume, chapter 5) to parallel the late Paleozoic suture between the allochthonous Patagonia terrane and Gondwana. In accord with this interpretation, Mosquera and Ramos (this volume) suggest that the widespread extension under the Neuquén Embayment correlates with the hanging wall of the suture. This structural pattern then controls the later geometry of the Neuquén Embayment (Franzese and Spalletti, 2001).

Early Subduction (Jurassic to Early Cretaceous)

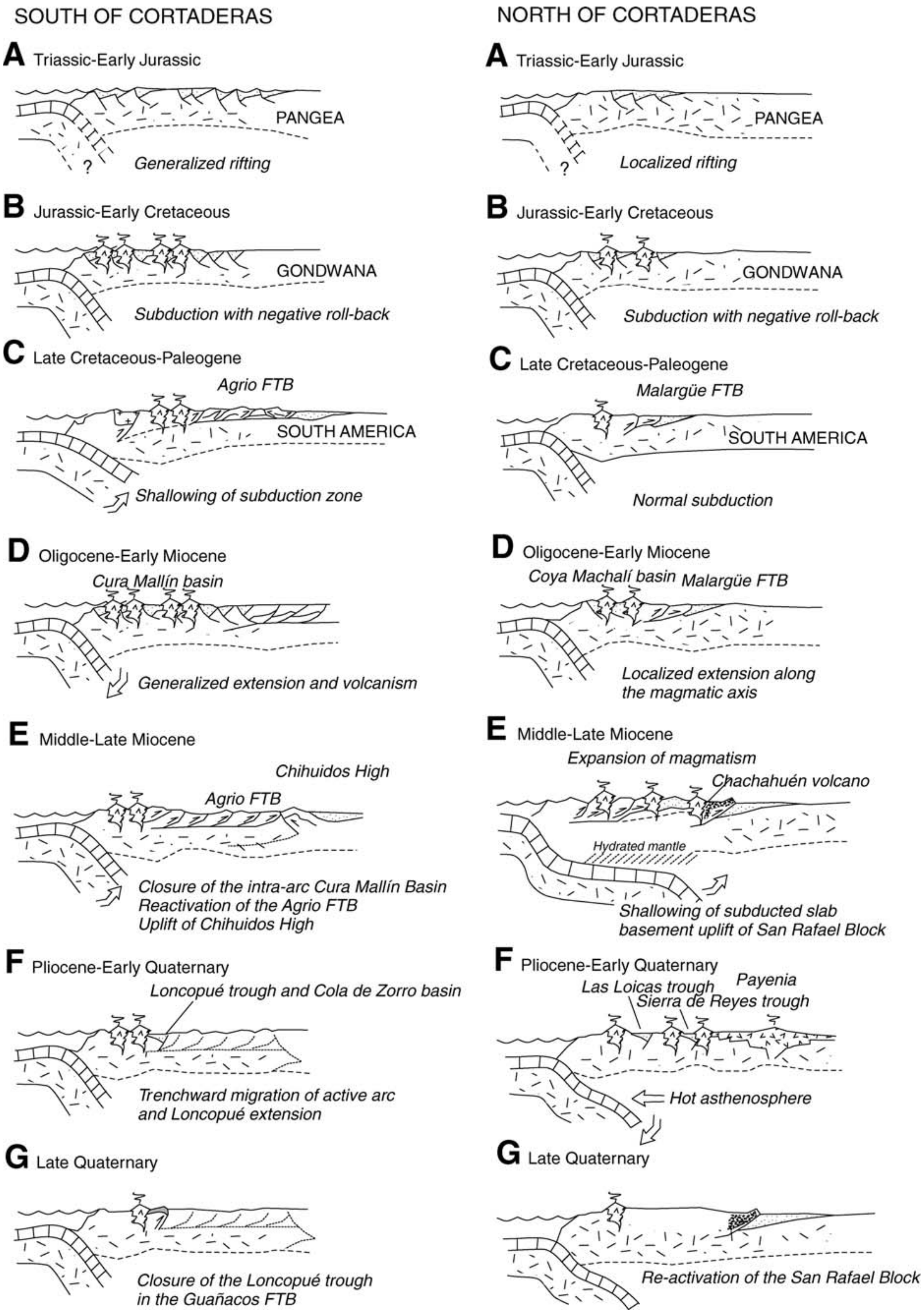
The initiation of subduction in the lower Jurassic at ca. 180 Ma is based on the appearance of arc magmatic rocks in Chile (see Mpodozis and Ramos, 1989; Parada 1990). The main difference between the northern and southern sectors is that arc volcanic rocks are either more abundant or are better preserved in the north (see Ramos and Folguera, 2005). The rift structures shown in the cartoon in Figure 7B are very similar to those shown in Figure 7A, since it is difficult to separate the faults related to early rifting from those produced by extension in the backarc after subduction began.

Tectonic Inversion (Late Cretaceous to Paleocene)

The cartoons in Figure 7C show the major differences between the southern and northern regions during the Late Cretaceous to Paleocene. In the southern region, the magmatic front migrated eastward and major contractional deformation occurred in the Agrio fold-and-thrust belt in the foreland. To the north, the arc remained stationary, and contractional deformation in the foreland Malargüe fold-and-thrust belt was less intense. In Figure 7C, the more pronounced eastward migration of the magmatic arc and the greater amount of crustal shortening in the south are tentatively linked to a relative shallowing of the Benioff zone in the south. Furthermore, as contractional deformation in both regions is primarily linked to tectonic inversion of basement faults and only secondarily to thin-skinned thrusting, the more intense deformation in the south can be correlated with a greater amount of previous extension.

Steepening of Benioff Zone in the Southern Sector (Oligocene to Early Miocene)

Major changes occurred in the latest Oligocene to early Miocene as the Nazca plate replaced the Farallón plate, the relative convergence rate increased and became nearly normal (e.g., Somoza, 1998), and negative trench roll-back caused generalized extension across the region (see Kay and Copeland, this volume, chapter 9). As shown in Figure 7D, extension at this time was localized in the Coya Machalí intra-arc basin along the main Andes to the north (e.g., Godoy et al., 1999; Charrier et al., 2002), whereas extension near the Cortaderas lineament to the south was more intense, with effects extending from the Cura Mallín intra-arc basin (e.g., Burns et al., this volume, chapter 8) into the retroarc where alkali olivine basalts were erupting (see Ramos and Barbieri, 1989; Kay, 2001b; Kay et al., 2004; Kay and Copeland, this volume, chapter 9). The cartoon in Figure 7D shows a return to a steeper subduction zone than


SOUTH OF CORTADERAS
A Triassic-Early Jurassic
PANGEA
?
Generalized rifting
B Jurassic-Early Cretaceous
GONDWANA
Subduction with negative roll-back
C Late Cretaceous-Paleogene
Agrio FTB
SOUTH AMERICA
Shallowing of subduction zone
D Oligocene-Early Miocene
Cura Mallín basin
Generalized extension and volcanism
E Middle-Late Miocene
Chihuidos High
Agrio FTB
Closure of the intra-arc Cura Mallín Basin
Reactivation of the Agrio FTB
Uplift of Chihuidos High
F Pliocene-Early Quaternary
Loncopué trough and Cola de Zorro basin
Trenchward migration of active arc
and Loncopué extension
G Late Quaternary
Closure of the Loncopué trough
in the Guañacos FTB
NORTH OF CORTADERAS
A Triassic-Early Jurassic
PANGEA
?
Localized rifting
B Jurassic-Early Cretaceous
GONDWANA
Subduction with negative roll-back
C Late Cretaceous-Paleogene
Malargüe FTB
SOUTH AMERICA
Normal subduction
D Oligocene-Early Miocene
Coya Machalí basin
Malargüe FTB
Localized extension along
the magmatic axis
E Middle-Late Miocene
Expansion of magmatism
Chachahuén volcano
Hydrated mantle
Shallowing of subducted slab
basement uplift of San Rafael Block
F Pliocene-Early Quaternary
Las Loicas trough
Payenia
Sierra de Reyes trough
Hot asthenosphere
G Late Quaternary
Re-activation of the San Rafael Block

that which existed in the Late Cretaceous to Paleocene in the southern region, which is in accord with extension in the Cura Mallín basin and into the backarc.

Shallowing of Benioff Zone in Northern Sector (Middle to Late Miocene)

As recognized by Kay (2001a, 2001b, 2002; Kay et al., this volume, chapter 2), an important transient shallowing of the subduction zone north of the Cortaderas lineament can explain the Miocene advance of deformation into the foreland and the eruption of volcanic rocks with arc-like magmatic signatures up to 500 km east of the trench. This shallowing, which is depicted in the cartoon in Figure 7E, fits well with the wave of deformation in the Malargüe fold-and-thrust belt and the foreland expansion of magmatism discussed already. The age and distribution of magmatic rocks in the Principal Cordillera and the synorogenic deposits in the foreland (Kraemer et al., 2000) are consistent with the eastward advance of the Malargüe thrust front from 15 Ma to 5 Ma as the magmatic arc broadened. During the time of shallow subduction, the San Rafael block and the Sierra de Chachahuén were uplifted in a manner analogous to that of the Sierras Pampeanas over the present Pampean (Chilean) flat-slab segment to the north. Because magmatism did not completely cease, the shallowing of the slab is considered to have been less pronounced than under the Pampean flat slab to the north (Kay, 2001b, 2002; Mancilla, 2001; Kay et al., this volume, chapters 2 and 10).

During this same period, the region south of the Cortaderas lineament was subjected to contractional deformation that led to the middle to late Miocene compressional inversion of the Cura Mallín basin, reactivation of the Agrio fold-and-thrust belt, and the uplift of the Chihuidos high. As magmatism in the south was restricted to the region of the Principal Cordillera and contractional deformation was less intense, the subduction zone for the southern segment in Figure 7E is shown as steeper (~30°) than that to the north.

Figure 7. Conceptual cartoons (not to scale) comparing the tectonic evolution of the sectors north and south of the Cortaderas lineament: (A) Triassic–Early Jurassic rifting associated with the breakup of Pangea and inception of early Jurassic subduction. (B) Jurassic–Early Cretaceous subduction with generalized extension associated with negative trench roll-back. (C) Late Cretaceous to Paleogene contraction in the Agrio fold-and-thrust belt (FTB) and less extensive tectonic inversion in the Malargüe fold-and-thrust belt. (D) Extension associated with steepening of the subduction zone related to negative trench roll-back velocity. (E) Differential shallowing of the subduction zone with Miocene contractional deformation and crustal shortening. (F) Steepening of the subduction zone, widespread extension and magmatism in the northern sector; localized extension and magmatism, and initiation of contraction in the Guañacos fold-and-thrust belt. (G) Present setting under contraction. More detailed early Miocene to late Quaternary lithospheric scale cross sections north of the Cortaderas lineament are included in Kay et al. (this volume, chapter 2), and more detailed Pliocene to late Quaternary sections comparing the regions north and south of the Cortaderas lineament are in Folguera et al. (this volume, chapter 12).

Steepening of the Benioff Zone (Pliocene to Quaternary)

The cartoons in Figures 7F and 7G show a return to a steeper subducting slab than in the late Miocene, with the most pronounced steepening in the north. Kay (2001b, 2002; Kay et al., this volume, chapter 2) argued that the end of arc-like magmatism far east of the trench followed by widespread Pliocene to Quaternary mafic volcanism with a progressively more intraplate-like chemical signature is best explained by such a steepening of the subducting slab north of the Cortaderas lineament. The widespread within-plate basaltic volcanism of the Payenia volcanic field is thought to be triggered by the reinsertion of hot asthenosphere into the thicker mantle wedge above the steepening slab (Kay et al., 2004). Such a scenario also fits with the Pliocene to Quaternary extensional collapse of foreland in this paper. Crustal melting by basaltic underplating linked to the injection of hot asthenosphere along the cordilleran axis north of the Cortaderas lineament can explain the formation of large Quaternary collapse calderas and the emplacement of rhyolitic domes along the Las Loicas trough (Folguera et al., this volume, chapter 12). Crustal weakening would favor shortening along the Pliocene-Pleistocene arc leading to the development of the Guañacos fold-and-thrust belt along the eastern slope of the Principal Cordillera (see Folguera et al., this volume, chapter 11).

The region south of the Cortaderas lineament records a contraction of the Pliocene-Pleistocene arc, which retreated westward to the present position in the southern sector of the Southern Volcanic Zone (Lonquimay) volcanic arc. Pliocene to Quaternary extension in this region is confined to the Loncopué trough. Local negative trench roll-back has been postulated to explain both the extension and minor retreat of the volcanic arc (see Lara and Folguera, this volume, chapter 14). This roll-back could be accompanied by a minor steepening of the subducting slab (Folguera et al., this volume, chapter 12). Roll-back could also play a role in events in the northern sector, but only shallowing followed by steepening of the subducting slab can easily explain expansion followed by disappearance of arc-like magmatic activity and compressional deformation far into the backarc.

CONCLUDING REMARKS

The tectonic evolution of the southern Mendoza and Neuquén Andes is characterized by changes in the position of the magmatic arc front, periods of expansion of Tertiary to Holocene volcanism into the foreland, and waves of compression or extension that are best linked to changes in the geometry of the Benioff zone. In detail, shifting or expansion of arc magmatism into the foreland is coeval with contraction in the foreland fold-and-thrust belt, whereas retraction of arc magmatism toward the trench is linked with extension and collapse.

There is no clear evidence to suggest a correlation of changes in slab geometry with subduction of aseismic ridges, as has been proposed for the Chilean flat slab farther north (e.g., Yáñez et al., 2001; Ramos et al., 2002). The simplest explanation for these changes is that subduction of a ridge produced a transient shallowing in the geometry of the subducted slab (see also Kay et al., this volume, chapter 9). These changes could have been enhanced by the absolute motion of the South American plate as normally encompassed in the overriding velocity of the upper plate (Jarrard, 1986; Sobolev and Babeyko, 2005). The overriding velocity is equivalent to the trench roll-back velocity plus the orogenic shortening rate. An increase in the overriding velocity may result in compression and shortening and positive trench roll-back velocities as proposed by Daly (1989); a decrease in the overriding velocity may produce an extensional regime coeval with negative trench roll-back.

Evaluation of the mechanisms that control changes in the tectonic regime in the Neuquén Andes requires taking into account changes that affect a broader area. For example, Miocene compression is well known all along the Andean margin. Silver et al. (1998) argued that the resulting contraction can be related to a relative increase in the overriding velocity of the entire South American plate as Africa slowed down. In another example, the extensional regime that controlled the inception of normal fault-bounded intra-arc basins in the Oligocene is well known to have occurred all along the Andean margin (e.g., Daly, 1989; Mpodozis and Ramos, 1989). This change could be attributed to a general decrease in the overriding velocity affecting the South America plate, which would produce a steepening of the subduction zone and a retreat of magmatic activity toward the trench. On the other hand, local conditions might have enhanced these effects, as seen in the southern sector of the Neuquén Andes, where widespread normal faults related to Mesozoic rifts played a major role in later contractional events.

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