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Evidence for Cenozoic extensional basin development and tectonic inversion south of the flat-slab segment, southern Central Andes, Chile (33°–36°S.L.)

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Abstract

The mainly volcanic Cenozoic deposits that make up much of the western part of the Principal Cordillera in Central Chile are generally subdivided into two major units: an older Abanico or Coya-Machalí Formation and a younger Farellones Formation. Difficulty in differentiating these units has led to considerable debate. On the basis of the wide distribution, great thickness, and presence of sedimentary intercalations, it has been postulated that these arc volcanics were deposited in an intermontane basin; more recently, it has been proposed that this basin developed under extensional conditions and underwent subsequent tectonic inversion. We present field, geochronologic, geochemical, and thermal maturity data that support the latter interpretation. Collectively, this new information clarifies the stratigraphic, tectonic, and paleogeographic evolution of these deposits.

The vast geographic extent of the Abanico Formation and lateral equivalents, which reach from at least 32°30′ to 44°S along the Principal Cordillera, its great thickness, and the presence of repeated thick fluvial and lacustrine intercalations all indicate deposition in a large, strongly subsident, and probably north–south oriented basin, developed between middle to late Eocene and Oligocene. The unconformable contact with underlying Mesozoic units observed at several localities indicates that deposition followed a substantial erosional episode during late Cretaceous and/or early Cenozoic time.

Basal deposits of the Abanico Formation near Termas del Flaco increase rapidly in thickness to the west. Still further to the west, a thick Abanico section contains, in its upper part, mammal fossils older than those found in the basal deposits near Termas. This evidence indicates a major space of deposition west of this locality, which had been filled before deposition took place at Termas. The east-vergent, high-angle El Fierro thrust fault on the east side of the westward-growing deposits is interpreted as an inverted normal fault associated with initial basin development and deposition. High-angle thrust faults observed elsewhere on the eastern outcrop margin of the Abanico Formation (i.e. the Chacayes-Yesillo Fault in the Maipo section and the Espinoza Fault in the Cachapoal–Las Leñas section) also have been interpreted as inverted normal faults. The irregular folding style of the Abanico Formation, with its highly variable amplitude, longitude, tightness, and vergency, suggests that deformation is attributable to the inversion of faults associated with basin development.

Geochemical characteristics of the Abanico Formation indicate a relatively thin crust during early basin development. Thermal maturity data reflect a deep burial of the deposits during accumulation, and thermal modeling indicates high heat flow conditions during burial. These data support a major extensional episode of the crust and the development of a large depositional space (basin) in this region. On the basis of this evidence, we suggest that deposition of the Abanico Formation is related mostly to crustal extension and its deformation to tectonic inversion.

In the western Las Leñas river valley, a growth structure indicates that deformation occurred between 20.8 and 16.1 Ma, while the Abanico Formation was still being deposited. Deformation apparently did not occur coevally throughout the region; however, sedimentation and

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volcanic deposition in the basin apparently occurred uninterrupted. This argues against a single, obvious unconformity separating the Abanico and Farellones Formations. Instead, it supports the existence of local angular unconformities where fault inversion affected the basin fill.

Comparison of the timing of extensional basin development and subsequent contraction (inversion) with the convergence rates between the Nazca and South American plates during the Cenozoic period shows a correspondence with periods of decreasing and increasing convergence rates, respectively.

Tectonic and volcanic events on the east versant of the Andes [Journal of South American Earth Sciences 15 (2002)], which are coeval with the basin inversion and crustal thickening episodes presented herein and, therefore, with the previously mentioned period of increasing convergence rate, are assumed to correspond with the same episode of major tectonic accommodation of the crust in this Andean region. It is not yet possible to determine if the collisional event of the Juan Fernández ridge at approximately 15 Ma in the flat-slab segment region had a local or a more regional effect on the late Cenozoic tectonic evolution of the continental margin in the Central Andes.

Keywords: Andes; Cenozoic; Tectonics; Chile

1. Introduction

1.1. Statement of the problem

The Andean Cordillera is the world's archetypal example of a subduction-related mountain belt (Dewey and Bird, 1970). This range derives from crustal shortening and thickening and magmatic addition along the western continental margin of South America above the subducting Nazca plate, as well as the action of the intervening mantle wedge (Jordan et al., 1983; Allmendinger, 1986; Isacks, 1988; Ramos, 1988; Kay and Abbruzzi, 1996; Allmendinger et al., 1997). Accordingly, the structural style of the southern Central Andes (18–40°S.L.) is generally considered to reflect subduction activity directly (Charrier, 1973a; Frutos, 1981; Jordan et al., 1983, 1997; Ramos, 1988; Mpodozis and Ramos, 1989), which, according to magmatic evidence, seems to have been rather continuous since the early Jurassic (Coira et al., 1982; Jordan et al., 1983, 1997; Ramos, 1988; Mpodozis and Ramos, 1989; Kay et al., 1991, 1999; Kay and Abbruzzi, 1996), or at least without the long interruptions that occurred during the late Permian and Triassic (Mpodozis and Kay, 1990). Although these observations suggest a continuous compressive strain regime along the active continental margin, the resulting tectonic style indicates that the stress regime underwent major changes during Andean evolution (Charrier and Vicente, 1972; Charrier, 1973a; Aguirre et al., 1974; Frutos, 1981; Malumián and Ramos, 1984; Mpodozis and Ramos, 1989; Jordan et al., 1997; Hartley et al., 2000; Charrier et al., 2000). Considerable effort has been directed at establishing the relationship between subduction and its effects on the tectonic conditions in the upper crust in this region. Alternating contractional and extensional episodes were once thought to have affected the Argentine–Chilean Andes on a regional scale (Charrier and Vicente, 1972; Aguirre et al., 1974; Frutos, 1981) and perhaps beyond (Charrier and Malumián, 1975; Malumián and Ramos, 1984). However, contractional and extensional conditions are now believed to have fluctuated on a much more local geographic scale. Therefore, understanding the relationship between subduction and alternating strain regimes involves the additional complication that different tectonic regimes have occurred in different parts of the range synchronously (Jordan et al., 1997; Hartley et al., 2000; Charrier et al., 2000).

Efforts to explain the relationship between subduction and the tectonic conditions in the upper crust have not been able to give satisfactory explanations of all observed situations. Most probably, other factors must be taken into account, as has been shown experimentally by numerical and analog models. These show variations in strain regimes across the mountain range (Willet et al., 1993), as well as the existence of doubly vergent patterns with two conjugated shear zones progressing toward the rear and front of the orogene (Malavieille, 1984; Willet et al., 1993). Such models may account, at least partially, for the time and space variations mentioned previously and the opposed vergencies observed in some regions of the Andes.

Evidence of sequential Cenozoic extension and contraction in the Chilean Andes has been reported as follows: the Precordillera and the western Altiplano in northernmost Chile, between 18°30′ and 19°30′S (García et al., 1996; Charrier et al., 1999); the Maricunga Belt, between 26°S and 28°S (Mpodozis et al., 1995); the Principal Cordillera in Central Chile, between 33 and 36°S (Charrier et al., 1994, 1996, 1997; Godoy and Lara, 1994); and South Central Argentina and Chile, between 36 and 38°S (Jordan et al., 2001).

Slow convergence along this continental margin last occurred during the Oligocene (Pardo-Casas and Molnar, 1987). The coincidence of this episode with extensional basin development (involving thick volcanic, volcaniclastic, and sedimentary deposition) suggests a link between subduction and deformation in the upper crust along this continental margin at this moment (Charrier et al., 1994, 1996, 1997, 1999; Godoy and Lara, 1994; Jordan et al., 2001). Although this short temporal coincidence between a low convergence rate and extensional tectonics in the upper continental crust does not necessarily indicate a cause–effect relationship, there seems to be a more significant coincidence between longer periods of decreasing and increasing convergence rate and extensional and contractional tectonic conditions, respectively, which we discuss subsequently.

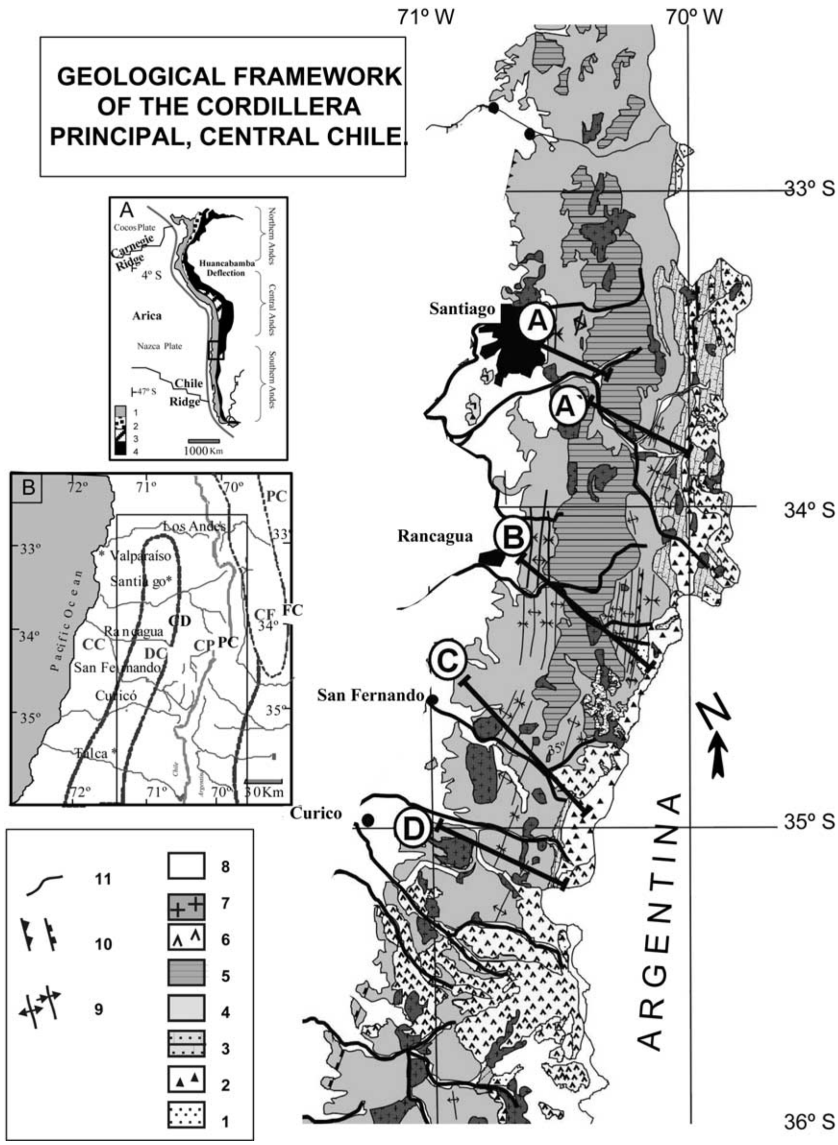

Fig. 1. Schematic geologic and tectonic maps of the Andean Cordillera and the study region and location of the structural sections presented in Fig. 5(A), (A′), (B), (C), and (D). Simplified and modified from Servicio Nacional de Geología y Minería (1982). Main subdivisions and morphostructural units, according to Aubouin et al. (1973). (1) Western and Coastal Cordilleras, (2) Central Cordillera, (3) Altiplano-Puna plateau, (4) Eastern Cordillera and Subandean Ranges. B. Location of the study region relative to South America and the morphostructural units for the Central Argentina–Chilean Andes: CC, Coastal Cordillera; CD, Central Depression; PC, Principal Cordillera; FC, Frontal Cordillera. C. Schematic geologic map of the study region in the Chilean Principal Cordillera between 33° and 36°S.L.: (1) Jurassic marine (Lias and Dogger) and continental (Malm) deposits, (2) latest Jurassic to early Cretaceous marine (Tithonian–Neocomian) deposits, (3) Colimapu Formation, BRCU, (4) west and east swaths of the Abanico Formation (late Eocene to early Miocene), (5) Farellones Formation (early to late Miocene), (6) Pliocene to Pleistocene volcanic deposits, (7) Cenozoic plutonic intrusives, (8) quaternary clastic continental deposits, (9) fold axis, (10) thrust fault, (11) road.

Only limited field evidence for extensional basin development during late Eocene and early Miocene in the Principal Cordillera of the Central Chilean Andes, between 33 and 36°S, has been published previously (Charrier et al., 1994, 1996, 1997; Godoy and Lara, 1994; Zapatta, 1995; Wyss et al., 1996; Godoy et al., 1999; Burns and Jordan, 1999; Jordan et al., 2001). We present new field, geochronologic, geochemical, and thermal maturity data that build on this interpretation for a region located immediately south of the flat-slab segment. Collectively, these results clarify the deformational process responsible for the tectonic inversion of the basin, which in turn has implications for understanding Andean evolution and uplift in general and permits comparison with evolution in the flat-slab segment.

1.2. Geologic setting of the study region

The geology of the Principal Cordillera of the Central Chilean Andes has been studied intensively for more than 40 years. The degree to which data collected over the past decade have revolutionized our understanding of this region's tectonic history was thus rather unexpected.

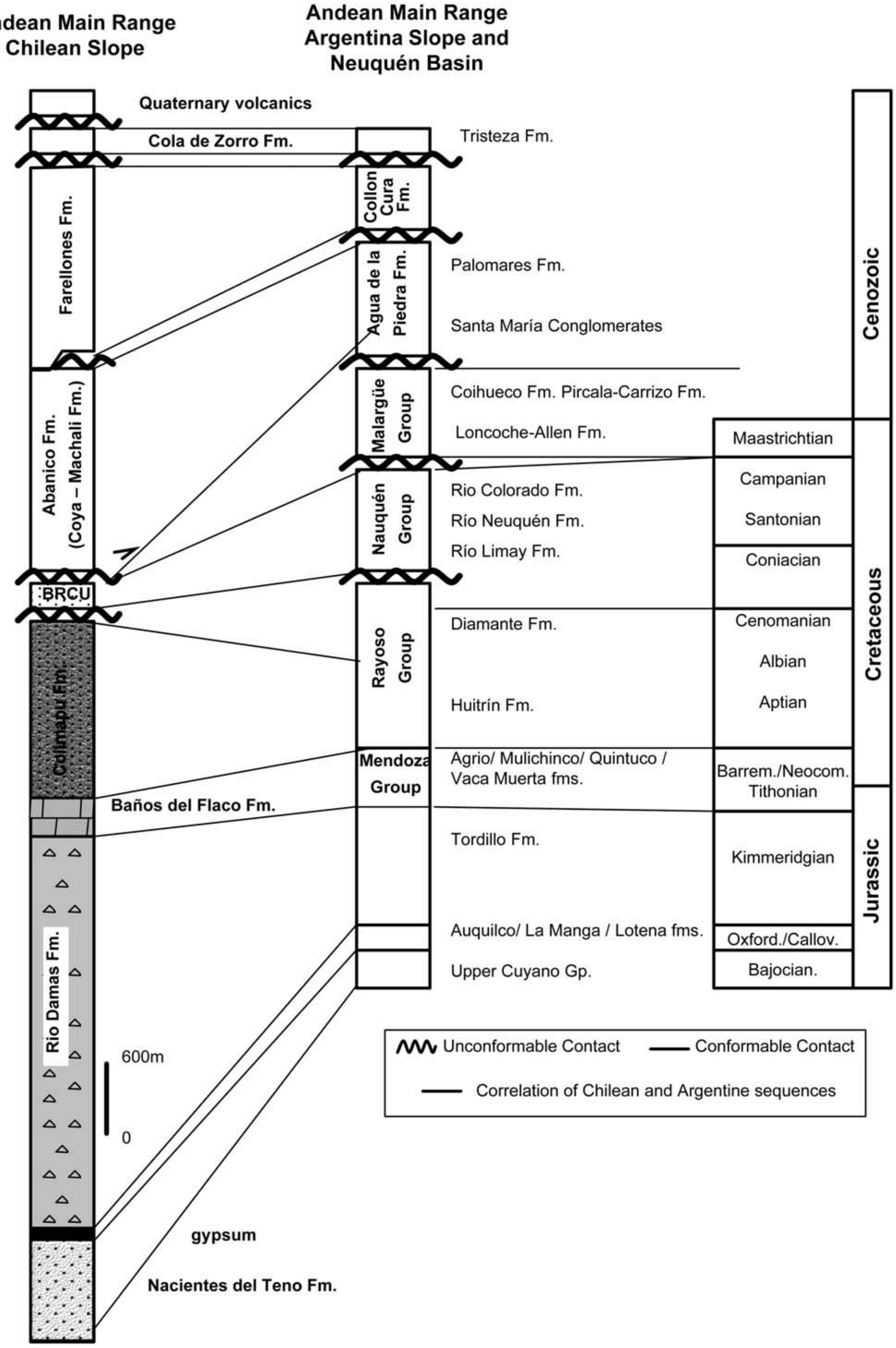

Fig. 2. Simplified stratigraphic columns of the western slope (left) of the Principal Cordillera and eastern slope of the Principal Cordillera and Neuquén Basin (right) at 34°–35°S.L., based on Klohn (1960), González and Vergara (1962), Davidson and Vicente (1973), Charrier (1973b, 1981b), Vergara and Drake (1979), Thiele (1980), Munizaga and Vicente (1982), Drake et al. (1982), Vergara et al. (1988), Ramos (1988), Mpodozis and Ramos (1989) and Charrier et al. (1996), and present work.

The bulk of the Andean Principal Cordillera in Central Chile (Fig. 1) consists of a several kilometers thick series of Jurassic to early–late Cretaceous marine and continental back arc, as well as Cretaceous to Cenozoic continental (mainly volcanic and volcaniclastic) deposits (Fig. 2). Excellent biostratigraphic control in marine units of the lower half of this sequence tightly constrain their ages and those of bracketing terrestrial units, making correlation to units in adjacent western Argentina straightforward. Until recently, however, the age and correlation for the post-Neocomian continental units remained poorly understood. These post-Neocomian units include: (1) regressive sediments of possible Aptian–Albian age (Colimapu Formation), (2) late Cretaceous fluvial deposits (BRCU in

Zapatta, 1995; Charrier et al., 1996), and (3) widespread volcanic and sedimentary deposits, variously named Abanico, Coya-Machalí, and Colbún Formations[1] by previous authors. Hereafter, this unit is referred to as the Abanico Formation.

The late Eocene (and possibly older) to early Miocene deposits in this region are covered by a thick sequence of generally less deformed and less metamorphosed (low-grade metamorphism) volcanic deposits of Miocene age named the Farellones Formation (Klohn, 1960). The Farellones Formation does not occur (or has not been recognized) south of the Tinguiririca River valley (34°45′S). South of the Teno River valley (35°S), a much younger volcanic sequence assigned to the Cola de Zorro Formation (González and Vergara, 1962) covers older Cenozoic rocks of the Abanico Formation.

The Abanico Formation was first ascribed a late Cretaceous age (Aguirre, 1960; Klohn, 1960) and thus was interpreted as the relic of a Mesozoic volcanic arc (Aubouin et al., 1973; Charrier, 1973b; Aguirre et al., 1974; Barrio, 1990). With the first radioisotopic age determinations (Vergara and Drake, 1978; Charrier and Munizaga, 1979), western outcrops of these deposits came to be recognized as Cenozoic in age and as having been deposited in a backarc basin (Charrier, 1981a,b; Malbran, 1986; Arcos, 1987) or to correspond to the deposits of an intermontane basin (Vergara and Drake, 1979). Only recently, by means of fossil mammals and $^{40}Ar/^{39}Ar$ determinations has, a Cenozoic age for the eastern deposits been established (Novacek et al., 1989; Wyss et al., 1990, 1993, 1994, 1996; Flynn et al., 1995; Charrier et al., 1996, 1997).

The previous lack of paleontologic control for the Abanico Formation and pervasive low-grade metamorphism, which limited the utility of K–Ar age determinations, represented the greatest obstacles to elucidating the Cenozoic tectonic evolution of the Central Chilean Andes. The nature of the stratigraphic relationship of this sequence to underlying and overlying units represents a second important geological problem in this region.

Systematic regional geologic studies in this segment of the Principal Cordillera in Central Chile (immediately south of the flat-slab segment) began with Klohn (1960), Aguirre (1960) and were followed by several authors (González and Vergara, 1962; Davidson and Vicente, 1973; Charrier, 1973b, 1981b; Thiele, 1980; Rivano et al., 1990; Charrier et al., 1996; Godoy et al., 1999; Rivera and Falcon, 2000). Deposits now recognized as Cenozoic in age are the most broadly exposed rocks in the region, and the literature on these units is extensive.

Since the late 1980s, several research groups have sought to address more precisely the Cenozoic evolution of this region and various associated problems. This activity stemmed from both the interest of the Chilean State CODELCO copper mining company in better understanding the geologic setting of the El Teniente copper mine and basic research interests. Recent progress has permitted clarification of the relationships of these deposits to bracketing stratigraphic units, as well as a better comprehension of the depositional history, tectonic evolution, and tectonic conditions prevailing during basin development.

2. The Abanico Formation

2.1. Geographic distribution

The Abanico Formation in this region is a thick, continental, dominantly volcanogenic unit (Aguirre, 1960; Klohn, 1960; González and Vergara, 1962; Charrier, 1973b; 1981b; Thiele, 1980; Gana and Wall, 1997) exposed between at least 32°30′S (Moscoso et al., 1982) and far beyond the southern boundary of the study region (González and Vergara, 1962).

Between 33 and 35°S, these deposits are mapped as two parallel, N–S-oriented swaths, separated from each other by the slightly folded, nearly unmetamorphosed Miocene volcanic deposits of the Farellones Formation. South of 35°S, the Farellones Formation is apparently absent, which allows the Abanico Formation to be followed continuously from Chile's Central Valley (Central Depression) east to the Mesozoic series, forming a 40–45 km wide band of outcrop.

In regions where the Coastal Range and the Principal Cordillera are continuous (north of 33°S), the western swath of the Abanico Formation is bounded to the west by Cretaceous units. Where the Coastal Range and Principal Cordillera are discrete (south of 33°S), the western swath is bounded to the west by quaternary deposits of the Central Depression (Fig. 1). The eastern swath of the Abanico Formation is bounded to the east by the Mesozoic sedimentary series; to the south, it is interrupted by a large batholith and covered by the Tinguiririca Volcanic Group, as well as extensive ice (Glaciar Universidad).

The Abanico Formation is overlain by the Farellones Formation and younger volcanic units, as well as quaternary sedimentary deposits.

Oligocene to Miocene lavas, volcaniclastic, and sedimentary deposits, plus small intrusive bodies, occur further to the south in the Principal Cordillera (López-Escobar and Vergara, 1997) and the Central Depression (Muñoz et al., 2000), forming the southward prolongation of the Abanico Formation. In the Principal Cordillera, these deposits include the well stratified, volcanic, and sedimentary

[1] These deposits were described with two different names at different areas in the Chilean Principal Cordillera: Abanico Formation near Santiago, between 32°30′ and 34°S (Hoffstetter et al., 1955; Aguirre, 1960) and south of 35°S (González and Vergara, 1962), and Coya-Machalí Formation, between 34° and 35°20′S (Klohn, 1960). More recent geological surveys demonstrated a N–S continuity between these deposits (Drake et al., 1982). Karzulovic et al. (1979) named a lithologically similar and chronologically equivalent rock series exposed along the west side of the Principal Cordillera at 35°30′S.L. the Colbún Formation.

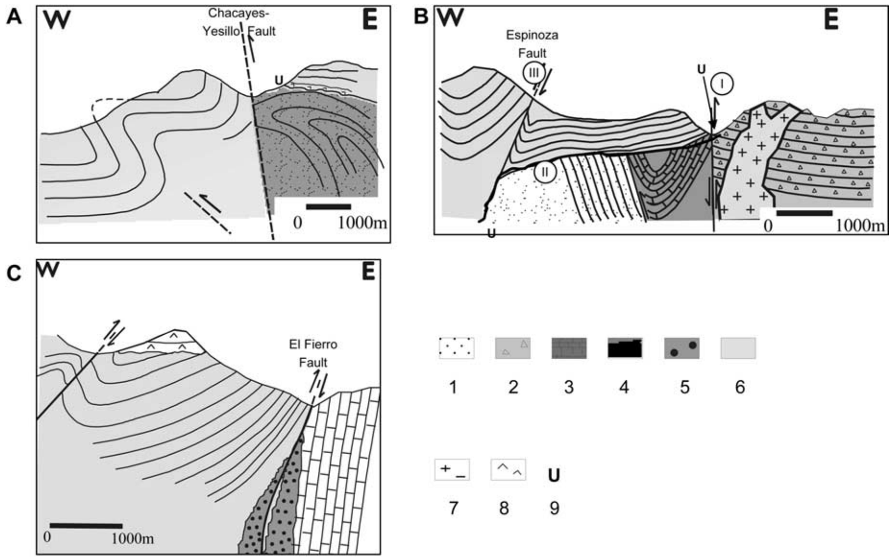

Fig. 3. Schematic cross-sections of the eastern border of the east swath of the Abanico Formation showing depositional and tectonic contacts with the Mesozoic units. (A) El Volcán river valley, the west-vergent Chacayes-Yesillo Fault thrusted the folded, Cretaceous Colimapu Formation over the Abanico Formation. East of the fault an undetermined volcanic sequence covers the Colimapu Formation. Locally, an unconformity has been observed along this contact (Bustamante, 2001). (B) Las Leñas River valley at the confluence of the Espinoza and Las Leñas valleys. I. An almost vertical fault that uplifted the Kimmeridgian Río Damas Formation into contact with the Abanico Formation in the eastern part of the section. This fault is comparable with that of the Chacalles-Yesillo Fault (see A). II. A slightly west-dipping unconformity separates the Abanico Formation from the underlying Leñas-Espinoza of possible Callovian age (Arcos, in preparation) and Baños del Flaco Formations. The unconformity covers also an older normal fault along which the Leñas-Espinoza and the Baños del Flaco Formations are in contact. III. A high-angle, east-vergent thrust fault at the left side of section (Espinoza Fault) cuts through the Abanico Formation and uplifts the west-side block, but the unconformity is not exposed on this side of the fault. (C) Tinguiririca River valley at Termas del Flaco: The east-vergent El Fierro Fault cuts through the unconformity separating the Abanico Formation from the underlying late Cretaceous BRCU (Charrier et al., 1996): (1) Leñas-Espinoza Formation, (2) Río Damas Formation, (3) Baños del Flaco Formation, (4) Colimapu Formation, (5) BRCU, (6) Abanico Formation, (7) quaternary volcanics, 8. unconformity.

Cura-Mallín Formation between 37 and 39°S (González and Vergara, 1962; Drake, 1976; Niemeyer and Muñoz, 1983; Muñoz and Niemeyer, 1984; Suárez and Emparán, 1995, 1997). The younger and mainly volcanic Trapa–Trapa Formation, between 36° and 37°30′S (Niemeyer and Muñoz, 1983; Muñoz and Niemeyer, 1984), can be considered a southern equivalent of the Farellones Formation. South of 36°S, deposits equivalent to the Abanico Formation are also exposed east of the continental divide in the Andacollo region in Argentina (Jordan et al., 2001) and can be traced further south in Argentine territory to approximately 44°S, where they form the Oligocene Ñirihuau Formation (Spalletti, 1983; Cazau et al., 1987) and local marine deposits of Eocene to Oligocene age (Estratos de Río Foyel) (Bertels, 1980; Spalletti, 1983). These deposits form a 1000 km band of nearly continuous exposures along the Principal Cordillera in Chile and Argentina and in the southern Central Depression.

2.2. Contact with mesozoic units

Depositional contacts between the Cenozoic deposits and Mesozoic units are exposed on the western and eastern margins of the exposures. On the western margin, a depositional contact occurs between 33° and 33°15′S, at the northern end of the Central Depression, and between 33°45′ and 34°S, between the Oligo-Miocene deposits and the Cretaceous Lo Valle (Gana and Wall, 1997; Sellés, 1999a) and Las Chilcas Formations (Sellés, 2000), respectively. Although at these localities, the contact is apparently conformable, it encompasses a 37 myr gap between a radioisotopic age of 71.9 Ma obtained in the Lo Valle Formation and the 34 Ma age, the oldest age obtained in the Cenozoic deposits in this region (Gana and Wall, 1997).

The contact on the eastern margin between the Cenozoic and Mesozoic units along the Principal Cordillera has been recently studied in detail at three localities along the eastern margin of the eastern swath of the study region. At 33°50′S, in the Maipo River valley, southeast of Santiago, the contact between the Cenozoic and Mesozoic deposits is the high-angle, west-vergent Chacayes-Yesillo thrust fault (Fig. 3(a)).

At 34°15′S, in the Las Leñas River valley in the Cachapoal River basin, east of the junction of the Espinoza and the Las Leñas Rivers, the Cenozoic deposits unconformably overlie marine deposits of the Callovian (Arce, in preparation) Leñas–Espinoza Formation and the Tithonian–Neocomian Baños del Flaco Formation (Klohn, 1960; Charrier, 1982), as well as coarse detrital continental deposits of the Kimmeridgian Rio Damas Formation (Zurita, 1999; Arce, in preparation) (Fig. 3(b)). This unconformity forms an undulating (folded), gently west-dipping surface that is

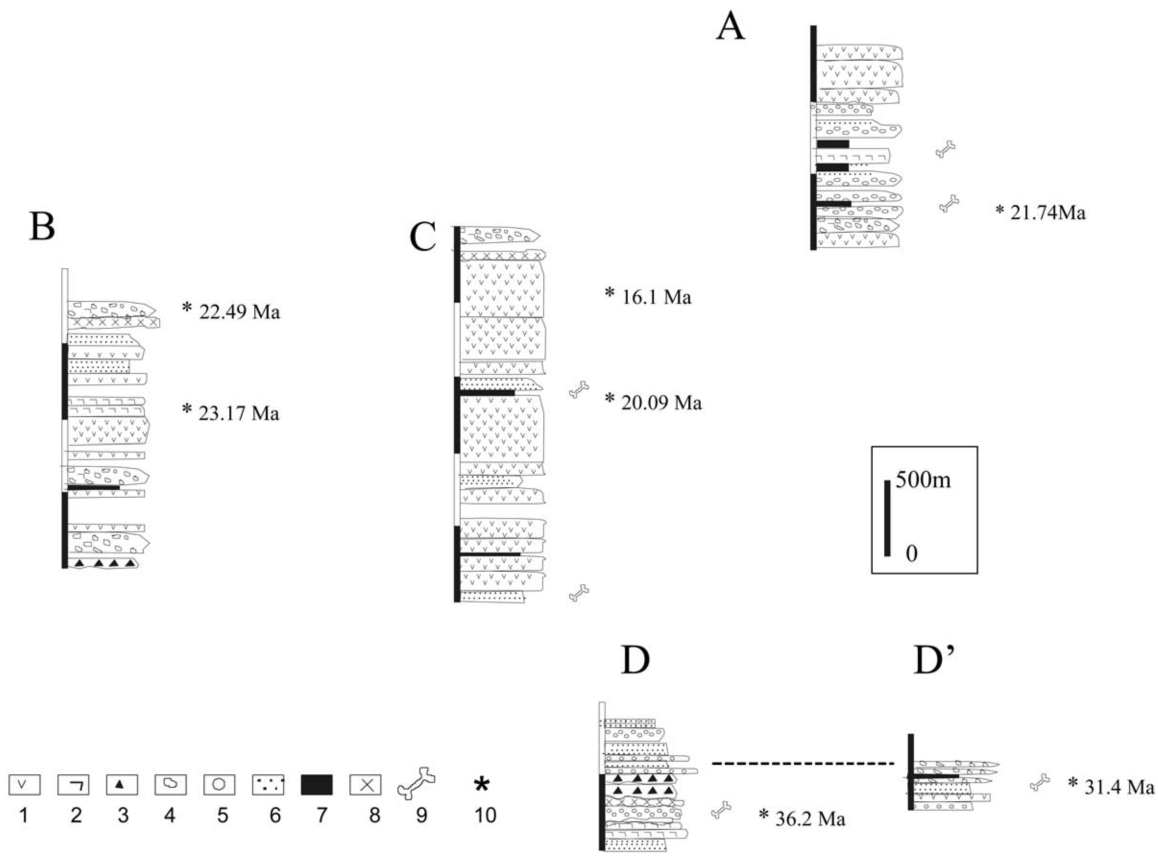

Fig. 4. Schematic stratigraphic columns of the Abanico Formation showing alternation of lavas, coarse volcaniclastic deposits, and lacustrine sediments and location of fossiliferous horizons and radioisotopically dated samples. (A) Maipo River valley, based on Aguirre (1999), Baeza (1999), and Elgueta et al. (1999, 2000) (Fig. 1(A′)); (B) Carretera El Cobre, based on Arce (in preparation) and Zurita (1999) (western part of section B in Fig. 1); (C) Las Leñas River valley, based on Charrier (1981b) and Zurita (1999) (eastern part of section B in Fig. 1); (D and D′) Westward growth deposits at Termas del Flaco in the Tinguiririca River valley, based on Zapatta (1995) and Charrier et al. (1996); (D) (eastern part of section C in Fig. 1). (1) Massive andesite and basaltic–andesite, (2) rhyolite, (3) breccious andesite, (4) coarse and fine-grained volcaniclastic deposits, (5) conglomerate, (6) epiclastic sandstone, (7) tuffaceous siltstone and calcareous mudstones, (8) sills, (9) horizon with mammal fossils, (10) $^{40}Ar/^{39}Ar$ age determination.

not exposed west of the Espinoza thrust fault. Godoy and Lara (1994) and Godoy et al. (1999) considered this unconformity to be a thrust fault, which they correlated with the El Fierro Fault.[2]

In the Termas del Flaco region (Tinguiririca River valley), the Cenozoic deposits unconformably rest on a steep, west-facing erosion surface, covering the lower part of the Tithonian–Neocomian Baños del Flaco Formation and a late Cretaceous brownish-red clastic unit (BRCU) (Zapatta, 1995; Charrier et al., 1996) (Fig. 3(c)). The basal unconformity of the Cenozoic deposits in this region is cut by the east-vergent, steep-dipping El Fierro thrust fault (Zapatta, 1995; Charrier et al., 1996).

2.3. Description of the deposits

Exposures of the Abanico Formation consist of an up to 2500 m thick series of volcaniclastic deposits and acidic to intermediate lavas with alluvial, fluvial, and lacustrine sedimentary intercalations, some of which form up to 500 m thick sedimentary lenses. Sedimentary intercalations are composed of coarse and fine-grained detrital deposits and micritic and rare oolitic limestones. There is no evidence of marine sedimentation. Sedimentary lenses are more common in the eastern than in the western swath. Abundant dikes and sills of andesitic to dacitic compositions cut these deposits. Stocks of mainly granodioritic composition were emplaced in these rocks during the early to early late Miocene. The Abanico Formation is pervaded by low-grade metamorphic minerals, indicating zeolite to prehnite–pumpellyite facies development (Levi et al., 1989; Vergara et al., 1993). This alteration strongly affects the matrix of the volcaniclastic and epiclastic rocks that obscure their petrographic features; associated penetrative structures have

[2] We use the name El Fierro Fault only for the west-dipping thrust fault in the Termas del Flaco region in the Tinguiririca River valley. Godoy and Palma (1990), Godoy and Lara (1994), and Godoy et al. (1999) consider the El Fierro Fault to be a regional, out-of-sequence thrust, associated with the Andean thrust fold belt and forming the contact between the Mesozoic and Cenozoic series in this region.

not been observed. Plutonic intrusives are little affected by this metamorphism.

No complete stratigraphic section of this unit has been observed. Rapid N–S and E–W lithologic variations and local strong deformation precludes characterization of this unit with a single stratigraphic column. We, therefore, briefly describe and schematically illustrate some selected stratigraphic columns to help clarify the nature of these deposits, their depositional environments, and available $^{40}Ar/^{39}Ar$ ages (see Fig. 4).

Basal deposits in the Las Leñas River valley, east of the junction with the Espinoza River, form a 80–100 m thick yellowish-white stratified band of finely laminated ash-flow deposits, autoclastic lava flows, surge deposits with large inclined sets, ignimbrites, and coarse, clast supported breccias containing mainly rhyolitic fragments. These correspond to proximal to medial volcaniclastic fan facies. The Abanico deposits that unconformably cover the Mesozoic units in the Tinguiririca River valley, next to Termas del Flaco, form a more than 900 m thick volcanoclastic and sedimentary series (Charrier et al., 1996). The more complete exposition at this locality shows a transition from volcaniclastic to sedimentary facies (Fig. 4(d)). The lower portion consists of a reddish-brown, well-stratified sequence of fine ash tuffs, lapilli tuffs, fine pyroclastic breccias, ignimbrites, and basaltic–andesite lavas, with sparce mudstone, sandstone, and conglomeratic intercalations. The sequence thickens north-westward in less than 1 km from 230 m in column D′ to 560 m in column D (Fig. 4(d) and d′). Sedimentary intercalations are more common in the thicker section. The upper sedimentary portion is more than 300 m thick and composed, according to Zapatta (1995), of upward coarsening and thickening cycles of siltstones, fine and coarse sandstones with calcareous concretions, and (para)conglomerates with mega cross-bedding, rich in volcanic components. Two intercalations of calcareous sandstones were observed at its upper part. Collectively, these deposits indicate the transition from a medial to distal volcaniclastic fan and high-energy fluvial facies to shallow lacustrine facies.

Rapid vertical and lateral lithological variations are well represented by the exposures in the eastern swath. In the Las Leñas River valley, the exposed thickness attains more than 2500 m (Fig. 4(c)). These deposits are formed by massive series of andesitic and dacitic lavas and coarse volcaniclastic deposits with thick intercalations of calcareous mudstones and sandstones and black shales with phoetid limestone intercalations. Sandstones are rich in pyroclastic components. It is interesting to note that, in this section, thick lacustrine deposits interfinger with lavas and coarse volcanoclastic deposits. One of these sedimentary intercalations, formed by fine-grained volcaniclastic breccias and sandstones, grades northward into lacustrine facies. In the Cachapoal River valley, immediately north of the Las Leñas valley, these deposits form an alternating series of 1–3 m thick, massive, red, fine-grained volcaniclastic deposits and 60 cm to 1 m thick limestone layers. A few kilometers to the north (La Engorda valley), they form a 500 m thick series of thinly stratified lacustrine sandstones, mudstones, and limestones.

Farther north in the Maipo River valley, an ~1500 m thick series of Cenozoic deposits consisting of lavas and volcaniclastic deposits contains a single 100–150 m thick lacustrine intercalation (Aguirre, 1999; Baeza, 1999; Elgueta et al., 1999, 2000) (Fig. 4(a)).

In the western swath, sedimentary intercalations are less common than in the eastern outcrops. Here, lithologic variations also occur laterally over short distances. Immediately north of Santiago, a 500–700 m thick sequence of basaltic to dacitic lavas and volcaniclastic deposits contain plant-bearing lacustrine intercalations (Sellés, 1999a). However, at the type locality of the Abanico Formation, east of Santiago, the 1900 m thick sequence of andesitic lavas and breccias and volcaniclastic deposits contains no sedimentary intercalations (Villarroel and Vergara, 1988). Thick series, exclusively composed of lavas and coarse volcaniclastic deposits, were observed on the western swath along the western Tinguiririca and Teno River valleys. Along the Carretera El Cobre (~34°10′S), however, a >1750 m thick series of fine to coarse volcaniclastic deposits and lavas alternate with thin sandstone and mudstone intercalations (Fig. 4(b)).

The most characteristic feature in these series is the existence of exclusively volcanic deposits in rather localized regions, indicating the location of volcanic centers, with more extended regions in which low-energy sediments (i.e. lacustrine) were deposited together with lavas and volcaniclastic fan deposits. This pattern documents the development of extended alluvial plains and lakes in the areas between eruptive centers.

2.4. Age

Field evidence from the western and eastern margins of the outcrop area indicates that the Abanico Formation is unconformably deposited on late Cretaceous and older units (Charrier et al., 1996; Gana and Wall, 1997; Sellés, 2000).

The oldest age obtained in Cenozoic deposits from the western margin, between 33° and 33°15′S, is 34 Ma (Gana and Wall, 1997). A similar age (about 36 Ma) was obtained at approximately 200 m above the basal unconformity in the Cenozoic deposits at Termas del Flaco in the Tinguiririca River valley (Charrier et al., 1996). Ten to 12 km west of Termas del Flaco, a thick volcaniclastic series contains mammal fossils of a clearly older age (Tapado Fauna; Wyss et al., 1994) than those existing next to the basal unconformity at Termas del Flaco. This situation indicates that the onset of deposition in this basin was earlier (late Eocene) west of Termas del Flaco.

The youngest age determination in the Abanico Formation gave a $^{40}Ar/^{39}Ar$ age of 16.1 Ma (Kay and Kurtz, 1995),

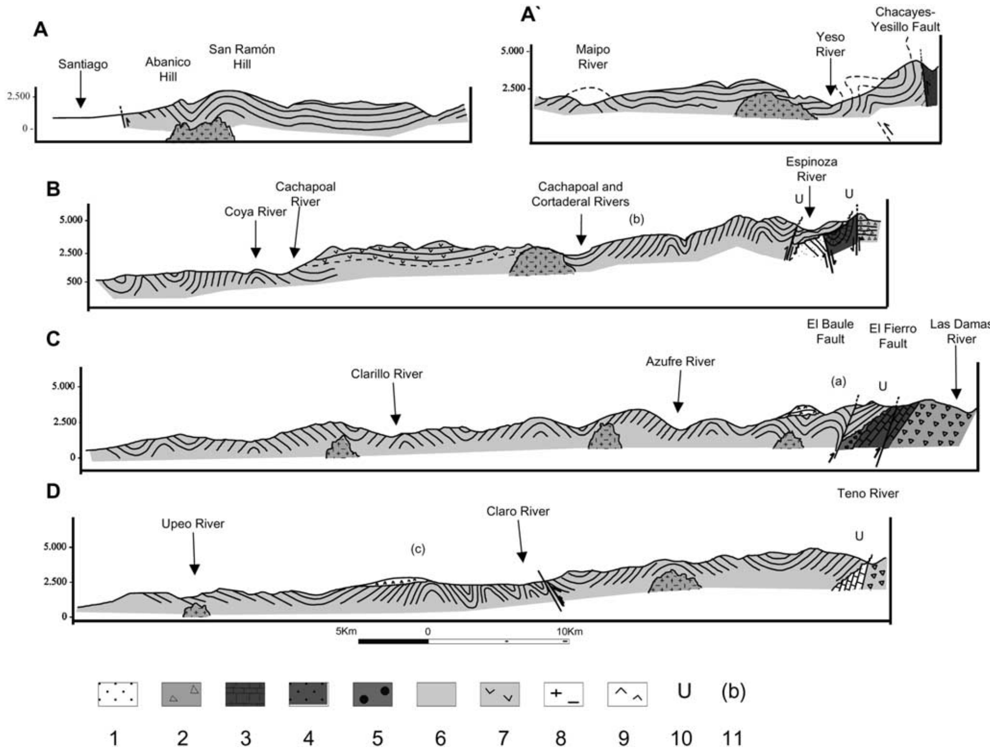

Fig. 5. Structural cross-sections of the Abanico Formation in the central Principal Cordillera, between 33°30′ and 35°15′S.L. (for location of sections, see Fig. 1). Sections A and A′ form an integrated profile of the region east of Santiago and along the Maipo River valley, respectively, between 33°30′S and 34°50′S. Section B was traced along the Cachapoal and Las Leñas River valleys and is representative of the region between 34° and 34°30′S. Section C was traced following the Tinguiririca River valley and is representative of the region between 34°45′ and 35°S. Section D was traced along the Teno River valley and is representative of the region between 35° and 35°15′S. Stratigraphy and structure are based on González and Vergara (1962), Davidson and Vicente (1973), Charrier (1973b, 1981b), Thiele (1980), Malbran (1986), Villarroel and Vergara (1988), Rivano et al. (1990), Zapatta (1995), Baeza (1999), Zurita (1999), Bustamante (2001), and Arce (in preparation). These sections illustrate the rather irregular development of folds and faults and variation of vergency within a given section and between sections. (1) Leñas-Espinoza Formation (Callovian), (2) Río Damas Formation (Kimmeridgian), (3) lower Baños del Flaco Formation (Tithonian), (4) Colimapu Formation (Aptian–Albian), (5) BRCU (late Cretaceous), (6) Abanico Formation, (7) Farellones Formation, (8) Miocene plutonic intrusion, (9) Cola de Zorro Formation (late Miocene–Pliocene) and quaternary volcanics, (10) unconformity, (11) location of growth structures: (a) Termas del Flaco, (b) Las Leñas River valley, (c) Upeo River Valley (see Fig. 8).

obtained in strongly folded lava in the Las Leñas River valley (Fig. 4(c)). On the basis of all the available faunal and radioisotopic age determinations, it is possible to constrain the age of the Abanico Formation to between middle to late Eocene and late Early Miocene.

2.5. Contact with the overlying Farellones formation

The Farellones Formation is a thick, gently folded, almost entirely volcanic unit forming a N–S band of outcrops between approximately 32 and 35°S (Vergara et al., 1988). In the study region, it reaches a thickness of 2400 m and is composed of andesitic to rhyolitic lavas, volcaniclastic deposits, and limited sedimentary deposits.

The deposits of the Farellones Formation typically cover the Abanico Formation. The contact has generally been reported as unconformable (Aguirre, 1960; Klohn, 1960; Jaros and Zelman, 1967; Charrier, 1973b, 1981b; Thiele, 1980; Moscoso et al., 1982). Other authors (Godoy, 1988, 1991; Godoy and Lara, 1994; Godoy et al., 1999) view the contact as (1) being conformable or pseudoconformable or (2) corresponding to a regional low-angle thrust that they connect with the El Fierro Fault at Termas del Flaco.

At the type locality for the Farellones Formation, immediately east of Santiago (33°20′S.L.), Rivano et al. (1990) reported an unconformable contact separating the two units. At the same locality, Carrasco (2000) distinguished a second, stratigraphically lower unconformity and extended the Farellones Formation to stratigraphically lower levels at least 21.6 Ma old (Aguirre et al., 2000). Immediately north of 33°S, the lower levels of the Farellones Formation covering the unconformity were dated by Munizaga and Vicente (1982) at 25.2 and 20.4 Ma.

In the Cachapoal River valley section, at 34°20′S, the relation between the two units is different. Navarro (2001) observed a continuous transition between more deformed deposits, ascribed to the Abanico Formation, and less deformed deposits of the Farellones Formation. Along this section, the two swaths of the Abanico Formation are strongly folded, whereas the Farellones Formation is only gently folded (Klohn, 1960; Charrier, 1973b, 1981b; Charrier et al., 1985) (Fig. 5(b)). In the eastern swath, the youngest radioisotopic age obtained in the folded Abanico Formation is 16.1 Ma (Kay and Kurtz, 1995), and the oldest radioisotopic age (K–Ar) obtained in deposits of the Farellones Formation is 14.1 Ma (Charrier and Munizaga, 1979). Considering that the horizon dated at 16.1 Ma is not from the uppermost portion of the Abanico Formation and that the 14.1 Ma age was not obtained from the lowermost levels of the Farellones Formation, there is little time for an unconformity. Therefore, as observed by Navarro (2001), the contact between the two Cenozoic units probably is transitional. Indeed, in the Las Leñas River valley, west of the western anticline, the layers of the Abanico Formation form a broad syncline that differs little in structural style from that of the Farellones Formation in this area (Fig. 5(b)).

Thus, the age of the basal Farellones deposits covering the Abanico Formation, and whether there is a significant unconformity between the units, varies considerably at the different localities. Considering that the youngest ages obtained for the Farellones Formation in the study region correspond to the late Miocene, it is possible to establish a Miocene age for this unit. From comparison of this age with that of the Abanico Formation, it becomes evident that upper portions of the series assigned to this last unit and lower levels of the series assigned to the Farellones Formation have a similar age.

3. Evidence for extensional basin development

3.1. Sedimentologic evidence

The great thickness of the Abanico Formation in the study region indicates the development of a huge depositional space. The existence of repeated lacustrine intercalations among the volcanic deposits and the great thickness of some of the intercalations indicate the continuous existence of widely extended depressed areas. Although this is evidence for basin development, it does not define conditions of basin formation.

One line of evidence for extensional basin development in the study region is the existence of growth strata at Termas del Flaco (Fig. 3(a)), which were formed fairly early in the deposition of the stratified series. Here, the basal Cenozoic deposits contain two basaltic–andesite lavas. One of these, 20 m thick, overlies the 15 m thick basal ignimbritic breccia at locality D′ (Fig. 4(d′)) and is overlain by a mammal-bearing pyroclastic layer dated at 31.4 Ma (Wyss et al., 1993). The other lava, located about 1 km further west, was dated at 37.5 Ma (see Charrier et al., 1996) and occurs at a level at more than 200 m above the lowest exposed layers at locality D (Fig. 4(d)). Thus, deposition over Mesozoic units at locality D was occurring prior to 36 Ma, whereas deposition over Mesozoic units at locality D′, immediately above the unconformity, began only shortly before 31.4 Ma. As indicated, the basal volcaniclastic member increases its thickness more than 300 m in less than 1 km northwestward. Deposition against the unconformity and development of growth strata on its west side indicates that this unconformity formed the border of the basin at an early moment at this locality. Similar to the situation described for the Espinoza Fault, the existence of the high-angle, east-vergent El Fierro thrust fault parallel to the unconformity suggests that this is an inverted normal fault that probably controlled the development of the basin.

Additional evidence for the existence of a great depositional space west of Termas del Flaco and for its development before deposition began at this locality is provided by the existence, west of Termas, of the 1000 m thick volcaniclastic series that contains, at its middle part, mammal fossils of the Tapado Fauna. This fauna, according to Wyss et al. (1994), is considerably older (possibly correlative to the Eocene Casamayoran assemblages) than the fauna collected at Termas del Flaco next to the basal unconformity (Tinguiririca Fauna; Wyss et al., 1990, 1993, 1994).

3.2. Structural evidence

The unconformable relation between the Abanico Formation and older units indicates that Cenozoic deposition occurred on a previously deformed and eroded basement.

The main structures in the Abanico Formation are distinctly N–S oriented. The vergency of folds and faults varies within any single profile and between profiles (Fig. 5). Most of the N–S-oriented faults in the Abanico Formation are high-angle thrusts and, therefore, probably correspond with inverted normal faults. Folds vary considerably in tightness, amplitude, and wavelength, and accordingly, the thickness of limbs is also highly variable. The irregular folding style and the variable vergency of folds is ascribed to the effect in the cover of inverted normal faults.

The west-dipping Espinoza thrust fault, immediately west of the Espinoza valley in the Las Leñas River valley, has features indicative of a previous normal movement. Its trace roughly parallels the unconformity between the Abanico Formation and Mesozoic units. The Espinoza Fault (Fig. 3(b)) cuts the gently west-dipping basal unconformity of the Abanico Formation, and though it uplifts the west-side block, the unconformity is not exposed west of the fault. We interpret this as the effect of a previous downward movement of the fault's west-side block that was greater than the subsequent uplift of the same block along the fault. This suggests the existence at this locality of a fault-controlled, west-facing scarp in the basin.

Although rare, WNW–ESE-oriented faults have been observed in the study region. Such faults probably controlled the emplacement of minor intrusives in the Abanico Formation (Rivera and Cembrano, 2000) and caused sinistral and dextral bending of some fold axes, affecting the Abanico Formation in the western swath (Charrier, 1981b; Malbran, 1986). Similarly, these faults might explain why folds observed north and south of the Tinguiririca River cannot be traced across the valley

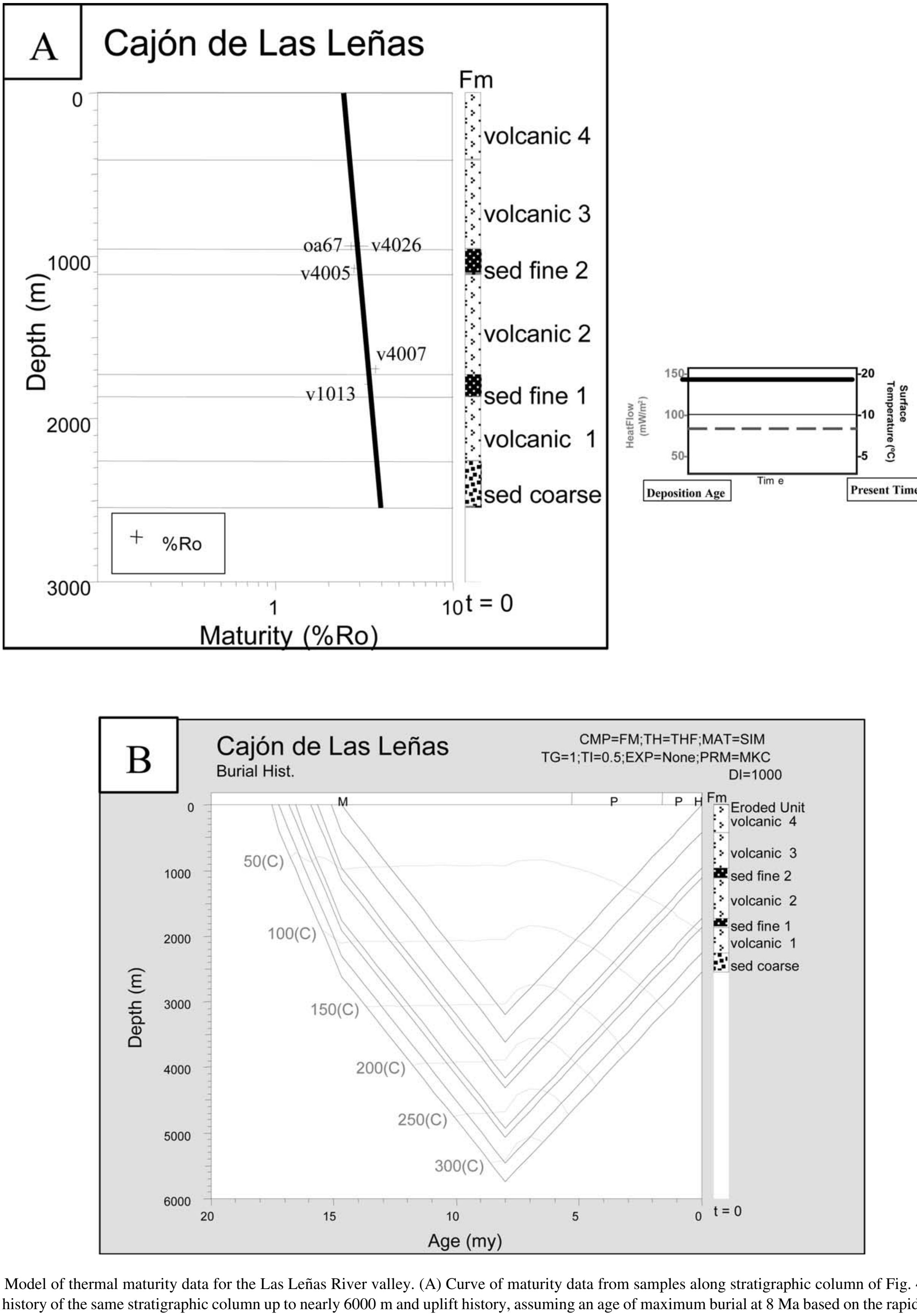

Fig. 6. Model of thermal maturity data for the Las Leñas River valley. (A) Curve of maturity data from samples along stratigraphic column of Fig. 4(c). (B) Burial history of the same stratigraphic column up to nearly 6000 m and uplift history, assuming an age of maximum burial at 8 Ma based on the rapid cooling at pluton Nacientes del río Cortaderal (Kurtz et al., 1997).

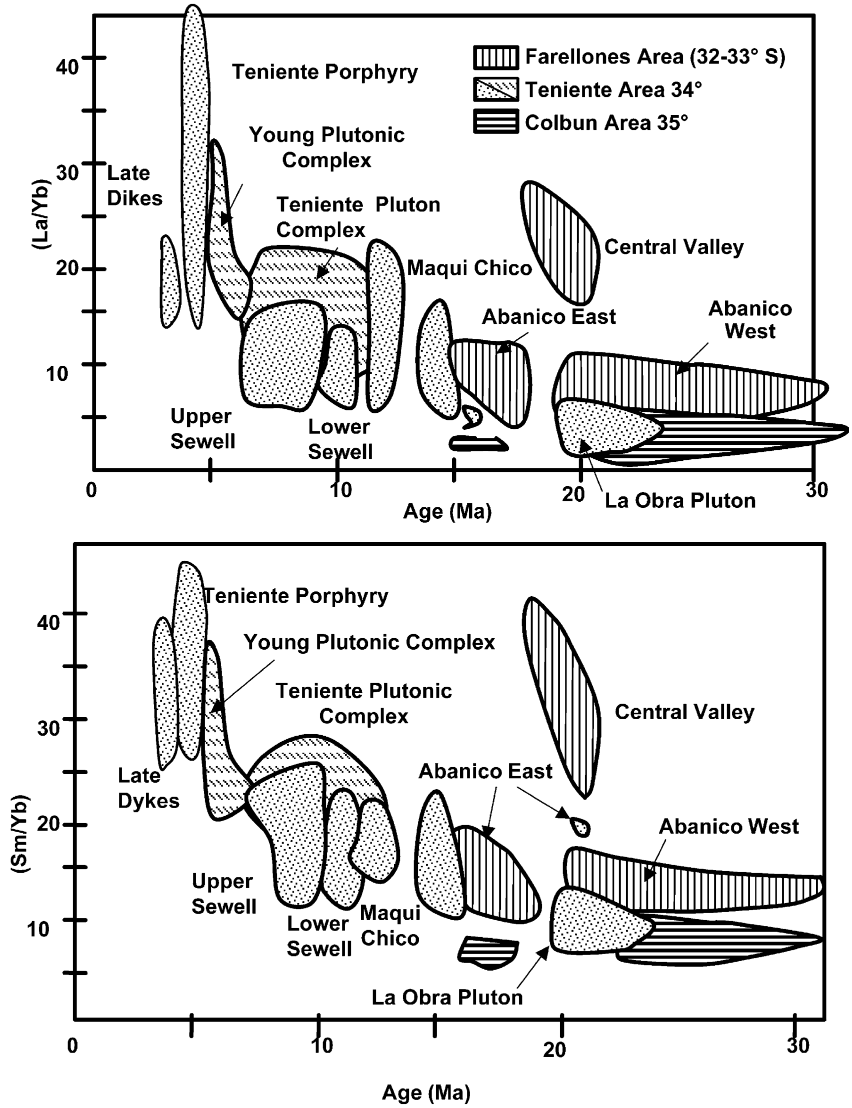

Fig. 7. Plots of La/Yb (a) and Sm/Yb (b) versus age for volcanic rocks of the Abanico and Farellones (Teniente Volcanic Complex) formations from the Principal Cordillera in the study region in Central Chile. Plots show that both minimum and maximum values for La/Yb and Sm/Yb ratios increase gradually throughout the late Oligocene and Miocene (30–6 Ma) and then jump to high values in the latest Miocene–Pliocene (5–3 Ma). Maqui Chico and Sewell are volcanic units pertaining to the Farellones Formation in the region of the El Teniente Copper Mine at 34°10′S.

(Malbran, 1986). This kind of fault does not occur in the east swath. We believe that these faults reveal the existence of accommodation zones associated with basin development.

3.3. Thermal maturity evidence

Modeling of the thermal maturity data based on vitrinite reflectance of the deposits along the Maipo River valley and the Cachapoal–Las Leñas sections has provided important information about the burial, subsidence, and heat flow conditions during deposition (Zurita, 1999; Zurita et al., 2000). Thermal maturity curves have been constructed for the Cachapoal–Las Leñas section only.

Along all analyzed stratigraphic columns, thermal maturity increases with stratigraphic depth, indicating that deformation occurred after the burial and heating process. Heat flow during burial was high to very high. Along the west part of the Cachapoal–Las Leñas section, along the Carretera El Cobre, heat flow was higher than 120 mW/m^2, whereas along the Las Leñas River valley, heat flow was lower than 100 mW/m^2. Thermal maturity measures for the lowest samples of the studied columns correspond to burial depths that exceed the present thickness of the columns, indicating that a considerable stratigraphic thickness has been eroded during exhumation (Fig. 6). Minimum values for the total thickness attained by the deposits during burial are as follows: 6000 m at the Las Leñas River valley, 4000 m at Carretera El Cobre, and 2500 m at the Maipo River valley, indicating high subsidence rates.

The thickness of the deposits accumulated in this region indicates powerful subsidence mechanisms accommodating their deposition. This, along with the high heat flows

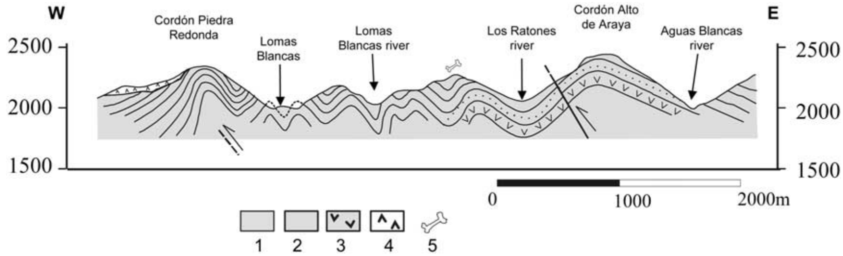

Fig. 8. Structural section of the Upeo River region (35°15′S) showing the stratigraphic position and the strong west-vergent folding of the fine, red, mammal-bearing volcaniclastic and sedimentary member intercalated between two volcanic members. The lower volcanic member is thrusted westward over the volcaniclastic and sedimentary red member. Growth structure is developed in the western part of section in the upper volcanic member and is unconformably covered by the 4.2 Ma volcanic deposits ascribed to the Cola de Zorro Formation. (1) Abanico Formation, (2) epiclastic deposits, (3) Andesitic–basaltic brecciated lavas, (4) volcanics of the Cola de Zorro Formation, (5) Mammal-bearing levels.

obtained for the Carretera El Cobre section, suggests that the mechanism was extensional. The heat flow asymmetry between the Carretera El Cobre and the Las Leñas River valley is interpreted as reflecting basin asymmetry and perhaps the existence of a hemigraben.

3.4. Geochemical evidence

Early geochemical and isotopic results for Cenozoic deposits between 32.5 and 34.5°S latitude were summarized by Nystrom et al. (1993), who pointed to a contrast between tholeiitic differentiation trends and primitive, mantle-like isotopic signatures in the Abanico Formation compared with calc-alkaline trends and crustal-like isotopic signatures in the Farellones Formation.

More recent geochemical studies of Cenozoic deposits between 34 and 36°S allow these conclusions to be extended. Spatial and temporal geochemical patterns point to important changes between 20 and 16 Ma (Kay and Kurtz, 1995; Kurtz et al., 1997). The chemistry of samples from the western swath shows that they originated as low- to medium-K basaltic to dacitic arc magmas (47–67% SiO_2) with high Al_2O_3 (15.6–18.7%) and low TiO_2 (mostly 0.6–1.3) concentrations and mantle-like isotopic compositions ($_{E}Nd = 5–6$, $^{87}Sr/^{86}Sr = 0.7036–0.7038$). Geochemical signals of arc affinity are high, arc-like La/Ta ratios (30–60) and Ba/La ratios (mostly from 20 to 40). Higher Ba/La ratios in the westernmost samples are in accord with their more proximal position to the trench. Increasing FeO/MgO ratios with increasing SiO_2 concentrations are consistent with silicic magmas evolving from mafic ones along a low-pressure tholeiitic trend. Supporting evidence for low-pressure differentiation comes from REE patterns characterized by moderate REE slopes (La/Yb = 3–7, Fig. 7), light REE enrichment (La/Sm ratios from 1 to 3), flat heavy REE slopes (Sm/Yb = 1–2), and Eu anomalies that become more negative as SiO_2 increases. Variations in these REE patterns are best explained by low-pressure plagioclase-, olivine-, and pyroxene-bearing residual assemblages. Plagioclase accumulation at low pressure explains the low REE levels, positive Eu anomalies, and high Sr/REE ratios in the feldspar-rich samples. Only two samples from the eastern belt sequence have been analyzed. One is a low-K andesite from the margin of a 12 Ma pluton (Alfalfalito Pluton) with a La/Ta ratio of 16, in accord with a back-arc setting relative to the western flows. The second is from the flow along the Las Leñas River valley whose minimum age is 16.1 ± 0.5 Ma (Kurtz et al., 1997). A somewhat high La/Yb ratio (7.7, Fig. 7), which results from a steeper heavy REE slope (Sm/Yb = 2.8) is in accord with a transition to the Farellones Formation.

In summary, chemical characteristics of magmatic samples of the Abanico Formation indicate a tholeiitic arc setting characterized by a thin continental crust and subcontinental mantle lithosphere. A comparison with recent South Volcanic Zone (SVZ) samples indicates that this sequence is similar to those in the SVZ south of ~38°S, where crustal thicknesses are estimated to be 30–35 km (see Hildreth and Moorbath, 1988; Tormey et al., 1991) and where young alkali basalts occur in the back-arc.

4. Evidence for subsequent tectonic inversion

4.1. Sedimentologic evidence

Syntectonic deposits associated with the growth of folds have been observed at two localities: the lower Las Leñas River valley and the Upeo River valley (Fig. 1(b) and (d)). These deposits, according to their location in the stratigraphic section, were developed late in the evolution of the Cenozoic deposits.

The growth deposits observed in the western part of the Las Leñas River valley occur on the west side of the western anticline (Fig. 5(b)). Their stratigraphic position is above a mammal-bearing volcaniclastic layer dated at 20.09 ± 0.27 Ma (Flynn et al., 1995) and coincides with the deposition of a 16.1 Ma old volcanic interval. These deposits indicate deformation activity at that time, probably associated with the growth of the adjacent anticline. The age of these syntectonic deposits and the proximity of this structure to the region, where Navarro (2001) observed the transitional contact between the more deformed Abanico Formation and the less deformed Farellones Formation

Table 1
K–Ar and $^{40}Ar/^{39}Ar$ age determinations

Potassium–Argon age

Sample no.	Lab. no.	Material	Potassium (%)	Radiogenic Ar (nl/g)	Atmospheric Ar (%)	Age (Ma)	Error (2σ)
V-250	P341.V-2	Whole rock	1.242	0.202	70	4.2	± 0.3

Ar/Ar ages

H-11 plag 22.49 ± 0.05 Ma $J = 0.0020784$

This sample yielded a nice plateau age of 22.49 ± 0.05 Ma (1σ) for 93% of the gas. I removed the first step of 21.5 Ma. The total fusion age for the sample was 22.43 Ma. K/Ca ratios for the steps on the plateau were 0.04 and the removed step had a ratio of 0.05. Signals were small due to the low K, but radiogenic yields were good (>90%) for most of the gas

T	t	40 (mol)	40/39	38/39	37/39	36/39	K/Ca	$\sum^{39}Ar$	$^{40}Ar^*$	Age (Ma)
700	15	2.7×10^{-14}	9.2544	4.7×10^{-4}	9.6351	0.0118	0.051	0.07335	0.624	21.5 ± 0.2
800	15	3.1×10^{-14}	6.8585	0.0	11.9736	0.0029	0.041	0.18506	0.876	22.4 ± 0.1
900	15	4.5×10^{-14}	6.5082	0.0	12.5347	0.0016	0.039	0.35600	0.928	22.5 ± 0.1
950	15	3.5×10^{-14}	6.3004	0.0	12.7157	0.0010	0.039	0.49312	0.953	22.4 ± 0.1
1000	15	3.3×10^{-14}	6.3578	0.0	12.6805	0.0010	0.039	0.62230	0.953	22.6 ± 0.1
1050	15	2.4×10^{-14}	6.4725	0.0	12.3868	0.0013	0.040	0.71552	0.939	22.6 ± 0.1
1150	15	2.2×10^{-14}	7.1862	0.0	11.7225	0.0041	0.042	0.79050	0.829	22.2 ± 0.2
1250	15	7.9×10^{-14}	9.3551	0.0	11.7203	0.0111	0.042	1.00000	0.650	22.7 ± 0.1

Total fusion age, TFA = 22.43 ± 0.05 Ma (including J)
Weighted mean plateau age, WMPA = 22.49 ± 0.05 Ma (including J)
Inverse isochron age = 22.44 ± 0.08 Ma (MSWD = 1.59; $^{40}Ar/^{36}Ar = 299.7 \pm 4.2$)
Steps used 800, 900, 950, 1000, 1050, 1150, 1250 (2–8/8 or 93% $\sum^{39}Ar$)
t = dwell time in minutes
40(mol) = moles corrected for blank and reactor-produced 40
Ratios are corrected for blanks, decay, and interference
$\sum^{39}Ar$ is cumulative, $^{40}Ar^*$ = rad fraction

RPD-43B PLAG 21.74 ± 0.04 Ma $J = 0.0020746$

This is generally a climbing spectrum with a nice plateau of 21.74 ± 0.04 Ma for the middle 66% of the gas. The total fusion age is 21.84 which reflects the old apparent ages of the 1050 and 1200 °C steps. K/Ca ratios were consistent throughout the experiment at 0.08 and radiogenic yields were above 90% on the plateau

T	t	40 (mol)	40/39	38/39	37/39	36/39	K/Ca	$\sum^{39}Ar$	$^{40}Ar^*$	Age (Ma)
700	15	6.6×10^{-14}	7.1535	3.4×10^{-2}	5.7078	0.0052	0.086	0.16571	0.787	20.9 ± 0.1
800	15	7.8×10^{-14}	6.3448	4.8×10^{-3}	6.1053	0.0017	0.080	0.38597	0.922	21.7 ± 0.1
900	15	7.9×10^{-14}	6.2422	1.1×10^{-4}	6.2315	0.0014	0.079	0.61439	0.934	21.7 ± 0.1
950	15	4.4×10^{-14}	6.1753	0.0	6.2137	0.0011	0.079	0.74198	0.945	21.7 ± 0.1
1000	15	3.0×10^{-14}	6.2539	0.0	6.0459	0.0013	0.081	0.82892	0.939	21.9 ± 0.1
1050	15	2.1×10^{-14}	6.4428	0.0	5.9677	0.0017	0.082	0.88684	0.921	22.1 ± 0.1
1200	15	8.1×10^{-14}	12.8338	0.0	6.0763	0.0219	0.081	1.00000	0.496	23.7 ± 0.1

Total fusion age, TFA = 21.84 ± 0.04 Ma (including J)
Weighted mean plateau age, WMPA = 21.85 ± 0.04 Ma (including J)
Inverse isochron age = 21.62 ± 0.06 Ma (MSWD = 1.57; $^{40}Ar/^{36}Ar = 321.0 \pm 2.5$)
Steps used 800, 900, 950, 1000, 1050, 1200 (2–7/7 or 83% $\sum^{39}Ar$)

Table 1 (*continued*)

C-799 PLAG 23.17 ± 0.10 Ma $J = 0.0020568$

This sample yielded a perfect plateau with an age of 23.17 ± 0.10 Ma for 100% of the gas. It was a low K sample with K/Ca ratios varying from 0.005 to 0.02. Using only the three steps with concordant K/Ca ratios yields a slightly older age of 23.23 ± 0.16 Ma for 36% of the gas

T	t	40 (mol)	40/39	38/39	37/39	36/39	K/Ca	$\sum{}^{39}$Ar	^{40}Ar*	Age (Ma)
700	15	1.9×10^{-14}	9.9796	4.2×10^{-2}	92.0594	0.0122	0.005	0.11876	0.637	23.4 ± 0.5
800	15	2.1×10^{-14}	7.3638	0.0	42.8507	0.0039	0.011	0.29015	0.845	22.9 ± 0.3
900	15	2.5×10^{-14}	6.8393	0.0	30.7009	0.0019	0.016	0.50673	0.918	23.1 ± 0.2
950	15	1.3×10^{-14}	6.7157	0.0	27.7785	0.0013	0.018	0.62306	0.942	23.3 ± 0.3
1000	15	8.6×10^{-15}	6.8363	0.0	27.8832	0.0020	0.018	0.69660	0.914	23.0 ± 0.4
1100	15	2.0×10^{-14}	6.9820	0.0	27.6928	0.0023	0.018	0.86477	0.903	23.2 ± 0.2
1250	15	2.0×10^{-14}	8.6534	0.0	31.5060	0.0080	0.016	1.00000	0.728	23.2 ± 0.3

Total fusion age, TFA = 23.18 ± 0.11 Ma (including J)
Weighted mean plateau age, WMPA = 23.17 ± 0.10 Ma (including J)
Inverse isochron age = 23.14 ± 0.18 Ma (MSWD = 0.26; ^{40}Ar/^{36}Ar = 298.3 ± 5.6)
Steps used 700, 800, 900, 950, 1000, 1100, 1250 (1–7/7 or 100% $\sum{}^{39}$Ar)
t = dwell time in minutes
40 (mol) = moles corrected for blank and reactor-produced 40
Ratios are corrected for blanks, decay, and interference
$\sum{}^{39}$Ar is cumulative, ^{40}Ar* = rad fraction

suggests that the same deformation pulse affected both regions.

The growth deposits observed in the Upeo River valley (35°S) are located, just as in the Las Leñas River valley, on the west limb of an anticline forming the Cordón de la Piedra Redonda (Fig. 8). This anticline is formed in an upper volcanic interval of the exposed series. A blind thrust fault that developed in the weak, fine-grained middle member and located beneath the western limb may account for this structure. The volcanic sequence hosting the growth structure is overlain unconformably by very gently west-dipping Pliocene lavas (4.2 Ma; see Table 1). The age of deposition and deformation of the underlying volcanic sequence thus is currently poorly constrained. Our recent discovery of fossil mammals in this series may permit refinement of these ages.

4.2. Structural evidence

Structural evidence provided for extensional basin development also favors tectonic inversion. The described faults are inverted, high-angle thrusts. Inversion of normal faults located in the basement of the basin also seems to be a satisfactory explanation for the irregular folding style.

An important structure that suggests inversion along steep faults is the N–S-oriented Chacayes-Yesillo Fault in the Maipo River valley, which represents the contact between the Abanico Formation and the Mesozoic units in this region. This is a high-angle, west-vergent thrust that cuts deeply into the basement of the Abanico Formation. On the east-side block of the fault, a tightly folded, west-vergent, recumbent anticline formed in rocks of the Cretaceous Colimapu Formation is exposed (Fig. 3(a)). The crest of the anticline is unconformably covered by volcanoclastic deposits assigned by Thiele (1980) to the Abanico Formation. Although this stratigraphic assignment has not been conclusively confirmed, we consider that the volcaniclastic deposits covering the anticline crest represent the uplifted base of the Cenozoic series along an inverted fault.

As already pointed out in the discussion of the contact between the Abanico and Farellones Formations, the upper stratal levels of the former are not the same everywhere and seem to depend on the age of (1) the unconformity that separates this unit from the Farellones Formation and (2) the boundary between more and less deformed rocks, where the contact is continuous. Growth strata development in the upper levels of the Abanico Formation indicates the existence of a deformation pulse during deposition of this unit that did not result in an unconformity. On this basis, we consider that syn- or post-depositional deformation of the Abanico Formation did not always result in a major unconformity associated with a single regional episode, but rather with different (in time and space) pulses that probably reactivated preexisting faults. Movement along these faults caused local, rather than generalized, deformation in this region.

4.3. Thermal maturity data

As indicated previously, the modeling of thermal maturity data demonstrated that considerable stratigraphic thickness is missing in the presently exposed stratigraphic columns. The minimum missing thicknesses for the different localities are as follows: 4000 m for the Las Leñas River valley, 2300 m for the Carretera El Cobre area, and 1000 m for the column in the Maipo River valley. Considering that the youngest age in the section studied along the Carretera El Cobre is 22.49 ± 0.05 Ma (Table 1), part of the missing thickness corresponds to upper portions of the Abanico Formation and probably also to part of the Farellones Formation. However, in the section studied at the Las Leñas River valley, the similarity of ages obtained for high stratigraphic levels of the Abanico Formation (^{40}Ar/^{39}Ar: 16.1 Ma; Kay and Kurtz, 1995) and for low levels of the Farellones Formation (K–Ar: 14.1 Ma; Charrier and Munizaga, 1979) supports depositional continuity (Navarro, 2001) and suggests that the missing thickness corresponds essentially to upper parts of the Farellones.

The missing thickness is considered to have been eroded during one or more exhumation episodes related to contractional episodes that uplifted and deformed the basin deposits. On the basis of the evidence for inverted normal faults affecting the Abanico Formation, the contractional deformation leading to exhumation is interpreted to correspond to basin inversion.

4.4. Plutonic evidence

Evidence for rapid Neogene exhumation is provided by mineral age differences in three Miocene to Pliocene subvolcanic to shallow, largely granodioritic plutonic groups (Older, El Teniente, and Younger Plutonic Groups; Kay and Kurtz, 1995; Kurtz et al., 1997) emplaced in outcrops of the Abanico Formation and Mesozoic units between 33° and 35°45′S (Kurtz et al., 1997). The older plutonic group, emplaced in the western outcrops of the Abanico Formation, has chemical affinities with the volcanic host rocks, whereas the two other groups have chemical affinities with the volcanic rocks of the Farellones Formation (Kurtz et al., 1997).

Plutons of the older group between 33°30′ and 34°30′S (La Obra and Santa Rosa de Rengo) have ^{40}Ar/^{39}Ar ages between 21.6 and 16.2 Ma and, further south, K–Ar ages of 14.1 Ma between the Tinguiririca and Teno River valleys (Malbran, 1986) and 23.8 Ma in the Maule River valley at 35°45′S (Drake et al., 1982). The early Miocene age of these plutons indicates that the intrusive activity occurred near the end of deposition of the Abanico Formation. This coincidence in time is consistent with the chemical affinity between the intrusive and volcanic host rocks.

The obtained difference in cooling ages on biotite and K-feldspar from the La Obra pluton indicates the existence of an exhumation episode between 19.6 and 16.2 Ma (Kurtz et al., 1997), that coincides with the proposed inversion episode. Differences in cooling ages obtained in the other plutonic groups indicate that exhumation continued after the end of deposition of the Abanico Formation, coinciding with the episode of erosion detected with thermal maturity modeling.

4.5. Geochemical evidence

Following the Abanico magmatic episode, there appears to have been a virtual lull in magmatism in the study region until ~16 Ma, when middle Miocene volcanic units began to erupt. The Older Plutonic Group is the only unit with ages near this gap (the Santa Rosa de Rengo pluton has a hornblende Ar/Ar age of 16.2 ± 1.2 Ma, and the La Obra pluton has a poorly defined hornblende Ar/Ar age of 21.6 ± 4.9 and a biotite age of 19.6 ± 0.5 Ma) (Kurtz et al., 1997). Chemical characteristics of the La Obra pluton are similar to those of the Abanico Formation, whereas those of the Santa Rosa de Rengo pluton are more like those of the oldest portions of the Farellones Formation (see Kurtz et al., 1997).

The middle to late Miocene volcanic units between the western and eastern swaths of the Abanico Formation in the El Teniente Copper Mine region (34°10′S) traditionally have been assigned to the Farellones Formation. Because of the broad definition of the Farellones Formation, Godoy (1993) referred to volcanic units with K/Ar ages from ~15–7 Ma between the Claro River valley, a tributary of the Maipo River (33°55′S), and the Cachapoal River valley (34°20′S) as the Teniente Volcanic Complex. Kay and Kurtz (1995) and Kurtz et al. (1997) assigned contemporaneous plutonic units in this area to the Teniente Plutonic Complex. Chemical characteristics of the Teniente Volcanic and Plutonic Complexes are presented by Kay and Kurtz (1995), Kurtz et al. (1997), and Kay et al. (1999).

As a whole, Teniente Volcanic Complex samples are tholeiitic to transitional calc-alkaline arc rocks plotting in the medial medium-K to the lower high-K field (see also Godoy, 1993; Koeppen and Godoy, 1994; Godoy et al., 1994). They generally can be distinguished from the units of the west swath of the Abanico Formation by their higher K_2O and Th concentrations, steeper REE patterns, and more upper crustal-like isotopic signature ($_E$Nd = 2.7–3.6; $^{87}Sr/^{86}Sr = 0.7039–0.7041$). Their La/Yb ratios (Fig. 7) mostly range from ~7 to 13, with the increase in steepness over samples of the west swath of the older sequence (<7) resulting from both steeper light and heavy REE slopes. La/Yb ratios over 13 are due to high La/Sm ratios that reflect fractionation REE-bearing minor phases (Kay and Kurtz, 1995). Within the Teniente Volcanic Complex, younger samples differ from older ones in having higher FeO/MgO ratios at a given SiO_2 (a more tholeiitic differentiation trend), steeper overall and heavy REE patterns, and a tendency for amphibole to replace pyroxene as the major mafic phenocryst. These geochemical differences signal higher-pressure residual mineral assemblages in equilibrium with the younger magmas. Younger units also have the highest La/Ta and La/Sm ratios, consistent with a more pronounced slab signature.

In summary, Teniente Complex magmas evolved in a progressively changing, mildly tholeiitic to calc-alkaline arc setting. A comparison with recent SVZ samples shows that older to younger magmas compare well with those in a south to north progression of SVZ centers between 36° and 34°30′S. Crustal thicknesses under these SVZ centers vary from ~35 to 45 km from south to north (see Hildreth and Moorbath, 1988; Tormey et al., 1991), consistent with Teniente Complex magmas progressively erupting through a thickening crust. The more abrupt change in chemical characteristics between the Abanico Formation and Teniente Complex magmas supports a time of compressional thickening of the crust between the two magmatic episodes.

Limited chemical studies of late Oligocene to early Miocene volcanic rocks between 33 and 36°S suggest that, like today, the lithosphere and crust at that time was thinner in the south. In particular, studies near 35°35′ to 36°S by Vergara et al. (1999) show that 27–16 Ma tholeiitic volcanic rocks in the Colbún area can have flatter REE patterns (La/Yb = 2–5; Fig. 7(a)), less extreme La/Nb ratios (1–2.6; La/Ta ~ 17–44), and more primitive isotopic signatures ($_E$Nd = 5.5–7.1; $^{87}Sr/^{86}Sr = 0.7036–0.7060$) than age-equivalent Teniente region magmas. Such characteristics are expected in magmas erupted through a thinner lithosphere. A common feature with the El Teniente region is an apparent volcanic gap from ~20 to 16 Ma.

To the north of the study region, in the Farellones Formation type locality, east of Santiago (33°20′–33°30′S), analyses in Kay and Kurtz (1995) show that samples from the Farellones Formation samples have chemical characteristics that are intermediate between those of the Abanico Formation and the Farellones Formation lavas in the El Teniente region. These characteristics include a borderline tholeiitic differentiation trend, arc-like La/Ta ratios (40–60), and intermediate La/Yb (4.5–8.5, Fig. 7(a)) and isotopic ratios ($_E$Nd = 3.8–5.3, $^{87}Sr/^{86}Sr = 0.70356–0.70382$). Ar/Ar ages of 21.6 ± 0.2 and 20.1 ± 0.3 Ma (Aguirre et al., 2000), along with K/Ar ages between 18.6 ± 0.6 and 16.6 ± 0.7 (Vergara et al., 1988), show a temporal equivalence of these eruptions with the end of the Abanico (Coya-Machalí) Formation stage to the south. To a first order, the chemistry of these samples implies a contemporaneously thicker lithosphere in the north. Dating is insufficient to determine if a magmatic gap occurs.

Studies between 32 and 33°S by Sellés (1999b) and Vatin-Perignon et al. (1996) show that early Miocene (~20 Ma) plugs in the Central Valley have relatively high La/Yb ratios compared with contemporaneous magmas in the region (Fig. 7). Sellés (1999b) speculated that the 'adakitic-like' high La/Yb ratios in these magmas reflected melting of the down-going slab, though such melting was difficult to reconcile with temperatures expected in the slab at the time. Kay and Kurtz (1995) speculated that further northeast, in the Cerro Colorado/Uspallata region in Argentina, the nearly contemporaneous magmas with high Ba and Sr concentrations and somewhat steep REE patterns (see Kay et al., 1991) were somehow associated with changes in the lithospheric configuration associated with arc migration. Although the exact tectonic conditions are not well understood, the chemistry of these magmas also appears to reflect changing tectonic conditions between 20 and 16 Ma.

5. Discussion and conclusions

On the basis of the foregoing data, we summarize evidence consistent with the development, and subsequent inversion, of an early to middle Cenozoic extensional basin in this region of the Andes and discuss various points regarding the Cenozoic deposits and Andean evolution.

(1) The vast geographical extent of the Abanico Formation and its southern equivalents across and along the Principal Cordillera, the great thickness of these deposits, and the strongly variable facies associations they encompass (lava, volcaniclastic and sedimentary deposits) suggest the existence of an extensive, large-scale basin or system of related basins. Compartmentalization of the basin system is suggested by the existence of WNW-oriented transcurrent faults, probably reactivated during deposition of the younger Farellones Formation. This basin or basin system developed on a deformed and eroded Mesozoic basement and, according to the essentially N–S orientation of faults and folds affecting the deposits accumulated in it, was probably similarly oriented. Deposition in the extensional system began by, at least, the late Eocene and went on until the early Miocene, after which contraction and tectonic inversion began.

The timing and mechanism of extension–inversion can be shown conclusively, however, only with identification of the major faults participating in these processes, in addition to information about their history of movement. In this regard, seismic reflection data from the Cura-Mallín Formation (the southern extension of the Abanico Formation) provides clear evidence for contraction along an inverted, basin-bounding normal fault (Burns and Jordan, 1999). This is an important piece of evidence for similar tectonic mechanisms active during early to middle Cenozoic in that region of the southern Central Andes.

West-dipping thrust faults located along the easternmost outcrops of the Abanico Formation and showing evidence of (1) previous normal movement that affected the basal unconformity (Espinoza Fault) and (2) westwardly growing strata formed early in the depositional history of this unit (El Fierro Fault) suggest the existence of a west-facing scarp controlling deposition in these regions. Although these faults might represent an important structural element associated with basin development, it is not possible to determine whether they represent the eastern border of the basin.

The described system of N–S-oriented depression(s) can be assigned to an intra-arc basin. Jordan et al. (2001) proposed to name this kind of basin 'active-margin'. Considering that the tectonic conditions prevailing during basin formation were most certainly extensional, we propose the name 'active-margin' extensional basins to differentiate them from basins developed in association with contractional events.

(2) Thermal maturity and geochemical studies in the Abanico Formation yield important evidence favoring extensional basin development during deposition of this unit.

The high thermal maturity detected for the Abanico Formation indicates that it was buried at a depth greatly exceeding its presently exposed thickness. This implies the existence of a highly subsident basin hosting these volcanic and sedimentary deposits. High heat flow during burial of the Abanico Formation, as deduced by thermal modeling, implies a major, deep-seated heat source. These conditions, together with geochemical evidence indicating that the tholeiitic arc Abanico magmas were generated while the crust and subcontinental mantle lithosphere were thin, strongly support extensional conditions affecting the upper crust in the late Eocene to early Miocene.

(3) Deformation occurred during and following the late depositional stages of the Abanico Formation and was probably controlled by inversion of pre-depositional extensional faults associated with basin development. One well-constrained deformation episode occurred between 20.09 and 16.1 Ma. This episode is evidenced by the development of syntectonic deposits. Considering the complexities discussed in this article, it is unlikely that deformation occurred throughout the region simultaneously. Thus, depositional processes (including volcanism) probably continued sporadically in this basin throughout the contractional episode, as is further supported by the lack of a clear stratigraphic 'break' between the Abanico and the Farellones Formations in some areas. In other parts of the basin, however, localized folding and erosion formed more than one angular unconformity, as in the Farellones region, east of Santiago. The possibility remains, however, that some unconformable relations between strata could simply be primary features associated with the development of volcanoes.

In light of the recent view about stratigraphic relations of various Cenozoic deposits in the Central Chilean Andes, it is appropriate to revisit the question of what kind of contact separates the Abanico from the Farellones Formation. Points to consider include (1) the absence of a clear structural boundary between the formations at some localities; (2) the existence of one or more angular unconformity(ies) at various localities, in some cases in stratigraphic levels contemporaneous with the Abanico Formation; (3) that within the same region, only a very small gap separates the youngest radioisotopic age determinations obtained within the youngest parts of the Abanico Formation from the oldest determinations obtained within the Farellones Formation; and (4) that radioisotopic age determinations for the Abanico Formation of some regions are considerably younger than those obtained in low levels of the Farellones Formation in other regions, illustrating the complexity and age variation of deposition of stratigraphic units in this basin.

(4) The coincidence of rapid exhumation of Miocene plutonic groups emplaced in Abanico deposits and Mesozoic units in this region, as well as the progressive evolution of mildly tholeiitic to calc-alkaline arc setting magmas, support compressional thickening of the crust occurring coevally with tectonic inversion in this region.

(5) The previously presented evolution for this region during the early to middle Cenozoic, that is, the development of a rapidly and strongly subsident, probably extensional basin during a period of relatively thin crust and high thermal flow, followed by a rapid transition to contractional conditions, provides the appropriate conditions to yield the development of low-grade metamorphic minerals in the Abanico Formation, but not in the Farellones Formation. The hypothesis advanced here explains why the presence or absence (or almost absence) of low-grade metamorphism and the more (Abanico) or less (Farellones) intense deformation traditionally have been the main differentiation criteria used to distinguish the Abanico and the Farellones Formations.

(6) The proposed early to middle Cenozoic evolution of this Andean region includes a long-term extensional episode followed by a contractional event. The extensional episode occurred while the crust was relatively thin, and the contraction al event coincided with a thickened crust. This strongly suggests that crustal thickness and strain regime are interrelated, at least in this case.

Extensional and contractional events on active continental margins generally have been associated, respectively, with periods of low and high convergence rates between the subducting and the overriding plates. Although a simple temporal coincidence between two processes does not establish a cause-and-effect relationship, the extensional and contractional episodes in the tectonic evolution of this segment of the Andes show correspondence in time, and possibly causation, to periods of decreasing and increasing convergence rates between the Nazca and South American plates during the Cenozoic (Pardo-Casas and Molnar, 1987).

Extension began before 36 Ma, probably in the late Eocene or earlier, and went on at least during the Oligocene, the age of most of the Abanico Formation. This is shortly after the peak of high convergence rate determined by Pardo-Casas and Molnar (1987), between 40 and 50 Ma. Considering that, in the Cenozoic deposits, there are unconformities capped by rocks assigned to the Farellones Formation with ages as old as 25.2 and 20.4 Ma (Munizaga and Vicente, 1982) and 21–22 Ma (Aguirre et al., 2000), it is possible to assume that contraction occurred throughout the period of increasing convergence rate. Deformation evidently did not occur throughout the region simultaneously but coincides with the overall period of increasing convergence rate that began at about 26 Ma and ended at 15 Ma. This seems to indicate that deformation did not occur only at the moment of highest convergence rate, but across a broader time span throughout the episode of increasing convergence rate. The unconformities within the Abanico Formation, which seem to correspond to local deformations along preexistent structures, can be interpreted as 'incrementals' of deformation or as a gradual accommodation of the upper crust to major global changes that affect the interaction between the ocean plate and the continental margin. If this is correct, we should not expect deformation everywhere at the same time along and across the orogene. Accordingly, major regional deformations (traditionally termed tectonic phases) may be regarded as the result of the accumulated deformational effects, including uplift, during rapid or long-lasting episodes of increasing convergence along a segment in an active continental margin.

(8) Tectonic inversion apparently occurred over a period of time, beginning before 21 Ma and ending at about 16 Ma, that is strikingly coincident with other tectonic and magmatic events known from the central Argentine and Chilean Andes. The contractional event detected in the Chilean Principal Cordillera overlaps in time with (1) uplift, erosion, and deposition of associated syntectonic sediments on the east-versant of the Principal Cordillera in the flat-slab Andean segment between approximately 20 and 8 Ma and (2) expansion of volcanism toward the retroarc domain between 19 and 15 Ma (Ramos et al., 2002). According to the results presented herein, these processes generally were coeval with a regional process of gradual thickening of crustal and subcontinental mantle lithosphere and, therefore, could be the result of a major tectonic accommodation of the crust in this region.

Collision of the Juan Fernández ridge at about 15 Ma (Pilger, 1981, 1984) is an approximately coeval event that might have caused some disturbance along the subduction zone, that is, flattening of the subduction plane between 27 and 33°S. It probably influenced later evolution of the Andean range along this region (see Ramos et al., 2002) and resulted in a lack of Plio-Pleistocene volcanic activity, as well as no development of the Central Depression. However, it is not yet possible to determine if this collision had only a local effect or if the plate reorganization associated with it more broadly affected the late Cenozoic tectonic evolution of the entire continental margin of the Central Andes.

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