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Tectonic and unroofing history of Neogene Manantiales foreland basin deposits, Cordillera Frontal (32°30′S), San Juan Province, Argentina

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Abstract

The Miocene Manantiales foreland basin is located in Cordillera Frontal of San Juan, between 32°30′ and 33°S. The unroofing study of the synorogenic Miocene deposits provides information about the structural evolution of Cordón de La Ramada fold-and-thrust belt. These Tertiary deposits are represented by the Chinches Formation and comprise seven members (Tc0–Tc6). They are the result of the uplift of Mesozoic sequences that crop out in La Ramada fold-and-thrust belt of the Cordillera Principal. Quaternary deposits unconformably overlying the Chinches Formation are composed of granitic and rhyolitic blocks, and represent the final uplift of the Cordón del Espinacito and a series of out-of-sequence thrusts. The unroofing studies also provide sufficient information to establish the out-of-sequence timing of the deformation at this latitude. Initial deposition of the Tertiary deposits can be dated at about 20 Ma, or early Miocene. Andesitic lavas dated in 9.2 ± 0.3, 10.7 ± 0.7, and 12.7 ± 0.7 Ma unconformably overlie the structure of La Ramada fold-and-thrust belt. These facts constrain the uplift of the High Andes between 20 and 10 Ma at this latitude. The unconformity between Tertiary and Quaternary deposits suggests final uplift during Pliocene–Pleistocene times.

Abstract

El estudio de destechado de los depósitos sinorogénicos miocenos de la cuenca de antepaís de Manantiales, ubicada en Cordillera Frontal (32°30′–33°S), provee información sobre la evolución estructural de la faja plegada y corrida de La Ramada. Estos depósitos neógenos de la cuenca Manantiales están representados por la Formación Chinches y fueron separados en siete miembros. Cada uno de estos miembros es el resultado del levantamiento y erosión de las diferentes unidades orográficas de las secuencias mesozoicas de la Cordillera Principal. Los depósitos cuaternarios de Manantiales compuestos por bloques de granitos y riolitas permotriásicas y que sobreyacen mediante discordancia angular a las secuencias terciarias de la Formación Chinches, representan el levantamiento final del cordón del Espinacito y la actividad de corrimientos fuera de secuencia. El estudio de destechado de las secuencias terciarias y sus relaciones estructurales, permitió establecer tiempos de deformación en este sector de los Andes. La base de la secuencia Terciaria puede ser datada en aproximadamente 20 Ma, indicando que la deformación podría haber comenzado hacia el Mioceno temprano. Lavas andesíticas datadas en 9.2 ± 0.3, 10.7 ± 0.7 y 12.7 ± 0.7 Ma sobreyacen en posición subhorizontal a las secuencias mesozoicas de la faja plegada y corrida de La Ramada. Estos datos señalan que el levantamiento de la Cordillera Principal y el consecuente desarrollo de la cuenca Manantiales habría ocurrido entre los 20 y 10 Ma. La discordancia entre los depósitos terciarios y cuaternarios sugiere que el último levantamiento habría ocurrido durante el Plioceno–Pleistoceno.

Keywords: Manantiales foreland basin; Unroofing synorogenic deposits; Continental Miocene deposits; Chinches Formation; Cordillera Frontal; Cordillera Principal; San Juan; Argentina

1. Introduction

The main objective of the present contribution is to study the Miocene continental strata of the Manantiales foreland basin (Pérez, 1995) represented by the Chinches Formation (Mirré, 1967). Deposition of the Chinches Formation followed uplift and erosion of the Cordillera Principal Mesozoic sequences (Pérez, 1995).

The Manantiales basin is located in Los Patos valley, between the Cordón del Espinacito and Cordillera del Tigre, at 32°00′S and 69°45′W, in the Cordillera Frontal (Fig. 1(a) and (b)). The basin measures approximately 65 km in north–south length and about 20 km in width.

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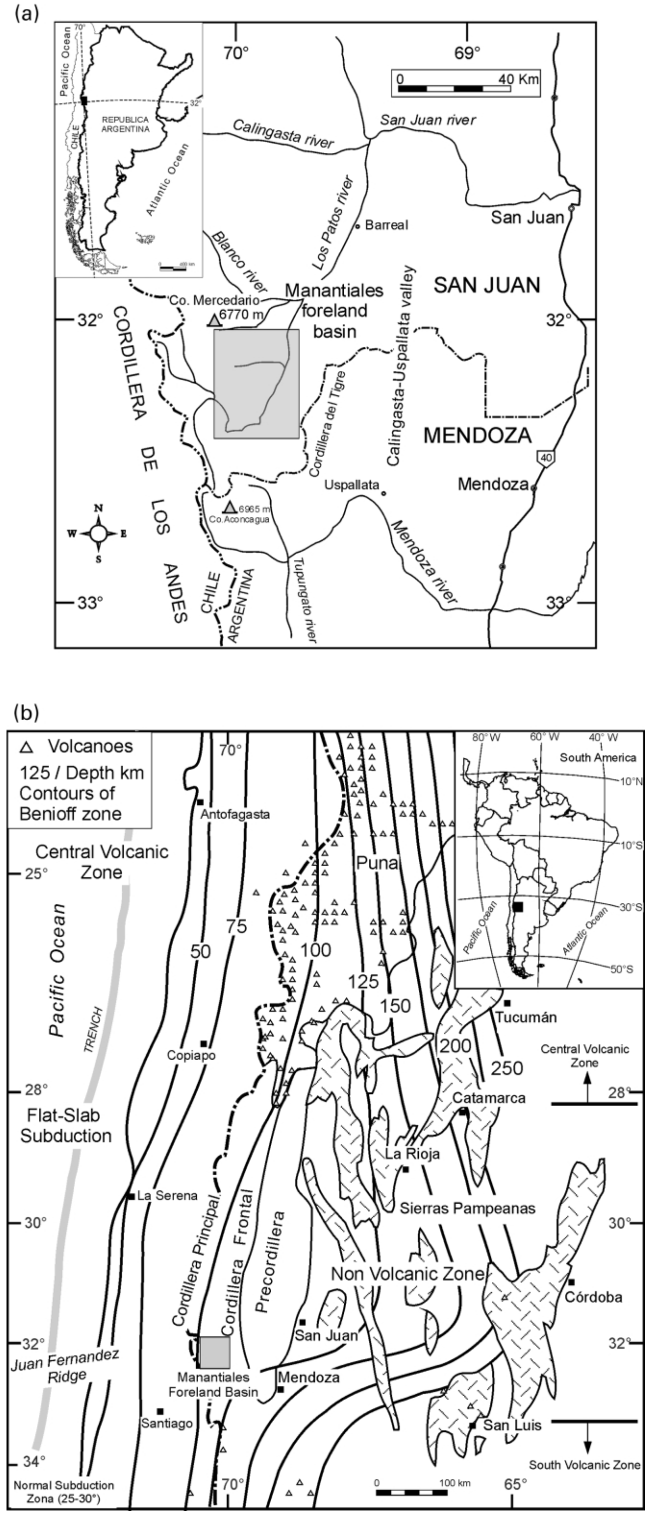

Fig. 1. (a) Geographic map of the study region between 31–33°S. The region of the Tertiary Manantiales foreland basin is indicated. (b) Simplified geologic map of the Andean region between 22–34°S showing location of the Manantiales basin, in the Cordillera Frontal, relative to ocean trench and major physiographic provinces. Contours of the Wadatti-Benioff zone and the modern volcanic centers of the Central Volcanic Zone, non-Volcanic Zone, and Southern Volcanic Zone are indicated (Isacks, 1988; Cahill and Isacks, 1992).

Tertiary deposits pinch out between the Cordón del Espinacito and Cordillera del Tigre ranges in the southern portion of the basin, exposed in the riverbank west of the Tigre Creek. Uplift of La Ramada system would have produced a tectonic subsidence of the crust, developing the Manantiales foredeep where Cordillera Principal materials were deposited (Fig. 2).

Stelzner (1873) had referred to these deposits as an old Tertiary, composed of sandstone, and overlie on granite and quartz–porphyry, with marly layers and conglomerate beds with andesitic clasts. Schiller (1912) mentioned the same old Tertiary to the east of Manantiales. Groeber (1951) summarized the main characteristics of the region and mentioned the cross section by Schiller (1912) at the latitude of Las Leñas River, as well as the observations carried out by Dr Cuerda (in Groeber, 1951) in the La Leona Creek (Fig. 2). Mirré (1967) defined the Chinches Formation for a sedimentary succession more than 2000 m thick exposed along the Los Patos River, between the Hornillas and Horcajo locations, overlying the volcanic rocks of the Horcajo Formation. He divided the Chinches Formation into the following members, from bottom to top: Areniscas Chocolate, Brecha andesítica, and Areniscas Conglomerádicas. Iglesia Llanos (1995) described in the eastern slope of Cordón del Espinacito, between the Hornillas and Las Leñas Rivers, more than 2000 m of coarsening-up sandstones, which she correlated with the Areniscas Conglomerádicas member of the Chinches Formation (Mirré, 1967). Pérez (1995) and Pérez and Ramos (1996) gave results of an unroofing study, supplemented with the radiometric data and magnetostratigraphic study of the Tertiary sequences by Jordan et al. (1996).

2. Neogene deposits of Chinches Formation

These deposits unconformably overlie the Permotriassic volcanic rocks of the Choiyoi Group. This relationship is observed in the Horcajo region and along the western slope of the Cordillera del Tigre to the Quebrada de los Indios River (Fig. 2). The upper boundary of the Tertiary deposits is tectonic. The Choiyoi Group volcanic rocks are the hanging-wall and are thrusted over the sedimentary rocks of the Chinches Formation footwall (Figs. 2 and 3). This relationship was observed from the Blanco River to exposures south of Los Patos River (Pérez, 1995).

The Tertiary sequences in the Manantiales basin and represented by the Chinches Formation, have been divided into seven members, designated Tc0–Tc6 (Pérez, 1995) (Fig. 2). Detailed sections were measured along the Aldeco Creek and Las Leñas River, where the seven members could be recognized. A third section measured in the Caballos River allowed the identification of the upper northern members. Finally, the integration of these sections allowed a reconstruction of the structure over the whole Manantiales basin.

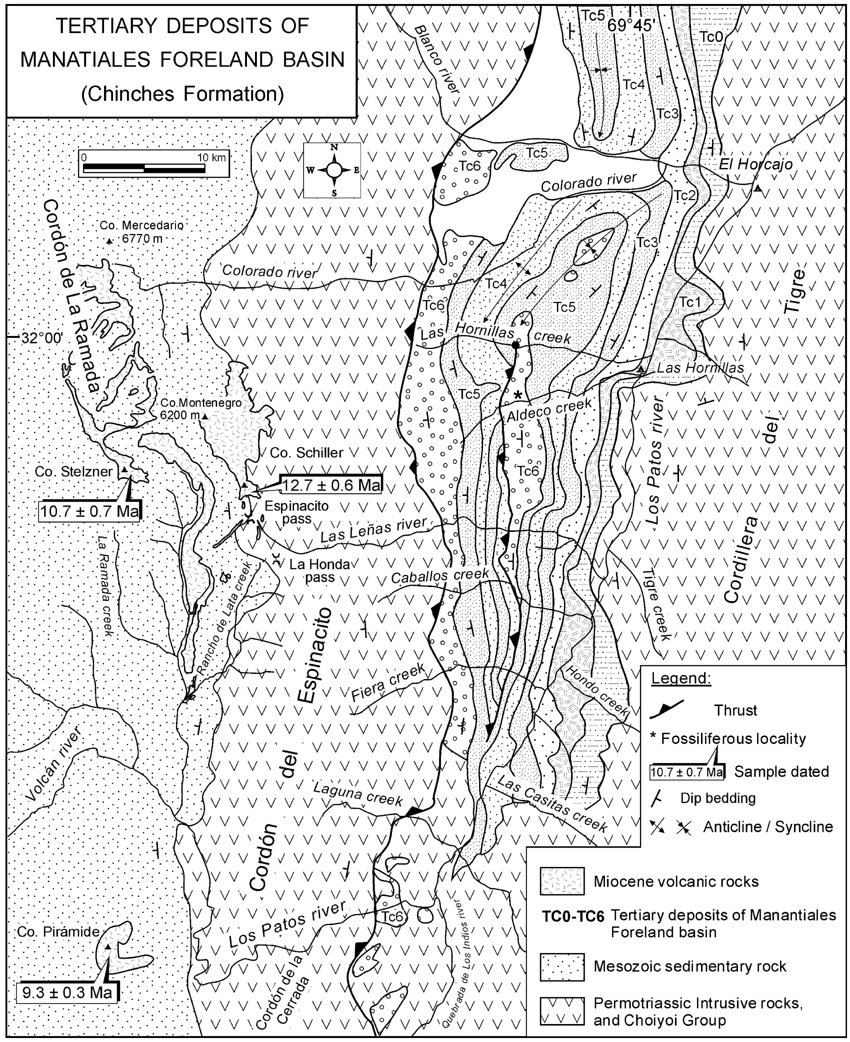

Fig. 2. Geologic map of the Manantiales foreland basin, showing the distribution of the Chinches Formation and members Tc0–Tc6 (Mirré, 1967; Pérez, 1995).

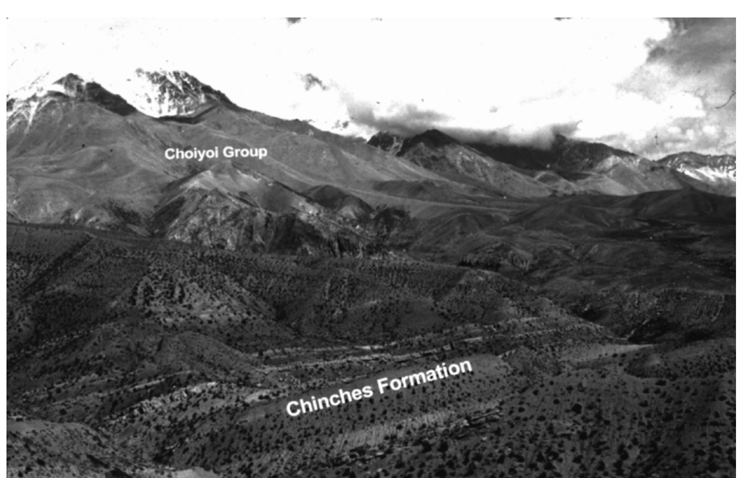

Fig. 3. View of the eastern hillside of the Cordón del Espinacito, showing the tectonic contact between the rhyolites of the Choiyoi Group and the Tertiary deposits of the Chinches Formation.

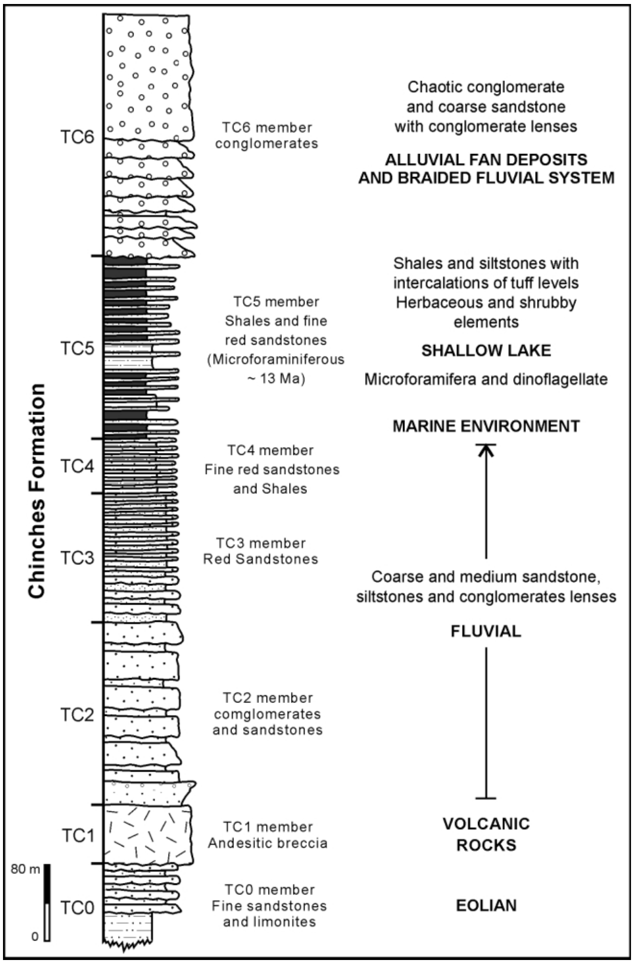

Fig. 4. Stratigraphy of the Chinches Formation, indicating member lithology and environment of deposition.

2.1. Member Tc0

This member unconformably overlies the pyroclastic rocks of the Choiyoi Group with a sharp and planar base (Figs. 2 and 4). The lower reaches of the Las Leñas River Member Tc0 are 90 m thick. It is characterized by yellow, red, and violet shale. It continues with red, medium-grained sandstone, possibly eolian in origin, which is capped by well-stratified, parallel-laminated sandstone, in beds 10–15 cm thick. In the Aldeco Creek this member is only 40 m thick, and it is composed of tabular reddish brown shale, with intercalation of reddish brown sandstone beds up to 10 m thick with cross-stratification. This member is equivalent to the Areniscas Chocolate of Mirré (1967).

2.2. Member Tc1 (andesitic breccia)

This member corresponds to the andesitic breccia exposed from the Blanco River until the Las Casitas Creek, and correlates with the andesitic breccia observed to the north of the Blanco River (Figs. 2 and 4) (Pérez, 1995). In Las Leñas River it is characterized by 80 m of grayish brown andesitic breccia. Breccias are matrix-supported. Clasts are andesitic, and they vary from a centimeter to several decimeters in diameter; they are rounded to sub-rounded. The matrix is mainly andesitic. The basal contact is sharp. Toward the south in the Aldeco Creek, this member only reaches 30 m in thickness (Mirré, 1967).

2.3. Member Tc2

This member is characterized by medium- to coarse-grained, massive, parallel-stratified sandstones interfingered with lenticular conglomerates (Figs. 2 and 4). In Las Leñas River it is 250 m thick and composed of clast-supported, cohesive, and very compact green conglomerates. Clasts vary from blocks to 5 cm in diameter, with a medium size of 20–30 cm. The matrix is medium-grained, green

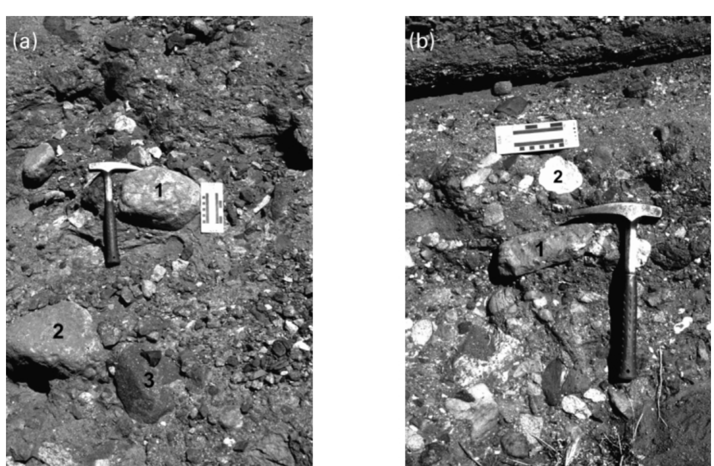

Fig. 5. Chinches Formation. (a) Tabular beds of Tc2 lithofacies showing clasts of andesitic rocks (Juncal Formation) (3), calcareous sandstone (Mendoza Group) (1) and red sandstone (Tordillo Formation) (2). (b) Tabular beds of Tc3/Tc4 lithofacies showing clasts of andesitic rocks (Juncal Formation) (2) and red sandstone (Tordillo Formation) (1).

sandstone. The basal contact is planar and sharp. The sequence is characterized by the alternation of medium- to coarse-grained, massive, reddish brown sandstones, with parallel stratification. Clast-supported conglomerate in lenticular beds varying from a few centimeters to 0.5 m in thickness are intercalated. The mean size of clasts varies from 1 to 5 cm, with a maximum of 30 cm. The clasts are rounded to sub-rounded. Clast composition mainly consists of rhyolites and volcanic breccia derived from the Choiyoi Group. Sandstone beds show parallel stratification and occur in tabular banks 50 cm thick. In general, limestone clasts become less common and smaller toward the top of the member. In the conglomerates, clasts of calcareous breccia with *Gryphaea* sp. and red sandstone have been observed, possibly derived from the Los Patillos and Tordillo Formations, respectively. In the Aldeco Creek, this member is less than 80.5 m thick and is composed of coarse- and very coarse-grained, green sandstone, in tabular beds 4 m thick alternating with fine lenticular conglomerates. They are intercalated with coarse and medium sandstone of reddish brown color, in beds 30 cm thick with sabulitic lenses to fine conglomerates and cross-stratification. They are interfingered with greenish gray, medium-grained sandstone, in tabular beds 0.50 m thick and parallel-stratified fine reddish brown sandstone in beds of until 1 m of thickness.

The main characteristic in this member is the presence of Choiyoi Group clasts, pyroxene andesitic rocks of the Juncal Formation, red sandstone of the Tordillo Formation and calcareous sandstone of the Mendoza Group (Fig. 5(a)).

2.4. Members Tc3/Tc4

These members are composed of medium- to coarse-grained, red, massive sandstones, lenses of conglomerate and beds of parallel-stratified sandstone, interfingered with shales, which prevail toward the top (Figs. 2 and 4). In the Aldeco Creek the thickness reaches 550 m, and it is composed of alternating medium- to coarse-grained, reddish brown sandstone, in beds 50 cm in thickness, and lenticular sabulitic to fine conglomerates. Fine sandstone with planar stratification and coarse greenish gray sandstone is interfingered lenticular in shape. They are dominant in the middle and upper sector of the sequence with coarse and very coarse poorly sorted grayish green conglomerates. They are tabular, matrix-supported beds, with clasts 2–30 cm in diameter. The upper sequence, member Tc4, is characterized by the alternation of very fine sandstone to siltstone of reddish brown color, in tabular beds 4–5 m thick that alternate with more cohesive black and green laminated. Clasts of rhyolites and tuff of the Choiyoi Group dominate in this member and red sandstone of the Tordillo Formation. Andesitic clasts are scarce (Fig. 5(b)).

2.5. Member Tc5 (Tuffaceous)

This member is composed of shales, siltstone, and medium to coarse sandstone with lenses of medium to fine conglomerate and several tuff levels (Figs. 2 and 4). With a thickness of almost 240 m in the Aldeco Creek, it is composed of reddish brown medium to fine sandstone and siltstone, in tabular beds. At the bottom of the sequence, a white and massive tuff is observed, present in tabulate beds of 0.50 m thick, with sharp and planar contacts. The upper part is composed of very fine sandstone and reddish brown siltstone, in tabular beds, interfingered with gray, red, and yellow finely laminated. Two levels of a massive, green to white, yellowish tuffs were recognized in a tabular bed less than 1 m thick. In this member, rhyolitic, andesitic, and limestone clasts dominate.

2.6. Member Tc6

This member is composed of coarsening-upward sequences of chaotic and poorly sorted conglomerates, cross-stratified coarse sandstones, and lenses of conglomerates (Figs. 2 and 4). It is well developed in the Caballos River with a thickness of 175 m, as well as in Las Leñas River and Aldeco Creek. It is composed of medium- to coarse-grained, red conglomerates, coarsening-upward, in poorly stratified beds 4–5 m in thickness. They are interfingered with medium-grained sandstones in beds 0.5 m thick. The clast size varies from 1 to 15 cm, prevailing those of rhyolitic composition. They alternate with green, clast-supported, massive conglomerate, with andesitic tuff matrix. Towards the top, clasts of hornblende andesites prevail. In the Fiera River, mostly andesitic clasts form this member. It has been distinguished almost exclusively from the northern hillside of the Caballos River to the southern hillside of the Fiera River as a compound lateral variation of Member Tc6 for andesitic clasts. The upper boundary of the unit is a tectonic contact with the Choiyoi Group. This member is characterized by the presence of large blocks of rhyolites, calcareous, tuff and red sandstone, those that reach 1 m in diameter. Members Tc2–Tc6 would correspond to the Areniscas Conglomerádicas of Mirré (1967).

3. Depositional environments

The fine-grained deposits in Member Tc0 indicate conditions of aridity and are probably eolian (Mirré, 1967). Member Tc1 is an andesitic breccia whose petrography and geometry suggest deposition from a pyroclastic flow of wide areal extent. The geochemistry corresponds to a typical retroarc sequence assigned to the lower Miocene (Pérez, 1995; Pérez and Ramos, 1996). The Tc2–Tc4 deposits represent fluvial meandering environments whose energy diminishes upward in the section (Pérez, 1995).

Member Tc5 is composed of brown to light brown beds of shale and siltstone interfingered with several tuff beds. Palynological studies identified herbaceous and shrubby elements together with chlorococcaleans, scarce microforaminifera,

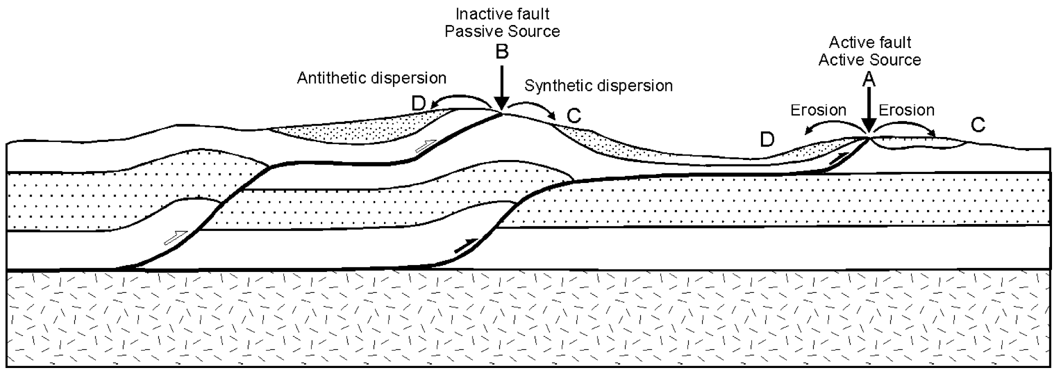

Fig. 6. Schematic diagram showing the structural setting for (a) active and (b) passive sources, and (c) synthetic and (d) antithetic dispersal in a thin-skinned thrusted terrain. Bold arrows on faults indicate motion related to generation of the tectonic sediments. Open arrows indicate inactive older faults (Steidtmann and Schmitt, 1988).

and dinoflagellate cysts (Ottone et al., 1998). These deposits indicate the presence of a shallow lake of relatively dry climate. The presence of planispiral microforaminifera characteristic of marine environment suggests some short-lived marine transgression for part of this member Tc5 (Pérez, 1995; Pérez et al., 1996). The member Tc6 is related to a braided fluvial system in a proximal environment, which quickly pass up to fans and talus dominated environments, close to an active thrust system.

4. Age and correlation

Schiller (1912) assigned the sequence of the Manantiales basin to the middle Tertiary. Groeber (1951) assigned beds in members Tc2–Tc6 to the Agua de la Piedra Group of Oligocene age and the andesitic breccia to the Mollelitense of Oligocene–Miocene age. Clearly Groeber (1951) interpreted the andesitic breccia as an intrusive, as he assigns it a younger age than the beds immediately above.

The Tertiary deposits dip 18° to the west and are unconformably overlaid by Quaternary deposits related to the uplift of the Cordón del Espinacito. Chemical correlation of the Tc1 andesitic breccia with some other lower Miocene volcanics, suggest an approximate age of 20 Ma for the andesitic breccia (Pérez and Ramos, 1996).

To the west of the Cordón del Espinacito, the andesitic lavas of the Cordón de La Ramada were deposited over the structures of the Mesozoic fold-and-thrust belt. These andesitic rocks have ages of 9.2, 10.7, and 12.7 Ma (Pérez and Ramos, 1996). According to these ages for the synorogenic deposits of the Chinches Formation, the uplift of the La Ramada fold-and-thrust belt occurred approximately between 20 and 10 Ma.

These ages are sustained by the fission-track studies of four tuff levels, from member Tc5, which yielded ages between 17.1 and 11.5 Ma, complemented by the magnetostratigraphy carried out by Jordan et al. (1996) for this sequence. Based on these data sedimentation of the Chinches Formation was constrained between 19 and 9.5 Ma. The study section by Jordan et al. (1996) does not include the basal member Tc0, the member Tc1 andesitic breccia of Las Hornillas, and the Tc6 conglomerate member of our study.

The lithology and age of the Manantiales basin fill allow correlation with other Tertiary deposits. Toward the north, the deposits of the transported (*piggy-back*) basin of Iglesias (30°S) have ages ranging from 16 to 6 Ma (Beer et al., 1990), those of the Las Juntas sector range from 18 to 9 Ma and those of the Azul River from 16 to 9 Ma (Jordan and Damanti, 1990). Toward the south (32°40′S) the Santa María Conglomerate has an age of 8 Ma at the top of the section (Ramos et al., 1990). In the Cacheuta and Tunuyán areas the Mariño Formation is 15.7–12.2 Ma, the La Pilona Formation ranges from 11.7 to 9 Ma, and the ash-rich unit of Tobas Angostura Formation is 8.9 Ma (Irigoyen et al., 1998). However, farther south in the Cerro Duraznito area, the Tertiary deposits of the Tunuyán Conglomerate (34°S) would have an age older than 5.9 Ma (Pérez, 1999).

This would indicate that the continental Tertiary deposits to the north and south of the Manantiales basin reflect uplift of the Cordillera Principal and Cordillera Frontal and were deposited diachronously during the early Miocene–late Miocene.

Geochemical data of the member Tc1 indicate that the High Andes were not yet structured and that it might be correlated with a part of Doña Ana Formation (Pérez and Ramos, 1996). These andesitic rocks interpreted as formed in a retroarc environment are equivalent to similar age rocks that crop out near Barreal (Leveratto, 1976), with ages between 18 and 20 Ma. This would indicate that the andesitic breccia of Member Tc1 could correspond to the beginning of the volcanism and the uplift of the Cordillera Principal in Manantiales region.

In members Tc2–Tc4, Carlini et al. (1996) found above the andesitic breccia, Marsupialia: Palaeothentidae indet.; Edentata: *Peltephylus* (Dasypodidae, Peltephilinae), and *Stenotatus* (Dasypodidae, Euphractinae); Liptoterna: Macrauchenidae indet.; Notongulata: *Protypotherium* (Interatheriidae), and Mesotheriidae indet.; Rodentia:

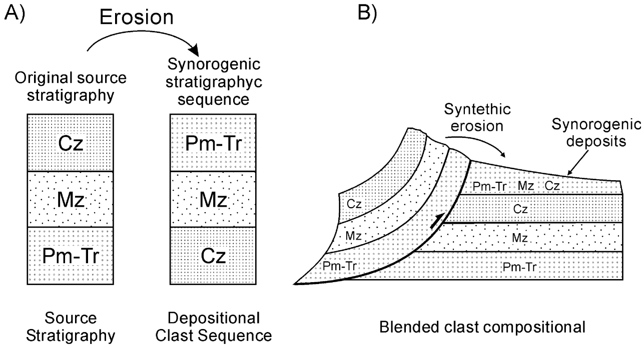

Fig. 7. Schematic diagram showing structural setting for the formation of a classic unroofing sequence with (a) inverted stratigraphy and (b) blended clast composition (Steidtmann and Schmitt, 1988).

Neoreomys (Dasyproctidae), Eocardia (Eocardiidae) and Caviidae indet. This fauna corresponds to a Colhuehuapense–Mayoense age (early–middle Miocene) on the base of the mammal ages recognized in Patagonia. The Chinches Formation is thus one of the most complete Miocene sequences outside Patagonia.

5. Synorogenic deposits of Manantiales unroofing sequences

In thin-skinned thrusting, much of the vertical component of tectonic transport, and thus much of the structural and topographic relief, is the direct result of ramping, where the thrusts cut up section through resistant units. Where a thrust ramps to the surface and forms a topographic high (Fig. 6(a)), an active source is formed that may or may not shed tectogenic sediment suitable for dating the fault motion. At the same time, however, terrain composed of older, inactive thrusts (Fig. 6(b)) in the hanging-wall of the active thrust is also transported over ramps and may form topographic highs. These terrains are considered passive sources if they supply sediment to intramontane basins, but dispersal of these sediments dates motion on the active fault (Fig. 6(a)) and not faulting in the interior of the thrust belt. Misinterpretation of sediments derived from passive sources can result in attributing younger motion to faulting than was actually the case (Steidtmann and Schmitt, 1988).

Transport of tectogenic sediments in the same direction as tectonic transport is commonly assumed for the

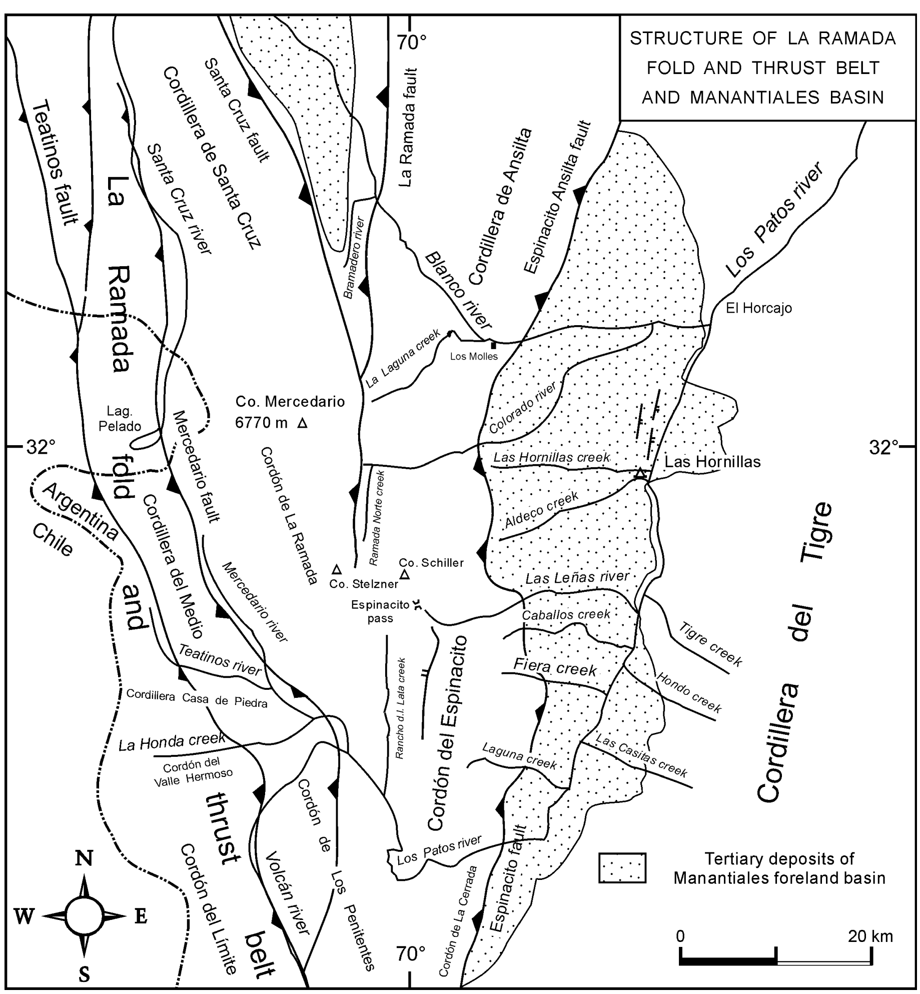

Fig. 8. Generalized structure map of La Ramada fold-and-thrust belt (based on Cristallini, 1996), in relation with the Manantiales foreland basin (Pérez, 1995).

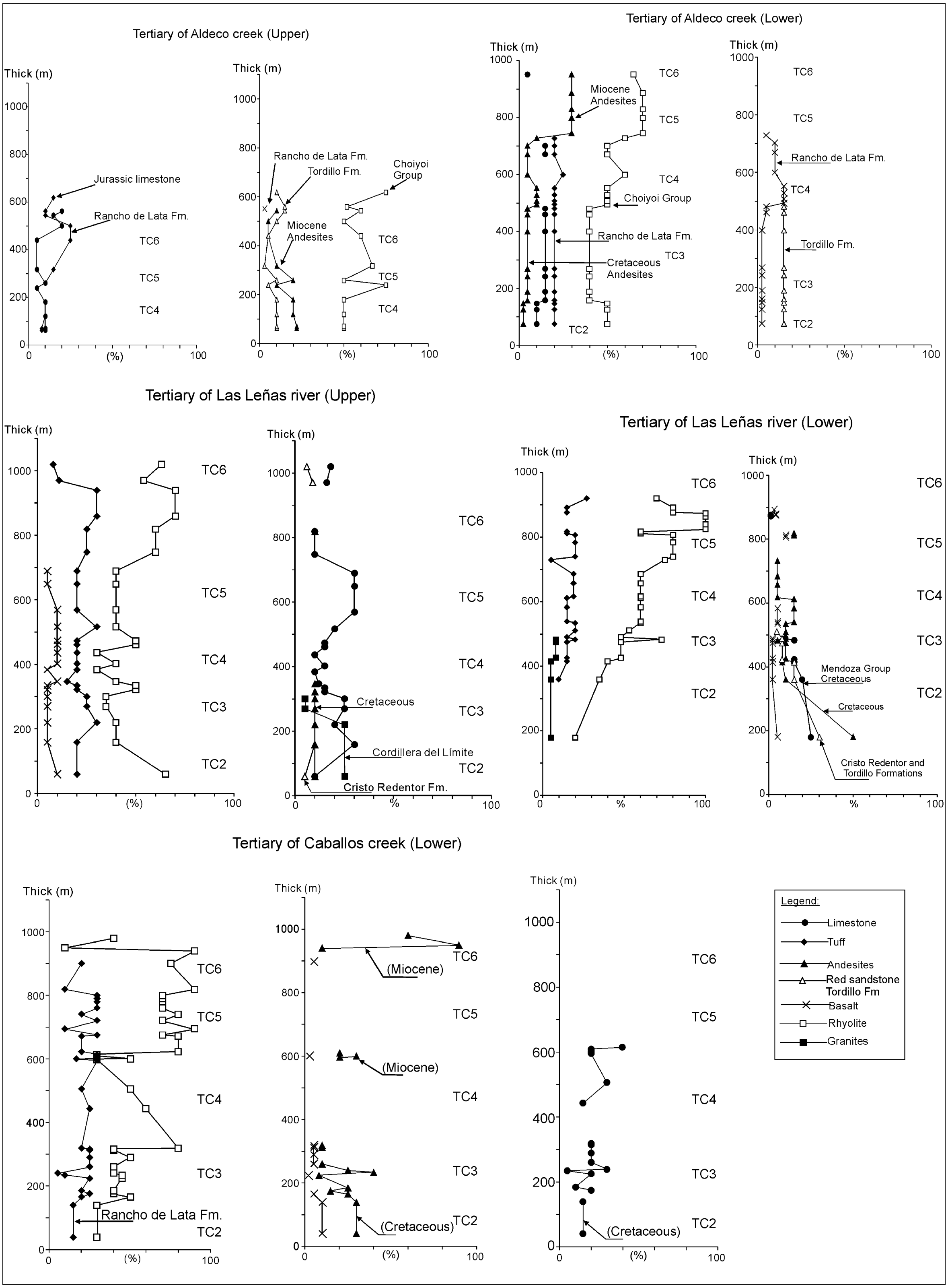

Fig. 9. Plots showing the stratigraphic variation in clast lithology for the Aldeco, Caballos, and Las Leñas section.

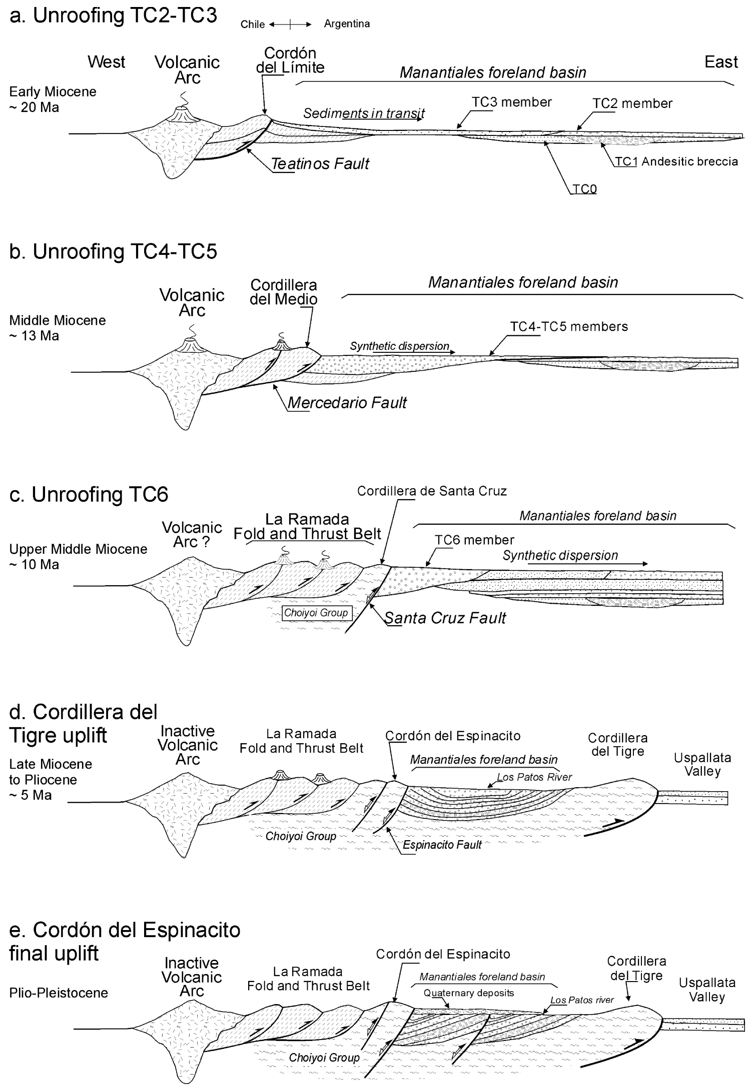

Fig. 10. Schematic sections of the structural and unroofing evolution of the Manantiales foreland basin. (a) Members Tc2 at Tc3. Uplift of the Cordillera del Límite, with contribution of Permotriassic granites, Cretaceous andesites, and Mesozoic limestone and red sandstone. The peneplain at the foot of the fault allowed the erosion of the rhyolites of the Choiyoi Group and rocks of the Rancho de Lata Formation. (b) Members Tc4 at Tc5. Activity of the Mercedario fault was responsible for the uplift of the Cordillera del Medio. Provenance was mainly from rocks represented in the Tordillo Formation and the Mendoza Group. In the northern sector the oldest Miocene andesites are observed. (c) Member Tc6. The main source was the rhyolites and tuffs of the Choiyoi Group and of the Rancho de Lata Formation, and clast dispersal was synthetic proximal. (d) The migration of the thrust front toward the east, producing the uplift of the Cordillera del Tigre with dip to the west of the Tertiary basin. This situation separates and broken the Manantiales Miocene deposits with the Tertiary deposits of the Uspallata Valley. (e) Quaternary deposits. Final elevation of the Cordón del Espinacito and deposition of the granitic and rhyolitic blocks unconformably on the Tertiary deposits of the Chinches Formation.

clastic-wedge/thrust association (Fig. 6(c)). Nonetheless, where hanging-wall beds dip toward the interior of the thrust belt, paleoslope, and therefore sediments dispersal, is opposite to tectonic transport (Fig. 6(d)). This source/transport relation is referred to as antithetic dispersal, following the structural terminology common to thrusted terrains. Similarly, sediment transport in the same direction as tectonic transport is referred to as synthetic dispersal (Steidtmann and Schmitt, 1988).

In settings where distinct source rocks are eroded sequentially, as in the case of predominantly vertical uplift of a stratigraphic section, unroofing sequences are commonly formed in the resultant clastic wedge (Fig. 7(a)). The inverted clast stratigraphy can provide valuable information about the evolving source and aid in the identification of specific source areas. However, in thin-skinned, thrusted terrains, where horizontal transport dominates, layered rocks consisting of different lithologies are commonly exposed to erosion together as they pass up and over a ramp (Fig. 7(b)), providing a ‘conveyor belt’ of several rock types that are blended during erosion and dispersal. Tectogenic deposits thus formed may show no unroofing sequences but contain the same blended clast composition throughout, in some cases for relatively great stratigraphic thickness (Steidtmann and Schmitt, 1988).

6. Potential source areas of the Manantiales basin

Sediments deposited in the Manantiales basin were derived exclusively from the western mountain ranges (Pérez, 1995). The potential source areas for the Manantiales basin were the following (Fig. 8):

1. Cordillera del Límite: along the Argentina–Chile border, composed of andesitic rocks of the Juncal Formation of Lower Cretaceous age, intruded by quartz–porphyry feldspathic, and dacites of Miocene age (Pérez, 1995; Cristallini, 1996). This is the westernmost source for the Manantiales basin (Fig. 8).
2. Cordilleras del Medio, Casa de Piedra and Penitentes: constituted by the Auquilco and Tordillo Formations, the Mendoza Group and the Diamante, Cristo Redentor and Farellones Formations. The dominant lithology is red sandstone and Neocomian limestone with abundant chert nodules (Fig. 8).
3. Cordón de La Ramada: with rhyolites of the Choiyoi Group, and the Rancho de Lata, Los Patillos, La Manga, Auquilco, and Tordillo Formations. Unconformably overlying all these units are the hornblende andesitic rocks of the Farellones Formation with ages of 10.7 ± 0.7 and 12.7 ± 0.7 Ma (Pérez, 1995) (Fig. 8).
4. Cordón del Espinacito: formed almost exclusively by rhyolites of the Choiyoi Group, in the east intruded by Triassic granites and in the west overlain by the Rancho de Lata, Los Patillos, and La Manga Formations (Fig. 8).

7. Unroofing sequences of the Manantiales foreland basin

The western boundary of the Manantiales basin is at the reverse Espinacito fault, which uplifts the rhyolites of the Choiyoi Group over the Tertiary sediments. The composition of the clasts in the Manantiales basin deposits records derivation from the La Ramada fold-and-thrust belt. In order to reconstruct the unroofing history of the Cenozoic sequences, a systematic petrographic count of clasts was carried out in the sections of the Aldeco Creek and Las Leñas and Caballos Rivers. The study revealed evidences of uplift and consequent erosion in the areas of the Cordillera del Límite, Cordillera Principal, and Cordillera Frontal, and possibly also the internal mountain ranges of Chile. The Las Leñas River section is the most complete in the Manantiales basin, crossing the western basin border and reaching the andesitic exposures of the Farellones Formation (Fig. 8).

The member Tc1 andesitic breccia, of wide distribution in the Manantiales basin, located in the bases of the Tertiary synorogenic deposits, indicates that the volcanic activity predates the structuring of the region. Based on this it is possible to suggest the uplift and tectonic piling at the time of deposition of the member Tc2, which is the oldest with clasts coming from the Cordillera Principal. The origin of the clasts and the eventual source areas, for different intervals, are shown in Fig. 9. The following conclusions can be presented.

7.1. Lower section (Tc2–Tc3)

These deposits are the first evidence of the uplift of the Cordillera del Límite, and they mark the beginning of the development of the La Ramada fold-and-thrust belt. Their position above the Tc1 andesitic member indicates that the basin would have begun to be formed at around 20 Ma, in the early Miocene (Fig. 10(a)). It has been interpreted that sediment dispersal was of the synthetic type because of the close relationship between lithology and the westernmost source areas (Pérez, 1995). An important change has been observed between the lithology of the clasts of the members Tc2–Tc3 and those of Member Tc4: the supply of granite clasts from the Chilean sector is interrupted and there is an abrupt decrease in the provision of Cretaceous andesitic rocks. The presence of Cretaceous pyroxene andesites are characteristic in early Miocene contrary to the hornblende andesites that are dominant during the late Miocene (Fig. 9). This change in clast composition suggests the existence of a barrier, conformed by the uplift of Medio and Casa de Piedra mountain ranges in the middle Miocene, to the influx of clasts from western sources. Beside that situation, the supply of lithology coming from the Rancho de Lata Formation and the Choiyoi Group is observed, so it is interpreted that this material was being transported above a peneplain where Cordón del Espinacito is located today.

7.2. Middle section (Tc4–Tc5)

During this interval the Mercedario fault was probably active, judging from the clasts of the Mendoza Group and red sandstone of the Tordillo Formation (Fig. 10(b)) in the Aldeco River. In the autochthonous portion of Las Leñas River, calcareous Cretaceous rocks are observed, the same as in the Caballos Creek. In this interval, they record the first Miocene andesites, especially in the lower Aldeco River. As in the previous interval, rhyolitic rocks of Choiyoi Group are present, as well as clasts derived from the Rancho de Lata Formation, interpreted as material in transit incorporated in the extensive slopes developed to the east of the Mercedario fault. The dispersal of the sediments was again synthetic. In the upper part of this interval, tuff beds of Plinian fall type possibly mark activity of the eruptive center of La Ramada. At this time enhanced tectonic subsidence due to the uplift along the Teatinos and Mercedario faults favored the brief transgression of the sea into the preandean region (Pérez et al., 1996).

7.3. Upper section (Tc6)

This section spans a change in clast provenance related to the uplift of the Cordillera de Santa Cruz and partly of the Cordón del Espinacito. Judging from the age and geochemical characteristics of Cordón de La Ramada andesites, the change would have taken place around 10 Ma, toward the late Miocene (Fig. 10(c)). If the marine nature of member Tc5 is accepted, the Cordón del Espinacito would have risen after 13.5 Ma, the assumed age for the marine transgression (Pérez et al., 1996). The main evidence of this uplift is the synorogenic proximal facies at the top of this member, in both margins of the Las Leñas River. At this locality, 2 m blocks of rhyolitic rocks have been observed, indicating derivation from the Cordón del Espinacito (Fig. 3). After 9 Ma the sedimentation would have been interrupted in the Manantiales basin, associated with the migration of the thrust front, responsible for the uplift of Cordillera del Tigre (Fig. 10(d)).

7.4. Quaternary section

The strong angular unconformity between the Tertiary and Quaternary deposits and the presence of large blocks of the Granite Manantiales in the basin would indicate that the final uplift of the Cordón del Espinacito took place in the late Pliocene to Quaternary (Figs. 3 and 10(d)). The relation between Tertiary and Quaternary deposits shows that uplift pulses of the Cordón del Espinacito correspond to an out-of-sequence thrust, since the thrust front would have migrated at that time to the eastern sector of the Precordillera. In the Quaternary deposits, large blocks of granitic and rhyolitic rocks are observed. Seemingly, there would have been a quiet period with strong erosion of the Manantiales basin, interrupted in some poorly constrained interval of the Plio–Pleistocene. This age would be indicating that the La Ramada fold-and-thrust belt was fully structured toward the middle–late Miocene, at the same time the sedimentation in Manantiales basin was interrupted.

8. Tectonic synthesis

The Manantiales foreland basin developed in early–late Miocene times as a response to the uplift and erosion of the La Ramada fold-and-thrust belt. Initial development of the Manantiales basin is represented by the andesitic breccia Tc1 associated with retroarc volcanism with medium La/Yb (12–14) ratio, suggesting that it would have formed in a non-thickened crust because the mountain range still had not been structured (Pérez and Ramos, 1996). The main volcanic arc was developed in the Chilean sector of the Cordillera Principal.

The evolution of the La Ramada fold-and-thrust belt has three main stages. It begins with thin-skinned thrusts where it deformed the Mesozoic deposits. Following is a stage of tectonic inversion that involves the basement and controlling the initial uplift of the Espinacito and La Ramada mountains, together with other large basement blocks. A third stage produces the out-of-sequences thrust in the inner region (Pérez et al., 1996). These three stages have a different answer to the subsidence. The first one begins the sinking by tectonic load in the foreland basin by viscoelastic subsidence as proposed by Jordan (1981).

The development of the fold-and-thrust belt of the Cordillera Principal began in the early Miocene with the uplift of the Cordillera del Límite; this stage is recorded in members Tc2–Tc3. Because the weight of the tectonic load was incipient and the thrust front was located to the west of the Manantiales basin, the tectonic load did not cause great subsidence. The supply of deposits with alluvial fans and proximal fluvial sediments filled the basin (overfilled basin of Jordan, 1995). Uplift of the Cordillera del Medio in the middle Miocene is recorded in members Tc4–Tc5 with the displacement of the deformation toward the foreland.

At the same time that the basement is involved in the deformation, the thrust front approaches the Manantiales basin and a quick subsidence begins tectonic loading. The basin obtains its maximum subsidence rate and the supply of sediments does not reach to fill the depression formed (underfilled basin of Jordan, 1995). This new situation begins as a lacustrine deposit, where the existence of a high sea level, as the one related to the marine transgression allows the entrance of the sea that reached the foothills of the Miocene mountain range (Pérez et al., 1996). In the upper section of Member Tc5, deposits of the Paranense marine transgression constitute one of the westernmost records for this marine deposits (Pérez et al., 1996).

Toward the late Miocene, the advance of the thrust front continues and it causes initial uplift of the Cordón del Espinacito, as recorded by large blocks in Member Tc6. At this time, the mountain range was already uplifted and the deposition of La Ramada andesites took place. These volcanics have ages from 10 to 12 Ma (Pérez and Ramos, 1996), and they have La/Yb ratios of 16–22, indicating that the La Ramada fold-and-thrust belt was already structured with an important thickened crust. These andesitic rocks date the end of the development of the Manantiales foreland basin.

The thrust front migrated toward the east in the Miocene–Pliocene, uplifting the Cordillera del Tigre (Ramos and Cortés, 1993) by means of deep basement faults, tilting the whole Manantiales basin to the west. As a final stage in the Plio–Pleistocene, the Espinacito out-of-sequence thrust developed, with little shortening in the thrust front and a minimum subsidence in the basin. This stage is associated with thick conglomerates with granitic and rhyolitic blocks deposited by angular unconformity over the Tertiary synorogenic sediments, in alluvial fan facies, filling the basin and leveling the surrounding peneplain.

9. Basin type

Strata of Member Tc6 in the Blanco River sector overlie the rhyolitic rocks of the Choiyoi Group, indicating that they were deposited in a piggy-back basin, similar to the Iglesias basin at 30°S (Beer, 1989). The Iglesias basin would have developed between the middle and late Miocene (16.6–6.6 Ma), during thrust activity of the Precordillera (Beer et al., 1990). The Miocene deposits to the east of the Cordillera del Tigre contain clasts of calcareous rocks (Cortés, 1993), indicating westerly provenance from the Cordillera Principal. The Miocene deposits of the Uspallata valley indicate their connection with those of the Manantiales basin, suggesting that the Cordillera del Tigre had not risen when the sediments of Manantiales were deposited.

These data indicate that the synorogenic Tertiary deposits of the Manantiales basin were genetically linked to the development of the La Ramada fold-and-thrust belt. This basin was cannibalized when the Espinacito fault uplifted the Cordón del Espinacito. The uplift of Cordillera del Tigre marks the beginning of the broken foreland basin. Later during the Pliocene and Pleistocene, the Espinacito fault was reactivated, giving rise to the present structural configuration.

10. Conclusions

The study of the synorogenic Tertiary sequences of the Chinches Formation, the analysis of the structure and of the development of the Tertiary volcanism during the deformation associated with the La Ramada fold-and-thrust belt at 32°S, allowed establishment of the age of uplift and shortening for the High Andes at these latitudes. The volcanism associated with the andesitic breccia of Member Tc1 has an approximate age of 20 Ma, and the andesitic lavas unconformably deposited over the Mesozoic sediments of Cordón de La Ramada has ages of 9.2 ± 0.3, 10.7 ± 0.7, and 12.7 ± 0.7 Ma (Pérez, 1995). These data showed that the uplift of the Cordón de La Ramada fold-and-thrust belt and the deposition of Chinches Formation should have taken place between 20 and 10 Ma.

The angular unconformity between the Quaternary and Tertiary deposits and the synorogenic proximal facies of the Quaternary deposits are the first evidence of exhumation of the Manantiales Granite. This suggests a significant neotectonic uplift of the Cordón del Espinacito and later reactivation of the Espinacito fault during the Pliocene and Pleistocene times. These latter faults are out-of-sequence thrusts.

The Tertiary deposits of the Chinches Formation correspond to a foreland basin developed at the same time as the Tertiary deposits of the Precordillera. This connection was interrupted after 10 Ma when the rise of the Cordillera del Tigre gave way to a broken foreland basin.

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