
Volume 28, issue 2, August/September 2009
ISSN 0895-9811
ELSEVIER
Journal of
South American
Earth Sciences
Including Mexico, Central America, The Caribbean and the Antarctic Peninsula
EDITOR-IN-CHIEF
James N. Kellogg
University of South Carolina, USA
REGIONAL EDITORS
Felipe Audemard
PDVSA EPM, Caracas, Venezuela
Reynaldo Charrier
Universidad de Chile, Santiago, Chile
Hermann Duque-Caro
Bogotá, Colombia
Reinhardt A. Fuck
Universidade de Brasília, Brazil
Minard L. Hall
Escuela Politécnica Nacional, Quito, Ecuador
Cinna Lomnitz
Instituto de Geofísica UNAM, Mexico
Victor A. Ramos
Universidad de Buenos Aires, Argentina

Journal of South American Earth Sciences 28 (2009) 142–154

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Middle Eocene deformation–sedimentation in the Luracatao Valley: Tracking the beginning of the foreland basin of northwestern Argentina

Patricio Payrola Bosio[a,*], Jaime Powell[b], Cecilia del Papa[a], Fernando Hongn[a]

[a] CONICET, Facultad de Ciencias Naturales, UNSa, Av. Bolivia 5150, 4400 Salta, Argentina
[b] CONICET, Facultad de Ciencias Naturales, UNT, Miguel Lillo 205, 4000 Tucumán, Argentina

ARTICLE INFO

Article history:
Received 15 December 2008
Accepted 1 June 2009

Keywords:
Quebrada de los Colorados Formation
Growth strata
Middle Eocene
Initial Andean foreland basin
NW-Argentina

ABSTRACT

The Andean foreland basin overlaps the Cretaceous-Paleogene Salta rift basin in northwestern Argentina. Knowledge of the relationship between rift and foreland basins is key to understanding the initial stages of foreland basin development related to Andean shortening. We present a new stratigraphic scheme for the Luracatao Valley, revealing that the Quebrada de los Colorados Formation (Payogastilla Group) lies over the Santa Bárbara Subgroup (Salta Group) through an erosional unconformity that turns into an angular unconformity close to folds and faults recorded in the Santa Bárbara Subgroup. The base of the Quebrada de los Colorados Formation shows growth strata along the west frontal limb of an anticline with Santa Bárbara units in its core. The finding of a mammalian fossil at the base of the Quebrada de los Colorados Formation allows us to assign a Middle-Upper Eocene age to the sedimentation; therefore, the time elapsed between the deposition of the final postrift strata and the beginning of Andean sedimentation was brief and constrained to the Lower-Middle Eocene. This data indicates that the Eocene deformation phase described in other portions of the Puna-Cordillera Oriental transition (e.g., the northern Calchaquí Valley and Aguilar range) is also present in the Luracatao Valley, offering new tools for interpreting the ages and distributions of the initial episodes of sedimentation and deformation related to the Andean shortening. Thus, the Luracatao Valley provides new evidence for tracking the distribution of the Paleogene deformation in northwestern Argentina.

ARTICLE INFO

Article history:
Received 15 December 2008
Accepted 1 June 2009

Palabras claves:
Formación Quebrada de los Colorados
estratos de crecimiento
Eoceno medio
inicio cuenca de antepaís andina
NO-Argentina

RESUMEN

En el noroeste argentino la cuenca de antepaís andina se desarrolló sobreimpuesta a la cuenca de rift cretácica del Grupo Salta. El estudio de las relaciones entre estas cuencas es clave para comprender las etapas iniciales de la cuenca de antepaís relacionada al acortamiento andino. En este trabajo se presenta un nuevo esquema estratigráfico para el Valle de Luracatao revelando que la Formación Quebrada de los Colorados (Grupo Payogastilla) se asienta sobre el Subgrupo Santa Bárbara a través de una discordancia angular en cercanías de pliegues y fallas. La base de la Formación Quebrada de los Colorados presenta estratos de crecimiento en el flanco frontal de un anticlinal del Subgrupo Santa Bárbara. El hallazgo de un fósil en la Formación Quebrada de los Colorados ha permitido su asignación al Eoceno medio-superior, por lo cual, el intervalo de tiempo entre la depositación de postrift y el comienzo de la sedimentación andina fue breve y queda comprendido entre el Eoceno inferior a medio. Estos datos indican que la fase de deformación eocena descripta en otros sitios de la transición Puna-Cordillera Oriental (p.ej. norte del Valle Calchaquí y Sierra de Aguilar) está también presente en el Valle de Luracatao, brindando nuevas herramientas para la interpretación de la edad y distribución de los episodios iniciales de sedimentación y deformación relacionados al acortamiento andino. Consecuentemente, el Valle de Luracatao ofrece nuevas evidencias para el entendimiento de la distribución de la deformación paleógena en el noroeste argentino.

1. Introduction

The Central Andes is a non-collisional orogen resulting from the subduction of the Nazca Plate beneath the South American Plate.

* Corresponding author. Tel.: +54 3814221888.
E-mail address: ppayrola@hotmail.com (P.P. Bosio).

0895-9811/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsames.2009.06.002

The building of the Central Andes (including the Altiplano-Puna Plateau, Cordillera Oriental and Sierras Subandinas) is the result of a complex evolution that is still poorly understood. However, a considerable amount of recent research has improved our understanding of this region (Coira et al., 1982; Mon and Salfity, 1995; Allmendinger et al., 1997; DeCelles and Horton, 2003; Strecker et al., 2007; Hilley et al., 2007; among others). The complex evolution of the Central Andes involved the development of foreland, piggy-back and intramontane basins in response to the eastward propagation of the deformation (Jordan and Alonso, 1987; DeCelles and Horton, 2003). One of the main events involving uplift, magma extrusion and sedimentation in related basins in the Central Andes was the Quechua phase in the middle Miocene (e.g., Mégard et al., 1984; Salfity et al., 1984; Jordan and Alonso, 1987; Pardo-Casas and Molnar, 1987; Allmendinger et al., 1982, 1997; Somoza, 1998). However, information is still lacking on earlier deformation related to Andean shortening, the initial uplift of the Puna Plateau, and the associated development of the foreland basin.

The first known episode of deformation related to the Andean shortening was the middle Eocene Incaic phase (Steinmann, 1929; Mégard, 1978; Noble et al., 1979), which is widely recognized in Chile and Perú (Maksaev, 1979; Coira et al., 1982; Lavenu and Marocco, 1984; Mégard, 1984; Hammerschmidt et al., 1992; Jaillard et al., 1992; Salfity et al., 1993). However, a broad range of ages have been proposed for this earlier deformation in Bolivia. Sempere et al. (1990) suggest a Late Oligocene - Early Miocene tectonic event, but Sempere et al. (1997) postulate a major tectonic event in the Late Paleocene – 58.2 Ma based on an erosional unconformity and reinterpreted biostratigraphic data. More recently, deformation and sedimentation occurring in the Eocene–Oligocene (DeCelles and Horton, 2003; Horton, 2005) and uplift of the Bolivian Altiplano at 40 Ma (Kennan et al., 1995; Benjamin et al., 1987; Müller et al., 2002; Farías et al., 2005) have been reported. In northern Argentina, the first record of Andean deformation and the beginning of the Andean foreland basin (Puna and Cordillera Oriental) are the subject of an ongoing controversy due to the lack of clear field evidence. Several authors have proposed different ages, including the Late Eocene (Kraemer et al., 1999), the Eocene-Oligocene (Boll and Hernández, 1986; Donato, 1987; Monaldi et al., 1993; Coutand et al., 2001; Haschke et al., 2005; Carrapa and DeCelles, 2005; Coutand et al., 2006), the Oligocene (Galli and Hernández, 1999; Hernández et al., 1999), the Late Oligocene, and the Early Miocene (Schwab, 1985; Grier and Dallmeyer, 1990). However, del Papa et al. (2004) and Hongn et al. (2007) documented a middle Eocene deformation and sedimentation event in the Puna- Cordillera Oriental transition recording the Incaic phase in this area. The diversity of postulated ages suggests that the record of the initial episodes of sedimentation and deformation related to the Andean shortening display a rather complicated temporal and spatial distribution (Deeken et al., 2006; Hongn et al., 2007).

Despite the described complexity, detailed multidisciplinary surveys in key local areas are useful to elucidate both the tectonics and the sedimentation history of the initial stages of the Central Andes development. One of these key areas is the Luracatao Valley located in the Puna-Cordillera Oriental transition (Calchaquí Valley) (Fig. 1), south of the region where Eocene deformation–sedimentation was recently detected (Hongn et al., 2007). Our new stratigraphic study shows that this valley preserves sedimentary successions and structures recording Paleogene deformation.

Thus, the main goals of this paper are (1) to present a new stratigraphic column that redefines the stratigraphic frame for the central and southern part of the Luracatao Valley; (2) to analyze the relationship between the Cretaceous rift basin and the beginning of the Andean foreland basin in the Puna – Cordillera Oriental transition based on structural and stratigraphic data; (3) to record growth strata at the base of the Quebrada de los Colorados Formation (Payogastilla Group); and finally (4) to confirm the proposed age of this unit in the La Poma region (Powell, 2006) based on a mammal fossil of Middle-Upper Eocene age found at the base of the Quebrada de los Colorados Formation.

2. Geological setting

The Luracatao trough is a north-south elongated fault valley along the Puna-Cordillera Oriental transition between 24° 50' and 25° 25' south latitude (SL) (Figs. 1 and 2). It represents the westernmost depression of the Calchaquí Valley region or Calchaquí geological sub-province (Baldis et al., 1976; Salfity, 2008). Its western slope defines the eastern border of the Puna, which is considered a closed drainage region. The Luracatao Valley constitutes a minor lateral valley that branched off from the main Calchaquí Valley (Fig. 1). From a tectonic point of view, it is localized in the transition zone where the Nazca plate decreases in inclination from 30° to 5° in the southward direction (Isacks et al, 1982; Jordan et al., 1983). The Luracatao Valley is bounded by reverse faults showing opposite vergence (Fig. 2), with attitudes partially influenced by previous heterogeneities, mainly basement fabrics in the western thrust and Cretaceous normal faults in the eastern high-angle reverse fault (Riller and Hongn, 2003). This area recorded tectonic overprints from the Upper Neoproterozoic-Lower Paleozoic deformation affecting the basement, a widespread phenomenon in NW Argentina (Turner and Mon, 1979; Mon and Salfity, 1995) that has lasted to the present. Older structures were reactivated during subsequent deformation, especially during the Cretaceous rifting and Cenozoic Andean-shortening (Hongn and Seggiaro, 2001; Riller and Hongn, 2003; Carrera et al., 2006; Deeken et al., 2006).

The Calchaquí and related valleys (Luracatao, Colomé, Hualfín, and Pucará, Fig. 1) contain a thick sedimentary succession of clastic rocks that correspond to the Andean synorogenic fill of the foreland basin. They are generally included in the Payogastilla Group (Díaz and Malizzia, 1983). The Quebrada de los Colorados Formation (base of the Payogastilla Group, Fig. 3) overlaps the Cretaceous-Paleogene deposits of the Salta Rift basin. The age of this unit, and consequently of the initial foreland basin, has been questioned due to lack of both fossil and volcanic material (Díaz and Malizzia, 1983; Starck and Vergani, 1996; Galli and Hernández, 1999; Coutand et al., 2006; among others). Additionally, some authors have suggested that the orogenic front of the Paleocene Andean foreland basin was located westward of Luracatao, matching the west border valley fault that uplifted the Complejo Eruptivo Oire (Starck and Vergani, 1996; Galli and Hernández, 1999). Based on recent stratigraphic, structural and fossil evidence in the northern portion of the Calchaquí Valley (del Papa et al., 2004; Powell, 2006; Hongn et al., 2007), several conclusions can be drawn: (1) the Quebrada de los Colorados Formation is of middle Eocene age, (2) deposition of this unit was coeval with faulting and folding, and (3) little time elapsed between the deposition of the final postrift strata and the beginning of Andean sedimentation in the Calchaquí Valley. This picture offers new tools for analyzing the initial formation of the Andean foreland basins in northwest Argentina in general and in the Calchaquí valleys in particular.

3. Sedimentary record: background and new proposal

The main sedimentary record of the Calchaquí valleys corresponds to two principal Cretaceous-Cenozoic basins: the Early Cretaceous – Paleogene Salta Rift basin (Turner, 1959; Marquillas and Salfity, 1994) and the Eocene – Neogene Payogastilla Group Fore-

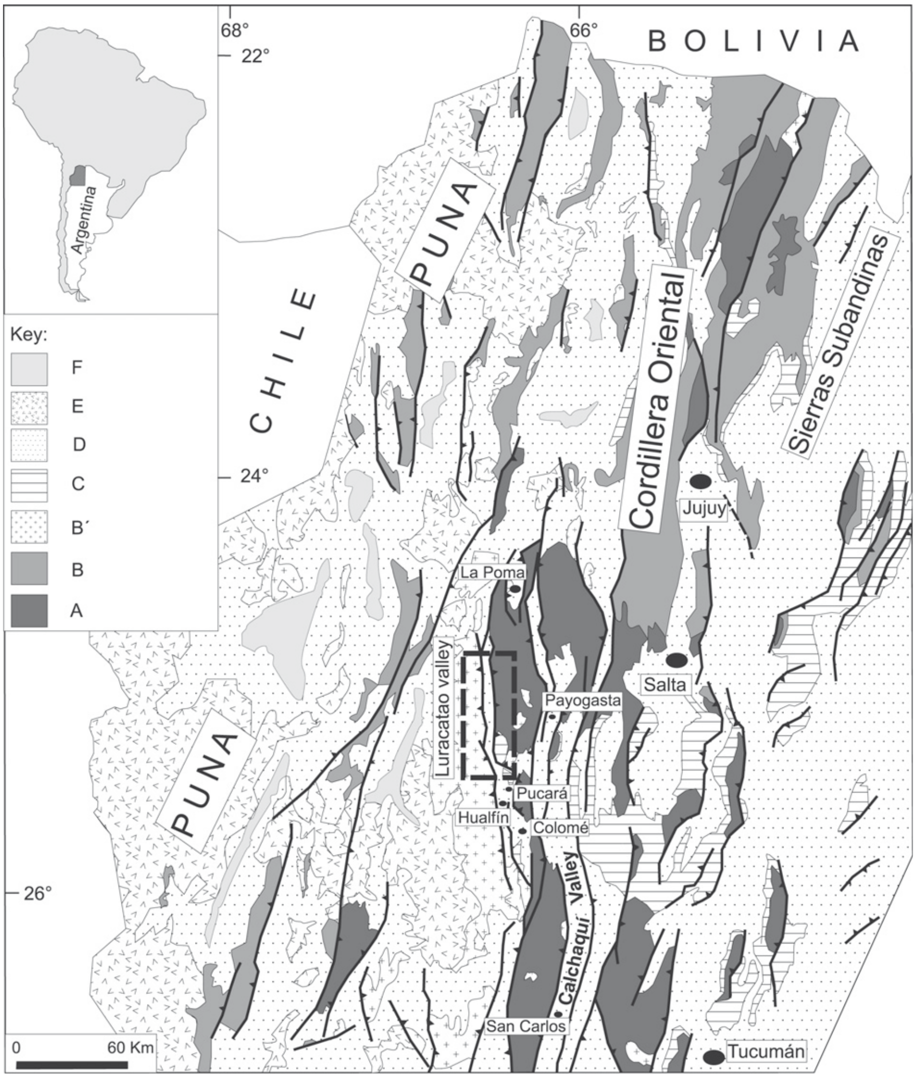

Fig. 1. Geologic map of northwestern Argentina. Key: A: Precambrian and Phanerozoic granitoids; B: Paleozoic sedimentary rocks; B́: Complejo Eruptivo Oire; C: Cretaceous units; D: Tertiary strata; E: Tertiary-Quaternary volcanic rocks; F: Salar (simplified from Mon and Salfity, 1995).

land basin (Díaz and Malizzia, 1983; Starck and Vergani, 1996; Hongn et al., 2007).

The Salta Group is composed of three main units: (from base to top) the Pirgua (Reyes and Salfity, 1973), Balbuena and Santa Bárbara (Moreno 1970) subgroups (Fig. 3). The Pirgua Subgroup represents the synrift deposits and the Balbuena and Santa Bárbara subgroups include the postrift strata (Salfity and Marquillas, 1994). Although extensive outcrops of the three subgroups have been mapped along the main Calchaquí Valley (see synthesis in Hongn and Seggiaro, 2001), only the Pirgua Subgroup has been clearly identified in the Luracatao Valley, where it is located along the eastern and southern boundaries of the valley (Brealito-Molinos deposits, Méndez et al., 1979; Boso et al., 1984).

The Payogastilla Group (Díaz and Malizzia, 1983) is a thick coarsening up succession and includes four lithostratigraphic units: Quebrada de los Colorados, Angastaco, Palo Pintado and San Felipe formations. The principal outcrops of this group extend along the central and southern portions of the main Calchaquí Valley, especially between Payogasta to the north and San Carlos to the south (Fig. 1).

Turner (1964) was the first to describe the thick sedimentary succession recorded in the Luracatao Valley. He defined the Luracatao Formation as including sedimentary rocks from the region of the valley northwards of 25° S and assigned it an Oligocene age. Hongn and Seggiaro (2001) extended the Luracatao Formation southwards (up to La Puerta village, Fig. 2), assigned it a probable Eocene-Oligocene age and distinguished the Quebrada de los Colorados (Eocene?-Miocene) and Angastaco (Miocene) formations at the south end of the valley.

Two sedimentary basins bounded by an erosional and local angular unconformity were recognized and differentiated based on geological mapping, logging, detailed mapping of key sedimentary contacts and fossil evidence. Older strata consist of greenish (coarse-grained) to reddish (fine-grained) beds assigned to the Santa Bárbara Subgroup (Fig. 3), while a younger reddish section was assigned to the Quebrada de los Colorados Formation (Payogastilla Group, Fig. 3). Thus, our analyses indicate that some outcrops previously assigned to the Luracatao Formation (Turner, 1964) in fact correspond to the Santa Bárbara Subgroup as previously suggested by Hongn and Seggiaro (2001).

3.1. Salta Group

The Mealla, Maíz Gordo and Lumbrera formations integrate the Santa Bárbara Subgroup, which outcrops along both margins as well as in the central part of the Luracatao Valley. The Mealla For-

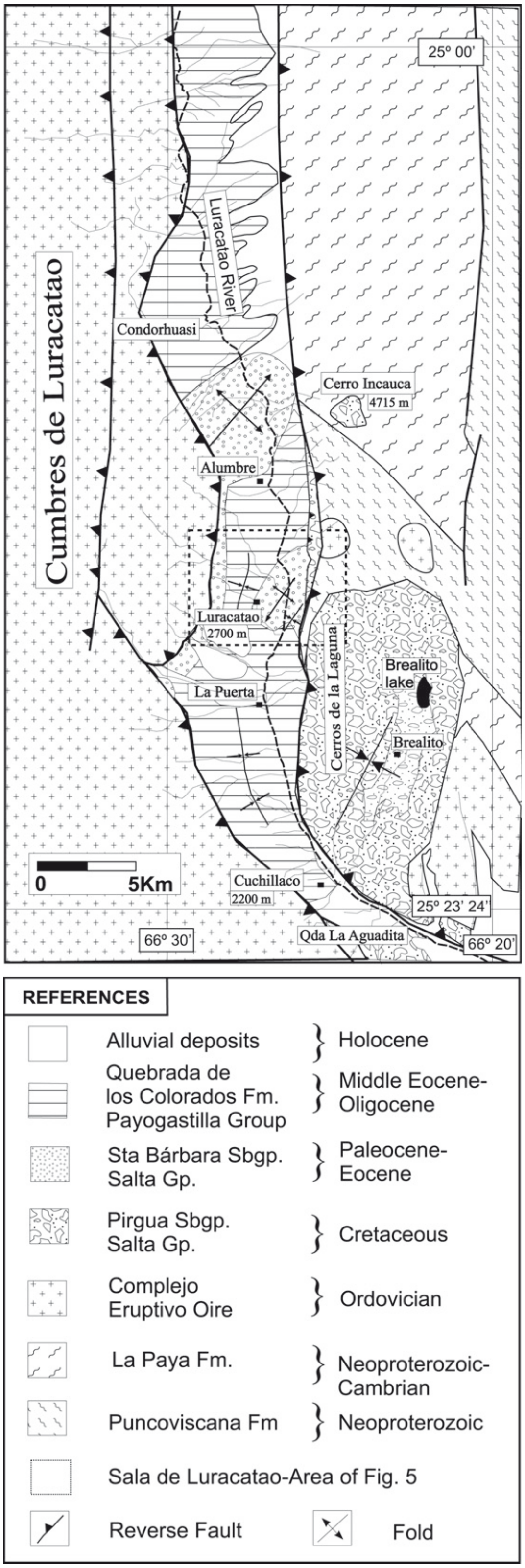

Fig. 2. Geological map of the Luracatao Valley (modified from Hongn and Seggiaro, 2001).

mation appears discontinuously or as isolated patches along the western margin of the valley. It consists of reddish to pinkish, coarse- to fine-grained, fluvial massive and horizontally stratified sandstones. The Maíz Gordo Formation comprises a succession of coarse- to fine-grained white sandstone (quartz-rich) and conglomeratic sandstone interbedded with minor green and purple siltstone layers (Fig. 4). Its maximum thickness is 285 m in the central region of the valley. The beds have erosive bases, and troughs, tabular cross-stratification, and plane-bedding are the most common sedimentary structures. In the middle to upper section, the Maíz Gordo Formation contains a purple, quartz-rich bed (7 m thick) with yellow stains that have been interpreted as ferric paleosols. This level acts as an excellent marker horizon for regional field correlation (del Papa, 1999). The Lumbrera Formation overlies the Maíz Gordo Formation through a paraconformity. The thickness of this unit is very irregular, ranging from 128 m to just a few meters. Its upper boundary is delineated by a disconformity that laterally changes to an angular unconformity, over which the sedimentary rocks of the Payogastilla Group were laid down. The Lumbrera Formation consists of gray, medium-grained micaceous sandstones, usually massive but eventually displaying parallel plane-bedding. Towards the top of the section, there is an increase of reddish to red massive claystones and siltstones producing a fining-upward trend (Fig. 4).

3.2. Payogastilla Group

The Quebrada de los Colorados Formation (Díaz et al., 1987) is over 455 m thick and its top is cut by an erosional and angular unconformity over which Pleistocene-Holocene sedimentary deposits lie. This unit rests unconformably on the Lumbrera Formation, but in some places it lies directly over the Maíz Gordo Formation (Fig. 5), recording the total removal of the former and complex geometrical relationship between the postrift (Santa Bárbara Subgroup) and the foreland (Quebrada de los Colorados Formation) deposits.

The Quebrada de los Colorados Formation is composed of red, medium- to coarse-grained sandstones, conglomerates, dark reddish siltstones and mudstones that are arranged in fining-upwards fluvial cycles. Sandstone and conglomerate dominate the lower 215 m of the sequence; in contrast, siltstone and mudstone dominate the upper 240 m. The sandstone layers display erosive bases and cross- and plane-bedding. Siltstone beds are massive and/or contain calcareous nodules and root traces representing paleosols. This sequence comprises sandy and gravelly channel-fill and floodplain facies of fluvial environments. Preliminary analyses of paleocurrent and clast composition indicate a provenance from source areas composed of granite and medium-grade metamorphic rocks located to the north and northwest (Fig. 4).

4. Structure

4.1. Faults and folds

The Luracatao Valley is a 70 km long N–S trending tectonic depression that ranges from a few hundred meters to about 6 km wide. The valley is bounded by the Luracatao and Cachi reverse faults, both verging toward the valley axis (Fig. 2). The 45° to 65° west-dipping, Luracatao fault overthrusts granites of the Complejo Eruptivo Oire (Cumbres de Luracatao; Blasco and Zapettini, 1995) on the Cenozoic successions of the Santa Bárbara Subgroup and Quebrada de los Colorados Formation. This east-vergent fault is the limit between the Puna and the Cordillera Oriental (Turner and Mon, 1979; Hongn and Seggiaro, 2001; Carrera et al., 2006). The location of the fault was partly controlled by inherited heterogeneities related to ductile deformation zones in the granites of the Complejo Eruptivo Oire (Hongn and Seggiaro, 2001; Riller and Hongn, 2003).

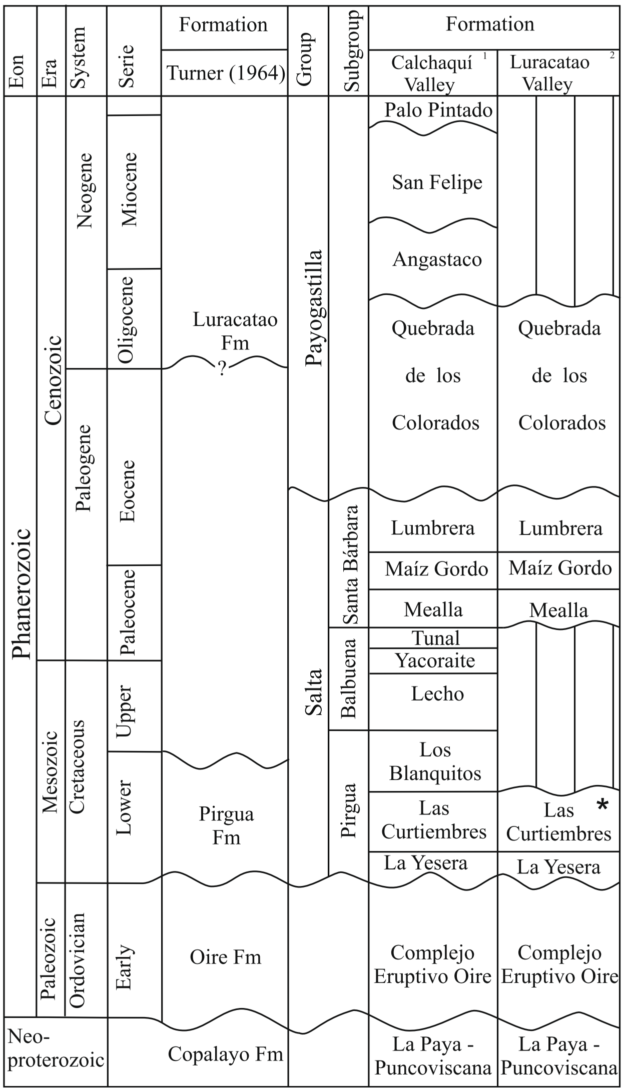

Fig. 3. Stratigraphic chart of the main units from the Luracatao Valley. Comparison between Turner (1964) units, Calchaquí Valley ([2]) units (based on Cortelezzi et al., 1973; Goin et al., 1986, Russo, 1948; del Papa and Salfity, 1999) and the units presented here ([3]). * Pirgua units, based on Sabino, 2004.

The 60° to 82° east-dipping Cachi fault overthrusts the Pirgua Subgroup and variable-grade metamorphic rocks of the Precambrian basement on the Quebrada de los Colorados Formation and the Santa Bárbara Subgroup (Fig. 2). Its general trend is N–S but further south it acquires a NW-SE orientation. The syn-rift Pirgua Subgroup crops out in the hanging wall of this fault but is not found in the footwall, where the Santa Bárbara Subgroup and the Quebrada de los Colorados Formation rest directly over the basement. The Pirgua Subgroup reaches maximum thickness near the fault (Hongn and Seggiaro, 2001; Sabino, 2004; Carrera et al., 2006). These relationships indicate that the southern portion of the eastern reverse fault was a normal fault of the Cretaceous rift border that was inverted by the Andean deformation during the Cenozoic (Hongn and Seggiaro, 2001; Riller and Hongn, 2003; Carrera et al., 2006). In addition, in the Quebrada de Aguadita, this fault cuts Quaternary alluvial deposits, indicating Pleistocene activity as well (Hongn and Seggiaro, 2001) (Fig. 2). In the Brealito syncline, the base of the Pirgua Subgroup is at 2200 m above sea level but to the north, the base is at the summit of Mount Incauca (4715 m above sea level), hence indicating different degrees of inversion (Hongn and Seggiaro, 2001).

The folds are well exposed around Luracatao farm (Luracatao in Fig. 2). Cenozoic sequences (Santa Bárbara Subgroup and Quebrada de los Colorados Formation) define a fold train including, from west to east, a western syncline (WS), a central anticline (CA) and an eastern syncline (ES) (Fig. 5A). The three folds plunge to the south. The biggest structure is the western syncline, a symmetric, open to gentle fold with a 2800 m wavelength that exhibits a curved, NNE-SSW (southern area) and N–S (northern area) oriented axis (Fig. 5A). Its core consists of the Quebrada de los Colorados and the western and eastern limbs show the Maíz Gordo Formation and the Maíz Gordo-Lumbrera Formations, respectively. These contact relationships reveal an erosive unconformity in the eastern limb and an erosive-angular unconformity in the western limb, between the Quebrada de los Colorados Formation and the Santa Bárbara Subgroup (Fig. 5A and B). In contrast, the Santa Bárbara-cored folds (CA and ES) are tight and moderately asymmetric with NE-SW axes (Fig. 5A). Geologic data of the central anticline expose a structural change from a faulted, westward vergence (Fig. 5B) to an eastward vergent fold in the south (Fig. 5C). In the north, the anticline core is truncated by a minor N–S trending and 70° eastward dipping reverse fault with a slight left strike-slip component that explains the observed variation in vergence (Fig. 5B). This minor reverse fault is probably linked to the Cachi fault due to its similar dip angle and direction. Because this small structure cuts the central anticline (Fig. 5B), the anticline is assumed to have been formed prior to propagation of the minor reverse fault. The third fold (eastern syncline), which is not well exposed, is tight with steeply dipping limbs (>60°) and exposes the Lumbrera Formation at its core.

4.2. Growth strata, geometry and interpretation

In the western limb of the central anticline, beds of the Maíz Gordo and Lumbrera formations are parallel and display approximately constant stratigraphic thickness (Figs. 5B and 6A). The strata of these units have variable dip, ranging from 80° at the base to 60° at the top of the succession. Overall, folding of these beds defines the structural geometry of the folds in the Luracatao Valley, suggesting that the Quebrada de los Colorados Formation folding may be controlled by the Santa Bárbara Subgroup structures. The beds of the Quebrada de los Colorados Formation rest on the Lumbrera Formation and are arranged in a fan-like geometry (Fig. 6B and C). The dip strata decreases progressively from 60° to 10° around the outer limb of the anticline (Fig. 6A) and bed thinning towards the anticline hinge is evident (Fig 6B). Syntectonic intraformational unconformities (Riba, 1976) are observed in the lower beds of Quebrada de los Colorados Formation. We interpret the Santa Bárbara Subgroup as pregrowth strata (Fig. 7A) and the lower beds of the Quebrada de los Colorados Formation as growth strata. In addition, the Lumbrera Formation thins towards the south along the western limb of the central anticline, confirming the unconformity between the Santa Bárbara Subgroup and the Quebrada de los Colorados Formation (Figs. 5A and 6C).

The growth strata models assume a forelimb that is deformed while erosion and syntectonic sedimentation occur at its front. There are two main mechanisms: hinge migration (Suppe, 1983; Suppe et al., 1997) and limb rotation (Hardy and Poblet, 1994). The geometric relationship between the forward strata and the anticline hinge allows us to identify which models are correct. As the growth strata set has been eliminated by erosion in the hinge of the faulted central anticline (Fig. 7A and B), the geometry of the structure is not well preserved, so the results of kinematic modeling are not unequivocal. From the preserved geometry (Figs. 6B, 7A and B), it is possible to devise two cross sections, the first with erosion of growth strata (Fig. 7D) and the second without erosion of growth strata (Fig. 7C) (Rafini and Mercier, 2002). The model without erosion implies the

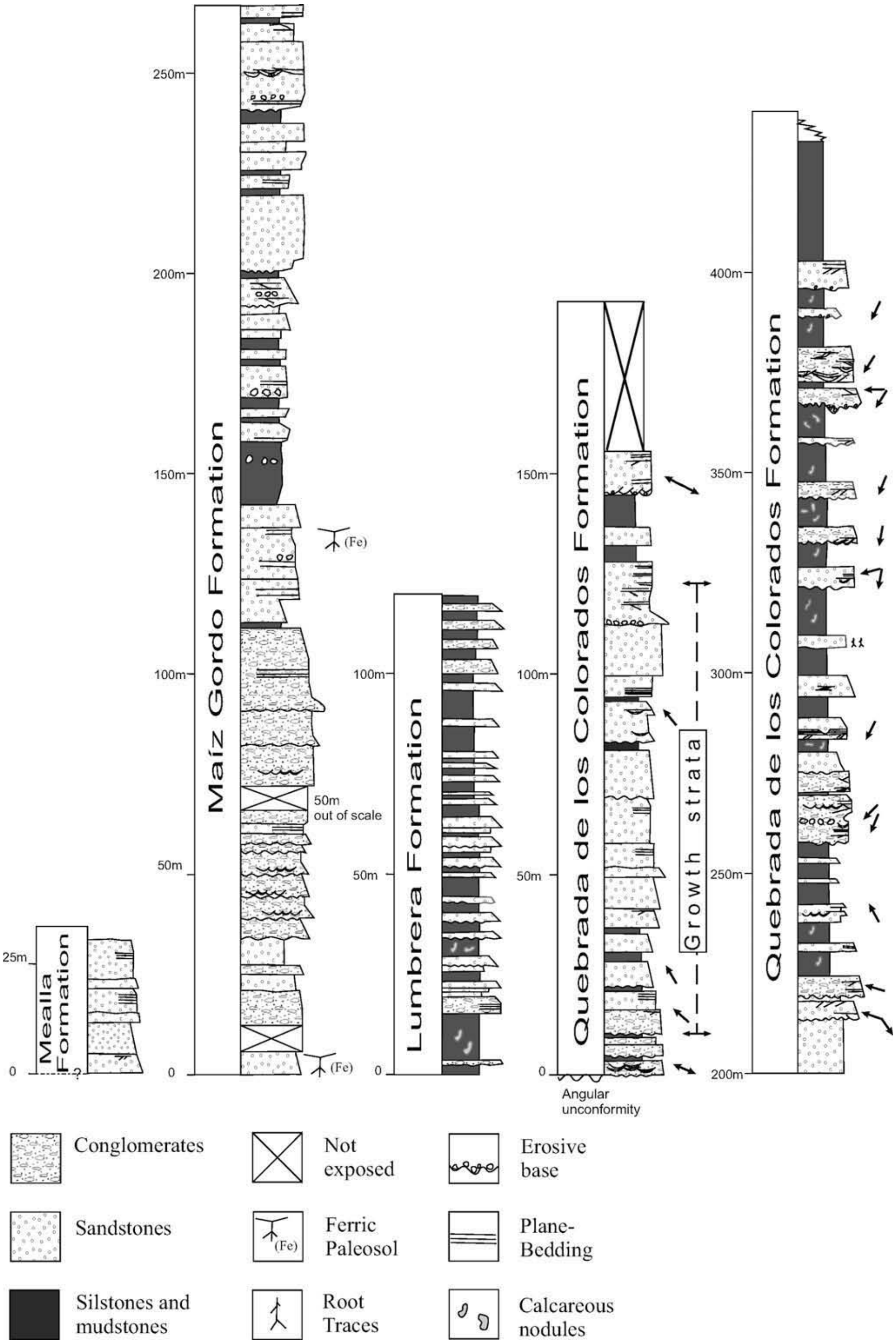

Fig. 4. Detailed sedimentological logs from the central area of Luracatao.

projection of the beds towards a point at the front limb of the anticline, which is not possible due to the structural attitude of the beds. In the second cross section, the layers, projected according to their dip, describe an inclined erosional surface within the growth strata and a wedge-like geometry between some parallel tabular layers. According to the sedimentary record and preserved structure (Fig. 7A), limb rotation is considered the most feasible mechanism for the generation of the growth strata (Fig. 7B and D). The arrangement of the Quebrada de los Colorados growth strata shows vergence to the west and a rotative onlap (Riba, 1976) involving west-dipping beds in a decelerated uplift regime when the sedimentation rate was faster than the uplift rate.

5. Age of Cenozoic deposits

5.1. Paleontology

Fossil remains were found close to the base of the Quebrada de los Colorados Formation at Luracatao and included a turtle

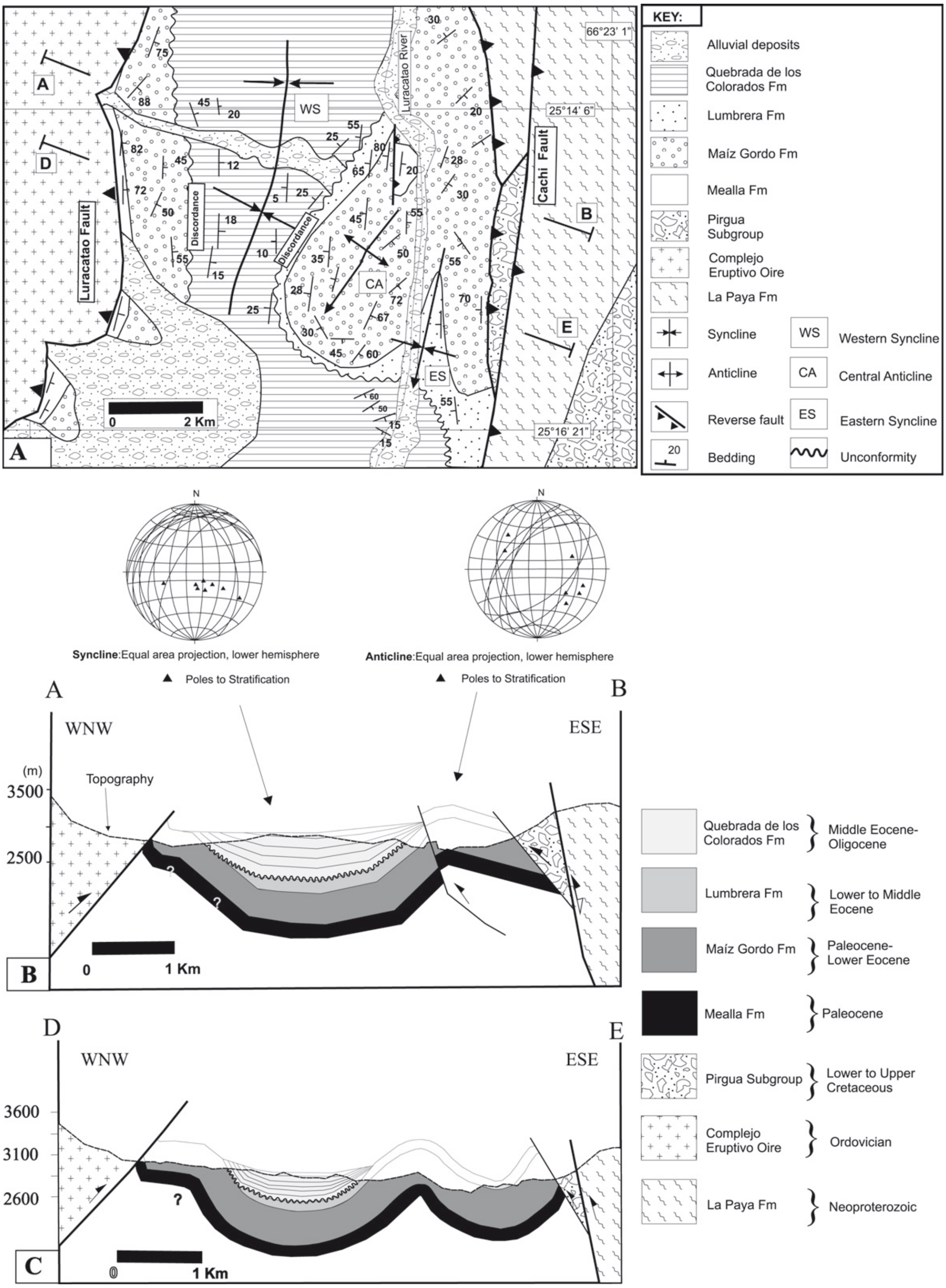

Fig. 5. A. Detailed geologic map of the Sala de Luracatao area. See Fig. 2 for location. B. Geological cross-sections of the Luracatao structure with stereonet diagrams show limb projection (great circle) C. Geological cross-sections of the Luracatao structure to the south of the cross-section shown in B. See A for cross-section location.

carapace, some dasypodid dermal scutes and a notoungulate skull (Fig. 8A). The material is not well preserved but provides important biostratigraphic and chronostratigraphic information concerning this formation. The notoungulate is an incomplete skull (PVL 6243) lacking the upper portion of the snout with all upper teeth except I2? (Fig. 8C), left PM1 and right PM1-2 (Fig. 8B). It is interpreted as an Isotemnidae, closely related to Pleurostylodon (Ameghino, 1897) and Pampatemnus (Bond and Vucetich, 1982).

5.2. Age discussion

The notoungulate found at Luracatao is clearly an isotemnid because of the morphology and proportions of the incisors and

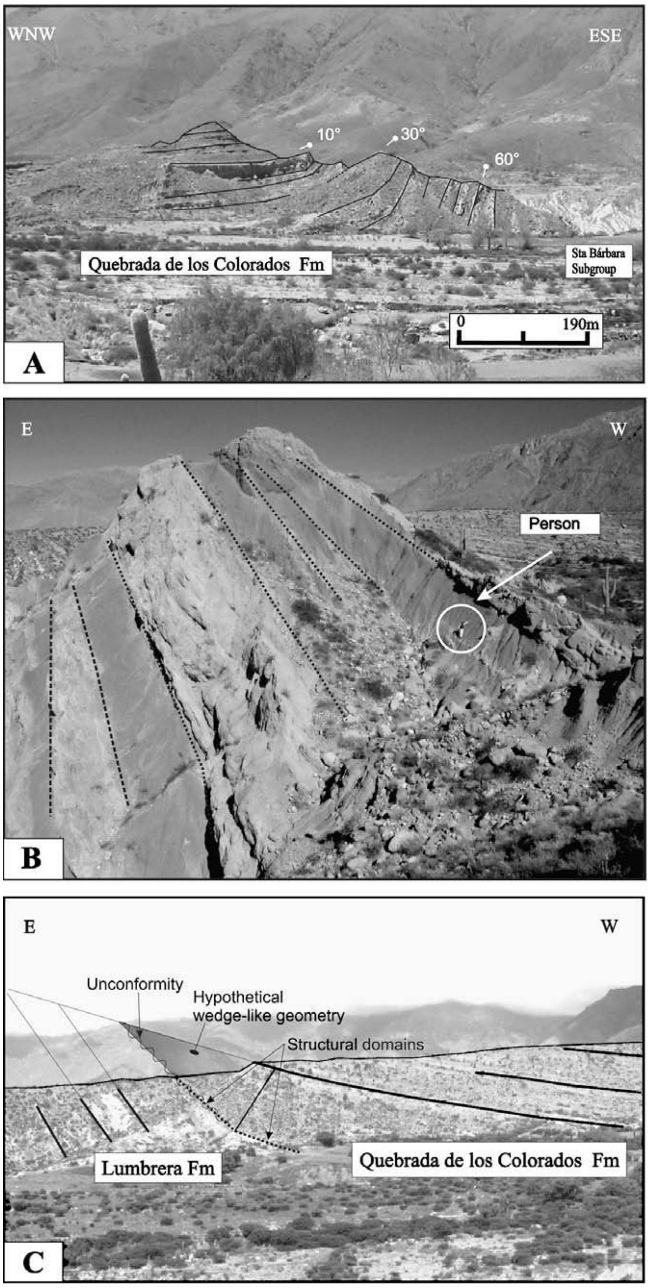

Fig. 6. A. Growth strata showing fan-like geometry at the base of the Quebrada de los Colorados Formation. Note the strata thinning towards the upper portion of the photograph. B. Outcrops of the western syncline at La Sala de Luracatao. Note that the dip of the Quebrada de los Colorados Formation strata progressively decreases upwards. C. Unconformity between the Lumbrera and Quebrada de los Colorados formations. Note that the projection of bedding traces shows the hypothetical wedge-like geometry in the lower strata of the Quebrada de los Colorados Formation. The view is to the south.

canine. Premolars and molars are brachyodont as in the Eocene isotemnid notoungulates, and the central fossa of premolars is closed rather than open mesially as found in Leontiniids and Notohippids. The fossil-bearing strata are similar in lithology and stratigraphic position to those at La Poma (Fig. 9), Salta Province, located 65 km north of Luracatao, where the remains of a Notohippid and a Leontiniid have been found (Hongn et al., 2007). The association of mammal fossils found at these levels of the Quebrada de los Colorados Formation indicates an Eocene age (probably Middle Eocene), and not Oligocene or Miocene as formerly thought.

6. Discussion

This study has revealed a new local picture of the Luracatao Valley that includes the Santa Bárbara Subgroup and the Quebrada de los Colorados Formation. The stratigraphic and structural relationships between these deposits reveal the existence of an erosive unconformity in the western limb and a low angular unconformity in the eastern limb of the western syncline of Luracatao. Moreover, the presence of growth strata indicates coeval deformation–sedimentation, at least for the base of the Quebrada de los Colorados Formation. Finally, the discovery of an isotemnid fossil has made it possible to constrain the deformation age to the Middle Eocene.

The map and stereoplots presented in Fig. 5 show two clear structural directions that indicate two different deformation styles: (1) the NNE-SSW to N–S trend defined by the axis of the Quebrada de los Colorados syncline (Western Syncline), Cachi fault and minor reverse fault, and (2) the NE-SW trend (oblique) delineated by Santa Bárbara folds (Central Anticline and Eastern Syncline) (Fig. 5A). The NNE-SSW to N–S trend is genetically linked to W-E Cenozoic Andean shortening, but the oblique structures are still problematic. Carrera et al. (2006) suggest that the oblique contractional structures were developed in the early stages of Andean inversion and that the younger structures tend to present a more N–S trend. However, the oblique Santa Bárbara fold axes can also be explained by a strike-slip component on the Cachi fault that generated a dextral rotation of the folds axes, as interpreted in the Salar de Antofalla area (Kraemer et al., 1999) and at several locations in the Calchaquí Valley (see Riller and Oncken, 2003).

The presence of an angular and erosive unconformity allows us to interpret a pre-Quebrada de los Colorados deformational phase ascribed to the Incaic phase. The erosive contact between the Quebrada de los Colorados Formation and the Maíz Gordo Formation in the western limb of Western Syncline (Fig. 5A) indicates a strong unconformity and suggests that the Luracatao fault was active prior to the deposition of the Quebrada de los Colorados Formation. In the opposite limb of the western syncline, the vergence of growth strata together with the thinning of Lumbrera Formation (Fig. 5A) reflects the inversion of the eastern reverse fault (western border of the Salta rift), probably during the Middle-Upper Eocene.

Preliminary analysis of the conglomerate clasts of the Quebrada de los Colorados Formation shows an abundance of granite and milonites similar to those of the Ordovician Complejo Eruptivo Oire (Fig. 2), the possible source area for this unit. Consequently, the Cumbres de Luracatao (composed of the Complejo Eruptivo Oire, see Fig. 2) may have been exhumed and probably acted as an incipient geographic barrier by the time of the deposition of the Quebrada de los Colorados Formation.

Given the deformation complexity, which is inherent in regions that have undergone inversion, it is usually difficult to differentiate between various stages of deformation. A number of features (including numerous reactivations, positive tectonic inversion, and ductile deformation zones) have demonstrated the difficulty of determining the relative ages of faults in the Luracatao Valley. However, the structural relationships, unconformities and provenance data confirm that the Luracatao fault was active before the Cachi fault.

6.1. Correlation and regional implications

The classic models of Andean orogenesis postulate that the deformation front migrated eastward while the Andes uplifted. To understand the deformation migration, it is necessary to localize the areas that record Late Mesozoic-Early Cenozoic deformation episodes. On the eastern margin of the modern volcanic arc, the first Andean deformation episode corresponds to the Middle Eo-

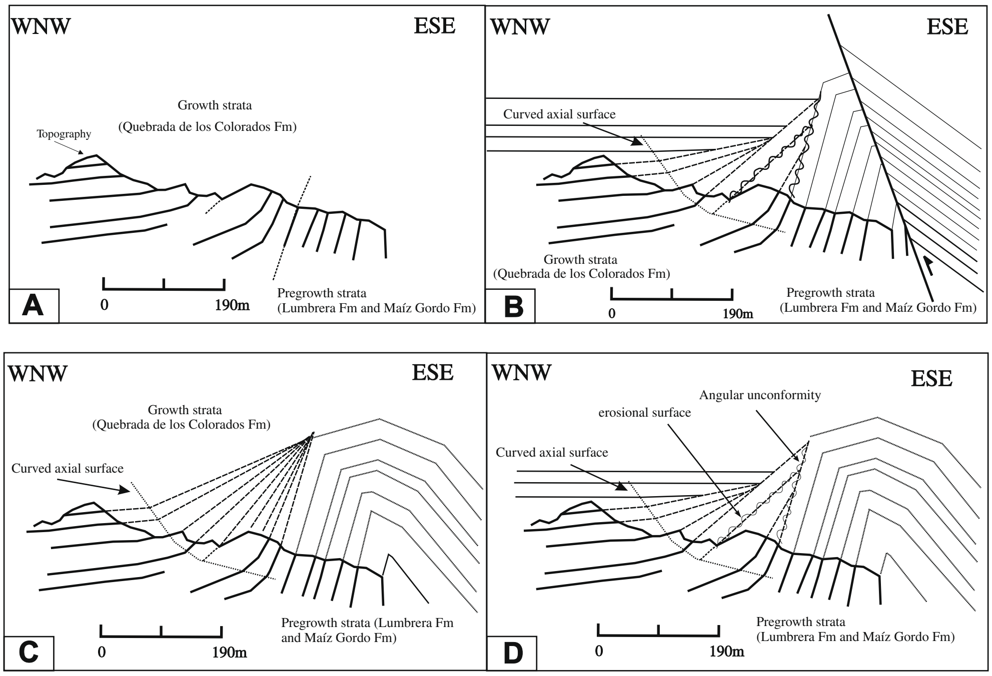

Fig. 7. A. Outcrops of the eastern limb of the western syncline of Luracatao. Note the low angle and west-dipping of the Quebrada de los Colorados Formation. B. Reconstructed geological cross-section displaying interpreted pre-erosion structure. The reverse fault formed later than the anticline. C. Possible pre-erosion scenario with the strata projected to form a point, assuming no erosion of growth strata (based on Rafini and Mercier, 2002). D. Second model (limb rotation) of possible pre-erosion scenario (based on Rafini and Mercier, 2002).

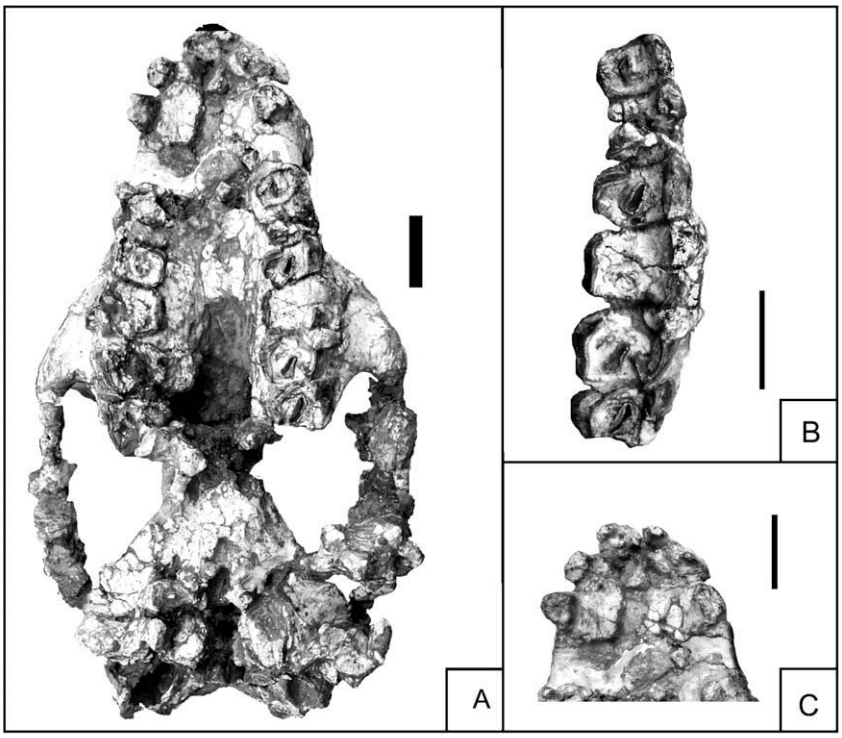

Fig. 8. Isotemnidae indet. PVL-S LU. A. Skull in palatal view. B. Upper premolars 2–4 and molars 1–3 in occlusal view. C. Upper canines and incisors in occlusal view. Scale (black bar) is 2 cm long. (PVL: Paleontología Vertebrados Lillo).

cene Incaic Phase. This earlier episode has been recorded in a few localized areas in northwestern Argentina. As noted by many authors, knowledge of the style and timing of the earlier deformational episodes would improve the understanding of the initial stages of the Andean foreland basin development.

The description and interpretation presented here for the Luracatao Valley become relevant when compared with data from other parts of northwestern Argentina where the first Andean deformation has been interpreted from sedimentological and structural data and geochemical (Apatite Fission Tracks, AFT) and

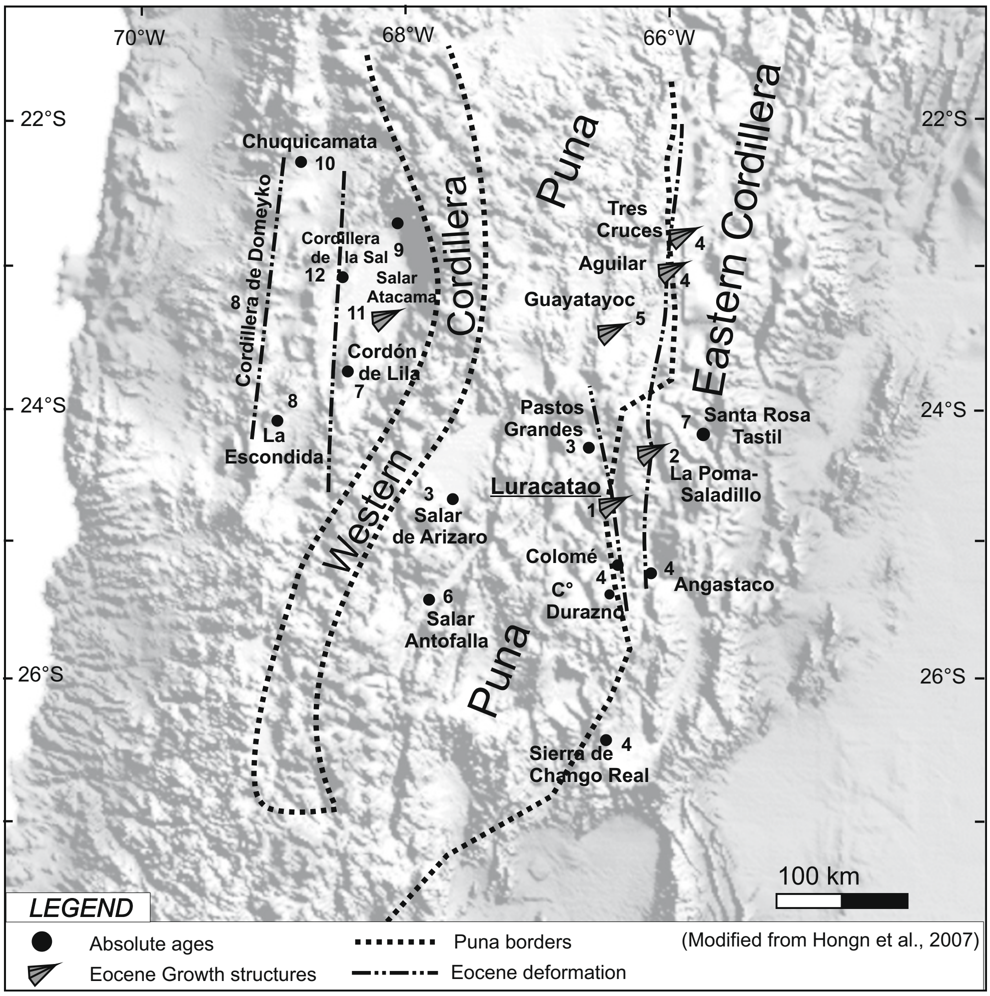

Fig. 9. Shaded relief map of southern Central Andes with location of the main areas recording Eocene deformation: 1. This paper; 2. Hongn et al., 2007; 3. Carrapa and DeCelles, 2008; 4. Coutand et al., 2001; 5. Monaldi et al., 1993; 6. Kraemer et al., 1999; Carrapa and DeCelles, 2005; 7. Andriessen and Reutter, 1994; 8. Maksaev and Zentilli, 1999; 9. Reutter et al., 1991;Charrier and Reutter, 1994; 10. Reutter et al.,1996; 11. Arriagada et al., 2006; Jordan et al., 2007; 12. Mpodozis et al., 2005.

isotopic (U-Pb in detrital zircon) analyses. These data can be compared to track the beginning of the Andean foreland basin. The Middle Eocene deformation–sedimentation age ascribed here to the Quebrada de los Colorados Formation is comparable to other deformational ages defined for distinct areas of northwestern Argentina (Puna and Cordillera Oriental), including the Altiplano and Cordillera Oriental of southeastern Bolivia (Horton, 2005; Ege et al., 2007) and the Atacama region of Chile (Arriagada et al., 2006).

Recent thermo-chronology (AFT) studies of granite from eastern Puna and Cordillera Oriental (Haschke et al., 2005) have suggested a contractional episode during the Late Eocene-Early Oligocene (Coutand et al., 2001; Coutand et al., 2006; Deeken et al., 2006). On the other hand, Hongn et al. (2007) documented a Middle Eocene deformation in the northern Calchaquí Valley (Fig. 9). They described syntectonic deposits near the base of the Quebrada de los Colorados Formation as well as activity of the west vergent fault coeval with the deposition of this unit. In addition, the Atacama basin in Chile also shows evidence of Eocene sedimentation and deformation (Arriagada et al., 2006; Jordan et al., 2007).

A regional analysis of the Eocene lithostratigraphic units can be summarized as follows: the Quebrada de los Colorados Formation is equivalent to the Casa Grande Formation of the Tres Cruces subbasin (Hongn et al., 2007), the Geste Formation of Pastos Grandes (Carrapa and DeCelles, 2008) and Salar de Arizaro, and, possibly, the Quiñoas Formation of Salar de Antofalla (Alonso, 1992; Kraemer et al., 1999) and the Loma Amarilla Formation of the Salar de Atacama basin. This correlation signifies spatially contemporaneous sedimentation. However, how were these apparently coeval units arranged? This question is important because the distribution of each depozone in foreland basins must be expressly considered to properly understand the migration and evolution of the deformation front (DeCelles and Gilles, 1996; Flemings and Jordan, 1989). Although the available data are not enough to propose a reliable regional model, there is enough information to envisage a regional scenario.

In the foreland basin model, the deposition of growth strata occurs ahead of fold-and-thrust belts (DeCelles and Gilles, 1996). Wedge-top basins are characterized by growth structures related to progressive deformation, local and regional unconformities and local sources of sediment (DeCelles and Gilles, 1996). Carrapa and DeCelles (2008) propose a wedge-top position (Fig. 10) for the Pastos Grandes basin (Fig. 9) located in the Puna (close to the Luracatao Valley) and correlate the Geste Formation with the Quebrada de los Colorados Formation. In addition, the record of growth strata and angular unconformities indicates that the Luracatao Valley also formed part of the Paleogene wedge-top depozone according to the classical model (DeCelles and Gilles, 1996). Similarly, the presence of growth faults, growth strata and western vergence inverted faults in La Poma-Saladillo (Figs. 9 and 10) suggest a similar tectonic setting. Thus, there are many scattered Eocene basins (see

Fig. 10) with characteristics of wedge-top depozones. The westernmost and easternmost records of the Eocene deformation are found between 24°30ˊ S at the Atacama basin in Chile (Fig. 9) and 23°30ˊ S at the La Poma- Saladillo basin in Argentina (Fig. 10). These basins are now 280 km apart and contain Eocene growth strata (coeval sedimentation-deformation). Assuming 15% Andean shortening (Coutand et al., 2001; or 25%, Drozdzewski and Mon, 1999), it is possible to estimate a minimum latitudinal distance between the Atacama and the Poma- Saladillo basins of about ~326 km wide (284 km + 15%). This distance is too large for a wedge-top depozone taking into account other basin widths, such as the 75 km in the Sevier Thrust belt (Coogan, 1992; DeCelles, 1994), the 30–40 km in the Pyrenean thrust belt (Puigdefabregas et al., 1986), the 50–100 km in southern Bolivia (DeCelles and Horton, 2003), and the 100 km of Huallaga in northern Peru (Hermoza et al., 2005).

Therefore, Eocene sedimentation and deformation may have taken place in distinct basins located tens to hundreds of kilometers apart (Fig. 9) and either partially or entirely separated from one another by structural highs in the Eocene. This scenario is consistent with the broken-foreland model, suggesting that the eastward migration of Andean shortening is not as simple as set forth in classical models, at least for the Central Andes. We emphasize here that the Andean deformation may have begun at the same time in the Puna and in the western margin of the Cordillera Oriental and that inherited Paleozoic and Mesozoic structures partially controlled the deformation (Coutand et al., 2001; Hongn et al., 2007).

According to recent work (Coutand et al., 2006; Deeken et al., 2006; Payrola Bosio et al., 2006; Hongn et al., 2007; Carrapa and DeCelles, 2008), the record of the first Andean deformational events has a very complex distribution (Fig. 9) and chronology (Fig. 10) in northwestern Argentina (Central Andes). Analysis of local observations (Figs. 9 and 10) could be used to elucidate the regional tectonic setting. The integration of local data based on direct (growth structures-unconformities) and indirect (AFT and U-Pb ages) evidence of Eocene deformation suggests that the Eocene deformational episode, possibly the Incaic orogenic phase, was more extensive and intense than formerly interpreted.

Finally, the Luracatao Valley shows several features, including tectonic inversion, oblique structures, kinematic evolution of faults and location of border faults in the Salta rift basin, which deserve further studies and thus were chosen as part of the first author's PhD thesis.

7. Conclusions

- The stratigraphic analysis of the Luracatao Valley has led to the proposition of a new lithostratigraphic column for the region that includes the abandonment of the formerly proposed Luracatao Formation. Its deposits are assigned to the Mealla, Maíz Gordo and Lumbrera Formations (Santa Bárbara Subgroup of the Salta Group) and to the Quebrada de los Colorados Formation (Payogastilla Group). An angular unconformity at the boundary between the Salta and Payogastilla groups indicates the existence of two different basins. This stratigraphic revision is key to understanding the structural evolution of the Luracatao Valley.
- The finding of a new fossil confirms a Middle Eocene age for the base of Quebrada de los Colorados Formation, which is comparable to the lower levels of this unit in the northern Calchaquí Valley.
- On the west side of the Luracatao Valley, the Luracatao fault uplifted Paleozoic granites over the Santa Bárbara Subgroup and the Quebrada de los Colorados Formation. Preliminary provenance analysis indicates that the granitic blocks located towards the western margin of Luracatao Valley served as the detrital source for the Quebrada de los Colorados Formation.

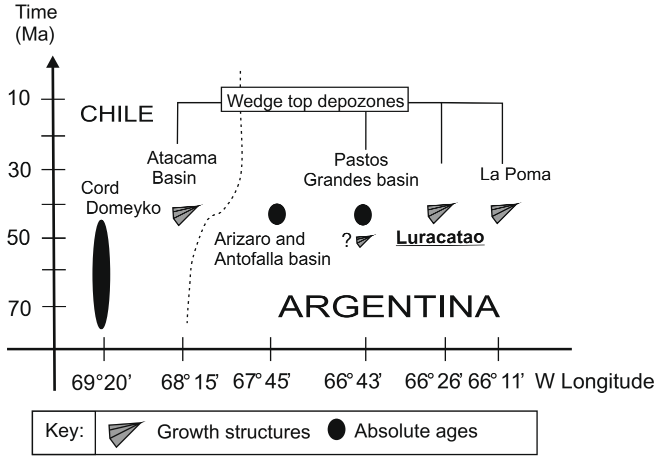

Fig. 10. Diagram showing the sites between 24° 30' and 23° 30' LS, Chile and Argentina with available age data. Notice the growth strata in the Atacama basin (Chilean Precordillera) and La Poma (Argentinean Cordillera Oriental).

- The origin of the growth strata in the western limb of the central anticline is directly related to the activity of the Cachi fault. However, there is no clear evidence of Paleogene fault activity due to the numerous reactivations related to the Andean tectonics. The characteristics of the growth strata and minor fault in the central anticline suggest a westward compression associated with positive Andean inversion in the region.
- The tectonic regime of the western border of the Cordillera Oriental has been compressive since the middle Eocene. The style was thick-skinned with reactivation of the Paleozoic heterogeneities and the inversion of Cretaceous rift border faults.

Acknowledgements

This work was supported by ANPyCT (PICT 2006-381) and CONICET (PIP 5255) grants. We thank Edwin Apps for reviewing the manuscript, Ricardo Mon for his comments and people from Luracatao Valley (Cañizares family) for their kindness and hospitality. Paulo Sergio Gomes Paim and Luis A. Spalletti are kindly acknowledged for their constructive and positive reviews.

References

Allmendinger, R., Jordan, T., Kay, S., Isacks, B., 1997. The evolution of the Altiplano–Puna Plateau of the central Andes. Annual Review Earth Planet Sciences 25, 139–174.

Allmendinger, R., Jordan, T., Palma, M., Ramos, V., 1982. Perfil estructural de la Puna catamarqueña (25°–27° S), Argentina. Actas 5° congreso Latinoamericano de Geología, vol. 1, pp. 499-518. Buenos Aires.

Alonso, R.N., 1992. Estratigrafía del Cenozoico de la cuenca de Pastos Grandes (Puna Salteña) con énfasis en la Formación Sijes y sus boratos. Revista Asociación Geológica Argentina 47, 189–199.

Ameghino, F., 1897. Mammiferes crétacés de l'Argentine. (deuxieme contribution a la connaisance de la faune mammalogique des couches a *Pyrotherium*. Boletín Instituto Geográfico Argentino 18, 406–429, 431–521.

Andriessen, P., Reutter, K., 1994. K-Ar and fission track mineral age determination of igneous rocks related to multiple magmatic arc systems along the 23 SL of Chile and NW-Argentina. In: Reutter, K. et al. (Eds.), Tectonics of the southern Central Andes. Springer Verlag, Berlin, pp. 141–154.

Arriagada, C., Cobbold, P. R., Roperch, P., 2006. Salar de Atacama basin: a record of compressional tectonics in the central Andes since the mid-Cretaceous, Tectonics 25.

Baldis, B., Gorroño, A., Ploskiewicz, J. and Sarudiansky, R., 1976. Geotectónica de la Cordillera Oriental, Sierras Subandinas y comarcas adyacentes. Actas 6 Congreso Geológico Argentino, vol. 1, pp. 3–22. Buenos Aires.

Benjamin, M.T., Johnson, N.M., Naeser, C.W., 1987. Recent rapid uplift in the Bolivian Andes: evidence from fission-track dating. Geology 15, 680–683.

Blasco, G., Zapettini, E., 1995. Geología. In Blasco, G., E. Zapettini and F. Hongn: Hoja Geológica San Antonio de los Cobres (Mapa), Escala 1:250.000. Secretaría de Minería de la Nación, Dirección Nacional del Servicio Geológico. Buenos Aires.

Boll, A., Hernández, R., 1986. Interpretación estructural del área de Tres Cruces: Boletín de Informaciones Petroleras, Tercera Época, III, no. 7, p. 2-14.

Bond, M., Vucetich, M.G., 1982. Indalecia grandensis gen. Et sp.nov. del Eoceno temprano del Noroeste argentino, tipo de una nueva subfamilia de los Adiantidae (Mammalia, Litopterna). Revista de la Asociación Geológica Argentina 38, 107–117.

Boso, M.A, Brandán, E.M., Salfity, J.A., 1984. Estratigrafía y paleoambiebntes del subgrupo Pirgua (Cretácico) en la comarca de Brealito, provincia de Salta. Actas IX Congreso Geológico Argentino, 1, 108-123. San Carlos de Bariloche.

Carrapa, B., DeCelles, P., 2005. Eocene sedimentation within the Argentine Puna: Implication for early plateau development. Geological Society America Abstract. Program 37, 163–165.

Carrapa, B., DeCelles, P.G., 2008. Eocene exhumation and basin development in the Puna of Northwestern Argentina. Tectonics, 27.

Carrera, N., Muñoz, J.A, Sábat, F., Mon, R., Roca, E., 2006. The role of inversion tectonics in the structure of the Cordillera Oriental (NW Argentinean Andes). Journal of Structural Geology 1, 12.

Charrier, R., Reutter, K. J., 1994. The Purilactis Group of Northern Chile: Boundary between arc and backarc from late Cretaceous to Eocene; In Tectonics of the Southern Central Andes (Reutter, K.-J.; Scheuber, E.; Wigger, P.; editors). Springer-Verlag, p. 189-202. Berlin.

Coira, B., Davidson, J., Mpodozis, C., Ramos, V., 1982. Tectonic and magmatic evolution of the Andes of Northern Argentina and Chile. Earth Science Review 18, 303–332.

Coogan, J.C., 1992. Structural evolution of piggyback basins in the Wyoming–Idaho-Utah thrust belt. In: Link, P.K., Kentz, M.A., Platt, L.B. (Eds.), Regional Geology of Eastern Idaho and Western Wyoming, Geological Society of America Memoir 179, 55–81.

Coutand, I., Carrapa, B., Deeken, A., Schmitt, A.K., Sobel, E.R., Strecker, M.R., 2006. Propagation of orographic barriers along an active range front: insights from sandstone petrography and detrital apatite fission-track thermochronology in the intramontane Angastaco basin, Basin Research. NW Argentina 18, 1–26.

Coutand, I., Cobbold, P., de Urreiztíeta, M., Gautier, P, Chauvin, A., Gapais, D., Rossello, E., López Gamundi, O., 2001. Style and history of Andean deformation, Tectonics, Puna plateau. Northwestern Argentina 20, 210–234.

DeCelles, P.G., 1994. Late Cretaceous-Paleocene synorogenic sedimentation and kinematic history of the Sevier thrust belt, northeast Utah and southwest Wyoming. Bulletin Geological Society of America 106, 32–56.

DeCelles, P.G., Gilles, K.A., 1996. Foreland Basin Systems. Basin Research 8, 105–123.

DeCelles, P., Horton, B.K., 2003. Early to middle Tertiary foreland basin development and the history of Andean crustal shortening in Bolivia. Geological Society of America Bulletin 115, 58–77.

Deeken, A., Sobel, E.R., Coutand, I., Haschke, M., Riller, U., Strecker, M.R., 2006. Development of the southern Eastern Cordillera, NW Argentina, constrained by apatite fission track thermochronology: From Early Cretaceous extension to middle Miocene shortening, Tectonics. 25.

del Papa, C., 1999. Sedimentation on a ramp type lake margin: Paleocene-Eocene _Maíz Gordo Formation, Northwestern Argentina. Journal of South American Earth Sciences. 12, 389–400.

del Papa, C., Hongn, F., Petrinovic, I., Domínguez, R., 2004. Evidencias de deformación pre-miocena media asociada al antepaís andino en la Cordillera Oriental (24 35′ S- 66 12′ O). Revista de la Asociación Geológica Argentina 59 (3), 506–509.

Díaz, J., Malizzia, D., 1983. Estudio geológico y sedimentológico del Terciario Superior del Valle Calchaquí (Dpto. San Carlos; Salta). Boletín Sedimentológico 2, 8–28.

Díaz, J., Malizzia, D., Bossi, G. 1987. Análisis estratigráfico del Grupo Payogastilla (Terciario Sup.) X Congreso Geológico Argentino, II, 113-117.

Donato, E., 1987. Características estructurales del sector occidental de la Puna Salteña. Boletín de Informaciones Petroleras 12, 89–97.

Drozdzewski, G., Mon, R., 1999. Oppositely-verging thrusting structures in the North Argentine Andes compared with the German Variscides. Acta Geológica Hispánica 34 (2–3), 185–196.

Ege, H., Sobel, E.R., Scheuber, E., Jacobshagen, V., 2007. Exhumation history of the southern Altiplano plateau (southern Bolivia) constrained by apatite fission track thermochronology, Tectonics 26.

Farías, M., Charrier, R., Comte, D., Martinod, J., Hérail, G., 2005. Late Cenozoic uplift of the western flank of the Altiplano: evidence from the depositional, tectonic, and geomorphologic evolution and shallow seismic activity (northern Chile at 19°30′ S). Tectonics 24 (4).

Flemings, P.B., Jordan, T., 1989. A synthetic stratigraphic model of foreland basin development. Journal of Geophysical Research 94, 3851–3866.

Galli, C.I., Hernández, R.M., 1999. Evolución de la Cuenca de Antepaís desde la zona de la Cumbre Calchaquí hasta la Sierra de Santa Bárbara, Eoceno inferior-Mioceno medio, provincia de Salta, Argentina. Acta Geológica Hispánica 34 (2–3), 167–184.

Grier, M., Dallmeyer, R.D., 1990. Age of the Payogastilla Group: Implications for foreland basin development. NW Argentina. Journal of South American Earth Sciences 3, 269–278.

Hardy, S., Poblet, J., 1994. Geometric and numerical model of progressive limb rotation in detachment folds. Geology 22, 371–374.

Hammerschmidt, K., Doebel, R., Friedrichsen, H., 1992. Implication of 40Ar/39Ar dating of early Tertiary volcanic rocks from the north-Chilean Precordillera. Tectonophysics 202, 55–58.

Haschke, M., Deeken, A., Insel, N., Sobel, E., Grove, M., Schmit, A.K., 2005. Growth pattern of the Andean Puna plateau constrained by apatite fission track, apatite (U-th)/He, K-feldespar $^{40}Ar/^{39}Ar$, and zircon U-Pb geochronology. In: 6th International symposium on Andean Geodynamics (ISAG 2005, Barcelona), Extended Abstracts, pp. 360–363.

Hermoza, W., Brusset, S., Baby, P., Gil, W., Roddaz, M., Guerrero, N., Molando, B., 2005. The Huallaga foreland basin evolution: thrust propagation in a deltaic environment, northern Peruvian Andes. Journal of South American Earth Sciences 19, 21–34.

Hernández, R., Galli, C., Reynolds, J., 1999. Estratigrafía del Terciario en el Noroeste Argentino, Relatorio, XIV Congreso Geológico Argentino, Tomo I: 316-328. Salta.

Hilley, G.E., Sobel, E.R., Trauth, M.H., 2007. Tectonics and climate of the southern central Andes. Annual Review Earth Planet Sciences 35, 747–787.

Hongn, F.D., Seggiaro, R.E., 2001. Hoja Geológica 2566-III, Cachi, 1:250.000. Mapa geológico y capítulo Tectónica (p.53-65). SEGEMAR. Boletín 248. Buenos Aires.

Hongn, F.D., del Papa, C., Powell, J., Petrinovic, I., Mon, R., Deraco, V., 2007. Middle Eocene deformation and sedimentation in the Puna-Eastern Cordillera transition (23–26 S): Control by preexisting heterogeneities on the pattern of initial Andean shortening. Geology 35, 271–274.

Horton, B., 2005. Revised deformation history of the central Andes: Inferences from Cenozoic foredeep and intermontane basins of the Eastern Cordillera. Tectonics, Bolivia. 24.

Isacks, B.L., Jordan, T.E., Allmendinger, R.W., Ramos, V.A., 1982. La segmentación tectónica de los Andes Centrales y su relación con la geometría de la placa de Nazca subductada. V Congreso Latinoamericano de Geología, Actas, III 58, 7–606.

Jaillard, E., Berrones, G., Ordóñez, M., Bengtson, P., Benitez, S., Jiménez, N., Zambrano, I., 1992. El Senoniano y el Paleogeno de la "Cuenca Célica-Lancones" (sur Ecuador-Norte Perú) datos preliminares e implicaciones tectónicas. El paleógeno de Sur América: libro de resúmenes/Lorente, M. A. éd 1-2.

Jordan, T., Isacks, B.L., Allmendinger, R.W., Brewer, J.A., Ramos, V.A., Ando, C.J., 1983. Andean tectonics related to geometry of the subduted Nazca plate. Geological Society of America Bulletin 94, 341–361.

Jordan, T.E., Alonso, R.N., 1987. Cenozoic stratigraphy and basin tectonics of the Andes Mountains, 20–28 south latitude. American Association of Petroleum Geologist Bulletin 71, 49–64.

Jordan, T.E., Mpodozis, C., Muñoz, N., Blanco, N., Pananont, P., Gardeweg, M., 2007. Cenozoic subsurface stratigraphy and structure of the Salar de Atacama Basin, northern Chile. Journal of South American Earth Sciences 23, 122–146.

Kennan, L., Lamb, S., Rundle, C., 1995. K-Ar dates from the Altiplano and Cordillera Oriental of Bolivia: Implications for Cenozoic stratigraphy and tectonics: Journal of South American Earth Sciences 8, 163–186.

Kraemer, B., Adelmann, D., Alten, M., Schnur, W., Erpenstein, K., Kiefer, E., van den Bogaard, P., Górler, K., 1999. Incorporation of the Paleogene foreland into Neogene Puna Plateau: The Salar de Antofalla, NW Argentina. Journal of South American Earth Sciences 12, 157–182.

Lavenu, A., Marocco, R., 1984. Continental sedimentation and tectonics in a fold belt related to a subduction zone–The Central Andes (Peru-Bolivia) during the Tertiary: Bulletin du centre de Recherche et d' Exploration-Production. Elf-Aquitaine 8 (1), 57–70.

Maksaev, J., 1979. Las fases tectónicas Incaica y Quechua en la Cordillera de los Andes del Norte Grande de Chile: II Congreso Geológico Chileno Actas 1, B63–B77.

Maksaev, V., Zentilli, M., 1999. Fission track thermochronology of the Domeyko Cordillera, northern Chile: Implications for Andean tectonics and porphyry copper metallogenesis. Explor. Min. Geol. 8, 65–89.

Marquillas, R.A., Salfity, J. A., 1994. Relaciones estratigráficas regionales de la Formacion Yacoraite (Cretácico Superior), norte de la Argentina. Actas 7° Congreso Geológico Chileno 1, 479-483.

Mégard, F., 1978. Etude géologique des Andes du Pérou central: París, Office de la Recherches Scientifique et Technique O_utre-Mer, Memoire 86, 310 p.

Mégard, F., 1984. The Andean orogenic period and its major structures in central and northern Peru. Journal Geological Society of London 141, 893–900.

Mégard, F., Nobel, D.C., McKee, E.H., Bellon, H., 1984. Multiple pulses of Neogene deformation in the Ayacucho intermontane basin, Andes of central Peru. Geological Society of America Bulletin 95, 1108–1117.

Méndez, V., Turner, J. C., Navarini, A., Amengual, R., Viera, O., 1979. Geología de la Región Noroeste, provincias de Salta y Jujuy, República Argentina. Dirección General de Fabricaciones Militares, 118 Buenos Aires.

Monaldi, R., Salfity, J.A., Vitulli, N., Ortiz, A., 1993. Estructuras de crecimiento episódico en el subsuelo de la laguna de Guayatayoc, Jujuy, Argentina: Proceedings, 12th Congreso Geológico Argentino, Mendoza. Argentina 3, 55–64.

Mon, R., Salfity, J.A., 1995. Tectonic evolution of the Andes of northern Argentina. In: Tankard, A.J., Suarez Soruco, R., Welsink, H.J. (Eds.), Petroleum basins of South America. American Association of Petroleum Geologists, Memoir 62, 269–283.

Moreno, J.A., 1970. Estratigrafía y Paleogeografía del Cretácico superior en la cuenca del noroeste argentino, con especial mención de los Subgrupos Balbuena y Santa Bárbara. Revista de la Asociación Geológica Argentina 24, 9–44.

Mpodozis, C., Arriagada, C., Basso, M., Roperch, P., Cobbold, P., Reich, M., 2005. Late Mesozoic to Paleogene stratigraphy of the Salar de Atacama Basin, Antofagasta, Northern Chile: Implications for the tectonic evolution of the Central Andes. Tectonophysics 399, 125–154.

Müller, J.P., Kley, J., Jacobshagen, V., 2002. Structure and Cenozoic kinematics of the Eastern Cordillera, southern Bolivia (21 S). Tectonics 21. doi:10.1029/2001TC001340.

Noble, D.C., Mckee, E.H., Mégard, F., 1979. Early Tertiary "Incaic" tectonism, uplift, and volcanic activity. Andes of central Peru: Geological Society of America Bulletin 90, 903–907.

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

Payrola Bosio, P.A., Powell, J., Hongn, F., del Papa, C., 2006. Registro de deformación eocena en el Valle de Luracatao. noroeste del Valle Calchaquí, XII Reunión de Tectónica. San Luís. Actas. 47.

Powell, J, M. Deraco; F. Hongn; C. del Papa, R. Mon, Petrinovic, I., 2006. Primer registro de mamíferos de la Formación Quebrada Los Colorados (Grupo Payogastilla). Consideraciones cronológicas de la unidad y de las primeras fases del levantamiento de los Andes. Jornadas Argentinas de Paleontología de Vertebrados. Museo de Paleontología. Universidad Nacional de San Juan. Libro de Resúmenes: p. 31. San Juan.

Puigdefabregas, C., Muñoz, J.A., Marzo, M., 1986. Thrust belt development in the eastern Pyrenees and related depositional sequences in the foreland basin. In: Allen, P.A., Homewood, P. (Eds.), Foreland Basins, Special Publication Int. Ass. Sedimentologist 8, 229–246.

Rafini, S., Mercier, E., 2002. Forward modeling of foreland basins progressive unconformities. Sedimentary Geology 146, 75–89.

Reutter, K., Scheuber, E., Helmcke, D., 1991. Structural evidence of orogen-parallel strike-slip displacements in the Precordillera of Northern Chile. Geol. Rundsch. 80 (1), 135–153.

Reutter, K.J., Scheuber, E., Chong, G., 1996. The Pre-Cordilleran fault system of Chuquicamata, northern Chile: evidence for reversals along arc-parallel strike-slip faults. Tectonophysics 259, 213–228.

Reyes, F.C., Salfity, J.A., 1973. Consideraciones sobre la estratigrafía del Cretácico (Subgrupo Pirgua) del noroeste argentino. Actas 5th Congreso Geológico Argentino 3, 355–385.

Riba, O., 1976. Syntectonic unconformities of the Alto Cardener. Spanish Pyrenees: A genetic interpretation. Sedimentary Geology 15, 213–233.

Riller, U., Hongn, F., 2003. Structural significance of Paleozoic discontinuities on Cretaceous to Quaternary tectonism in the eastern Cordillera. NW-Argentina, Geophysical Research Abstracts. 5.

Riller, U., Oncken, O., 2003. Growth of the central Andean Plateau by tectonic segmentation is controlled by the gradient in crustal shortening. Journal of Geology Ill: 367, 384.

Sabino, I.F., 2004. Estratigrafía de la Formación La Yesera (Cretácico): Base del relleno sinrift del Grupo Salta, noroeste argentino. Revista de la Asociación Geológica Argentina 59 (2), 341–359.

Salfity, J.A., 2008. Geología regional del Valle Calchaquí, Argentina. Boletín Academia Nacional de Ciencias, Córdoba (In press)

Salfity, J.A., Gorustovih, S., Moya, M., Amengual, R., 1984. Marco tectónico de la sedimentación y efusividad cenozoicas de la Puna Argentina. IX Congreso Geológico Argentino. Actas I 50, 5–515.

Salfity, J.A., Marquillas, R.A., 1994. Tectonic and sedimentary evolution of Cretaceous-Eocene Salta Group basin, Argentina. In: Salfity, J.A. (Ed.), Cretaceous Tectonics of the Andes. Earth Evolution Sciences, Friedr. Vieweg and Sohn, pp. 266–315.

Salfity, J., Monaldi, R., Marquillas, R., González, R., 1993. La inversión tectónica del Umbral de los Gallos en la cuenca del Grupo Salta durante la fase Incaica: Proceedings, 12th Congreso Geológico Argentino, Mendoza. Argentina 3, 200–210.

Schwab, K., 1985. Basin formation in a thickening crust–the intermontane basins in the Puna and the Eastern Cordillera of NW-Argentina (central Andes). IV Cong. Geol. Chileno 2, 138–158.

Sempere, T., Hérail, G., Oller, J., Bonhomme, M.G., 1990. Late Oligocene–Early Miocene major tectonic crisis and related basins in Bolivia: Geology 18, 946–949.

Sempere, T., Butler, R.F., Richards, D.R., Marshall, L.G., Sharp, W., Swisher, C.C., 1997. Stratigraphy and chronology of Late Cretaceous–Early Paleogene strata in Bolivia and northwest Argentina: Geological Society of America Bulletin 109, 709-727.

Somoza, R., 1998. Updated Nazca (Farallon)-South America relative motions during the last 40 My: implications for mountain building in the central Andean region. Journal of South American Earth Sciences 11, 211–215.

Starck, D., Vergani, G., 1996. Desarrollo tectosedimentario del Cenozoico en el sur de la provincia de Salta: Proceedings, 13th Congreso Geológico Argentino, Buenos Aires. Argentina 1, 433–452.

Steinmann, G., 1929. Geologie von Peru, Karl Winter. Heidelberg, Germany. 448 pp.

Strecker, M.R., Alonso, R.N., Bookhagen, B., Carrapa, B., Hilley, G.E., Sobel, E.R., Trauth, M.H., 2007. Tectonics and climate of the southern central Andes. Annual Review Earth Planet Sciences 35, 747–787.

Suppe, J., 1983. Geometry and kinematics of fault-bend folding. American Journal Sciences 283, 684–721.

Suppe, J., Sabat, F., Muñoz, J.A., Poblet, J., Roca, E., Vergés, J., 1997. Bed-by-Bed fold growth by kink-band migration: Sant Llorenç de Morunys, Eastern Pyrenees. Journal Structural Geology 19, 443–461.

Turner, J.C., Mon, R., 1979. Cordillera Oriental. In: Turner, A.F. (E.d.): Geología Regional Argentina. Segundo Simposio de Geología Regional Argentina. Academia Nacional de Ciencias I, 57-94. Córdoba.

Turner, J.C., 1959. Estratigrafía del Cordón de Escaya y de la sierra de Rinconada (Jujuy). Revista de la asociación Geológica Argentina 13, 15–39.

Turner, J.C., 1964. Descripción Geológica de la hoja 7c, Nevado de Cachi, provincia de La Salta. Dirección Nacional de Geología y Minería. Boletín 99, 79p., Buenos Aires.