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

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ABSTRACT

The Quebrada de los Colorados Formation, at the north end of Calchaquí Valley in Salta Province, northwest Argentina, preserves evidence of syndepositional deformation since the middle Eocene (ca. 40 Ma) that includes (1) an angular unconformity with the underlying Salta Group (Paleogene), and (2) internal unconformities and changes in vertical facies succession and provenance. Its fossil record [mammalian (notoungulates), middle Eocene] is correlatable to the Casa Grande Formation, which also unconformably overlies the Salta Group; both units record middle Eocene deformation along the eastern border of the Puna Plateau and outline previous first-order mechanical heterogeneities related to the Cretaceous rift basin border. Along the western margin of the Puna, Eocene deformation coincides with thermal (magmatic arc) and mechanical (basin inversion) heterogeneities. Thus, the distribution of Eocene deformation followed an irregular pattern as a consequence of the heritage of preexisting heterogeneities.

Keywords: Eocene deformation, initial foreland, preexisting heterogeneities, Central Andes.

INTRODUCTION

The geological peculiarities of the Central Andes and their plateau (a plate tectonics paradox; e.g., Allmendinger et al., 1997) have made this cordillera one of the most studied. Most previous work has been devoted to Miocene evolution because this was the time of main shortening and volcanic activity that distinguished the Western Cordillera, plateau (Altiplano-Puna), Eastern Cordillera, and Subandean Ranges (see synthesis in Allmendinger et al., 1997). In contrast, Paleogene evolution (especially in basin research) received less attention, and as a consequence there are still many unanswered questions concerning (1) the age, intensity, and distribution of the initial Andean shortening (Kennan et al., 1995; Jordan et al., 1997; Elger et al., 2005); (2) the map of the earliest foreland basins (Horton, 2005); and (3) Paleogene deformation as an extra source of shortening for compensating the deficit between calculated and actual crustal thickness of the Central Andes (Kley and Monaldi, 1998).

The lack of direct evidence for an Incaic unconformity (Steinmann, 1929) in south Bolivia and north Argentina led to hypotheses postulating a progressive and diachronous southward and eastward propagation of deformation in the Central Andes. Thus, shortening is thought to have begun in the Paleogene in the Bolivian Altiplano, and in the Neogene in the Puna (Jordan et al., 1997). Nevertheless, available ages for the uplift (e.g., Carrapa et al., 2005) and regional stratigraphic analyses (Boll and Hernández, 1986; Mpodozis et al., 2005) delineate Paleogene deformation south of the Bolivian Altiplano.

Models regarding a control by preexisting (thermal or mechanical) heterogeneities on localizing the plateau margins as zones of shortening (Elger et al., 2005), as well as models interpreting eastward propagation of deformation (DeCelles and Horton, 2003), focused on the Bolivian Altiplano. A late Eocene–Oligocene uplifting guided by preexisting structures was described along the Puna–Eastern Cordillera transition (Coutand et al., 2001; Deeken et al., 2006). This work presents new structural, stratigraphic, and paleontologic evidence for a middle Eocene deformation and sedimentation in the Puna–Eastern Cordillera transition between 24° and 26°S. Our results, along with others from the western Puna border (e.g., Mpodozis et al., 2005), suggest that preexisting crustal heterogeneities influenced the localization of the first manifestations of the Andean shortening from the middle Eocene in the southern portion of the plateau. Our data confirm that distribution of the initial shortening and sedimentation in the Central Andes was irregular, and that the classic models for Andean evolution postulating diachronous and eastward progressive deformation should be revised, because heterogeneities controlling shortening were activated along both plateau margins by the middle Eocene. Our data underscore a new key area to understand the initial evolution of the Andes, the archetype of a major noncollisional orogen.

GEOLOGICAL FRAMEWORK

The Argentine Eastern Cordillera is a bivergent fold-thrust belt affecting the oldest rocks known in the region. The North Calchaquí Valley (Fig. 1A) is limited by faults that thrust Neoproterozoic–Paleozoic basement on the Salta Group (Upper Cretaceous–Paleogene; rift basin infilling) and Payogastilla Group (foreland basin infilling). The Quebrada de los Colorados Formation is the lowest unit of the Payogastilla Group and its age was considered to be Neogene (Díaz and Malizzia, 1984), although some workers recognized that sedimentation might have started in the Paleogene (Marrett, 1990; Starck and Vergani, 1996).

EOCENE SYNTECTONIC SEDIMENTATION

Our structural, sedimentological, and paleontological analyses concentrated on two areas of the northern Calchaquí Valley, Saladillo and La Poma (Fig. 1A). Sedimentological and structural additional data on syntectonic sedimentation are available in the GSA Data Repository[1].

Stratigraphic Evidence: Sequences and Growth Strata

The 1500-m-thick Quebrada de los Colorados Formation consists of an upward-thickening and upward-coarsening continental succession (Fig. 1B). The internal stratigraphic arrangement includes three irregularly distributed sequences, locally bounded by unconformities. Next to

[1]GSA Data Repository item 2007058, Table DR1 (characteristic features of the sedimentary sequences) and Figures DR1–DR3 (main features of syntectonic strata) and Appendix with fossil description, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

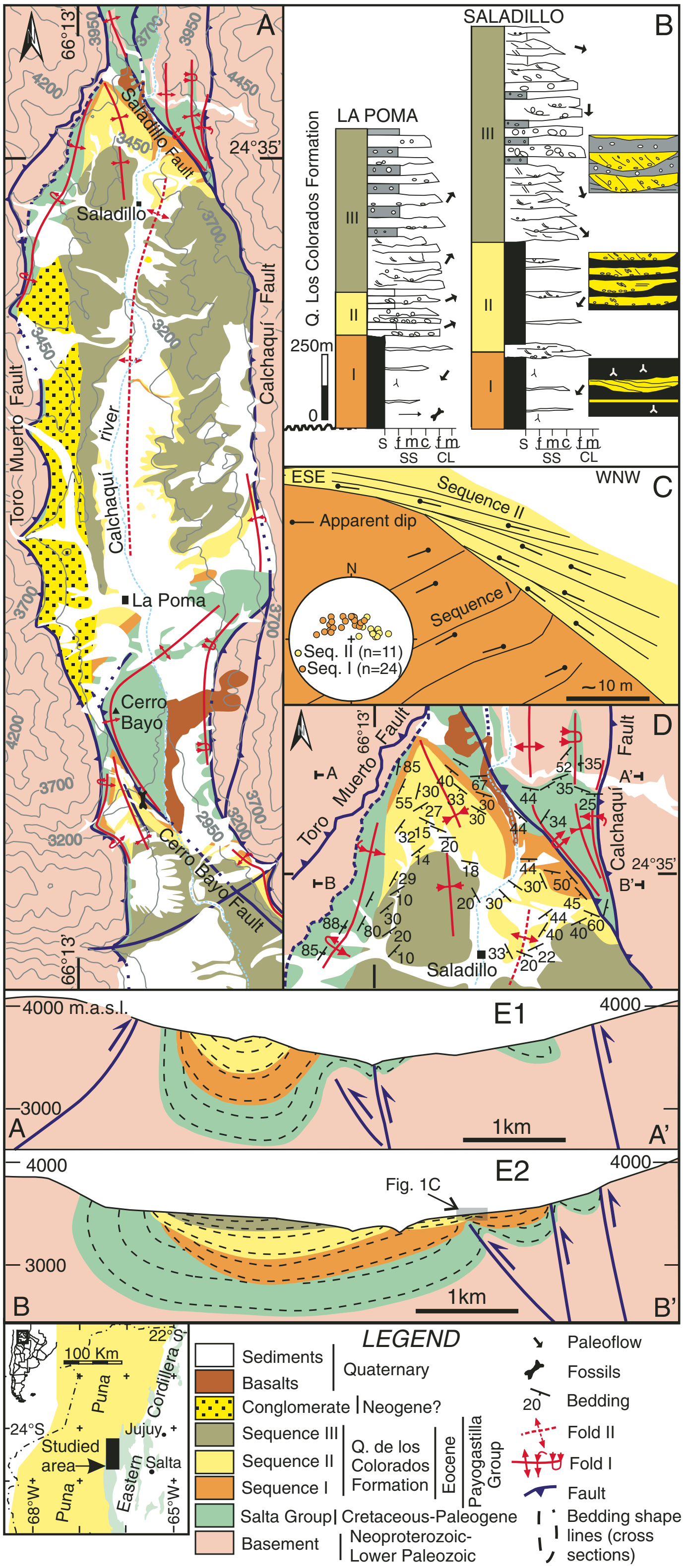

Figure 1. A: Geologic map of North Calchaquí Valley. B: Columns of Quebrada de los Colorados Formation in Saladillo and La Poma; schematic facies stacking is represented. C: Syntectonic angular unconformity between sequences I and II. Stereoplot shows poles to bedding in both sequences. D: Geology of Saladillo area. E: Profiles of Saladillo syncline (profile locations in D).

the Toro Muerto fault (Fig. 1A), younger unit III overlies older ones with variable angular relations (Figs. 1C, 1D, 1E).

Sequence I consists of fine-grained overbank, shallow sheet-like, and fixed isolated channel facies and paleosols deposited in flood plains and high-sinuosity rivers. Sequence II is composed of overbank, shallow fixed channels, and bars and/or channel facies of fluvial sandy braided and flood-plain environments. Analyses of provenance and paleoflows indicate source areas to the north, composed of low-grade metamorphic and granitic rocks. Sequence III comprises mudflow deposits, sandy and gravelly channel-fill facies, and fine-grained overbank deposits of alluvial fan environment. In Saladillo, paleoflows indicate a provenance from the north and northwest (Fig. 1B). In addition to these compositions, conglomerate clasts include Paleozoic volcanic rocks and Cretaceous sandstones and limestones. In La Poma, paleoflows indicate provenance from the southwest (Fig. 1B), and the composition is Paleozoic sandstones and volcanic rocks.

In Saladillo, intraformational deformation is recognized in sequences I and II (Figs. 1C, 1D, 1E) and involves fine-grained deposits except next to the growth folds, mainly related to the Saladillo and Calchaqui faults, where channelized gravelly sandstones were deposited at the lowest topographic levels. Toward the crest of anticline, strata show fan geometries defined by onlap relations, decreasing in dip upsection and thinning. A reduction in deformation rate generated stratal overlap and reestablishment of fine-grained sedimentation.

Stratal stacking patterns suggest a period of a high rate of intrabasinal deformation that caused local low accommodation for sequences I and II, followed by a period of high accommodation that allowed progradation of middle to proximal alluvial fans (sequence III).

The described features suggest that the tectonic-sedimentary evolution along the northern valley was not simple, but was conditioned by fault slip within a complex paleogeography.

Structural Indicators: Growth Faults and Growth Folds

The Saladillo and Cerro Bayo faults branch from the Calchaquí fault (Fig. 1A). The west limbs of related anticlines are either vertical or overturned, suggesting west-vergent faults. These are subvertical faults due to Quaternary reactivation. The Calchaquí, Saladillo, and Cerro Bayo faults controlled initial deposition of the Quebrada de los Colorados Formation. This relation is clearly defined at the Saladillo zone, where an angular unconformity separates the Quebrada de los Colorados Formation from the underlying Salta Group (del Papa et al., 2004). In addition, the lowermost beds of the Quebrada de los Colorados Formation preserve growth strata and syntectonic angular unconformities. Especially interesting is the contact between sequences I and II northeast of Saladillo, where the lower beds of sequence II define cumulative wedges of growth strata showing a rotational onlap (Fig. 1C) that indicates synorogenic deposition in a decelerated uplift regime (Riba, 1976).

Other evidence of synorogenic deposition is revealed by the Saladillo syncline. The eastern limb preserves the entire stratigraphic column of the Quebrada de los Colorados Formation, while the west one displays various relations ranging from progressive truncation of sequences I and II to sequence III being directly on top of the Salta Group (Figs. 1D, 1E). It indicates that folding of the Saladillo syncline was contemporaneous with deposition of the Quebrada de los Colorados Formation, and that the east-vergent Toro Muerto fault was also active during sedimentation.

Dating Initial Deformation: Paleontological Record

A fossiliferous level close to the base of the Quebrada de los Colorados Formation (Figs. 1A, 1B), which includes mammals (notoungulates) and reptiles (Chelonia and Crocodylia), has been detected. It includes poorly preserved osseous remains affected by diagenesis and weathering; nevertheless, its analysis allows some chronostratigraphic interpretation of the fossil-bearing strata.

A Mustersan South American Land Mammal Age (SALMA, middle Eocene) was inferred for the Casa Grande Formation based on primitive leontiniid notoungulates (Bond and López, 1995). Leontiniids found at the upper interval of the Lumbrera Formation (Alemanía Subbasin) suggest a similar age (Powell and Deraco, 2003). The association of leontiniids with a derived basal notohippid characterized by molar crowns higher than those of *Pampahippus arenalesi* (Bond and López 1993) suggests that the fossil-bearing strata at Cerro Bayo can be correlated with the Casa Grande Formation and the upper part of the Lumbrera Formation.

Thus, a middle Eocene age (Mustersan? or late Casamayoran SALMA) can be assigned to the basal level of the Quebrada de los Colorados Formation; sedimentation may have continued until the Oligocene–early Miocene.

Systematic Paleontology

Order **Notoungulata** Roth, 1903

Suborder **Toxodonta** Scott, 1853

Family **Notohippidae** Ameghino, 1985 (*sensu* Bond and Lopez, 1993)

Notohippidae new gen. and sp.

Material: Paleontología Vertebrados Lillo-Salta (PVL-S) C.B.02. Fragment of the anterior portion of the skull with all upper teeth except the right M3 and the right mandibular ramus with the complete dentary series poorly preserved except the incisors (only preserved in a plaster cast) and pm1.

This notohippid is closely related to *Pampahippus arenalesi* (Bond and López, 1993) from the Lumbrera Formation from Pampa Grande, Salta Province. This taxon was interpreted as a basal notohippid. Similarities with *Pampahippus arenalesi* include upper incisors forming an arc, an incomplete protoloph in the upper premolars, bunoid entoconid in the pm3-4 (plesiomorphic features also present in basal leontiniids from northwestern Argentina). However, the crown of the upper molars is slightly higher and with an angle between protoloph and ectoloph.

Family Leontiniidae Ameghino, 1895

Leontiniidae indet.

Material : PVL-S C.B.03 Incomplete skull including both partial premaxilla and maxilla with fragment of root of I2; alveoli of I3, C1 and P1; roots of left P2, P3 and P4; part of the crowns of the right P2? and portion of the crowns of the left M2 and M3. Fragments of nasals are also present. The upper dentition is complete: 3I-1C-4PM-3M. The teeth are brachyodont. No evident diastem is present. The root of the I2 is hypertrophied, being one of the Leontiniid's diagnostic features.

Abreviations PVL-S: Paleontología Vertebrados Lillo-Salta.

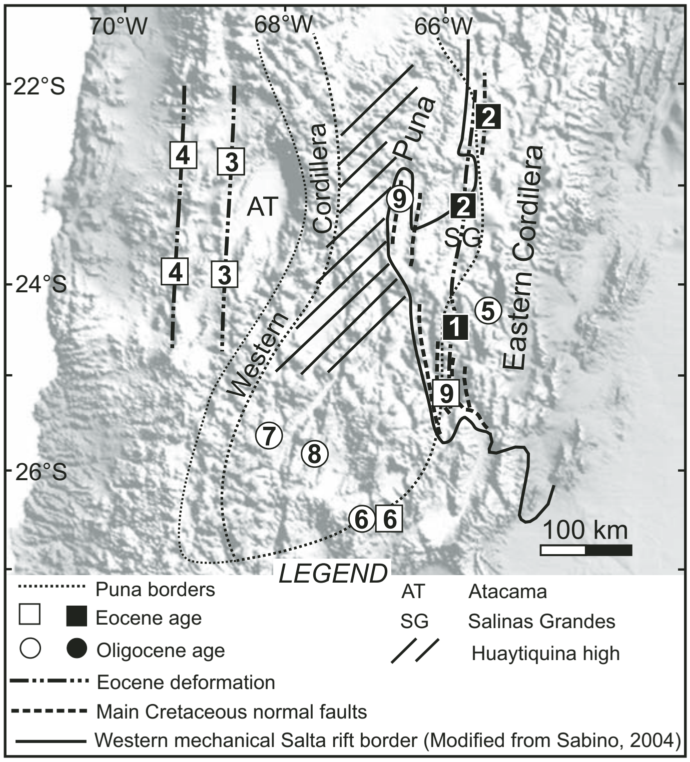

Figure 2. Shaded relief map of southern Central Andes with location of rift border and main areas recording Eocene deformation. Eocene deformation lines on edges of plateau are drawn from points with ages and relations that indicate uplift or synorogenic sedimentation. Ages are from fossils (black symbols) and from fission tracks or absolute dating (white symbols). References: 1—Quebrada de los Colorados Formation (this paper); 2—Casa Grande Formation (this paper; Monaldi et al., 1993; Coutand et al., 2001); 3—Mpodozis et al. (2005); 4—Reutter et al. (1996); 5—Andriessen and Reutter (1994); 6—Coutand et al. (2001); 7—Kraemer et al. (1999); 8—Carrapa et al. (2005); 9—Deeken et al. (2006). Western mechanical rift border is after Sabino (2004).

DISCUSSION

The notion that the Quebrada de los Colorados Formation accumulated during the middle Eocene affects the analysis of the first evolutionary stages of southern Central Andes. This is significant due to the fossil correlation of these strata with the Casa Grande Formation, which unconformably overlies the Salta Group (Mon et al., 1996) and displays growth strata (Monaldi et al., 1993; Coutand et al., 2001). Therefore, Eocene deformation in these areas might define a belt along the Eastern Cordillera–Puna transition (Fig. 2). This Eocene deformation belt outlines the mechanical heterogeneity related to the Cretaceous rift basin border, which was tectonically inverted during the Andean orogeny (Grier et al., 1991; Allmendinger et al., 1997; Ganghi, 1998; Deeken et al., 2006).

Mpodozis et al. (2005) described Eocene shortening on the western border of the Puna, in a foreland basin representing inversion of a Late Cretaceous backarc basin. Thus, Eocene deformation is concentrated along both Puna margins, as in the Bolivian Altiplano. Andriessen and Reutter (1994) and Salfity et al. (1993) suggested a role for the Incaic phase in the Eastern Cordillera and Santa Bárbara System, respectively. Jordan and Alonso (1987) and Carrapa and DeCelles (2006) proposed that the Geste Formation (southern Puna) was deposited during the Eocene with a sediment source located mainly to the west. In fact, this formation may record the filling of a complex fragmented foreland basin, as in Oligocene time (Kraemer et al., 1999), or in intramontane basins. In such a scenario, the Geste, Quebrada de los Colorados, Casa Grande, and upper section of the Lumbrera Formations record the infill of a tectonically active and geographically complex basin, or subbasins, during Eocene deformation extending across the Puna and Eastern Cordillera. The Eocene shortening is enough to define the middle Eocene proto–Eastern Cordillera proposed by Coutand et al. (2001) for the late Eocene–early Oligocene. Therefore, it is likely that a significant amount of the shortening at the Puna–Eastern Cordillera transition developed during the Paleogene, as in the northern portion of the plateau (Horton, 2005), which should compensate part of the deficit established for the Puna segment of the Central Andes (Kley and Monaldi, 1998). In the northern Calchaquí Valley, the Salta Group and sequence I record more shortening than sequence III (Figs. 1D, 1E).

Although Eocene deformation is recognized across the Puna and Eastern Cordillera, the main shortening occurred at the Puna margins, coinciding with the western thermal and mechanical heterogeneity (magmatic arc and Cretaceous basin border) and eastern mechanical heterogeneity (Salta Group rift basin border) that bound the Puna. From these zones of early activity, deformation and sedimentation propagated into the plateau and Eastern Cordillera, as described for the Altiplano (Elger et al., 2005). In this context, a more homogeneous basement block (Huaytiquina high, Fig. 2) was between Cretaceous basins along both margins of the plateau (Mpodozis et al., 2005), and enhanced an irregular distribution of deformation. In this scenario, the Eocene Puna basins (e.g., the Geste Formation) developed in a quiescent setting between two belts of faster deformation. Therefore, the Paleogene deformation followed an irregular pattern in which inherited crustal heterogeneities played a major role in the configuration of the Paleogene proto-Andes.

CONCLUSIONS

The Puna–Eastern Cordillera transition between 23° and 26°S preserves clear evidence for middle Eocene sedimentation and deformation, the location of which was controlled by the preexisting heterogeneity imposed by the mechanical rift basin border of the Cretaceous-Paleogene Salta Group. Thus, the time between deposition of the final postrift strata and the beginning of the Andean sedimentation was short, including only the lower-middle Eocene.

Eocene deformation had an irregular distribution because it took place synchronously in the west and east margins of the Puna, as in the Bolivian Altiplano, and very likely affected areas within the Puna and the Eastern Cordillera. The distribution of Eocene deformation in the Puna and the Eastern Cordillera requires further work in light of the new evidence for sedimentation and deformation. Nevertheless, available information is enough to conclude that the first stages of Andean shortening occurred during the Eocene all along the edges of the Central Andes plateau (Altiplano and Puna).

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