Geological Society of America Bulletin

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Geological Society of America Bulletin 2010;122;946-949
doi: 10.1130/B30133.1

Dynamics of deformation and sedimentation in the northern Sierras Pampeanas: An integrated study of the Neogene Fiambalá Basin, NW Argentina: Comment and Discussion

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In a recent contribution to the *Geological Society of America Bulletin*, Carrapa et al. (2008) provided an interesting geochronological and thermochronological database for the Fiambalá Basin, northern end of the Sierras Pampeanas, which, together with stratigraphic, sedimentological and structural data, led them to interpret a late Miocene–Pliocene foreland reorganization from a simple scenario (e.g., DeCelles and Giles, 1996) to settings dominated by intermontane basement thrusting. They associated this reorganization with the beginning of flat subduction, which would have been coeval (according to Carrapa et al., 2008) with broken foreland stages in the Bermejo Basin (>400 km south). One of the most crucial issues that Carrapa et al. (2008, p. 1518–1543) address (in their words) is "the structural and sedimentary behavior of broken forelands and their relationships with large-scale plate-tectonic processes such as flat-slab subduction" that can "contribute to a better understanding of the transition from unbroken foreland (thin-skinned) to broken foreland (thick-skinned) styles of deformation and related sedimentation." However, for some reason, they did not discuss the entire Andean stratigraphy of the area, superbly exposed much less than 50 km southward and 100 km northward of their study region (in central Famatina and Southern Puna, respectively; see Fig. 1). These two regions are evidently much closer than the Bermejo Basin exposures (see Jordan et al., 2001), which were used as a key correlation. The Bermejo Basin is located at ~31°S, i.e., ~400 km southward of Fiambalá (Fig. 1).

Although I do agree that the entire extent of the Sierras Pampeanas shows evidences of basement-thrusting tectonics during the late Miocene to Pliocene and even during the Quaternary (already demonstrated previously; e.g., Jordan and Allmendinger, 1986; Ramos et al., 2002; among others), there are sources that indicate the foreland partitioning would have begun earlier. Particularly, I disagree with: (1) the timing of transformation from "simple flexural stages" to "broken foreland scenarios" and (2) their interpretation about a synchronous slab shallowing at ca. 6 Ma.

This discussion is divided into four lines of reasoning: mapping and stratigraphy of Tertiary sequences in Famatina and Southern Puna; timing of basement thrusting in boundary regions; thermochronology; and evidences of flat subduction between 29°S and 26°S.

CENOZOIC STRATIGRAPHY BETWEEN 29°S AND 26°S

The Carrapa et al. (2008) work focuses in the Fiambalá Basin or Bolsón de Fiambalá (27°–28°S; see Fig. 1). Fiambalá is located in the northernmost part of the Famatina geological province (Fig. 1), where the Cenozoic strata are not fully exposed. The most complete Cenozoic record crops out in central Famatina (between 29°–28°S; Fig. 1), where Dávila and Astini (2007) interpreted the evolution of the northern Sierras Pampeanas foreland in order to bridge the basin dynamics between the Bermejo Basin (at 31°–30°S) and the Puna Plateau (at 26°S).

In the work presented by Carrapa et al. (2008), maps and stratigraphic columns of the Upper Miocene to Pliocene of the northern Famatina are correct (Fig. 1). However, the relationship between Upper Miocene and Lower–Middle Miocene, although not mentioned, is exposed extensively immediately south of the Fiambalá Basin, as near as 20 km to Carrapa et al.'s study zone (see Fig. 1). This relationship is also observed in other regions of Famatina (De Alba, 1979).

The Lower Miocene in central Famatina (since Dávila et al., 2004) is known as the Del Crestón Formation. Mapping, structural, stratigraphic, and sedimentological features of this unit are described in Dávila and Astini (2007, and references therein). Two Ar-Ar dates (on amphiboles) of two andesite boulders collected from a primary volcaniclastic layer (see Figure 4b of Dávila and Astini, 2007) supplied an age of ca. 17 Ma (Dávila et al., 2004). These ages have been supported by magnetostratigraphy and paleomagnetic analysis (Zambrano, 2006; Zambrano et al., 2008), and they allow us to constrain the top of the succession at ca. 14.5 Ma.

It is critical to notice that the stratigraphic columns of Carrapa et al. (2008) do not show a basal section (see their Figs. 1C and 5). Recurrently, they also mention that thousands of meters of older Cenozoic stratigraphy would have been exhumed and unroofed. As depicted by Figure 1 of this discussion, Upper Miocene

Figure 1. (A) Perspective view from above and to the NW of the Famatina geological province and boundary regions (Vinchina, Bermejo, and Puna). Note the Fiambalá Basin (location of Carrapa et al., 2008) in the northernmost part of Famatina. The central Famatina (location of Dávila and Astini [2007] study) exposes the Lower–Middle Miocene. The Upper Miocene of central Famatina, overthrusted by the Lower Miocene, is not shown in A (for mapping details, see Dávila and Astini, 2007). (B) Inset transitional region that bridges the Carrapa et al. (2008) and the Dávila and Astini (2007) papers, depicting the relationship between Lower and Upper Miocene. (C) Cenozoic stratigraphic column of central Famatina. (D) Cenozoic stratigraphic column of Fiambalá. Note the Fiambalá column does not expose the Lower Miocene.

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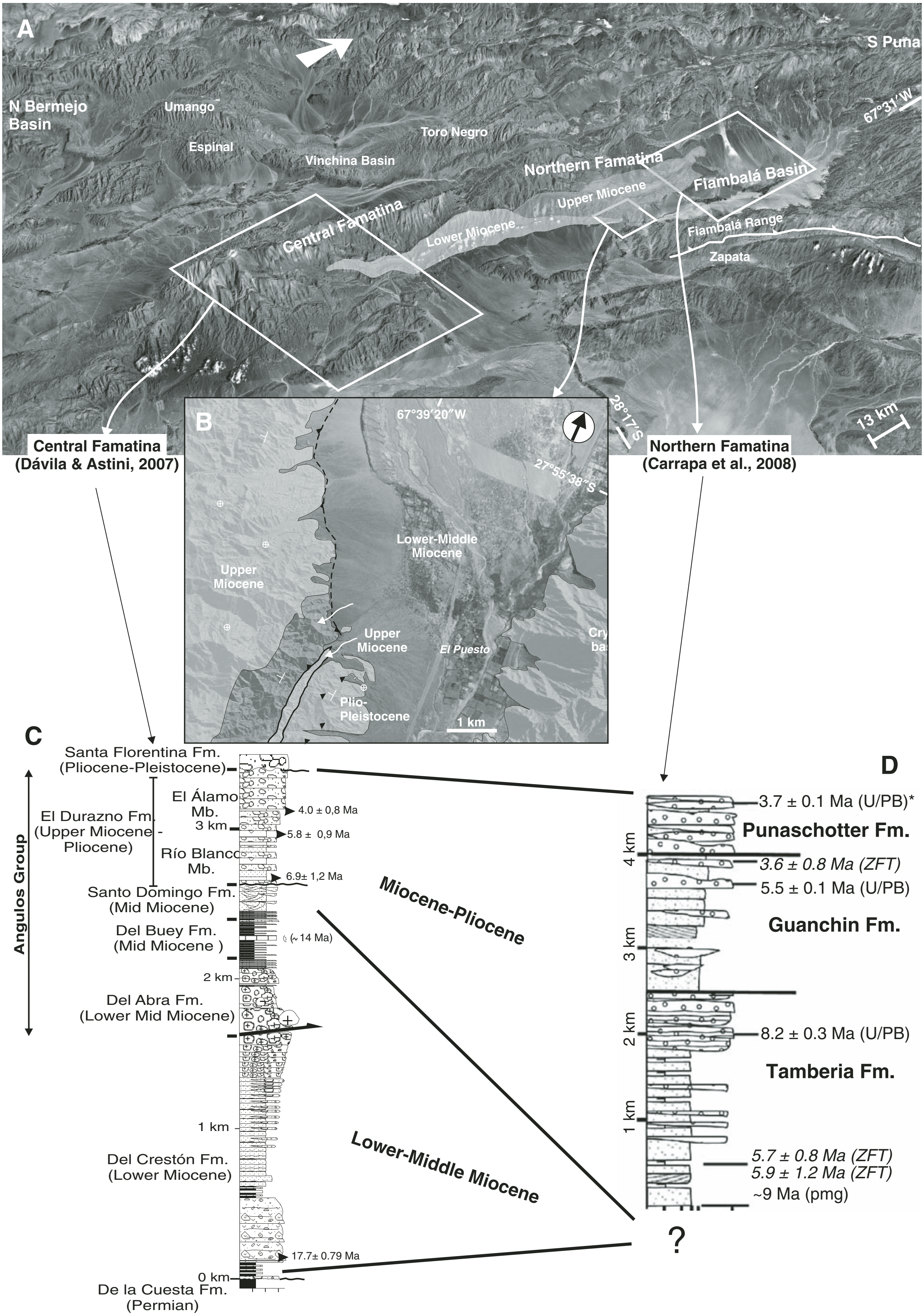
GSA Bulletin; May/June 2010; v. 122; no. 5/6; p. 946–949; doi: 10.1130/B30133.1; 1 figure.



A
S Puna
N Bermejo Basin
Umango
Espinal
Toro Negro
Vinchina Basin
Northern Famatina
Flambalá Basin
67°31′W
Upper Miocene
Central Famatina
Lower Miocene
Flambalá Range
Zapata
28°17′S
13 km
Central Famatina
(Dávila & Astini, 2007)
Northern Famatina
(Carrapa et al., 2008)
B
67°39′20″W
27°55′38″S
Lower-Middle Miocene
Upper Miocene
Upper Miocene
El Puesto
Plio-Pleistocene
1 km
C
Santa Florentina Fm.
(Pliocene-Pleistocene)
El Álamo Mb.
El Durazno Fm.
(Upper Miocene - Pliocene)
3 km
4.0 ± 0,8 Ma
5.8 ± 0,9 Ma
Río Blanco Mb.
6.9± 1,2 Ma
Santo Domingo Fm.
(Mid Miocene)
Del Buey Fm.
(Mid Miocene)
(~ 14 Ma)
2 km
Del Abra Fm.
(Lower Mid Miocene)
Angulos Group
1 km
Del Crestón Fm.
(Lower Miocene)
17.7± 0.79 Ma
0 km
De la Cuesta Fm.
(Permian)
Miocene-Pliocene
Lower-Middle Miocene
D
3.7 ± 0.1 Ma (U/PB)*
Punaschotter Fm.
3.6 ± 0.8 Ma (ZFT)
5.5 ± 0.1 Ma (U/PB)
Guanchin Fm.
8.2 ± 0.3 Ma (U/PB)
Tamberia Fm.
5.7 ± 0.8 Ma (ZFT)
5.9 ± 1.2 Ma (ZFT)
~9 Ma (pmg)
4 km
3 km
2 km
1 km
?

to Pliocene strata of the Fiambalá region continue to the south, and the bottom of the Tamberias Formation would rest in unconformity on Lower–Middle Miocene strata (Del Crestón Formation), suggesting the occurrence of an older sedimentary basin history.

Carrapa et al. (2008) avoided discussing the papers by Kraemer et al. (1999) and Voss (2002), or even Carrapa et al. (2005), who describe superb exposures of Oligocene–Lower Miocene to Pliocene strata to the north of Fiambalá, in the Puna scenario (see Fig. 1). This is evidence of basin evolution much older than 9 Ma in the southernmost Puna Plateau, much closer than the Bermejo Basin.

TIMING OF BASEMENT THRUSTING IN FAMATINA, VINCHINA, AND SOUTHERN PUNA

However, the most interesting issue of the Lower–Middle Miocene strata of Famatina is that conglomerates, from bottom to top, record a progressive compositional increment of Ordovician granite and mylonite boulders as well as Cambrian-Ordovician low-grade metamorphic pebbles (see also photographs in Figures 4C and 4D of Dávila and Astini, 2007), suggesting an unroofing sequence and the crystalline-basement exhumation of the Central Famatina Range (located in the area of Fig. 1) during the early–middle Miocene. The Lower Miocene strata also preserve progressive unconformities associated with basement thrusting (see Dávila and Astini, 2003). On the basis of the central Famatina record, Dávila and Astini (2007) suggested that foreland partitioning in the northern Sierras Pampeanas began earlier, between ca. 17 and 14 Ma. The minimum age for this deformation was constrained by the deposition of the Del Buey Formation, the age of which is ca. 14 Ma (Barreda et al., 2006), and magnetic studies (Zambrano, 2006).

To the SW, Fiambalá Basin strata correlate with Vinchina Basin strata, located <<150 km (see Fig. 1) and, evidently, much closer than the Bermejo Basin outcrops. The Vinchina Basin is formed by the Vinchina and Toro Negro Formations, a thick alluvial sequence (>10,000 m thick) dated between ca. 14 and 4 Ma (Tabbutt, 1986; Re and Barredo, 1993). Although the Vinchina Basin is located at the foothills of the Andes, it preserves granite and metamorphic pebbles in conglomerates (Tripaldi et al., 2001) at midsection (~1500 m from the base), suggesting a contribution from the northern Sierras Pampeanas (Umango and Espinal Ranges in Fig. 1), previous to 8 Ma.

Along strike, less than 150 km north of Fiambalá Basin, in the Salar de Antofalla (southern Puna), a Paleogene to Pliocene stratigraphy also records protracted basement thrusting in the Andes (see Kraemer et al., 1999; Voss, 2002; Carrapa et al., 2005). The Lower–Middle Miocene Chacras and Potrero Grande Formations (ca. 24–10 Ma; Kraemer et al., 1999), for example, preserve subangular pebbles up to 0.5 m, originated from crystalline basement. According to Kraemer et al. (1999), the nature of the alluvial conglomerates, the stratigraphic relationships, and the progressive angular unconformities indicate two major basement-involved tectonic episodes, D1 and D2 (28–25 Ma and 20–17 Ma, respectively).

THERMOCHRONOLOGY

Carrapa et al. (2006), then used by Carrapa et al. (2008), provided a valuable low-temperature thermochronology database. A single, but representative, apatite fission-track age of 13.1 ± 1.7 Ma was yielded by the Alto Grande Paleozoic granite, on the back limb of the east-vergent, basement-involved Fiambalá thrust sheet (see AG caption in Figure 1B of Carrapa et al. [2008] and in Fig. 1 of this discussion). In fact, the map presented by Carrapa et al. (2008) depicts this basement thrust overriding onto the Tamberias-Guanchin Formations exposed in the Bolsón de Zapata (Zapata in Fig. 1). The composition of Guanchín Formation clearly indicates the Miocene-Pliocene exhumations of the Fiambalá Range, in agreement with the conclusions made by Carrapa et al. However, the ca. 13 Ma cooling age would indicate that the "Tamberias Formation" in Zapata, overthrusted by the Fiambalá basement, would be older than 13 Ma, or it would be a different and older unit (likely the northeastern extension of the Del Creston Formation of central Famatina). In any case, this older lithostratigraphy (older than 13 Ma) yields basement pebbles in the conglomeratic layers (González Bonorino, 1972). Therefore, the basement exhumation in the Fiambalá Range would have been: (1) previous to (cf. evidences reported in the "older Tamberías Formation" of Zapata), (2) synchronous with (cf. the apatite fission-track datum of Carrapa et al., 2006), and (3) subsequent to (cf. basement pebbles of Guanchin Formation of Zapata) 13 Ma.

SYNCHRONOUS FLAT SUBDUCTION IN THE CENTRAL ANDES SINCE 6 MA? IS IT CONSISTENT WITH VOLCANISM?

Cratonward migration of deformation followed by closing stages of foreland partitioning, as shown by Jordan et al. (2001) and Vergés et al. (2001) at 31°S, has been largely used to interpreted flat slab regimes in many orogens. High coupling and crustal refrigeration due to mantle wedge reduction would favor deformation and basement thrusting within the most distal part of the foreland. However, we have learned from different regions that slab flattening can occur with subtle foreland basement thrusting (e.g., flat slab from Perú; Espurt et al., 2007) or even without foreland partitioning (e.g., México; Manea et al., 2006). Broken forelands can also develop under "normal" subduction regimes (e.g., Tapponnier and Molnar, 1979). Evidently, a critical clue for the interpretation of ancient flat subduction stages is volcanism, an issue poorly discussed by Carrapa et al. (2008).

Kay and Mpodozis (2002) presented a vast database and a detailed review of volcanic and geochemical studies in the Central Andes, which contributed to our understanding of the migration and broadening of the volcanism within the Andean foreland, as well as comprehension of the slab angle evolution, from the Oligocene to early Miocene to present day.

The late early Miocene along ~26°–28°S, at the latitudinal belt coinciding with Fiambalá-Famatina, was characterized by an eastward expansion of volcanism (Kay and Mpodozis, 2002). Between ca. 20 and 16 Ma, a reduction in arc volcanism and an apparent magmatic lull along these latitudes (in the Maricunga belt; see Kay et al., 1994) suggest slab shallowing. As mentioned before, by ca. 17 Ma retroarc magmatism had also developed in central Famatina, interpreted as a magmatic broadening during the late early Miocene (Dávila et al., 2004).

Between 15 and 10 Ma, this belt along ~26°–28°S (Maricunga and northern Sierras Pampeanas) also showed conspicuous evidence of volcanism, in agreement with a flat subduction regime, which was associated with the arrival of the Juan Fernandez Ridge axis (Kay and Mpodozis, 2002). Examples are the 15–14 Ma ignimbrites of the Valle Ancho, the ca. 12.5 Ma eruptions in Farallón Negro (located east of study area; Sasso and Clark, 1998; Halter et al., 2004), and the 11–10 Ma volcanic rocks in northern Precordillera (Leveratto, 1976).

The magmatic signature and volcanic distribution within the retroarc and within the foreland are consistent with a southward migration and eastward broadening of volcanism between ca. 20 and 10 Ma between 26°S and 28°S, supporting progressive slab flattening. This region encompasses the study area of Carrapa et al. (2008). This magmatic history leads to a markedly different interpretation than Carrapa et al.

(2008) suggest, based only on a basin record, which is that the slab flattening would have begun ca. 6 Ma, and, moreover, it would have been synchronous along strike from 26°S to 30°S.

SUMMARY

From north to south, there is strong evidence that suggests that foreland partitioning and basement thrusting within the northern Sierras Pampeanas and southern Puna occurred much earlier than Carrapa et al. (2008) hypothesize. In the Puna, basement exhumation would have begun at 28 Ma and extended up to 17 Ma. In central Famatina, a few tens of kilometers southward of the Fiambalá region, the exhumation of the crystalline basement of central Famatina would have started at ca. 17–14 Ma. That evidence contradicts the hypothesis that the transition from simple foreland stages to broken foreland occurred at ca. 6 Ma (e.g., Carrapa et al., 2008). As clearly stated by Jordan et al. (2001), this transition seems to have occurred only in the southern Sierras Pampeanas.

Based on magmatic, stratigraphic, and thermochronological evidence, slab flattening in the northern Sierras Pampeanas and southern Puna likely began at ca. 20 Ma. This is in strong contradiction with the synchronous beginning of the slab flattening in the Central Andes at ca. 6 Ma proposed by Carrapa et al. (2008).

ACKNOWLEDGMENTS

I appreciate comments and suggestions from V.A. Ramos (associate editor). I also thank T.E. Jordan (Cornell University) for her thoughtful review of an early draft version and the comments from colleagues at the Basin Analysis Center (Centro de Investigaciones en Ciencias de la Tierra-Centros de Investigationes Científicas y Técnicas-Universidad Nacional de Córdoba).

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Manuscript Received 15 July 2009
Manuscript Accepted 24 August 2009

Printed in the USA