

# Middle Miocene tectonic development of the Transition Zone, Salta Province, northwest Argentina: Magnetic stratigraphy from the Metán Subgroup, Sierra de González

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## ABSTRACT

Magnetostratigraphy, isotopic dating, and sandstone petrography establish age limits on the depositional history of ~2100 m of foreland basin strata in the Neogene Metán Subgroup of northwest Argentina. The strata were deposited between ca. 15.1 and 9.7 Ma in the eastern Sistema de Santa Bárbara. The region is positioned above the Cretaceous Salta rift basin, in the Transition Zone between modern relatively steep and flat subducting segments of the Nazca plate.

Formations within the subgroup are shown to be diachronous over a 60 km distance; the younger ages are in the east. Changes in paleocurrent flow directions and the lithic clast component of sandstones collected from the Arroyo González section suggest that basal fluvial strata were derived from the craton to the east beginning in middle Miocene time, just prior to 15.1 Ma. By ca. 14.5 Ma, the paleocurrent flowed from a source in the west and sedi-

ment accumulation rates increased dramatically. These changes correlate with contemporaneous tectonism in the west. A local increase in basin accommodation may be partly related to a zone of weakness near the eastern boundary of the Salta rift.

Uplift in the western Cordillera Oriental apparently began by 13.7 Ma and thrusting rapidly migrated eastward. The eastern Cordillera Oriental ranges began to rise between 25° and 26°S ca. 10 Ma. As thrusting migrated eastward, low-energy depositional environments were overwhelmed ca. 13.7 Ma. Above an erosional unconformity that removed strata to an age of ca. 9.7 Ma, basal strata from the overlying Jujuy Subgroup were deposited beginning after 9 Ma.

Sandstones from Río Yacones suggest that the Cordillera Oriental uplift continued for several million years longer between 24° and 25°S. Uplift of the Sistema de Santa Bárbara, in the distal portion of the foreland, did not begin until after ca. 9 Ma.

**Keywords:** Argentine Andes, magnetostratigraphy, Neogene, Salta Argentina, tectonics, transition zones.

## INTRODUCTION

The Central Andes are frequently cited as a type example for mountain ranges generated from the subduction of oceanic lithosphere beneath a continent (e.g., Moores and Twiss, 1995; van der Pluijm and Marshak, 1997). The foreland deformational style between Peru and northwest Argentina may behave as a classic Davis et al. (1983) type of orogenic wedge, but surprisingly little is known about the chronology of deformation in the foreland region to confirm that the strata deformed in the classic fashion.

The Subandean zone (Fig. 1) is host to hydrocarbon production and exploration along most of its length in Bolivia and north of 27°S in Argentina, but few numerically dated horizons exist in the foreland basin strata. Published interpretations of structural history, tectonic reconstructions, and petroleum genesis models that are applied today lack a concise chronological foundation. To rectify this situation we are attempting to determine the age of basin-filling strata from the best-exposed stratigraphic sections in the foreland region to understand their relationships to the structures and to determine the provenance of their sediment. This will allow the construction of new

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models that describe the paleogeographic evolution of the basins and mountain ranges.

The work reports the chronologic development of middle Miocene sedimentation in the Sistema de Santa Bárbara portion (Fig. 1) of the Transition Zone at the southern end of the Subandean zone. Using dating from magnetic polarity stratigraphy aided by a fission-track age and chronologic information from other areas in the Transition Zone, crosscutting relations, and changes in the lithic content of the sandstones, we interpret the middle Miocene tectonic development of the region.

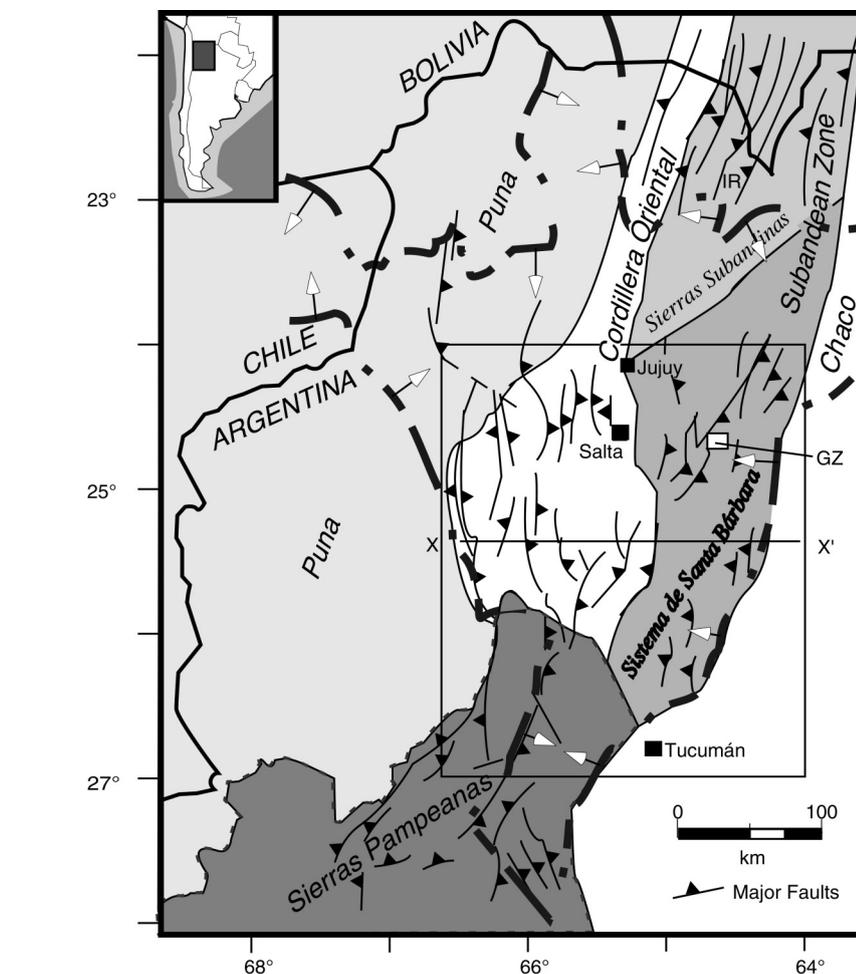
Nazca plate subduction is characterized by significant along-strike subduction angle changes beneath the western margin of South America (Jordan et al., 1983). Foreland structural provinces of northwest Argentina developed in three tectonic domains characterized by differences in the subduction angle and the orientation of preexisting structural fabrics. An area of inclined subduction where the Nazca plate descends at an angle of about  $30^\circ$  to the east is between  $18^\circ$  and  $24^\circ$ S. Farther to the south, between  $28^\circ$  and  $33^\circ$ S, is an area of subhorizontal ( $\sim 5^\circ$ ) subduction (Barazangi and Isacks, 1976). The Transition Zone is situated between these subduction domains ( $24^\circ$ – $28^\circ$ S).

### TRANSITION ZONE PROVINCES

Our work focuses on the middle Miocene tectonic history of the northern part of the Transition Zone ( $24^\circ$ – $26^\circ$ S). Structural aspects of the Neogene foreland provinces to the north of the Transition Zone continue along strike through the Transition Zone but undergo marked changes before terminating at the southern margin (Barazangi and Isacks, 1976; Jordan et al., 1983; Allmendinger et al., 1983). Bevis and Isacks (1984) proposed that the subducting plate is deformed by a broad gentle flexure through the Transition Zone.

### Salta Rift Basin

Grier et al. (1991) demonstrated that the geometries of Andean tectonism in the Transition Zone are consistent with the inversion of the Cretaceous Salta rift basin and with Neogene shortening by thrust reactivation of Cretaceous listric normal faults. Westward vergence in the western Cordillera Oriental portion of the Transition Zone (Fig. 2) is localized near the western boundary of the Salta rift basin, where the Puna and the western Cordillera Oriental meet (Grier et al., 1991). The eastern part of the Sistema de Santa Bárbara (discussed in the following) is located above the



**Figure 1.** Map illustrating the structural provinces in northwest Argentina (adapted from Grier et al., 1991). The boundary between the Transition Zone and the inclined subduction area to the north is located at  $\sim 24^\circ$ S, where the Cordillera Oriental narrows. Cross-section X–X' is shown in Figure 2. The area illustrated in Figure 3 is outlined by the open rectangle. The Arroyo González area (Fig. 4) is shown by the white rectangle. The Subandean zone boundary between the Sierras Subandinas and the Sistema de Santa Bárbara follows the trend of the Santa Bárbara Ranges (Fig. 3B). The irregular southern limit of the Transition Zone is marked by the boundary with the Sierras Pampeanas. Heavy dashed lines denote the approximate boundaries of the Salta rift (white arrows on downthrown side). Río Iruya (IR) is located in the Sierras Subandinas.

eastern boundary of the rift. The northern limit of the Sierras Pampeanas is located roughly along the southern rift margin.

The rift is partitioned into six named sub-basins: the Lomas de Olmedo, Tres Cruces, Sey, Alemania, El Rey, and Metán (Fig. 3). The subbasins are grouped around the central Salta-Jujuy structural high (Fig. 3; Marquillas and Salfity, 1988; Mon and Salfity, 1995) and are filled with Salta Group strata (Table 1).

Compressional regional stresses were initiated by Neogene time. Continental clastic strata of the Orán Group buried the rift during the Quechua phase of the Andean orogeny as

a foreland basin developed eastward across the area (Comínguez and Ramos, 1995).

### Puna

The Puna Plateau is situated along the Argentina-Chile border between the main range of the Andes and the Cordillera Oriental. It represents the southern extension of the broader Altiplano that is to the north in Bolivia and Peru. The Puna-Altiplano is characteristic of the inclined subduction region. It continues through the Transition Zone, tapering to its terminus at the southern margin. Mean basin

MIDDLE MIOCENE TECTONIC DEVELOPMENT OF THE TRANSITION ZONE

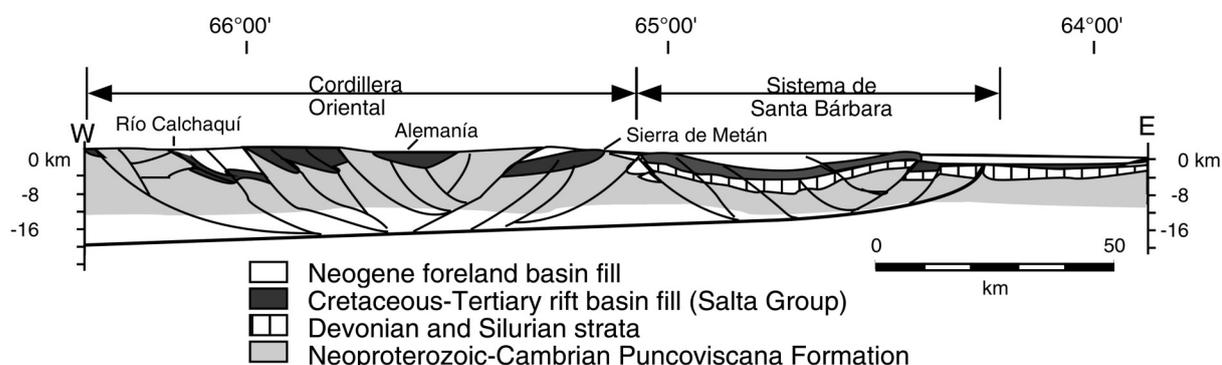


Figure 2. Balanced cross section of the Transition Zone at 25°30'S (modified from Grier et al., 1991).

TABLE 1. STRATIGRAPHY OF THE ORAN AND SALTA GROUPS

Group	Subgroup	Formation	Age
Orán	Jujuy	Piquete	Pliocene–Pleistocene
		Guanaco	Miocene–Pliocene
	Metán	Jesús María	Middle–upper Miocene
Salta	Santa Bárbara	Anta	Middle Miocene
		Río Seco	Middle Miocene
		Lumbrera	Paleocene–Eocene
	Balbuena	Maiz Gordo	Paleocene
		Mealla*	Paleocene
	Pirgua	Olmedo*	Paleocene
		Yacoraite	Maastrichtian
		Lecho*	Campanian
	Undivided	Albian–Campanian	

\*Not present in Arroyo González.

elevations of ~3400 m characterize this internally draining region. Hundreds of Pleistocene volcanoes with summit elevations above 5000 m are present across the plateau system. Vandervoort et al. (1995) dated Neogene evaporite deposits on the Puna and concluded that internal drainage was probably established by ca. 15 Ma, suggesting a similar age for the initiation of uplift.

A wide range of lithologies is present on the Puna (Cladouhos et al., 1994). The oldest strata are Neoproterozoic–Cambrian shallow-marine metasedimentary rocks of the Puncoviscana Formation. Ordovician metasedimentary and metavolcanic rocks are the most abundant rocks exposed on the Puna. Cretaceous and Tertiary continental strata of the Salta Group fill the Tres Cruces subs basin of the Salta rift. Neogene sedimentary and volcanic strata cover large areas.

**Cordillera Oriental**

The Cordillera Oriental is a predominantly eastward-verging fold-thrust belt bounding the eastern edge of the Puna (Fig. 1) in the inclined subduction region. Vergence in the

Transition Zone varies from predominantly westward verging in the west to eastward verging in the east (Fig. 2), resulting from reactivation of the rift-bounding faults (Grier et al., 1991). The Cordillera Oriental is wider in the Transition Zone than it is in the inclined subduction area (Fig. 1). Grier and Dallmeyer (1990) suggested that eastward progression of deformation in the Cordillera Oriental at these latitudes was faster than that in the Sierras Pampeanas immediately to the south.

Many peaks rise above 5000 m along steeply dipping fault planes. Rapid Neogene uplift caused significant unroofing of these ranges. In many ranges, greenish phyllites are exposed along with the Phanerozoic strata. Like the Puna, the Cordillera Oriental and Subandean zone also terminate along the irregular southern boundary of the Transition Zone (Jordan et al., 1983). Uplift of the Cordillera Oriental began in the late Oligocene in Bolivia (Horton, 1998) but appears to have started in the middle Miocene in northern Argentina (Reynolds et al., 1996; Hernández et al., 1996, 1999).

In the southern Transition Zone, two ranges of the Sierras Pampeanas are wedged between the Puna and Cordillera Oriental, extending to the north of 26°S. The Sierras Pampeanas are Laramide-style basement uplifts found in the eastern foreland region of the flat subduction domain (Jordan and Allmendinger, 1986).

**Sistema de Santa Bárbara**

The Subandean zone in the Transition Zone is defined by the Sistema de Santa Bárbara, the only structural province confined exclusively to the Transition Zone (Fig. 1). The region is densely vegetated and humid, subtropical conditions cause deep weathering profiles. Exposure is limited to arroyos incised into the flanks of Neogene mountains, where rapid

downcutting provides fresh, relatively continuous exposures along select streams.

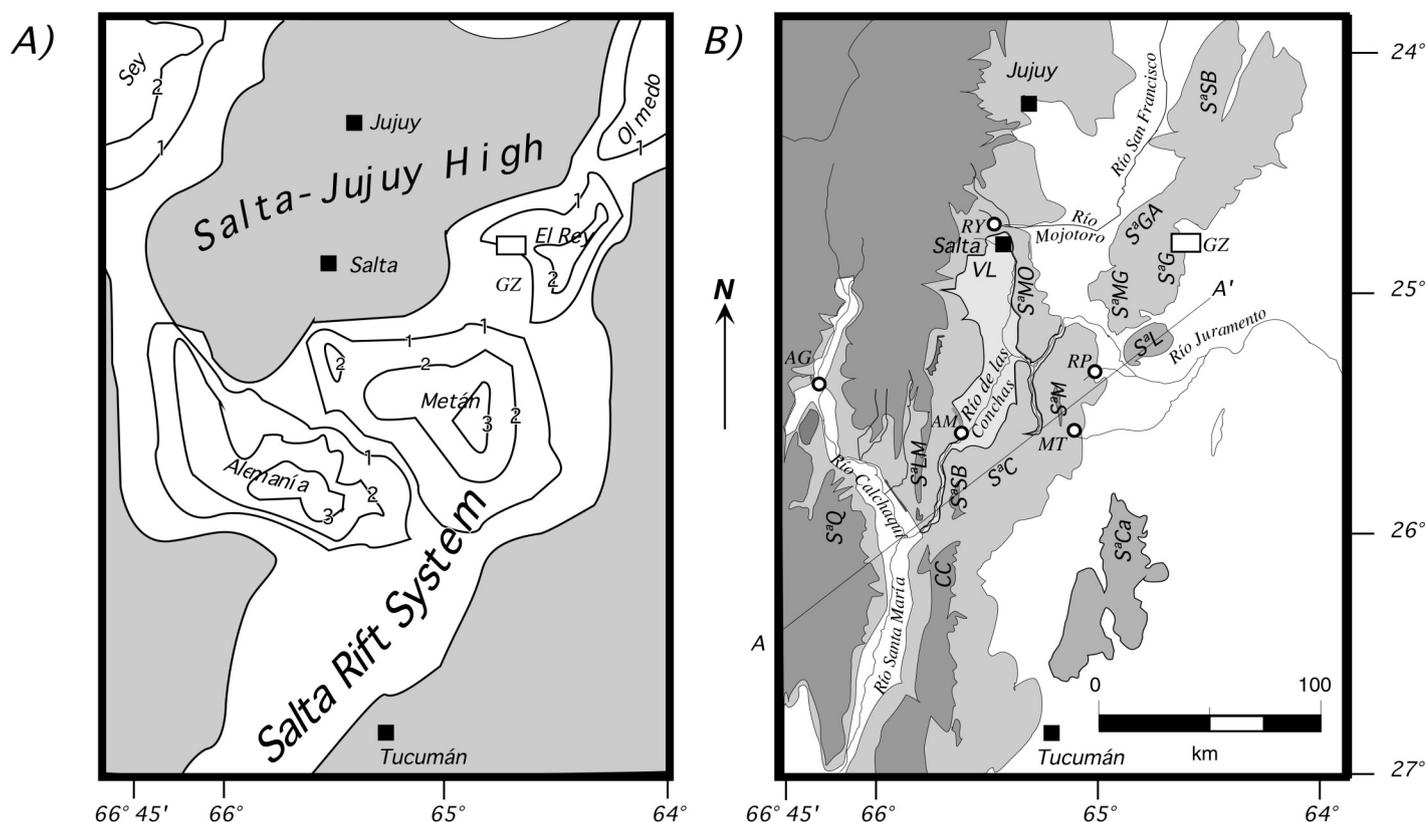
Structures in this province exhibit affinities with the basement block uplifts of the Sierras Pampeanas immediately to their south. The basement cores of the Sistema de Santa Bárbara ranges have not been unroofed due to a thick sedimentary cover provided by infilling of the Salta rift basin thrusting (Allmendinger et al., 1983). Like the Sierras Pampeanas, the Sistema de Santa Bárbara is characterized by predominantly broad, low-amplitude folds generated by predominantly westward-vergent thrusting (Allmendinger et al., 1983).

Gebhard et al. (1974) summarized the Tertiary lithostratigraphic units and published a good regional geologic map. Other stratigraphic contributions by Russo and Serraiotto (1978) and Mingramm and Russo (1972) constitute the basis of the stratigraphic work in the region. Jordan and Alonso (1987) included the province in their regional analysis of the Subandean zone.

To the north of the Transition Zone, the Subandean zone on the east side of the Cordillera Oriental is occupied by the Sierras Subandinas. The Sierras Subandinas arose along predominantly eastward-verging thrust faults, beginning in the late Miocene (Hernández et al., 1996, 1999; Reynolds et al., 1993, 1996). Nearly all of the rocks exposed in this region are Neogene foreland basin-filling strata. These rocks were uplifted and exposed as eastward-migrating thrusting progressed through western parts of the Subandean basin. Older strata are exposed in Bolivia. The region has recently received much attention from the petroleum industry (Belotti et al., 1995; Hernández et al., 1996, 1999; Moretti et al., 1996; Giraudo et al., 1999), but is still relatively unknown in the geologic literature.

**Field Area**

Our work was conducted in the El Rey subs basin area of the Salta rift (Fig. 3A). Arroyo



**Figure 3.** Location maps of localities referred to in this work. (A) Map of the Salta rift, modified from Marquillas and Salfity (1988), showing Salta rift subbasins and the Salta-Jujuy high. Isopachs (in km) denote the thickness of Salta Group strata in the various subbasins. The Tres Cruces subbasin (not shown) trends northward north of Jujuy (Fig. 1). (B) Map showing the location of mountain ranges, rivers, valleys, and paleomagnetic sections. The mountain ranges are: CC—Cumbres Calchaquíes, SC—Sierra de Carahuasi, SCa—Sierra de Candelaria, SGA—Sierra de Gallo, SG—Sierra de González, SLM—Sierra del León Muerto, SL—Sierra de Lumbreira, SMG—Sierra de Maíz Gordo, SM—Sierra de Metán—Sierra del Crestón, SMO—Sierra de Mojotoro, SQ—Sierra de Quilmes, SSB—Sierra de Santa Bárbara. VL—Valle de Lerma. The paleomagnetic sections (white circles) are: AG—Angastaco, AM—Alemania, MT—Río Metán, RP—Río Piedras, RY—Río Yacones. A map of the Arroyo González (GZ) area (white rectangle) is shown in Figure 4. White areas are lowlands and valleys. Light gray areas are relative highlands, generally at elevations between 1500 and 3000 m. Dark gray areas are highlands with elevations above 3000 m, including a basin outlined in the northwest corner high on the Puna.

González is located on the eastern flank of the Sierra de González in the eastern Sistema de Santa Bárbara (Fig. 3B). It is one of many tributaries of the Río Juramento, the trunk stream in the region. Headwaters of the antecedent Río Juramento flow from the eastern flank of the Puna, northern Sierras Pampeanas, and Cordillera Oriental (Fig. 3B). Located in the eastern portion of the Transition Zone, the Arroyo González section provides the best-exposed and thickest record of middle Miocene distal foreland basin sedimentation at  $\sim 25^{\circ}\text{S}$ .

The Sierra de González is located in the eastern part of the Salta rift and was uplifted along a westward-verging fault. Mon and Salfity (1995) attributed the westward vergence to a backthrust splaying off an eastward-verging fault that probably is a reactivated Cretaceous normal fault. The Sierra de González is a broad anticlinal structure that exposes Devo-

nian, Upper Cretaceous, Paleogene, and Neogene strata (Fig. 4). Most of the mountains in this region strike north-northeast, but the Sierra de González and the ranges immediately to the west have a northerly strike.

## STRATIGRAPHY

### Pre-Neogene Strata

The subbasins filled with synrift continental clastic sediment and basalt flows of the Upper Cretaceous Pirgua Subgroup at the base of the Salta Group (Table 1). The Salta Group continued infilling with postrift strata throughout the Late Cretaceous and Paleogene. The only significant departure from clastic sedimentation was the deposition of limestone and marl in the Maastrichtian Yacoraite Formation. The Yacoraite limestone is the major source and

reservoir rock for the hydrocarbon resources in this area. Above the Yacoraite Formation is the Lumbreira Formation, which consists of dark reddish sandstones, siltstones, and mudstones deposited in Paleocene and Eocene time (Sempere et al., 1997).

### Orán Group

We investigated the Orán Group, a package of Neogene, continental, foreland basin-filling units distributed unevenly across the Transition Zone above the Salta Group. A disconformable relationship exists between the Lumbreira Formation and the overlying Orán Group (Gebhard et al., 1974; Russo and Serraiotto, 1978), where our work took place.

Orán Group strata in the Arroyo González section are  $\sim 5000$  m thick (Gebhard et al., 1974). They provide the distal record of oro-

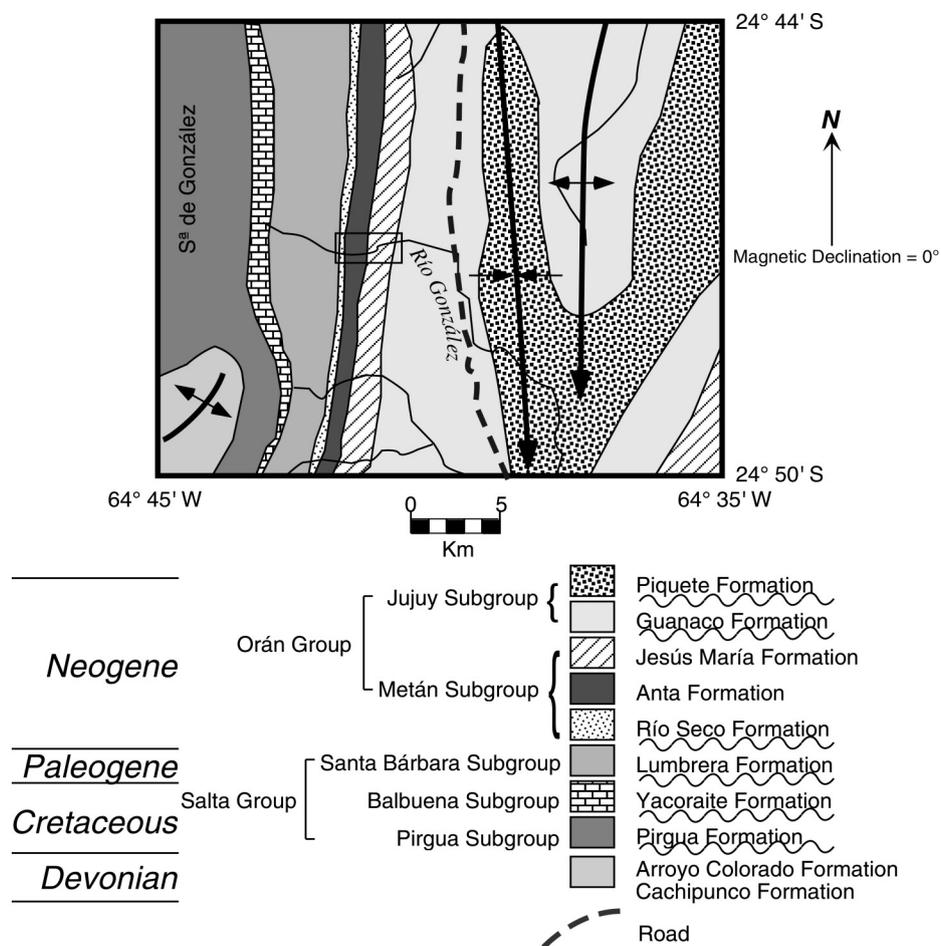


Figure 4. Geologic map of the Arroyo González area, modified from Gebhard et al. (1974). The paleomagnetic section (rectangle) covered the Metán Subgroup and terminated in the lower part of the Guanaco Formation.

genic activity in the Andes 60–200 km to the west. The wide distribution of the lower units suggests deposition across a region with little topographic relief. The modern Chaco Plain (Fig. 1) may be similar to some of the Neogene environments within the Cretaceous rift.

The Río González crosses a nearly complete section of the Orán Group (Fig. 4). These strata are subdivided into the Metán and Jujuy Subgroups (Table 1). The older Metán Subgroup is generally fine grained, in contrast with the much coarser grained Jujuy Subgroup strata.

Relatively good (~60%) exposure of the Metán Subgroup is present in Arroyo González (Fig. 5). Outcrops of these moderately consolidated strata are fresh due to incision of the stream into the rising flank of the range. Jujuy Subgroup strata are poorly exposed, because incision on the eastern anticlinal limb diminishes with decreasing stream gradient.

#### Metán Subgroup

The Metán Subgroup is subdivided into three formations (Gebhard et al., 1974). The basal Río Seco Formation unconformably overlies the Paleogene strata. It is overlain by the Anta Formation, which is capped by the Jesús María Formation (Figs. 4 and 5). An unconformity at the top of the Jesús María Formation separates the Metán Subgroup from the superposed Jujuy Subgroup.

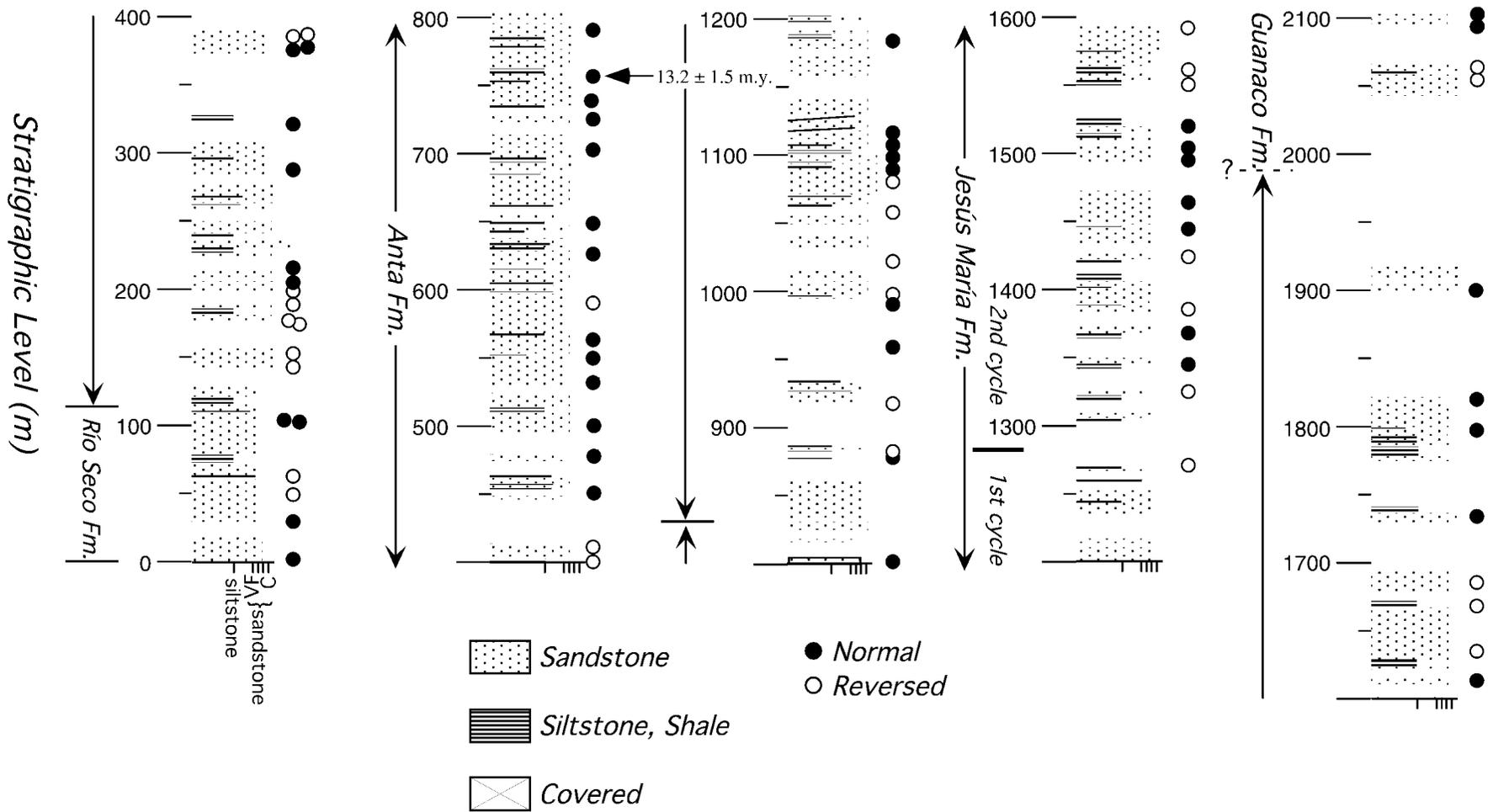
**Río Seco Formation.** The Río Seco Formation is spatially associated with the sides of the rift basin and tends to be absent in the central part of the basin. Reddish sandstones and siltstones with conglomeratic lenses make up the entire formation. It is exposed in streams cutting into the flanks of most ranges in the Sistema de Santa Bárbara (Gebhard et al., 1974). At Arroyo González, Río Seco strata are ~110 m thick (Fig. 5).

On the basis of lithostratigraphic correlation with distant fossil-bearing beds, the Río Seco Formation was considered to be early Eocene by Gebhard et al. (1974). Other workers suggested that the unit was Eocene to Oligocene (Mingramm and Russo, 1972) and Oligocene to Miocene (Russo and Serraiotto, 1978). Preliminary results by Reynolds et al. (1994) demonstrated a middle Miocene age based on magnetostratigraphic data and isotopic dating; those data are presented here.

**Anta Formation.** Unlike the Río Seco Formation, the Anta Formation is a widespread unit found across the Sistema de Santa Bárbara. The Anta Formation is ~265 m thick in the Cordillera Oriental, near Alemaña (Fig. 3B), and thickens to the east (Galli, 1995). At Arroyo González and other parts of the eastern Sistema de Santa Bárbara, the unit is ~720 m thick. Anta beds are characterized by predominantly red, very fine grained sandstones, siltstones, and mudstones (Gebhard et al., 1974). The strata are generally well laminated. Oolitic limestones are present in restricted marine horizons in some parts of the Anta Formation (Russo and Serraiotto, 1978; Galli et al., 1996). No marine strata were recognized in Arroyo González. Greenish horizons found in the formation mark the presence of volcanic air-fall beds.

Gebhard et al. (1974) assigned an Eocene to Oligocene age to the unit near Alemaña, on the basis of a correlation with what they believed to be laterally equivalent, fossil-bearing units. We obtained a  $13.2 \pm 1.5$  Ma fission-track age from zircons collected from a tuff at the 760 m level at Arroyo González (Table 2). Isotopic ages from two other Anta Formation sections to the southwest of Arroyo González also provide middle Miocene ages. A zircon fission-track sample from an intercalated tuff at Alemaña (Fig. 3B) gave an age of  $14.5 \pm 1.4$  Ma (Table 2) and hornblende from a tuff collected in the lower part of the Anta Formation at Río Piedras (Fig. 3B) produced an  $^{40}\text{Ar}/^{39}\text{Ar}$  date of  $13.95 \pm 0.72$  Ma (Table 2). Reynolds et al. (1994) dated the lowest exposed Anta beds as 15.2 Ma at Río Piedras using magnetic stratigraphy (Fig. 3B), but the base of the formation is not exposed (Galli et al., 1996). They placed the contact with the overlying Jesús María Formation at 14.2 Ma at Río Piedras.

**Jesús María Formation.** The Jesús María Formation concordantly overlies the Anta Formation. Like the Anta Formation, it is widely distributed across the Sistema de Santa Bárbara. It is characterized by red and gray interbedded siltstones, sandstones, and intraformational conglomerates. At Arroyo González,



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Figure 5. The Arroyo González stratigraphic section (adapted from Yacimientos Petrolíferos Fiscales field records). Paleomagnetic site locations and their polarities are marked with black and white circles. The dated tuff is located at the 760 m level in the Anta Formation.

TABLE 2. FISSION TRACK AGES (ZIRCON) FROM AIR-FALL VOLCANIC BEDS IN THE ANTA FORMATION

Sample number	$\rho_s$ (tracks/cm <sup>2</sup> )	$\rho_i$ (tracks/cm <sup>2</sup> )	Grains (number)	Age (Ma $\pm$ 2 $\sigma$ )
Arroyo González GZT-3	$2.49 \times 10^6$ (638)	$6.74 \times 10^6$ (1725)	5	$13.2 \pm 1.5^*$
Alemanía AMT-2	$7.71 \times 10^6$ (785)	$3.49 \times 10^7$ (1777)	5	$14.5 \pm 1.4^*$

\*zeta—342 (SRM 962);  $\rho_d$ — $2.094 \times 10^5$  (2010 tracks).  
†zeta—319.6 (SRM 962);  $\rho_d$ — $2.05 \times 10^5$  (2878 tracks).

TABLE 3. <sup>40</sup>Ar/<sup>39</sup>Ar—TOTAL FUSION AGE (HORNBLLENDE) FROM AIR-FALL VOLCANIC BEDS IN THE ANTA FORMATION

Sample number	<sup>40</sup> Ar/ <sup>39</sup> Ar	<sup>37</sup> Ar/ <sup>39</sup> Ar	<sup>36</sup> Ar/ <sup>39</sup> Ar	<sup>39</sup> Ar <sub>K</sub> (moles)	<sup>40</sup> Ar* (%)	Age (Ma $\pm$ 2 $\sigma$ )
Río Piedras RPT-1	1.5815	1.7452	0.002445	$2.79 \times 10^{-12}$	61.67	$13.95 \pm 0.72$

Note: Ratios corrected for extraction line blank, discrimination (0.33%/m.u.), and decay of <sup>37</sup>Ar and <sup>39</sup>Ar.  $J = 0.0079470 \pm 0.5\%$ .  $(^{40}\text{Ar}/^{39}\text{Ar})_K = 2.4 \times 10^{-2}$ ,  $(^{36}\text{Ar}/^{37}\text{Ar})_{Ca} = 2.8 \times 10^{-4}$ ,  $(^{39}\text{Ar}/^{37}\text{Ar})_{Ca} = 7.0 \times 10^{-4}$ . Age calculated using the decay constants recommended by Steiger and Jäger (1977).

TABLE 4. CONTACT AGES WITHIN THE METÁN SUBGROUP AT ALEMANÍA, RÍO PIEDRAS, AND ARROYO GONZÁLEZ

Contact	Alemanía* (Ma)	Río Piedras† (Ma)	Arroyo González (Ma)
Top of Jesús María	N.P.	ca. 13.0	ca. 9.7
Anta–Jesús María	14.8–14.6 (14.7 est.)	14.9–14.8	ca. 13.7
Río Seco–Anta	15.0–14.9	>15.2	ca. 14.8
Base of Río Seco	N.P.	N.P.	ca. 15.1

Note: N.P.—not present.

\*Reynolds et al. (1994)—Magnetostatigraphy revised to Cande and Kent (1995) global polarity time scale (GPTS).

†Galli et al. (1996)—Magnetostatigraphy revised to Cande and Kent (1995) GPTS.

the Jesús María Formation exhibits two subtle coarsening-upward cycles (Fig. 5). The upper cycle is truncated disconformably by the overlying Guanaco Formation. The Jesús María Formation also thickens toward the east, attaining a thickness of ~1120 m at Arroyo González. On the basis of a K-Ar date from an interbedded air-fall tuff at nearby Río Castellanos, Gebhard et al. (1974) considered the Jesús María Formation to be an Oligocene unit. Reynolds et al. (1994) showed that the magnetic stratigraphy corresponds to middle Miocene time between 14.2 Ma and ca. 13.0 Ma at Río Piedras (Table 3).

### Jujuy Subgroup

The Jujuy Subgroup consists of the older Guanaco and younger Piquete Formations (Fig. 4). Only the basal part of the Guanaco Formation was sampled in the Arroyo González paleomagnetic section.

**Guanaco Formation.** In most places the Guanaco Formation unconformably overlies the Jesús María Formation (Gebhard et al.,

1974). The contact is usually disconformable, but an angular unconformity is observed in some areas. Like the Jesús María Formation, the Guanaco Formation coarsens upward. These beds are found in intermontane basins across the Transition Zone and exhibit basin-dependent compositional variation.

The contact is not exposed in Arroyo González. Guanaco Formation strata commonly exhibit medium- to coarse-grained grayish-red sandstones and conglomerates with interbedded red to orange siltstone horizons. The basal strata frequently resemble those of the Jesús María Formation, making distinction of the two units subtle.

Due to a rapid upsection increase in distances between exposures, the only Guanaco Formation paleomagnetic samples were obtained from the basal 120 m (Fig. 5). Gebhard et al. (1974) estimated the total thickness in this area to be ~2150 m. On the basis of an isotopic age they assigned a middle to late Miocene age to the formation. Viramonte et al. (1994) dated a 900-m-thick portion of the Guanaco Formation as 10.9–6.9 Ma (modified

here to the Cande and Kent [1995] global polarity time scale) at Río Yacones, ~100 km west of Arroyo González (Fig. 3B).

**Piquete Formation.** The Piquete Formation is composed of dark red to pinkish beds of polymictic cobble to boulder conglomerate, coarse- to fine-grained sandstone, and rare siltstone. Portions of the Piquete Formation are exposed farther downstream in Arroyo González (Fig. 4), but were not sampled in our study. Limestone clasts are common within the Piquete Formation in this area. Gebhard et al. (1974) estimated a thickness of 830 m for the Piquete Formation along the Río González and assigned a Pliocene age to the unit. Reynolds et al. (1994) confirmed this age with 5–2 Ma magnetostratigraphic ages from the Piquete Formation at Río Metán (Fig. 3B). Malamud et al. (1996) reported a Pleistocene fission-track age from a tuff in the upper part of the Piquete Formation from the Lerma Valley ~100 km to the west of Arroyo González (Fig. 3B).

### Paleocurrent Data

Ripple marks, cross-beds, and pebble imbrication indicate west-directed paleoflow throughout the Río Seco Formation (Galli, 1995). This continues into the lower portion of the Anta Formation at Arroyo González, as indicated by cross-bedding in fine-grained sandstones. In the upper part of the Anta Formation, however, the paleoflow direction is toward the east (Galli, 1995). Ripple marks, cross-bedding, and pebble imbrication suggest a west to east transport throughout the Jesús María Formation.

### Interpretation

The Río Seco Formation is interpreted to represent an ephemeral fluvial system derived from the craton to the east. The Anta Formation represents a playa lake and/or mudflat system. The lake was connected to the marine environment during a sea-level highstand. The reversal of source directions between lower and upper portions of the unit suggests that the lake migrated eastward.

Jesús María Formation strata indicate a return to an ephemeral stream depositional environment. Deposition migrated eastward, following the Anta depocenter. The Jesús María coarsening-upward cycles at Arroyo González suggest two uplift events in the source area.

We associate the Guanaco Formation with a high-energy fluvial environment. These strata are best modeled as distal facies of an alluvial fan. The very coarse grained Piquete

Formation can best be interpreted as a medial alluvial fan deposit, probably related to uplift of the Sierra de González, the nearest source for the limestone clasts.

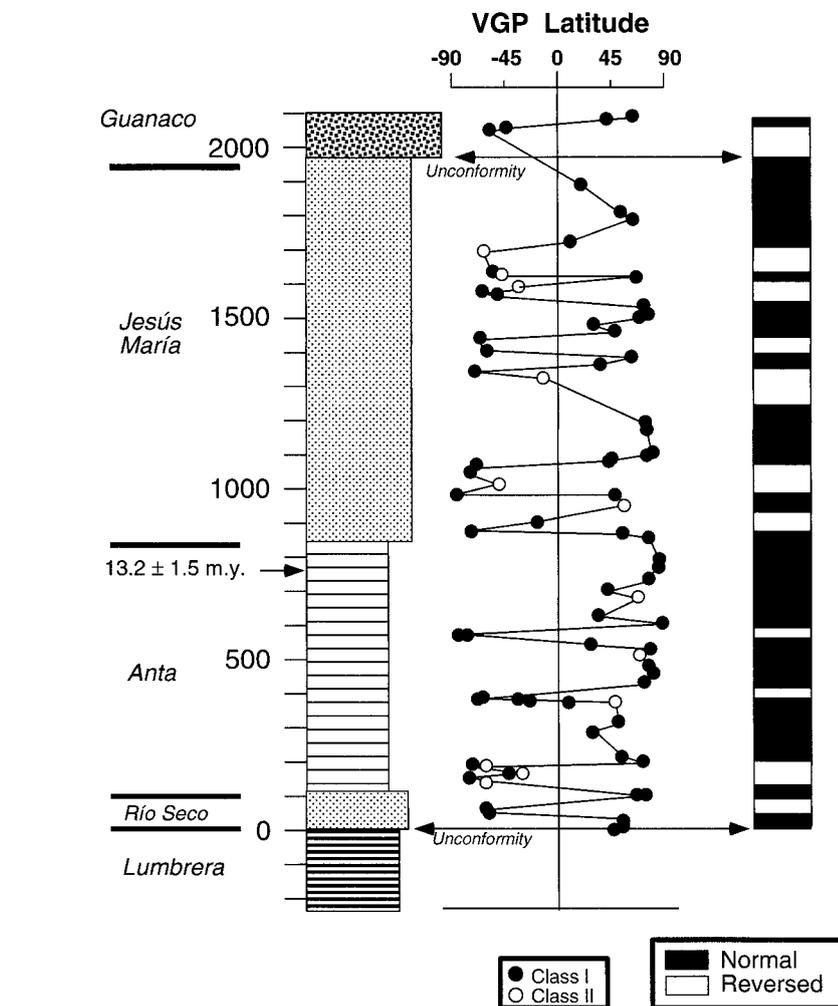
### MAGNETOSTRATIGRAPHY OF THE ARROYO GONZÁLEZ SECTION

Magnetic polarity stratigraphy was used to correlate ~2105 m of detrital beds from the Arroyo González section with the global polarity time scale (GPTS). Our sampling program included the complete Metán Subgroup and the lowest 120 m of the overlying Guanaco Formation. We found 22 geomagnetic field reversals in the section, defining 23 polarity zones (Fig. 6). A summary of the paleomagnetic collections, laboratory techniques, and data analysis is reported in the Appendix.

A  $13.2 \pm 1.5$  Ma zircon fission-track age (Table 2) from an ~2-m-thick air-fall tuff at the 760 m level in the upper part of the Anta Formation is used to calibrate the magnetostratigraphic column with the GPTS (Cande and Kent, 1995). The wide error range of the fission track age (14.7–11.7 m.y.) allows possible correlations with several different GPTS normal polarity zones. We choose the correlation shown in Figure 7 because it allows the closest pattern match with the GPTS. All other possible correlations force correlation of a long polarity zone with a short zone on the GPTS, or vice versa. Such correlations would result in erratic changes in the sediment accumulation curve (Fig. 8). We see no field evidence to support widely varying sediment accumulation rates and choose the interpretation that produces the sediment accumulation rate shown in Figure 8.

In our correlation we place the base of the Neogene portion of the section at ca. 15.1 Ma (Fig. 7). Our correlation in the Guanaco Formation at the top of the section is tenuous, due to diminished exposure and the disconformable relationship between the Jesús María and Guanaco Formations. We tentatively place the top of the Jesús María Formation at ca. 9.7 Ma based on extrapolation of the sediment accumulation rate below the formation boundary (Fig. 8). Given the polarity change in the vicinity of an unexposed unconformity and lack of outcrop, the age may be as old as ca. 10 Ma. Alternative interpretations are shown in dashed gray lines in Figure 7. In this interpretation the top of the paleomagnetic section is no older than ca. 9 Ma.

In our temporal interpretation, three short normal polarity zones were missed in the Metán Subgroup: two between 13.0 and 12.5 Ma and one between 11.5 and 10.9 Ma. Polarity



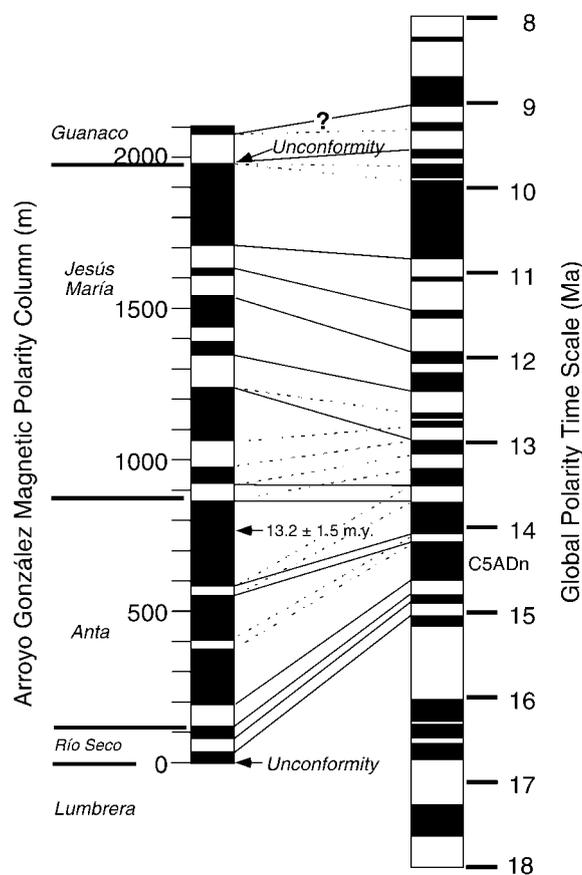
**Figure 6. Plot of virtual geomagnetic pole (VGP) latitude of paleomagnetic sites vs. stratigraphic level. Polarities are abstracted to the standard black and white magnetic polarity scale to the right. Reversals are placed halfway between sites of different polarities except at the unconformable contact between the Jesús María and Guanaco Formations.**

zone durations vary between 30 and 60 k.y. (Cande and Kent, 1995). Given the vicissitudes of continental sedimentation, deposition may not have occurred during some of these intervals. It is also probable that our sample spacing was not detailed enough to encounter all reversals present in the section.

Our correlation reveals one short reversed polarity zone, between 380 and 400 m (Figs. 6 and 7), that is not seen on the GPTS (Fig. 7). It was found in the middle of polarity chron C5ADn (14.612–14.178 Ma; Cande and Kent, 1995). Reynolds et al. (1990) showed a magnetic excursion within this same polarity interval at Las Juntas in La Rioja Province, Argentina. An excursion is also seen at Río Piedras (Galli et al., 1996). McDougall et al. (1984, their Fig. 4) reported a reversal at about this same time in the latitude of virtual pole

column from the basaltic lava pile in northwest Iceland. We suggest that we serendipitously sampled this excursion. Its reversed polarity was confirmed at Arroyo González with four closely spaced (1 m) samples in 1995.

An alternative interpretation is that the reversed zone between 380 and 400 m is not an excursion within C5ADn but should be correlated with another chron (shown in dashed gray lines in Fig. 7). The alternative interpretation forces correlation of a 280-m-thick normal polarity zone (590–870 m) defined by nine stations (Fig. 6) with a GPTS normal zone that lasted ~210 k.y. This would translate to a sustained sediment accumulation rate of 1.33 mm/yr over the length of the polarity zone. This extremely rapid rate would appear as an accumulation spike in the Anta Formation. The Anta Formation exhibits no remark-



**Figure 7.** Correlation of the Arroyo González magnetic stratigraphy with the global polarity time scale of Cande and Kent (1995). The preferred correlation suggests that the Metán Subgroup was deposited between 15.1 and 9.7 Ma. A less favored alternative correlation is shown with dashed gray lines. Dashed gray lines at the top of the column provide alternate interpretations for the age of the unconformity.

able changes in its upper part to justify such a spike. To the contrary, its constitution is remarkable only in its uniformity in the upper 450 m (Fig. 5). For this reason and the reasons stated herein, we reject the alternative model in deference to a model with a short, new, reversely polarized zone between 14.612 and 14.178 Ma.

The ages of the formation boundaries, based on our correlation with the GPTS, appear in Table 3. The base of the Río Seco Formation is dated as 15.2–15.0 Ma at Arroyo González. The Río Seco–Anta contact is placed at 14.8 Ma and the Anta–Jesús María contact is placed at 13.7 Ma. The youngest Jesús María strata were deposited ca. 9.7 Ma at Arroyo González (Table 3).

A plot of the stratigraphic level of reversals vs. their age (Fig. 8) indicates a mean sediment accumulation rate of 0.3 mm/yr in the Río Seco Formation. This rate continues in the Anta Formation until ca. 14.5 Ma, when it doubles to 0.6 mm/yr. It then diminishes to

0.3 mm/yr in the Jesús María Formation. In contrast, sediment accumulated at a relatively constant rate of 0.3 mm/yr throughout the 2.3 m.y. for which there is a record at Río Piedras. At Río Piedras, <100 m of the Anta Formation are exposed and the Jesús María Formation is ~400 m thick (Galli et al., 1996). Due to the uncertainties in our correlation of the Guanaco Formation, we do not present its sediment accumulation history.

#### PROVENANCE STUDY

We collected 18 medium-grained sandstones from the Neogene portion of the Arroyo González section to study sediment provenance: 2 samples from the Río Seco Formation, 3 from the Anta Formation, 11 from the Jesús María Formation, and 2 from the Guanaco Formation. Except at the base of the unit, the Anta Formation was too fine grained for the method to be effective. Six additional sandstones were sampled from the Guanaco Formation within

the section investigated by Viramonte et al. (1994) at Río Yacones, west of Arroyo González (Fig. 3B).

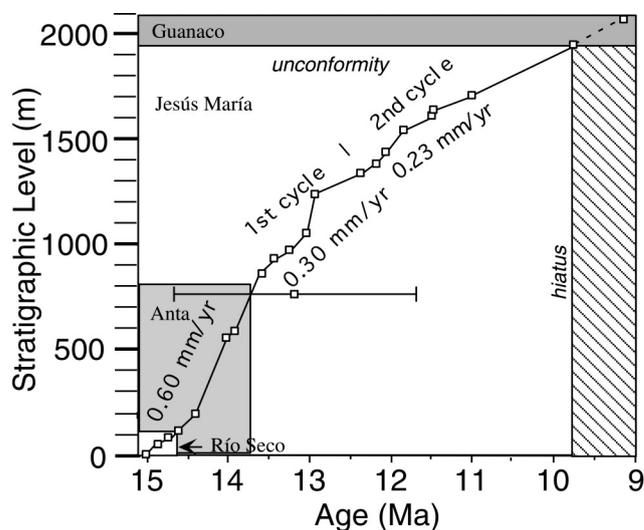
Provenance was determined using the modified Gazzi-Dickinson method, counting 300 points per slide (Ingersoll et al., 1984). Thin sections were stained using techniques described by Houghton (1980). Breakdowns of the lithic clast component are shown in Figure 9.

#### Arroyo González

The Arroyo González samples (Fig. 9A) show that percentages of metamorphic, plutonic, and volcanic clasts are high in the Río Seco and basal Anta Formations while sedimentary fragments are nearly absent. Greenish-gray tourmalines are also present in the two sandstones from the Río Seco Formation (ca. 15.1–14.8 Ma). Metamorphic fragments consist of schists and phyllites. The oldest part of the Jesús María Formation also contains an abundance of metamorphic, plutonic, and volcanic clasts with few sedimentary fragments. The sedimentary percentage increases in the lower third of the Jesús María Formation, beginning at the 1100 m level (13.1 Ma). This trend continues to the 1225 m level (ca. 12.9 Ma) and corresponds to decreases in both the metamorphic and plutonic components. Beginning at the 1225 m level (ca. 12.9 Ma), the sedimentary abundance decreases while the metamorphic percentage increases. These metamorphic fragments are overwhelmingly phyllites. At the top of the Jesús María Formation (ca. 11.5 Ma) sedimentary fragments increase again as the metamorphic and plutonic components diminish (Hilliard et al., 1996). Limited data from the Guanaco Formation suggest a decreasing sedimentary abundance upsection as metamorphic and plutonic abundances increase. The metamorphic fraction is composed of phyllite fragments.

Most metamorphic fragments seen in the sandstones were slates and phyllites from the Neoproterozoic–Cambrian Puncoviscana Formation exposed in the Puna and Cordillera Oriental. In the Río Seco sandstones, high-grade crystalline rocks are found along with slates and phyllites. The two metamorphic fragment pulses seen in the Jesús María Formation are overwhelmingly phyllites.

Vadose ooids (Carozzi, 1993) are present in the Jesús María Formation between the 1500 and 1600 m levels (11.9 to ca. 11.5 Ma). These were the only samples that contained secondary calcite.



**Figure 8.** Sediment accumulation history for the Metán Subgroup at Arroyo González using measured thicknesses. The sediment accumulation rate doubled ca. 14.5 Ma during deposition of the Anta Formation and at about the time that a reversal in paleocurrent flow direction took place. The point with error bars denotes the location and age of the dated tuff. Due to the presence of the unconformity at the top of the Jesús María Formation, the age of the Guanaco Formation (diagonal lines) and its sediment accumulation rate (dashed line) cannot be established.

### Río Yacones

Virtually all metamorphic fragments found in the Río Yacones sandstones (Fig. 9B) were phyllites from the Puncoviscana Formation. Sedimentary fragments are absent in the basal part of the section (older than 8 Ma); metamorphic and volcanic clasts account for most of the lithic content. The two uppermost samples (younger than 8 Ma) exhibit a much higher percentage of sedimentary fragments, accompanied by a decrease in the metamorphic content.

### INTERPRETATION

Westward-directed paleoflow directions in the Río Seco and lower Anta Formations combined with clasts of phyllites and high-grade metamorphic rocks suggest that sediment in this area was initially derived from a cratonic source. The onset of sediment accumulation indicates that foreland subsidence in this area, in response to the Puna uplift, began by ca. 15.1 Ma. The source of the sediment may have been the forebulge, but was more likely the eastern boundary of the rift basin, which is located ~45 km to the east. By this time the low-energy Anta depositional system was established to the southwest of the field area (Reynolds et al., 1994; Galli et al., 1996) in the Metán and Alemania subbasins (Fig. 3A). The reversal of paleoflow directions and the

rapid transition to a high sediment accumulation rate in the Anta Formation (Fig. 8) suggest that detritus shed from the rising Andes overwhelmed the local depositional system ca. 14.5 Ma (e.g., high volcanic content).

During Anta time at Arroyo González (ca. 14.8–13.7 Ma), the distal foreland region was covered by a playa lake and/or mudflat situated largely within the Cretaceous rift basin (Fig. 10). The same depositional environment is reported for part of this time at Río Piedras (Galli et al., 1996). Similar, contemporaneous facies are also found in the Río Mañero Formation ~500 km to the southwest in the western Sierras Pampeanas (Malizia et al., 1995), suggesting that this could be part of a vast distal foreland depositional system.

The high accumulation rate of westerly derived sediment in the Anta (Fig. 8) compared to the lower rate at Río Piedras (Galli et al., 1996) may be related to increased basin accommodation caused by anomalously rapid basin subsidence in the distal portion of the foreland. This possibility is supported by the location of the area in a subsiding foreland basin near the zone of weakness along the eastern boundary of the Salta rift.

The rise of the sedimentary lithic clast content in the lower Jesús María Formation (Fig. 9A), followed by a rise in metamorphic clast content as the sedimentary component decreases, suggests the unroofing of a rising

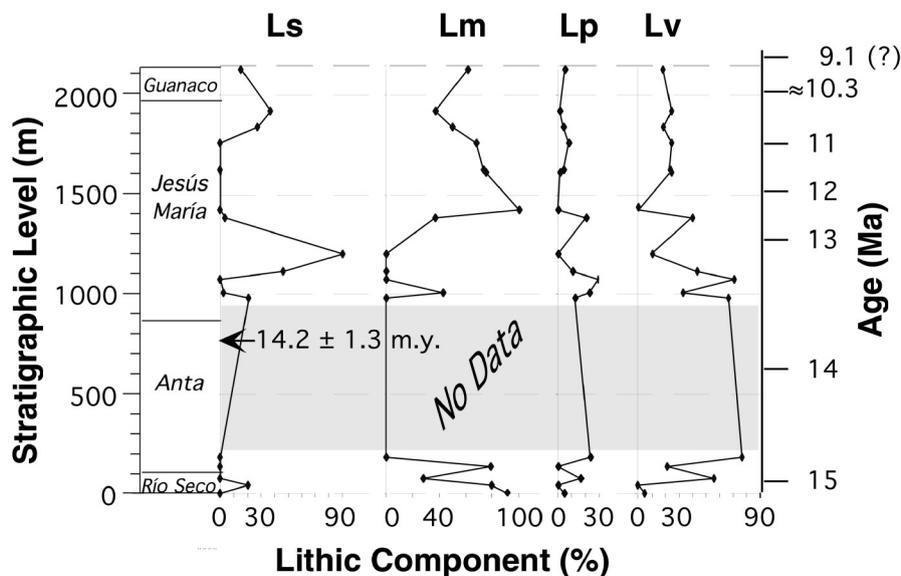
mountain range ca. 13 Ma. The second increase in sedimentary lithic fragments occurs at the top of the Jesús María Formation ca. 11.9–9.7 Ma. Metamorphic fragments increase in the basal Guanaco strata above the unconformity.

The presence of phyllite as the primary metamorphic component suggests possible source areas in the Puna, Cordillera Oriental, or the Sierra de Quilmes and Cumbres Calchaquíes, in the northern Sierras Pampeanas (Fig. 3B). Although the Puna is a possible source, Butz et al. (1995) found that Puna-derived sands contained both Puncoviscana phyllites and high-grade metamorphic fragments. Butz et al. (1995) eliminated the Sierra de Quilmes as a possible source by demonstrating that it began to rise ca. 12 Ma.

Cordillera Oriental uplifts exposing the Puncoviscana Formation are numerous. Ranges around the city of Salta are drained today by the Río Mojotoro (Fig. 3B). Sandstones from the Río Yacones section are all derived from the Cordillera Oriental and suggest that uplift and unroofing of one of the ranges began ca. 8 Ma. Rocks younger than ca. 6.4 Ma are cut by an eastward-verging fault at the Río Yacones section near the boundary between the Cordillera Oriental and the Sistema de Santa Bárbara (Viramonte et al., 1994). We cannot place a limit on the earliest Cordillera Oriental uplift at this latitude, but to the north of Jujuy, in the inclined subduction area, Reynolds et al. (1996) tentatively dated the initiation of Cordillera Oriental uplift as ca. 13 Ma.

The Río Juramento system drains the Sierra del León Muerto and the Sierra de Santa Bárbara in the western part of the Cordillera Oriental. It also has tributaries draining the Sierra de Carahuasi in the central part, and the Sierra de Metán–Sierra del Crestón on the eastern boundary, ~80 km southwest of Arroyo González (Fig. 3B). Vilela and García (1978) and Galván (1981) mapped the Sierra de Santa Bárbara in the western part of the Cordillera Oriental (Fig. 3B). (This is a different range from the eponymous range in the northern Sistema de Santa Bárbara; Fig. 3B.) The Sierra de Santa Bárbara in the western Cordillera Oriental is located immediately to the north of the Cumbres Calchaquíes (Fig. 3B) in the northern Sierras Pampeanas. The westward-verging thrust fault in the Sierra de Santa Bárbara (Vilela and García, 1978) terminates within the Puncoviscana in the Cumbres Calchaquíes (Galván, 1981) and suggests that uplift of the two is related. Grier and Dallmeyer (1990) demonstrated that there were positive topographic features in the northern Sierras

## A) Arroyo González



## B) Río Yacones

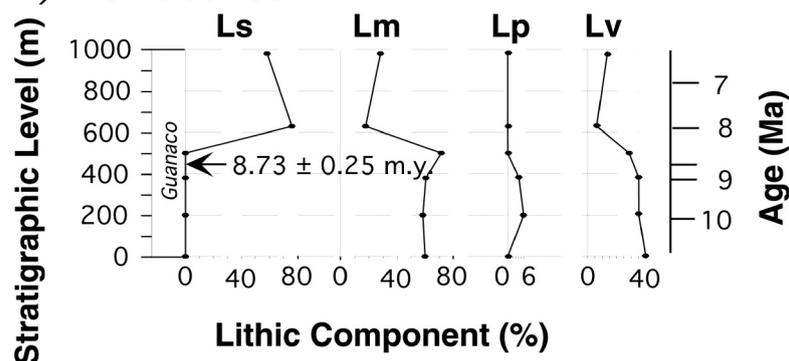


Figure 9. Results of sandstone provenance studies in (A) Arroyo González and (B) Río Yacones. Lithic fragment components are designated Ls—sedimentary, Lm—metamorphic, Lp—plutonic, and Lv—volcanic. The isotopic age in B was reported by Viramonte et al. (1994).

Pampeanas by that time. Given the age of the Sierra de Quilmes uplift (Butz et al., 1995), we suspect that the Sierra de Santa Bárbara and Cumbres Calchaquies are the sediment sources for the base of the Jesús María Formation, predating the rise of the Sierra de Quilmes. We cannot, however, eliminate the possibility of sources in the Sierra de León Muerto or Sierra de Carahuasi.

Uplift of the Sierra de Metán—Sierra del Crestón contributed the second pulse of lithic fragments, starting ca. 10.5 Ma. Support for this interpretation comes from work in the Orán Group at Río Piedras and Río Metán along the eastern base of the Sierra de Metán—Sierra del Crestón (Fig. 3B; Reynolds et al., 1994; Galli et al., 1996). Sedimentary beds

deposited 14–12 Ma are present in both sections, but neither section has strata deposited 11–10 Ma (Galli et al., 1996). In both areas, the 11–10 Ma interval is absent due to a significant unconformity, suggesting that these areas were positive features at that time.

Between Arroyo González and the Sierra de Metán—Sierra del Crestón are two Sistema de Santa Bárbara ranges: the Sierra de Maíz Gordo, to the west, and the Sierra Lumbreira, to the southwest (Fig. 3B). Our sampling and petrographic analyses were unable to establish the uplift ages of these ranges and the Sierra González because they are apparently recorded in strata above the top of our paleomagnetic section. This suggests that all three ranges rose after deposition of the top of the paleomagnetic

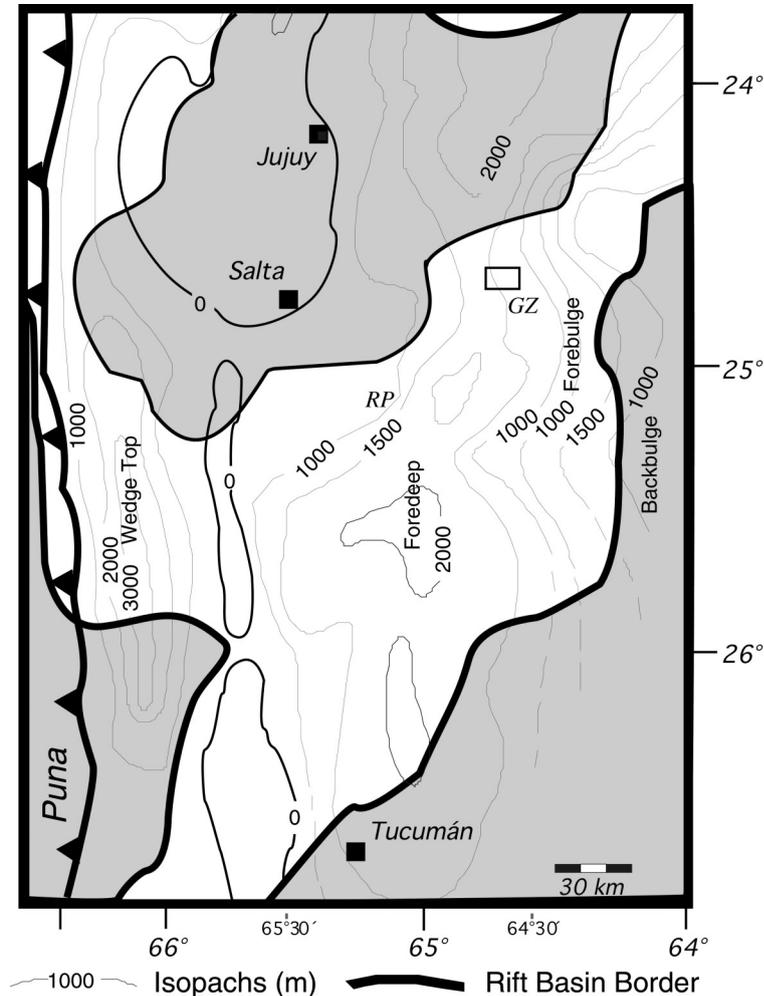
section, after ca. 9 Ma. We speculate that the distal fan facies of the Guanaco Formation, in the eastern Sistema de Santa Bárbara, will contain abundant sedimentary lithic fragments derived from the Sierra de Gallo, Sierra de Maíz Gordo, and the Sierra Lumbreira. These ranges probably arose in the late Miocene and Pliocene. Medial fan facies in the Piquete Formation, in the study area, were probably deposited as the Sierra de González rose in late Pliocene and possibly Pleistocene time.

The Río Seco, Anta, and Jesús María Formations (and probably the Guanaco and Piquete Formations) are diachronous across the Transition Zone (Table 3). The Río Seco—Anta boundary was dated between 15.0 and 14.9 Ma at Alemania (Reynolds et al., 1994). The base of the Anta Formation is older than 15.2 Ma at Río Piedras (Galli et al., 1996), but is 14.8 Ma at Arroyo González. The Anta—Jesús María contact is at 14.9–14.8 Ma at Río Piedras and 13.7 Ma at Arroyo González. The top of the Anta Formation at Río Piedras is contemporaneous with the top of the Río Seco at Arroyo González. Similarly, the strata at the top of the Jesús María Formation at Río Piedras are contemporaneous with those near its base at Arroyo González. The Jesús María—Guanaco contact is unconformable in both locations; the top of the Jesús María is ca. 13.0 Ma at Río Piedras (Galli et al., 1996) and ca. 9.7 Ma at Arroyo González. Younging-to-the-east diachroneity of formational contacts supports models that invoke eastward migration of uplift.

The vadose ooids found between 11.9 and 11.5 Ma suggest arid conditions during that time. Because this time interval does not correlate closely with the uplifts mentioned here, we attribute the aridity to climatic variation.

## TECTONIC SYNTHESIS

Uplift of the Puna spawned development of a foreland basin superposed on the Salta rift basin. The playa lake and/or mudflat environment of the Anta Formation was established at the basin center (Río Piedras; Table 3) before 15.2 Ma. The foreland basin began subsiding in the Arroyo González area by ca. 15.1 Ma, about the same time as internal drainage was established on the Puna (Vandervoort et al., 1995). Rivers draining the eastern boundary of the rift carried Río Seco sediment westward into the foreland region (Figs. 11A and 12A). Río Seco Formation deposition on the western side of the basin followed the residual topographic low of the Salta rift basin. Migration of the Anta Formation depositional environment first reached Arroyo González ca.



**Figure 10.** Isopach map of the Metán Subgroup and its lithostratigraphic equivalents (modified from Galli, 1995). A thick, poorly dated pile of wedge-top strata (Payogastilla Group) is present in the west to the east of the Puna thrust. The thickest accumulation of the Metán Subgroup corresponds to the eastern part of the Salta rift basin (white area). The Río Piedras section is located at RP.

14.8 Ma, but sediment flow from the west did not dominate in the area until ca. 14.5 Ma, when paleocurrent flow directions reversed and the sediment accumulation rate doubled.

Tectonic disruption of the western portion of the foreland basin began ca. 13 Ma as the Sierra de Santa Bárbara rose along a westward-verging thrust fault (Figs. 11B and 12B), in conjunction with uplift of the Cumbres Calchaquíes in the northern Sierras Pampeanas. Starting ca. 12 Ma (Figs. 11C and 12C), the Sierra de Quilmes, the northernmost range in the Sierras Pampeanas, began to rise (Butz et al., 1995) on the western boundary of the rift basin. This contrasts with the younger than 5.5 Ma age reported by Strecker et al. (1989) at the southern end of the range. We are unable to establish the uplift of the Sierra del León

Muerto, but speculate that it occurred between 13 and 11 Ma (Figs. 11D and 12D). Thrusting with mixed vergence rapidly migrated eastward across the central part of the rift basin. By 10 Ma (Figs. 11D and 12E), eastward-verging uplift of the Sierra de Metán–Sierra del Crestón commenced. The time of uplift of the Sierra de Carhuasi remains unknown, but we speculate that it also started to rise ca. 10 Ma.

We conclude that westward-verging thrusting in the Sistema de Santa Bárbara occurred after 9 Ma, uplifting the Sierra de Gallo, Sierra de Maíz Gordo, and Sierra de Lumbraera (represented by the Sierra de Lumbraera in Figs. 11E and 12F). Uplift of the Sierra de González area (Figs. 11F and 12F) accompanied the development of the Sistema de Santa

Bárbara province. We speculate that this is the youngest event, but precise uplift ages within the Sistema de Santa Bárbara are not yet established by chronostratigraphy. We cannot eliminate the possibility that post-middle Miocene uplift in the eastern part of the foreland basin migrated from east to west, as it appears to have done in the Sierras Pampeanas to the south (Malizia et al., 1995; Coughlin et al., 1998).

As Transition Zone thrusting migrated eastward, the foreland basin filled, driving additional eastward progradation. Flexural subsidence was impeded beyond the eastern side of the former rift basin due to the mechanical break at the rift boundary. Instead, the load produced by the eastward-migrating thrusting was accommodated by short-wavelength, high-amplitude subsidence in the zone of weakness along the boundary of the rift basin (Watts et al., 1995). This allowed continued deepening of the basin in the Arroyo González area, at least throughout the time of the Anta–Jesús María Formations (Fig. 9), during which the low-energy Anta environment gradually migrated eastward. It was eventually overwhelmed by progradation of the higher energy lithofacies of the Jesús María.

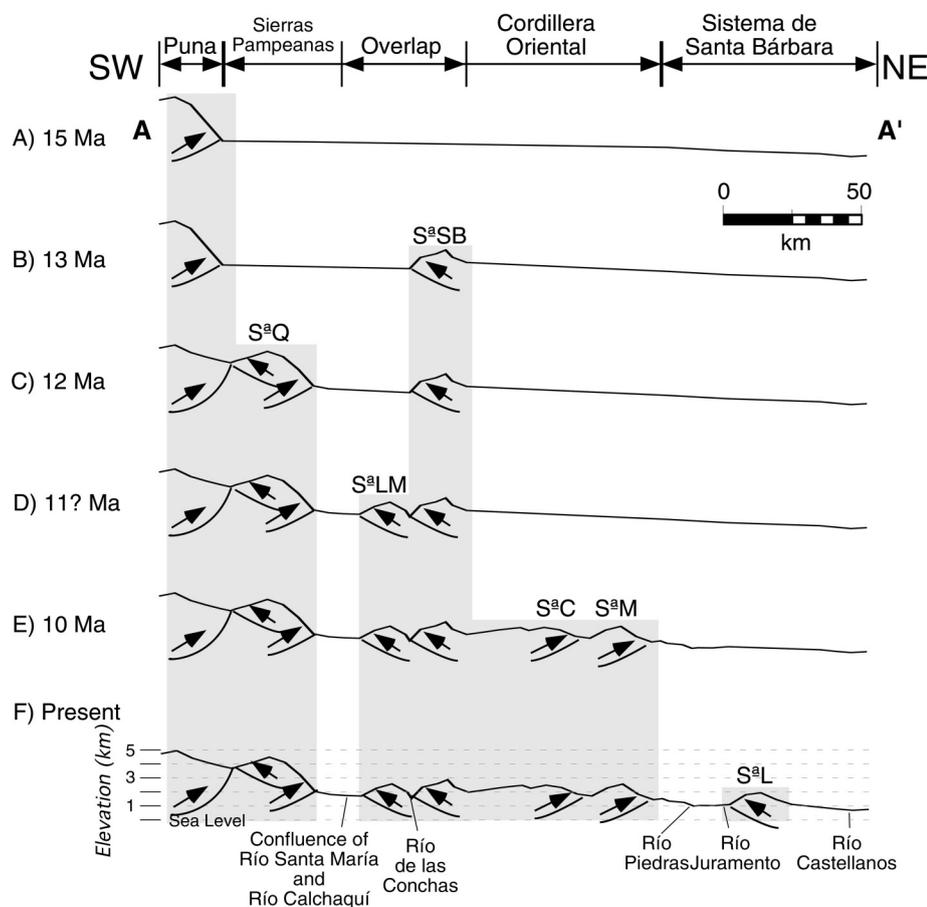
Data from Río Yacones suggest that uplift of the Cordillera Oriental in the northern part of the Transition Zone (Viramonte et al., 1994; Kotila et al., 1996) was contemporaneous with uplift in the Sistema de Santa Bárbara in the east (Fig. 11E).

### Drainage Pattern Development

Figure 11 depicts our model for the evolution of the modern drainage system. We assume that, once the internally draining Puna was established as a positive topographic feature ca. 15 Ma (Vandervoort et al., 1995), all rivers on the eastern flank of the plateau flowed eastward and then followed an axial drainage in the Salta rift basin. Westward-flowing streams on the east side of the Salta rift basin (Fig. 11A) were sourced on the craton.

By 13 Ma (Fig. 11B), uplift of the Cumbres Calchaquíes diverted eastward-flowing streams in the southwestern part of the map northward to form the Río Santa María. Further stream diversion occurred when the Sierra de León Muerto rose to form the south-flowing Río Calchaquí. The Río de las Conchas formed at the confluence of the Río Calchaquí and Río Santa María and flowed northeastward, probably along the base of the Salta–Jujuy high (Fig. 11C). We speculate that the Río de las Conchas joined the Río Mojotoro between Salta and Ar-





**Figure 12. Proposed model for the timing and sequence of uplift along cross-section line A–A' (Fig. 3B). Arrows indicate westward and eastward thrust vergence. Locations of individual ranges and elevations are based on modern topography. Crustal shortening and continuing uplift are not depicted. The overlap zone results from location of the Sierra de León Muerto to the north of the Sierras Pampeanas termination latitude.**

bandean zone of the foreland region, was not elevated until after 9 Ma. Uplift in the Subandean zone in the inclined subduction area to the north was probably initiated 9–8 Ma (Reynolds et al., 1996; Hernández et al., 1996, 1999).

#### APPENDIX 1. PALEOMAGNETIC COLLECTIONS, METHODS, AND ANALYSIS

Oriented samples were collected from 77 stations, initially at ~30 m stratigraphic intervals, in 1990. A minimum of three, fist-sized samples was collected at each station. An additional 21 stations were collected in 1992 and 1995 to support single-site polarity zones and to clarify problem areas. Sandstones were also collected in 1995 for petrographic analysis. Measurement of the section with a Jacob's Staff and Abney Level proceeded as the 1990 samples were collected. Sites were located with respect to an existing measured section provided by Yacimientos Petrolíferos Fiscales (Fig. 5).

Samples were generally collected from reddish siltstones or mudstones with the hope that the mag-

netic minerals would be sufficiently fine grained to retain a reliable magnetic signal. Some samples in the Anta Formation were very fine grained sandstones. All 1990 samples were milled into 2.5 cm cubes at Universidad Nacional de Salta. Samples collected in 1992 and 1995 were taken with a Pomero Drill using standard coring techniques.

The natural remanent magnetizations (NRM) of the 1990 samples were measured on the three-axis vertical ScT cryogenic magnetometer at the Hawaii Institute of Geophysics. The 1992 and 1995 samples were measured with the three-component 2G Superconducting Rock Magnetometer (SRM) at the University of Pittsburgh. NRM magnetic dipole moment per unit volume ( $M$ , amperes per meter) values varied between  $9.1 \times 10^{-3}$  A/m and  $1.3 \times 10^{-1}$  A/m.  $M$  values approximate an even distribution between the two extremes.

We subjected 12 samples to stepwise alternating field demagnetization experiments to determine the magnetic properties of the strata. This treatment was successful with some samples but with others failed to separate the components of the NRM. All other samples were subjected to stepwise thermal demagnetization (Fig. A1). Samples collected in 1990 were treated less rigorously than the 1992 and 1995

samples. They were demagnetized until they produced a consistent orientation, but were not completely demagnetized. The 1992 and 1995 samples were treated to total demagnetization. Results from the demagnetization experiments suggest that the principal carrier of remanent magnetization is hematite in the Río Seco and Anta Formations and both magnetite and hematite in the Jesús María Formation.

A statistical mean direction of the paleomagnetic vector was determined for each site using the method described by Fisher (1953). Statistically significant results, using the  $R$  statistic (Watson, 1956), suggested that the stable component of magnetization had been isolated. As used here, class I sites are those whose mean direction satisfies Watson's criteria. When the number,  $N$ , of samples = 3, an  $R > 2.62$  is considered to be statistically significant (Watson, 1956). Class II sites designate stratigraphic levels for which only two samples from the site survived to be analyzed.

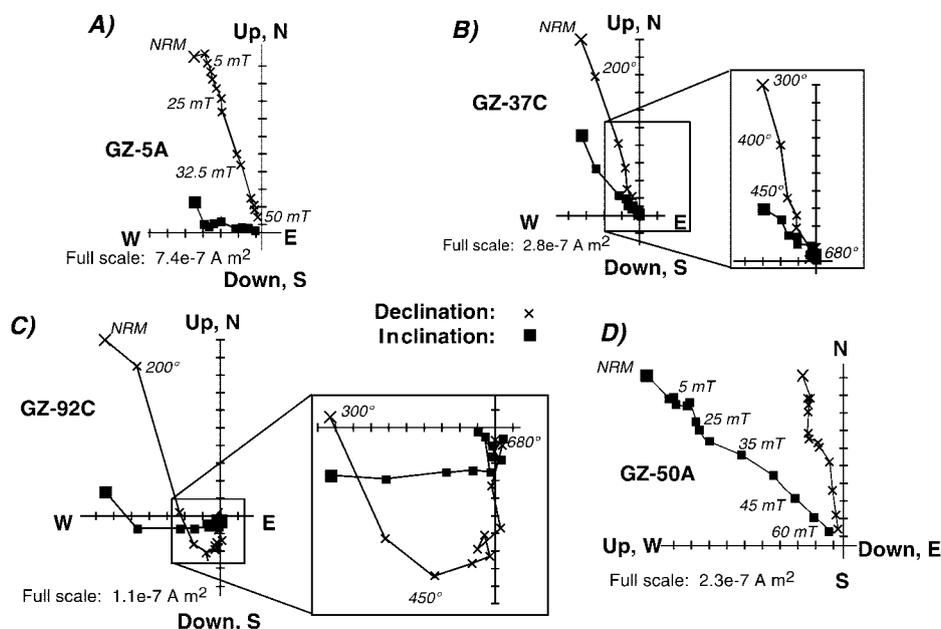
Of the 98 paleomagnetic sites, 8 were collected in the Lumbraera Formation and are not included in our data set. Of the Neogene sites, 79 are shown in the magnetic polarity column (Fig. 8). Of the sites, 67 provided class I data and 12 are class II. Six sites failed to fit into a class I or II category. Samples from five very friable horizons were destroyed during transport to the lab or during analysis. All of the sites that were destroyed and all of the indeterminate sites were collected in 1990 and were resampled during subsequent visits.

Figure A1 illustrates the thermal demagnetization behavior of one sample from the Río Seco Formation, two from the Anta Formation, and one from the Jesús María Formation. All exhibit a present-day viscous component that was removed by the first several thermal treatments, after which relatively stable readings were acquired and continued through high temperatures (680 °C) and field intensities (60 mT). Site GZ-5 (Fig. A1a) was collected from a red siltstone in the middle of the Río Seco Formation. After the initial alternating field treatment, it exhibited relatively stable behavior. Site GZ-37 (Fig. A1b) came from one of the green zones of the Anta Formation, just above the dated tuff. Site GZ-92 (Fig. A1c) is typical of the Anta redbeds. After removal of the normal viscous overprint, intensities remained relatively stable for both Anta samples, suggesting that hematite is the primary carrier of remanent magnetization. Site GZ-50 (Fig. A1d) is a typical Jesús María red siltstone from the middle part of the formation. Both magnetite and hematite appear to be carriers of remanent magnetization.

Accuracy of the paleomagnetic results was examined with a reversal test for the site means of all Neogene class I data (Fig. A2). Mean normal and reverse directions are within  $13.5^\circ$  ( $\gamma_c$ ) of antipodal, providing a positive reversal test (class C; McFadden and McElhinney, 1990). These results suggest that the magnetic component isolated by the demagnetization treatments represents the detrital remanent magnetization and not a thermal or chemical postdepositional overprint. Mean inclinations are considerably shallower than the projected  $\pm 44^\circ$  inclinations for this latitude. We attribute this discrepancy and the high  $\gamma_c$  to incomplete demagnetization of the 1990 sample set.

#### APPENDIX 2. ANALYTICAL PROCEDURES— $^{40}\text{Ar}/^{39}\text{Ar}$ DATING

Hornblende was separated from tuff RPT-1 by standard heavy liquid and magnetic techniques. Ad-



**Figure A1.** Vector end-point diagrams (Zijderveld, 1967) showing the thermal demagnetization of representative samples from the Arroyo González section. (A) GZ-5A—a red siltstone from near the top of the Río Seco Formation. (B) GZ-37C—a green siltstone from above the dated tuff in the Anta Formation. (C) GZ-92—a red siltstone from a possible new reversed zone between 14.2 and 14.6 Ma in the Anta Formation. (D) GZ-50A—a red siltstone from the middle of the Jesús María Formation. A normal overprint was removed from the sample by the first several treatments.

ditional cleanup was accomplished by hand-picking under a binocular microscope to achieve a final purity of >99%. The separate was packaged in Sn foil and sealed, together with other unknowns, in an evacuated quartz vial. Five packets containing ANU monitor mineral GA-1550 biotite (97.9 Ma; McDougall and Roksandic, 1974) were evenly spaced throughout the tube to monitor the vertical variation in neutron flux within the irradiation container.  $\text{CaF}_2$  and  $\text{K}_2\text{SO}_4$  were also included in the irradiation package to monitor neutron-induced interferences due to Ca and K, respectively. The samples were irradiated for 40 h in position L67 at the Ford Reactor at the University of Michigan.

Argon extraction was performed by fusing the sample in a double-vacuum tantalum resistance furnace and the evolved gas was purified on SAES getters and a cold finger cooled to liquid-nitrogen temperature. The argon isotopes were measured in a substantially modified, computer-controlled MS-10 mass spectrometer operated on-line to the extraction system. Blank contribution from the extraction line was  $\sim 1 \times 10^{-14}$  mol  $^{40}\text{Ar}$  at the extraction temperature of 1350 °C. The measured isotopic ratios were corrected for line blank, mass discrimination (0.33%/amu), radioactive decay of  $^{37}\text{Ar}$  and  $^{39}\text{Ar}$ , neutron-induced interferences on K and Ca, and atmospheric contamination. The uncertainty in the age reported for RPT-1 in Table 2 incorporates both the precision of the analytical measurements and a 0.5% uncertainty in the J value.

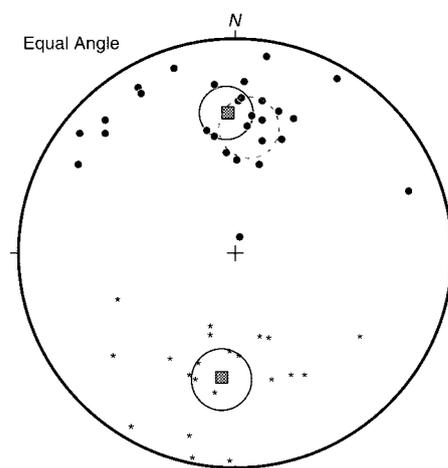
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**Figure A2.** Reversal test for class I data in the Arroyo González section. Class I, site-mean orientation data cluster in two antipodal groups and pass the reversal test (projection of the southern circle of confidence shown with the dashed gray circle). The mean declination for the normal sample is  $354^\circ$  with a mean inclination of  $-22.5^\circ$  and  $\alpha_{95} = 9.5^\circ$ . For the reversed sample, the mean declination is  $186^\circ$  with a mean inclination of  $+29.5^\circ$  and  $\alpha_{95} = 11.8^\circ$ . The mean normal and reverse directions are within  $\gamma_c = 13.5^\circ$  of antipodal, providing a positive reversal test (class C; McFadden and McElhinney, 1990). The projected inclinations should be  $\sim \pm 44^\circ$  for a site at this latitude. Low mean inclinations and the high  $\gamma_c$  are attributed to incomplete demagnetization of the 1990 sample set.

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