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Magnetostratigraphy of the Quebrada La Porcelana section, Sierra de Ramos, Salta Province, Argentina: age limits for the Neogene Orán Group and uplift of the southern Sierras Subandinas

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Abstract

We present a magnetostratigraphic investigation of Neogene Orán Group strata at Quebrada La Porcelana. The area is located in the southern Sierras Subandinas of northwestern Argentina within the zone of 'normal' subduction. The oldest datable Neogene strata were deposited ~8.1 Ma at the base of the Terciário Subandino. We estimate that the youngest strata are considerably younger than 1 m.y. The basal age is millions of years younger than lateral correlative units farther to the south in the Transition Zone. These chronostratigraphic results suggest that foreland thrusting was initiated much later in northernmost Argentina than it was in the Transition Zone.

The data suggest that generation and migration of hydrocarbons from the Los Monos source horizon began about 3.8 Ma. Growth strata deposition began at ~4.2 Ma, suggesting that trapping structures were available in the region when migration began.

Keywords: Magnetostratigraphy; Orán Group; Transition Zone; Sierras Subandinas

1. Introduction

Distinct structural provinces in the Andes Mountains of northwestern Argentina are closely related to the subduction angle of two segments of the Nazca Plate and an intervening Transition Zone (Jordan et al., 1983). Recognition of this relationship generated numerous chronostratigraphic studies in an attempt to establish the deformational history of the different structural provinces. To date, most of this work has focused on the 'flat' subduction area to the south (28–36°15′S) (Johnson et al., 1986; Bercowski et al., 1986; Reynolds et al., 1990; Jordan et al., 1990; Re and Jordan, 1999; Malizia et al., 1995; Milana, 1991; Irigoyen et al., 2000). Similar work has appeared, to a lesser extent, from strata in the Transition Zone (24–28°S) (Butler et al., 1984; Reynolds, 1990; Viramonte et al., 1994; Galli et al., 1996; Reynolds et al., 2000). Three abstracts (Reynolds et al., 1993, 1996, 2001), a preliminary report about the Río Iruya section (Hernández et al., 1996), and a synthesis of the Subandean tectonic history (Hernández et al., 1999) are the only published chronostratigraphic records from the 'normal' subduction area (10–24°S) in northern Argentina. Several papers concerning latest Oligocene–earliest Miocene strata are available for the Bolivian portion of this segment (MacFadden et al., 1985; McRae, 1990; Erikson and Kelly, 1995). Current lithostratigraphic usage unites Neogene strata of northernmost Argentina with moderately well-dated strata from the Transition Zone.

The Neogene stratigraphy of the Sierras Subandinas (Fig. 1) in the Argentine portion of the normal subduction area (22–24°S), has a complicated history due to a variety of nomenclatures applied by workers in the past. In this paper, we lay a chronostratigraphic foundation for the Neogene strata exposed in the east-central portion of the southernmost Sierras Subandinas in an attempt to clarify present problems in the current lithostratigraphic classification. Our chronology was developed with the aid of magnetostratigraphy supported by two $^{40}Ar/^{39}Ar$ ages from intercalated airfall tuffs. These data also appear in graphic format in Reynolds (1999) and Hernández et al. (1999).

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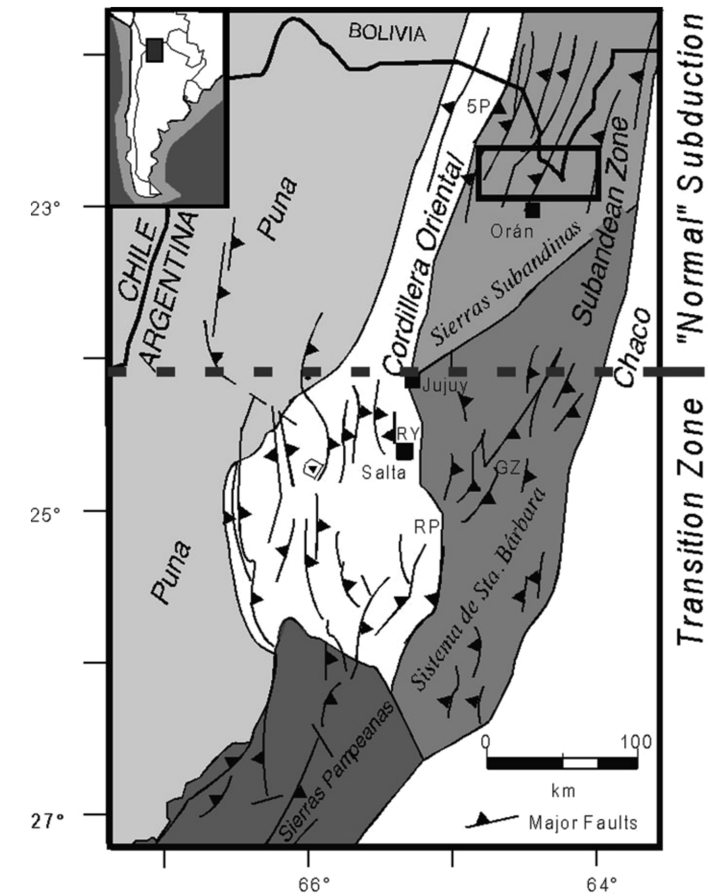

Fig. 1. Map showing the structural provinces of northwestern Argentina. The approximate boundaries of the Transition Zone are at 24 and 28°S. The rectangular area in the northeastern corner is shown in Fig. 2. Stratigraphic sections referred to in the text are GZ, Arroyo González; RP, Río Piedras; RY, Río Yacones. 5P denotes the Sierra de Cinco Picachos on the western edge of the Sierras Subandinas.

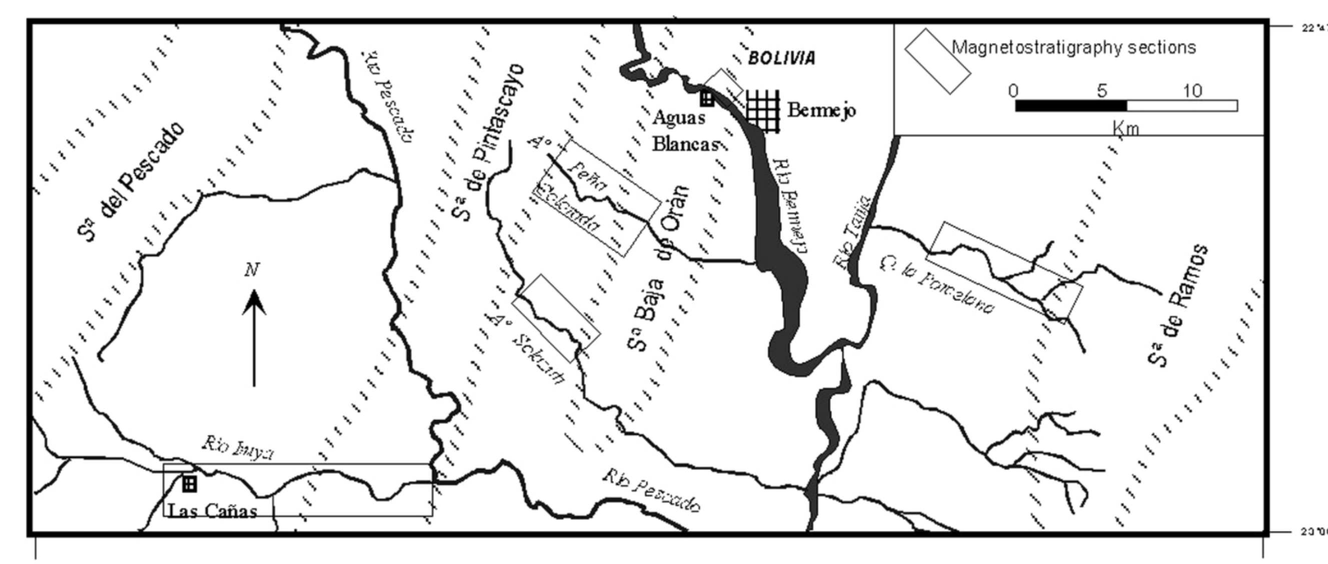

Fig. 2. Map showing the location of mountain ranges and magnetostratigraphy sections in the central Sierras Subandinas (adapted from Hernández et al. (1999)). The abbreviations used are S^a, Sierra; A°, Arroyo.

Lithostratigraphic Nomenclatures

"Normal" Subduction Area						Transition Zone		
Bonarelli (1921)		*Schlagintweit (1938)*	*Zunino (1944)*	***Current usage***		*Gebhard et al. (1974)*	*Russo (1972)*	
Terciário Jujeño	Orán Complex	Jujuy Formation	Terciário Subandino Superior	El Simbolar Terciário Subandino Superior	Orán Group	Piquete Fm. Guanaco Fm.	Jujuy Subgroup	Orán Group
Terciário Subandino		Chaco Formation	Terciário Subandino Medio	Terciário Subandino Medio		Jesús María Fm.	Metán Subgroup	
			Terciário Subandino Inferior	Terciário Subandino Inferior		Anta Fm. Río Seco Fm.		
Areniscas Superiores		Tranquitas Formation	Areniscas Superiores	Tranquitas Formation				

Fig. 3. Stratigraphic nomenclatures that have been applied to the strata discussed in this work (adapted from Gebhard et al. (1974)).

2. Field area

The Quebrada La Porcelana section crops out on the western flank of the Sierra de Ramos anticline (Fig. 2) in a ravine incised by the Río Seco. The Sierra de Ramos is the southernmost structure in the N–S striking, box-folded San Antonio range (Belotti et al., 1995). Its southern terminus is near the normal faults on the northern margin of the Lomas de Olmedo Sub-basin of the Cretaceous Salta Rift in the Transition Zone.

At the western base of the range, the Río Seco empties into the Río Tarija, which serves as the international border with Bolivia (Fig. 2). Structurally, the Río Seco is located along the western limit of the Sierras Subandinas Orientales. Most of the >4-km Neogene strata are exposed, but some parts are covered with dense subtropical vegetation. Numerous gaps are present in the lowest 2000 m, but a nearly complete section is found in the upper 2000 m. The section is only accessible on foot. A road that provides access to the drilling pads along the crest of the anticline intersects a tributary of the Río Seco (Fig. 2). A path worn by smugglers bearing contraband from Bolivia must be followed for ~3 km along the tributary before reaching the main stream where the section was sampled.

3. Stratigraphy

Three lithostratigraphic units comprise the Quebrada La Porcelana section. At the base is the Tranquitas Formation. It is overlain by the thickest unit, informally referred to as the Terciário Subandino. The section is capped by another informal unit: the Estratos El Simbolar. All of these strata are included in the Orán Group. Stratigraphic nomenclature and correlation within the Orán Group is complicated (Fig. 3). Much of the foundation work is found in unpublished oil company reports. The salient points of the lithostratigraphic terminology are discussed later.

3.1. Orán Group

Schlagintweit (in Fossa Mancini (1938)) grouped strata described by Bonarelli (1921) into the Orán Complex (Fig. 3). Russo (1972) formalized the Orán Complex, changing it to the Orán Group, and extended the group southward into the Transition Zone. He also divided the Orán Group into the basal Metán Subgroup and the overlying Jujuy Subgroup based on exposures in the Transition Zone (Fig. 3).

Gebhard et al. (1974) subdivided the strata of the Metán and Jujuy Subgroups into formations. The Metán Subgroup is composed of three formations. 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 (Fig. 3). An unconformity at the top of the Jesús María Formation separates the Metán Subgroup from the superposed Jujuy Subgroup. The Jujuy Subgroup is composed of two formations: the older Guanaco and younger Piquete (Gebhard et al., 1974).

Transition Zone tectonics are now recognized as distinct from those of the normal subduction area. Transition Zone units are foreland basin strata deposited above the Cretaceous Salta Rift Basin (Grier et al., 1991; Reynolds et al., 2000). The formational descriptions of Gebhard et al. (1974) bear only a distant resemblance to the strata exposed in the arroyos around the city of San Ramón de la Nueva Orán (usually referred to as Orán), the type area for the Orán Group that is located in the normal subduction area.

The strata around Orán were first referred to as the Upper Sandstones (Areniscas Superiores), overlain by the Terciário Subandino (Fig. 3), and in turn, capped by the Terciário Jujeño (Bonarelli, 1921). Schlagintweit (in Fossa Mancini (1938)) introduced the Tranquitas Formation, which correlates with the Upper Sandstones. He renamed the Terciário Subandino as the Chaco Formation, and the Terciário Jujeño became the Jujuy Formation. All of these units were grouped in the Orán complex (Fig. 3).

Zunino (1944) introduced the terms Terciário Subandino Inferior (Tsi), Terciário Subandino Medio (Tsm), and

Terciário Subandino Superior (Tss) to describe the strata above the Tranquitas Formation (Fig. 3). The Tsi and Tsm refer to the strata described earlier as the Terciário Subandino (Bonarelli, 1921) and Chaco Formation (Fossa Mancini, 1938). The Tss is the same as the Terciário Jujeño (Bonarelli, 1921) and the Jujuy Formation (Fossa Mancini, 1938). Russo (1972) and Gebhard et al. (1974) correlated the Metán Subgroup with the Tranquitas Formation, Tsi, and Tsm, whereas the Jujuy Subgroup is correlated to the Tss. Petroleum exploration geologists active in the region refer to the youngest strata in the region as the Estratos El Simbolar.

This paper will use the following stratigraphy (in ascending order): Tranquitas Formation, Tsi, Tsm, Tss, Estratos El Simbolar (Fig. 3). Rather than add to the existing confusion, we attempt to date these strata using the current oil company terminology to provide a baseline temporal foundation upon which future workers can build. These units are described later following Mingramm and Russo (1973).

3.2. Tranquitas Formation (referred to as the Areniscas Superiores by Mingramm and Russo (1973))

The Tranquitas Formation normally consists of weathered gray-green to yellow, flinty, coarse- to fine-grained sandstones with rounded grains. Some conglomerates are present in the lower part. Unlike the overlying units, fresh exposures of the Tranquitas Formation have an altered appearance, perhaps, due to weathering or the migration of hydrothermal fluids.

At Quebrada La Porcelana, only the upper ~100 m of the Tranquitas Formation is exposed. Oil company data suggest a total thickness of ~400 m in this area. More than 600 m of Tranquitas strata are exposed at Río Iruya (Fig. 2). In our regional program, we have attempted magnetostratigraphy on these rocks at Quebrada La Porcelana, Río Iruya, Arroyo Peña Colorada, and on both sides of the border near the international bridge across the Río Bermejo at Aguas Blancas (Fig. 2). The age of these strata is Tertiary and is presumed to be lower Miocene. Hernández et al. (1999) demonstrate that it is older at Río Iruya, ~11.4 Ma.

3.3. Terciário Subandino

Terciário Subandino strata attain an exceptional thickness of nearly 7 km at Río Iruya (Hernández et al., 1996). More often the unit is 2–5 km thick. In spite of its great thickness, these strata are remarkably monotonous and difficult to subdivide on the basis of their appearance. Workers in this unit traditionally circumvent this problem using intercalated tuffs and conglomerates as guides, dividing it into lower, middle, and upper members.

3.3.1. Lower member (Terciário Subandino Inferior)

Strata of the Tsi are described by Mingramm and Russo (1973) as sandstones and very red siltstones with massive to fine stratification containing parallel- and cross-bedding. The unit extends from the top of the Tranquitas Formation to the first of the lower dark gray tuffs that regionally appear 1000–1500 m above the base of the Terciário Subandino. At Quebrada La Porcelana, the Tsi is ~1250 m thick. Mingramm and Russo (1973) correlate these beds with the Yecua Formation of Bolivia. Erikson and Kelly (1995) report a 24.4 ± 1.3 Ma fission track age from a Yecua tuff at Quebrada Bartolo (Jordan et al., 1997). Gebhard et al. (1974) correlate these beds with the Río Seco Formation and the lower part of the Anta Formation found in the Transition Zone portion of the Orán Group. Reynolds et al. (2000) dated Río Seco strata between 15.1 and 14.8 Ma at Arroyo González (Fig. 1).

3.3.2. Middle member (Terciário Subandino Medio)

Tsm strata comprise those beds situated between the lowest dark gray tuff and the first white tuff. The lower part of the unit contains sandstones and red to red-brown mudstones. Fine- to coarse-grained conglomerates occur in the upper part. Tsm strata are ~1100 m thick at Quebrada La Porcelana. Gebhard et al. (1974) correlate the Tsm beds with the upper part of the Anta Formation and the Jesús María Formation in the Transition Zone portion of the Orán Group. At Arroyo González (Fig. 1), Anta strata were deposited between 14.8 and 13.7 Ma and Jesús María beds accumulated between 13.7 and 9.7 Ma (Reynolds et al., 2000).

3.3.3. Upper member (Terciário Subandino Superior)

The Tss, situated above the lowest white tuff, is characterized by the overwhelming dominance of coarse-grained conglomerates with cobbles derived from the Cordillera Oriental. Interbedded with the conglomerates are sandstones and sandy mudstones. Strata in this unit are characterized by brownish-pink to brownish-yellow colors. The pinkish beds dominate in the lower part, and the yellowish strata are more common in the upper part. Tss beds are ~1525 m thick in the Quebrada La Porcelana. Gebhard et al. (1974) correlate these strata with the entire Jujuy Subgroup (Guanaco and Piquete Formations) that are exposed in the Transition Zone portion of the Orán Group. Guanaco strata are younger than 9.0 Ma at Arroyo González (Reynolds et al., 2000) and were dated between 10.5 and 6.4 Ma at Río Yacones (Viramonte et al., 1994).

3.4. Estratos El Simbolar

The Estratos El Simbolar beds are not recognized as a formal stratigraphic unit. As used by exploration geologists in the Sierras Subandinas, they refer to the coarse cobble to boulder conglomerates found at the top of the Neogene section. Earlier workers included these strata in the Terciário Subandino (Fig. 3). Interbedded siltstones and mudstones are extremely rare. Sandstones are somewhat more common but never abundant. About 650 m of these strata are exposed in the Quebrada La Porcelana. Hernández

Table 1
$^{40}Ar/^{39}Ar$ ages of Quebrada La Porcelana Tuffs (age calculated using the decay constants recommended by Steiger and Jager (1977))

Sample	Material	J ($\times 10^{-4}$)	$^{40}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Moles ^{39}Ar ($\times 10^{-14}$)	$^{40}Ar^*$ (%)	Age (Ma)	$\pm 2\sigma$ (Ma)
LP 26	Biotite	2.351	97.71	0.1998	0.01660	0.2861	1.56	13.38	5.55	0.42
LP 26	Sanidine	2.351	64.56	0.0503	0.13405	0.1700	0.09	21.94	6.05	0.29
Weighted average age									5.88	0.48
LP 19A	Biotite	2.378	105.30	0.1905	0.01185	0.2999	1.38	15.76	7.12	0.34

et al. (1999) present data that suggest these strata were deposited between 2.1 and 0.8 Ma at Río Iruya (Fig. 2).

3.5. Interpretation

Weathering and/or hydrothermal alteration evident in the Tranquitas Formation leads us to believe that it is a Paleogene or early Neogene unit that is probably capped by a disconformity. Tsi strata are interpreted to represent distal foreland deposits in distal alluvial fan to braided stream environments. The lack of conglomerates suggests that the area was located far from the sediment source area. Strata in the lower Tsm are similar to those in the Tsi with the addition of some airfall beds. The appearance of conglomerates in the upper part of the unit suggests an increase in stream gradient, which we interpret to result from uplift in the west. We place the base of the growth strata at the ~2500 m stratigraphic level where conglomerates first become abundant. Extremely coarse-grained conglomerates of the Tss and Estratos El Simbolar are interpreted to be growth strata resulting from uplift of structures in the immediate vicinity of the section. We identify two distinct episodes of growth strata deposition between ~2500 to ~2750 and ~3550 m to the top of the section.

4. Magnetostratigraphy of the Quebrada La Porcelana section

Magnetic polarity stratigraphy was used to correlate ~3800 m of detrital beds from the Quebrada La Porcelana section with the Global Polarity Time Scale (GPTS) of Cande and Kent (1995). Sampling was undertaken in the fall of 1992 by a team of Yacimientos Petrolíferos Fisicales geologists (YPF, the former Argentine national oil company). Measurement of the section with a Jacob's Staff and Abney Level proceeded as the samples were collected. The section was described during measurement. A minimum of three, fist-sized, oriented, block samples was collected at each station. Samples were collected from mudstones, siltstones, and fine-grained sandstones in the hope that the magnetic mineral grains would be fine enough to deliver a consistent signal from each station. Oriented samples were collected from 133 stations. Where possible, an attempt was made to space the sample sites approximately 30 m apart, stratigraphically. Considerable variation exists in the actual spacings because of incomplete exposure in the lower portion and the presence of coarse-grained strata at some desired levels, particularly in the upper part of the section. The samples were milled into 2.5 cm cubes on a grinding wheel using carborundum disks.

Our sampling program included the exposed portion of

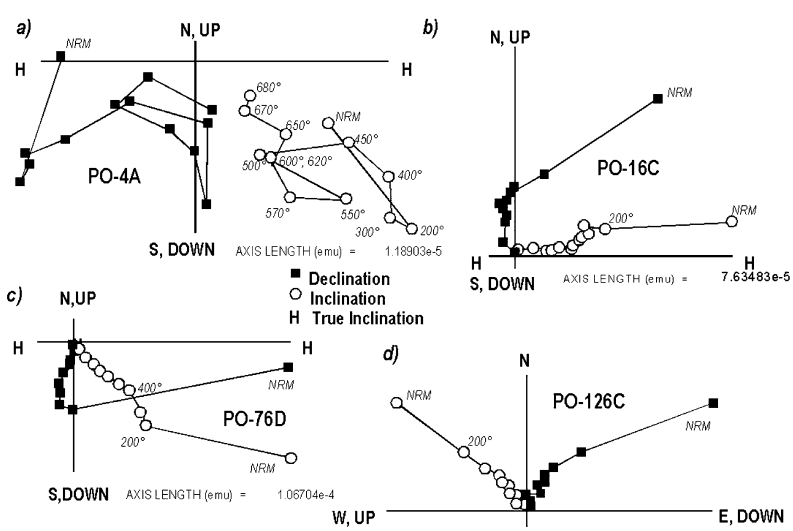

Fig. 4. Vector end-point diagrams (Zijderveld, 1967) showing the thermal demagnetization of representative samples from the Quebrada La Porcelana section.

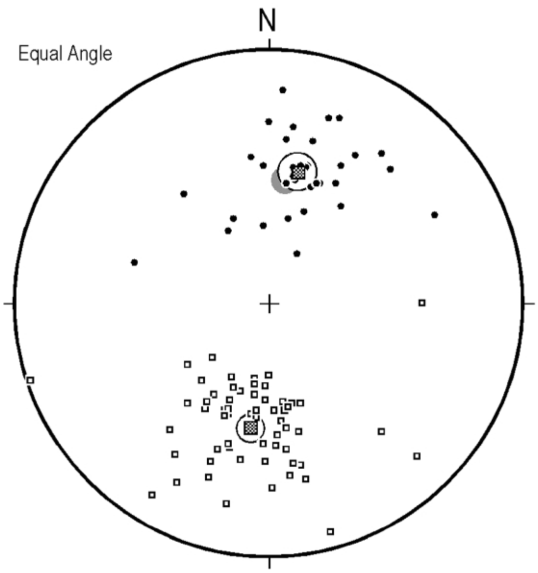

Fig. 5. Reversal test for Class I data in the Quebrada La Porcelana section. Class I, site-mean orientation data cluster in two antipodal groups and pass the reversal test (projection of the southern circle of confidence shown by the gray circle). The mean declination for the normal sample is 14° with a mean inclination of −36° and $\alpha_{95} = 7°$. For the reversed sample, the mean declination is 189° with a mean inclination of 38° and $\alpha_{95} = 5°$. The data suggest a clockwise rotation on the order of ~12 ± 6°. Mean normal and reverse directions are within 9.5° (γ_c) of antipodal, providing a positive reversal test (Class B; MacFadden and McElhinny, 1990).

the Tranquitas Formation and nearly the entire Terciário Subandino. No suitable lithologies for paleomagnetic study were found in the uppermost 200 m of the Tss. Fine-grained rocks were too widely spaced in the Estratos El Simbolar to produce meaningful results, and sampling in this unit was not attempted. Two $^{40}Ar/^{39}Ar$ dates were obtained from biotites and sanidines collected from intercalated tuffs (see Appendix A). A 7.12 ± 0.34 m.y. age (Table 1) came from a ~2-m-thick airfall tuff, at the ~1225 m level in the upper part of the Tsi. A 5.88 ± 0.48 m.y. date came from a sphene-bearing tuff in the middle portion of the Tsm at the ~1760 m level. This tuff, referred to as 'la toba titanífera', is recognized across the Sierras Subandinas in Argentina and is used as a marker bed. These dates calibrate the magnetostratigraphic column with the GPTS.

4.1. Analytical results

All samples were analyzed for natural remanent magnetization (NRM) on the three-component 2G superconducting rock magnetometer (SRM) at the University of Pittsburgh. NRM magnetic dipole moment/unit volume (M, A m^{-1}) values varied between 9.1×10^{-3} and 1.3×10^{-1} A m^{-1}. M values approximate an even distribution between the two extremes. Thirteen samples were subjected 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. 4).

Fig. 4 presents representative vector end-point thermal demagnetization plots (Zijderveld, 1967) from the (a) Tranquitas Formation, (b) Tsi, (c) Tsm, and (d) Tss. Nearly all of the samples from the Tranquitas Formation (Fig. 4(a)) exhibited erratic behavior. Limonite appears to be the primary carrier of remanent magnetization in the Tranquitas samples. New magnetic minerals appear to form at elevated temperatures. In contrast, most samples from the other units (Fig. 4(b–d)) exhibit a Bruhnes normal overprint that was removed by the initial treatments. In most cases, a single component of magnetization was revealed that exhibited a steady decline in intensity as temperatures were elevated. Hematite is the primary carrier of remanent magnetization in most samples. Magnetite is present in some samples, particularly in the upper 2000 m and in those sites located amongst the tuffaceous horizons.

A statistical mean direction of the paleomagnetic vector was determined for each site (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 of samples $N = 3$, 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.

A reversal test of the Class I data (Fig. 5) shows that the data fall into two distinct, antipodal fields, suggesting that the magnetic component isolated by the demagnetization treatments represents the detrital remanent magnetization and not a thermal or chemical postdepositional overprint. Mean normal and reverse directions are within 9.5° (γ_c) of antipodal, providing a positive reversal test (Class B; MacFadden and McElhinny, 1990). Fig. 5 also suggests an 8–12 ± 6° clockwise rotation of the region. Inclinations at this latitude should plot around 44°. Our results are between 34 and 37°, suggesting some flattening due to compaction of the strata.

Of the 133 paleomagnetic sites, 117 are shown in the magnetic polarity column (Fig. 6). One hundred sites provided Class I data, and 17 are Class II. Sixteen sites failed to fit into a Class I or II category. Most Tranquitas Formation sites were uninterpretable. Thirty-two geomagnetic field reversals were found in our sampling program, defining 33 polarity zones (Fig. 6). All sites within the Tranquitas Formation exhibit reversed polarity. The first reversal is found at the contact with the overlying Tsi.

Seven single-site, Class I, polarity zones are present in our data set. Ordinarily, we would attempt a resampling program to substantiate these sites, but because of the difficult access and potential problem with smugglers, we

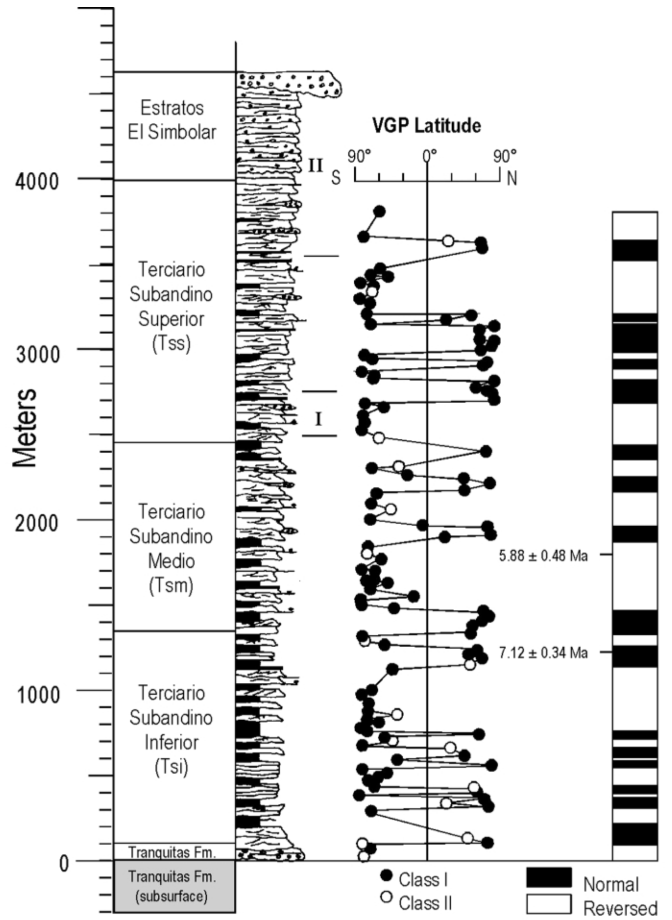

Fig. 6. Plot of Virtual Geomagnetic Pole (VGP) latitude of the paleomagnetic sites versus their stratigraphic level. Lithostratigraphic units are shown on the left. Polarities are abstracted to the standard black and white magnetic polarity scale on the right. Reversals are placed halfway between adjacent sites with opposite polarities. The I and II refer to growth strata intervals.

elected to present the ambiguities in our data set and not return to the section for further sampling.

4.2. Ages of the strata

Poor data quality from the Tranquitas Formation hinders precise dating of the unit. Similar disappointing results were obtained in the Tranquitas Formation at Río Iruya, Peña Colorada, and Aguas Blancas (Fig. 2). By correlation with the GPTS, we place the base of the Terciário Subandino at ~8.1 Ma (Fig. 7); the Tranquitas Formation must be older than 8.1 m.y. At Río Iruya, the Tranquitas Formation was shown to be older than 11.4 Ma (Hernández et al., 1999). These limits support our belief that a disconformity exists at the Tranquitas-Terciário Subandino contact.

The Tsi–Tsm contact occurs between 6.6 and 6.3 Ma. The lowest white tuff that marks the base of the Tss was deposited ~4.2 Ma. The top of our sampling program in the Tss is situated within the reversed polarity zone between 1.77 and 1.07 Ma (Cande and Kent, 1995), suggesting that the top of the paleomagnetic section was deposited ~1.5 Ma. Extrapolating these results, we estimate that the top of the Tss was deposited ~1.2 Ma. Further extrapolation implies that the beds at the top of the Estratos El Simbolar are considerably younger than 1 m.y. Ages of the lithostratigraphic unit boundaries, based on our correlation with the GPTS, appear in Table 2. The ages of the two phases of growth strata are placed between 5.3–4.2 and ~2 Ma and the top of the section.

In our temporal interpretation, Chron C3n.3n is missing (Fig. 7). We chose this chron because there appears to be a much wider gap between the preceding and the following normal polarity chrons (C3n.2n and C3n.4n) than is present on the GPTS. We further substantiate this choice below to alleviate the necessity of presenting several alternate interpretations for this 1.5 m.y. time frame. We are also missing a short normal polarity zone between 2.15 and 2.14 Ma (C2r.1n; Fig. 7).

Several explanations exist for the absence of these polarity zones. Deposition may not have occurred during these missing intervals because of their short duration (Cande and Kent, 1995). It is also possible that our sample spacing was not detailed enough to register all reversals present in the section. A depositional hiatus could also be present at this level.

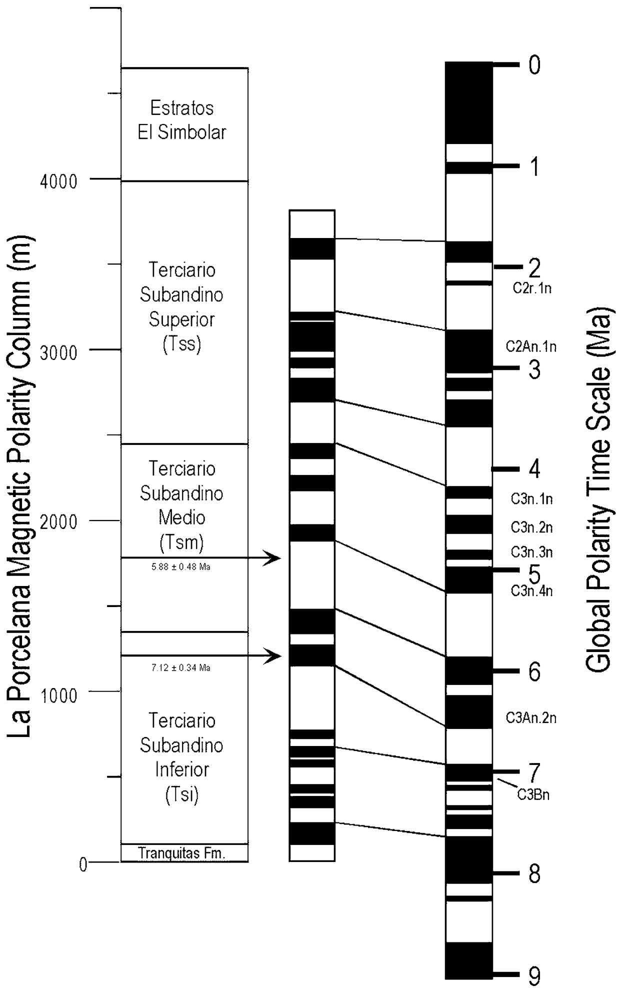

Fig. 7. Correlation of the Quebrada La Porcelana Magnetic Polarity Scale with the GPTS of Cande and Kent (1995). The correlation suggests that deposition of the Tsi began about 8.1 Ma. The youngest samples collected in the Tss were deposited ~1.5 Ma. Most of the Estratos El Simbolar are probably younger than 1 Ma.

We show one short reversed polarity zone in Chron C2An.1n (3.04–2.58 Ma) and one normal polarity zone between normal polarity chrons C3An.2n and C3Bn (6.94–6.57 Ma) that are not seen on the GPTS (Fig. 7; Cande and Kent, 1995). Both polarity zones are defined by a single paleomagnetic site. We cannot ascertain their validity.

Table 2
Magnetostratigraphic ages of Orán Group lithostratigraphic contacts at Quebrada La Porcelana

Contact	Age (Ma)
Top of El Simbolar	$\ll 1$
Tss-El Simbolar	~ 1.2
Tsm–Tss	4.2–4.3
Tsi–Tsm	~ 6.2
Base of Tsi	~ 8.1
Top of Tranquitas Formation	$>$ 8.1
Base of Tranquitas Formation	?

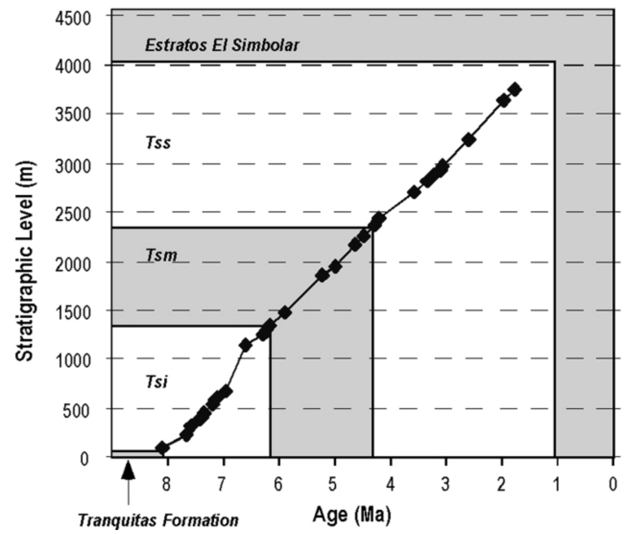

Fig. 8. Quebrada La Porcelana sediment accumulation history. The plot begins at the top of the undated Tranquitas Formation. A 0.5 mm a^{-1} linear rate is present throughout the section. The brief increase in the rate between 6.9 and 6.7 Ma is interpreted to result from ~250 m of strata repeated along a thrust fault near the anticlinal axis.

4.3. Sediment accumulation rate

A plot of the stratigraphic level of reversals versus their age (Fig. 8) reveals an incredibly linear sediment accumulation rate of 0.5 mm a^{-1} throughout the Terciário Subandino. The only deviation from a perfectly linear plot occurs between 6.93 and 6.57 Ma where the rate increases abruptly before returning to 0.5 mm a^{-1}. This is also the location of the extra normal polarity zone mentioned earlier. Because the sediment accumulation rate is exactly the same before and after this brief interval, we suggest the possibility that a previously unrecognized thrust fault is present near the crest of the anticline. Removal of approximately 250 m of repeated strata at this level would delete the extra normal polarity zone and make the sediment accumulation plot linear throughout the depositional history of the section.

This plot also lends credence to our contention that the sampling program missed the 4.89–4.80 Ma normal polarity zone and not one of the other three normal zones in the 5.23–4.18 Ma interval (Fig. 7). Removal of any of the other three zones produces brief increase or decrease in the accumulation rate as opposed to the steady-state presented here.

5. Regional correlation

Our results and those presented by Hernández et al. (1999) demonstrate that the entire Terciário Subandino is temporally equivalent to the Jujuy Subgroup farther to the south (Fig. 9). The Terciário Subandino at Quebrada La Porcelana is younger than 8.1 Ma. At Arroyo González, 200 km to the south (Fig. 1), the base of the Guanaco Formation was shown to be not older than 9.0 Ma (Reynolds

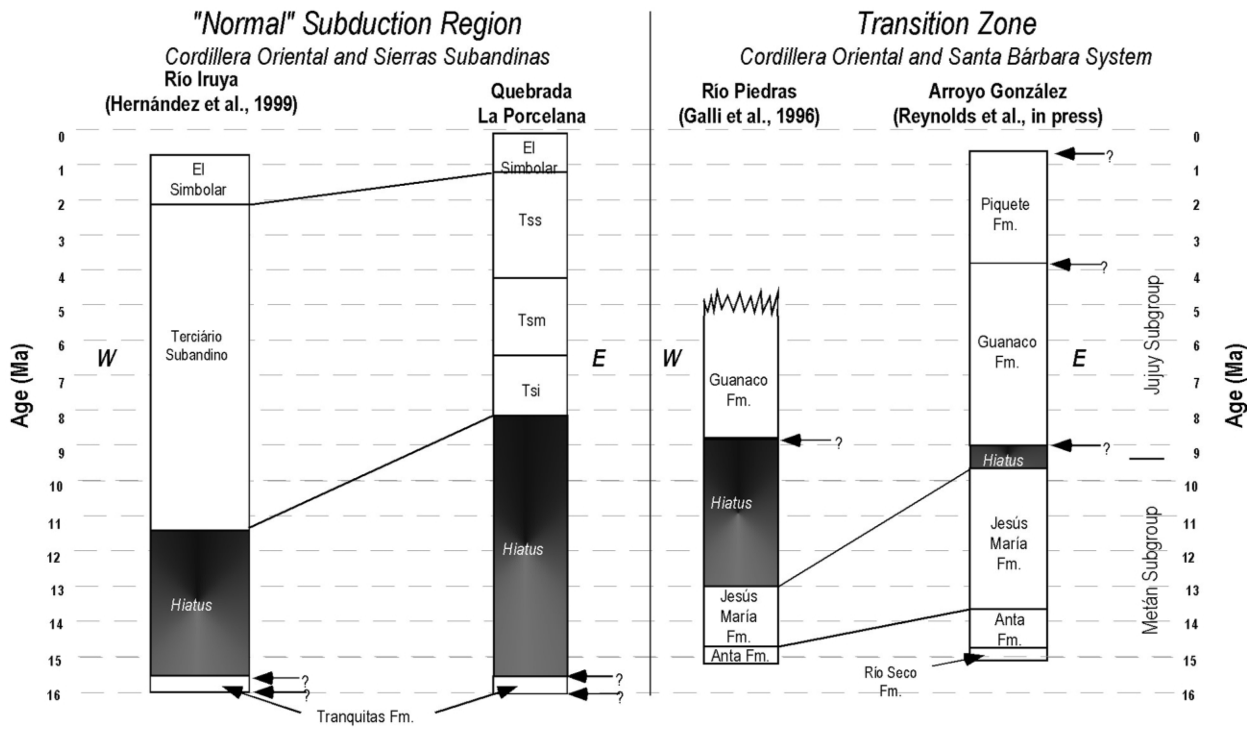

Fig. 9. Chronostratigraphic correlation of the Orán Group between and within the normal subduction region and the Transition Zone (Fig. 1). Question marks indicate levels for which no numerical ages exist. The basal age of the Río Piedras section was modified by Reynolds et al. (2000). Lithostratigraphic units in both areas exhibit a diachronous depositional history with younger contact ages in the east. This temporal framework demonstrates that Neogene strata in the Sierras Subandinas are contemporaneous with Jujuy Subgroup strata in the Transition Zone and are younger than the Metán Subgroup strata except for minor overlaps.

et al., 2000). At Río Yacones (Fig. 1), Viramonte et al. (1994) reported that the base of the exposed portion of the Guanaco Formation may be as old as 10.5 Ma. The basal contact, however, is not exposed, suggesting that an older age is possible.

Ages of the formations of the Metán Subgroup, with which the Tsi and Tsm are correlated (Gebhard et al., 1974), were determined at two localities in the south (Fig. 1): Río Piedras (Galli et al., 1996) and Arroyo González (Reynolds et al., 2000). Using the Cande and Kent (1995) GPTS, the base of the Metán Subgroup at Río Piedras must be >15.2 Ma while the top is ~ 13.0 Ma. At Arroyo González, the base of the Río Seco Formation was dated at ~ 15.1 Ma (Fig. 9), and the top of the Jesús María Formation was deposited ~ 9.7 Ma (Reynolds et al., 2000).

Table 3
Proposed initial uplift ages for ranges in the western and central Sierras Subandinas

Range	Age (Ma)
S^{a} de Cinco Picachos	~ 8.2
S^{a} Pescado and S^{a} de Pintascayo	~ 6.9
S^{a} Baja de Orán–S^{a} Bermejo	4.2–3.6
S^{a} de Ramos–S^{a} de San Antonio	~ 2.5

Stratigraphic units in the Andean foreland basins in the flat subduction area and Transition Zone to the south are diachronous with the younger ages found in the east (Reynolds et al., 1990, 2000). Data from other parts of the Sierras Subandinas (Hernández et al., 1999) suggest that the Terciário Subandino is also diachronous. Its base is always millions of years younger than the base of the Metán Subgroup (base of the Orán Group) in the Transition Zone where the Metán Subgroup was originally defined.

6. Interpretation

6.1. Local implications

Given the uniform weathered appearance of Tranquitas strata across the region and the diachronism expressed in the basal ages of the Terciário Subandino between Río Iruya and Quebrada La Porcelana, we suggest the presence of a disconformity at the basal contact with the Tranquitas Formation. Other possibilities that might explain the altered appearance of the Tranquitas Formation and the poor quality of the paleomagnetic results from the unit across the region are as follows: (1) a regional thermal event that altered the magnetic minerals or (2) migration of hydrocarbons or other fluids through the strata. We suggest that the Tranquitas beds were deposited in response to the initial uplift of the

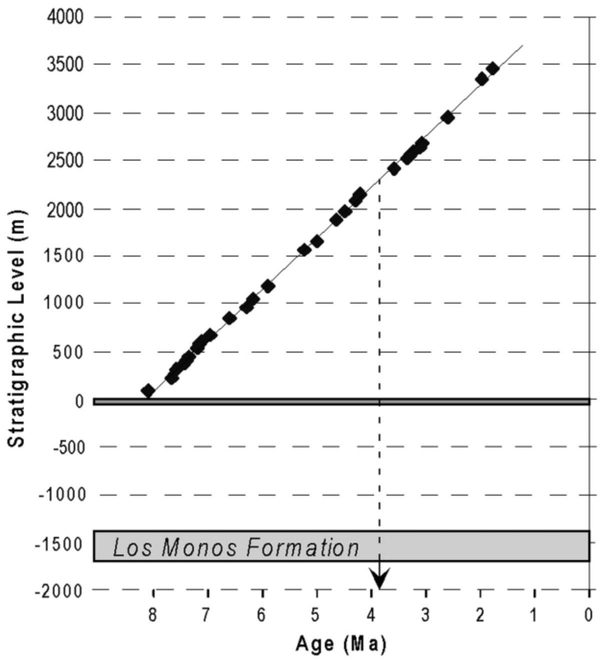

Fig. 10. A hydrocarbon generation age model based on the sediment accumulation rate shown in Fig. 8. About 250 m of repeated strata were removed to give the plot the proposed 0.5 mm a^{-1} steady-state accumulation history. The 4-km-long vertical dashed line is the assumed hydrocarbon generation depth. It extends from the base of the Los Monos source horizon to its intersection with the modified sediment accumulation plot. The best fit occurs at ~3.8 Ma, suggesting this age for the initiation of hydrocarbon generation and migration.

Puna (Fig. 1). Vandervoort et al. (1995) present evidence that implies that Puna uplift commenced around 16 Ma. We suggest a probable age of ~16 Ma for the base of the Tranquitas Formation (Fig. 9).

Tsi strata were determined to have their source area in the Cordillera Oriental at Río Iruya (Reynolds et al., 1996; Hernández et al., 1996, 1999). At La Porcelana, the base of the Tsi is placed at ~8.1 Ma or slightly younger than the uplift age of the Sierra de Cinco Picachos (Table 3) on the western edge of the Sierras Subandinas (Fig. 1) at ~8.2 Ma (Reynolds et al., 1996). This chronology suggests that Tsi strata, at La Porcelana, may actually be reworked Neogene beds derived from uplift of the Sierra de Cinco Picachos.

Reynolds et al. (1996) suggest that uplift of the Sierra Baja de Orán occurred sometime soon after 4.0 Ma based on the age of the youngest strata truncated by thrust faults that uplifted the range seen in Arroyo Peña Colorada and Arroyo Solazuti (Reynolds et al., 2001; Fig. 1; Table 3). The presence of growth strata between 4.2 and 3.6 Ma could be related to uplift in the Sierra Baja de Orán–Sierra de Bermejo complex (Fig. 1). The second phase of growth strata development begins with an increased rate of sediment accumulation at ~2.0 Ma. We suggest that this marks the initiation of uplift of the Sierra de Ramos (Table 3).

6.2. Regional implications

The results suggest that Neogene orogenic activity along the southern margin of the normal subduction region began later than it did in the Transition Zone immediately to the south. Reynolds et al. (2000) show that the strata at Arroyo González and Río Piedras (Galli et al., 1996) were being deposited by 15 Ma. The southern part of the Transition Zone was strongly affected by activity in the Sierras Pampeanas in the flat subduction area to the south. Uplift occurred in the western foreland of the flat area by 16 Ma (Reynolds et al., 1990). The oldest uplift ages in the Sierras Pampeanas are from the Sierra de Velasco (Malizia et al., 1995) and the Sierra de Quilmes in the southern part of the Transition Zone (Reynolds et al., 2000) at ~12 Ma. Strata at the base of the Terciário Subandino at Río Iruya were derived from uplift of the Cordillera Oriental (Reynolds et al., 1996). The revised Río Iruya magnetostratigraphy (Hernández et al., 1999) suggests that the base of the Terciário Subandino at Río Iruya is not older than 11.4 Ma.

Migration of foreland thrusting commenced later in the Sierras Subandinas than in the Transition Zone. The locus of thrust migration in both areas is currently situated between 64 and 65°W (Fig. 1). Because foreland deformation began later in the north, this observation suggests that foreland thrusting (and crustal shortening) progressed at a faster rate in the north than in the south.

7. Application to petroleum geology

Our chronostratigraphic data permit an estimate of ages of hydrocarbon maturation/migration in the Quebrada La Porcelana area. Subsidence of source strata through the generation window can be modeled using the ages of the overburden beds. The base of the paleomagnetic section is situated ~1700 m above the base of the 300-m-thick Devonian Los Monos Formation (Fig. 10)—the hydrocarbon source horizon (Belotti et al., 1995).

Magnetostratigraphic chronology suggests that growth strata derived from rising anticlinal structures accumulated between 4.2 Ma and the top of the section (<1 Ma). Using outcrop thicknesses, removing 250 m of repeated strata, and assuming a generation depth of 4 km, the base of the Los Monos Formation probably attained generating depths at ~3.8 Ma. This relatively young maturation age suggests that trapping structures were available locally during initial hydrocarbon generation and migration. This interpretation is substantiated by the recent discovery of hydrocarbons in this part of the Sierras Subandinas (Gómez Omil and Lúquez, 1998). Applying the same method in the 7.5-km-thick Río Iruya section suggests a probable maturation/migration age of ~7 Ma. Cross-cutting, trap-forming structures, however, cannot be older than ~6.9 Ma. Many are considerably younger, so most hydrocarbon resources probably migrated away from this part of the basin.

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Appendix A. Analytical procedures—^{40}Ar/^{39}Ar dating

Samples of tuffs LP 19A and LP 26 weighing 2–3 kg each were disaggregated in a blender, washed thoroughly in tap water, and sieved to remove fine material (<125 μm). Biotite and sanidine were separated from the remaining coarse fraction using standard heavy liquid and magnetic techniques. Additional cleanup was accomplished by hand-picking under a binocular microscope to achieve a final purity of $>99\%$. Aliquots of the separates weighing ~3 mg each were packaged in Sn foil and sealed, together with other unknowns, in evacuated quartz tubes. Packets containing monitor mineral GA-1550 biotite (97.9 Ma; McDougall and Roksandic, 1974) were spaced evenly throughout the tubes to record the vertical variation in neutron flux within the irradiation container. CaF_2 and K_2SO_4 were also included in the irradiation package to monitor neutron-induced interferences due to Ca and K, respectively. The samples were irradiated for 3 h in position L67 of the Ford Reactor at the University of Michigan.

The ^{40}Ar/^{39}Ar analyses were conducted in the geochronology laboratory at Lehigh University. Argon was extracted from the samples by fusing them in a double-vacuum tantalum resistance furnace at 1350 °C. The evolved gases were purified using a cold finger cooled to liquid-nitrogen temperature and SAES getters operated at room temperature and 400 °C. The argon isotopes were analyzed in a VG 3600 noble gas mass spectrometer operated in the static mode. An electron multiplier with an overall sensitivity of $\sim 5 \times 10^{-17}$ mol Ar mV^{-1} was used to measure the argon beams. The total blank contribution from the furnace and extraction line was $\sim 3 \times 10^{-15}$ mol ^{40}Ar.

The measured isotopic ratios were corrected for line blank, mass discrimination (0.51% amu^{-1}), radioactive decay of ^{37}Ar and ^{39}Ar, neutron-induced interferences on K and Ca, and atmospheric contamination. Uncertainties in the ages are reported at the 2σ level and incorporate both the precision of the analytical measurements and a 0.5% uncertainty in the J value.

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