Magnetic Polarity Stratigraphy and $^{40}$K-$^{40}$AR Dating of Late Miocene and Early Pliocene Continental Deposits, Catamarca Province, NW Argentina

Robert F. Butler  
*University of Portland, butler@up.edu*

Larry G. Marshall

Robert E. Drake

Garniss H. Curtis

Follow this and additional works at: http://pilotscholars.up.edu/env_facpubs

Part of the Earth Sciences Commons

Citation: Pilot Scholars Version (Modified MLA Style)

http://pilotscholars.up.edu/env_facpubs/2

This Journal Article is brought to you for free and open access by the Environmental Studies at Pilot Scholars. It has been accepted for inclusion in Environmental Studies Faculty Publications and Presentations by an authorized administrator of Pilot Scholars. For more information, please contact library@up.edu.
MAGNETIC POLARITY STRATIGRAPHY AND $^{40}$K – $^{40}$Ar DATING OF LATE MIOCENE AND EARLY PLIOCENE CONTINENTAL DEPOSITS, CATAMARCA PROVINCE, NW ARGENTINA

ROBERT F. BUTLER, LARRY G. MARSHALL, ROBERT E. DRAKE, AND GARNISS H. CURTIS

Department of Geosciences, The University of Arizona, Tucson, Arizona 85721
Department of Geology and Geophysics, University of California, Berkeley, California 94720

ABSTRACT

Magnetostratigraphic and $^{40}$K – $^{40}$Ar data on a 2300 m thick sequence of continental sediments at Puerta de Corral Quemado in Catamarca Province, NW Argentina permit calibration of land mammal faunas of late Tertiary (Huayquerian and Montehermosan) age. The sequence represents (oldest to youngest) the Chiquimil, Araucanense, and Corral Quemado Formations. Paleomagnetic samples were collected from 99 stratigraphic levels. Strong-field thermomagnetic and isothermal remanent magnetization experiments indicate that the dominant ferrimagnetic mineral is magnetite. Progressive alternating-field (AF) and thermal demagnetization of the natural remanent magnetism (NRM) demonstrates that AF demagnetization to 20 mT peak field is sufficient to isolate the primary NRM which is of depositional origin. The resulting paleomagnetic data provide a well-defined magnetic polarity zonation, although sampling is less dense in the upper half of the section. $^{40}$K – $^{40}$Ar data obtained from mineral separates of four tuffs within the section allow reliable age determinations for those levels. The combined magnetostratigraphic and $^{40}$K – $^{40}$Ar data allow the magnetic polarity zonation to be correlated with the magnetic polarity time scale. This correlation indicates a nearly constant rate of sediment accumulation between ~8.0 Ma and 3.5 Ma. The boundary between the Araucanense and Corral Quemado Formations approximates the boundary between the Huayquerian and Montehermosan land mammal age faunas at this locality. The data presented here allow the boundary between the Araucanense and Corral Quemado Formations to be dated at 6.4 Ma. Combined with geochronologic data from similar age rocks and faunas from San Carlos, Mendoza Province, west-central Argentina, the geochronologic data from Puerta de Corral Quemado allow the Huayquerian-Montehermosan land mammal age boundary to be placed tentatively at 6.0 Ma. A specimen of the fossil land mammal Cyonasa (family Procyonidae) from unit 14 of the Araucanense Formation is dated at 7.0 to 7.5 Ma. This specimen is the earliest known representative of this North American group in South America and repre- cants the oldest dated participant in the Great American Faunal Interchange on that continent.

INTRODUCTION

The continents of North and South America are today connected by the Panamanian land bridge, a structure which has permitted the reciprocal interchange of terrestrial biotas following its final emergence about 3.0 Ma. This biotic event is known as the Great American Faunal Interchange (Webb 1976), and it represents the best documented example in the fossil record of an interchange of two long separated continental faunas.

Two primary phases of the Great American Faunal Interchange are recognized, the participants in which are identified on the basis of their time and means of dispersal (Simpson 1940, 1950, 1980). One phase occurred after the appearance of the land bridge and involved most of the interchange participants, which dispersed north and/or south after 3.0 Ma. The other phase occurred prior to emergence of the land bridge and involved fewer participants. The land mammals in this phase were waif immigrants in the Late Miocene and dispersed on rafts of vegetation and/or by island hopping along island chains. The participants are known to include members of the North American raccoon family Procyonidae (and possibly the rodent family Cricetidae), which dispersed to South America, and members of the ground sloth families Megalonychidae and Mylodontidae, which dispersed to North America. In this paper we provide geochronologic data that securely calibrates the beginning of this early phase of the Great American Faunal Interchange in South America.

Late Tertiary land mammal faunas which include fossil Procyonidae have been recorded from a thick sedimentary sequence at Puerta de Corral Quemado and Chiquimil

623
in Catamarca Province, northwest Argentina (fig. 1). A large collection of fossil vertebrates from these localities was made by Elmer S. Riggs in 1926 and is deposited in the Field Museum of Natural History, Chicago. Detailed stratigraphic profiles of each locality were made by Rudolph Stahlecker, geologist on the Riggs’ expedition, and record was kept of the position of most fossils collected within this stratigraphic framework. Stahlecker’s sections were published by Riggs and Patterson (1939) along with a preliminary study of the faunas. The section from Chiquimil recorded 1,525 m of sediment and that from Puerta de Corral Quemado 1,913 m. Fossil mammals and tuff beds were indicated to be especially abundant in the upper half of each section.

These published data indicated potential for calibrating the age of these mammal-bearing rocks using magnetostratigraphic and \(^{40}K-^{40}Ar\) dating techniques. In May 1977, Butler, Marshall, and personnel from the Museo de La Plata and Museo Municipal de Ciencias Naturales “Lorenzo Scaglia” in Argentina visited these localities to deter-
mine the feasibility of such a study. The results of that trip are reported by Marshall et al. (1979). The rocks at Puerta de Corral Quemado proved particularly suitable for paleomagnetic analysis, and two sections, each including a securely dated tuff, were sampled. The dated tuff in the upper part of our lower 400+ m section we believed to be Stahlecker’s unit 8, and the dated tuff in the top of our upper 500+ m section we believed to be his unit 29. Correlation of our two sections with units in Stahlecker’s section was based largely on the identity of these tuff levels.

Our preliminary study demonstrated the ideal nature of these rocks for magnetostratigraphic and $^{40}\text{K} - ^{40}\text{Ar}$ analyses. We felt confident that additional work at Puerta de Corral Quemado would permit us to sample the sequence between our upper and lower sections. The anticipated results would provide a more secure correlation of our data with Stahlecker’s section and would permit chronostratigraphic calibration of the fossil faunas, including three specimens of Procyonidae. The mammal faunas are assigned to the Huayquerian and Montehermosan Land Mammal Ages (see below). Thus, the opportunity existed to date the Huayquerian-Montehermosan boundary at this locality.

An unpublished manuscript by Stahlecker on the geology of Puerta de Corral Quemado and Chiquimil has been discovered in the archives of Field Museum in late 1979 and published in Marshall and Patterson (1981). Subsequent study of this manuscript revealed to us that the stratigraphic thickness of Stahlecker’s sections as published by Riggs and Patterson (1939) were erroneously off by a factor of two. Thus, his Puerta de Corral Quemado section is not 1,913 m thick, as published in Riggs and Patterson (1939), but is closer to 4000 m. In addition, no detailed descriptions of the lithologies were published by Riggs and Patterson (1939). Additional field work was needed to clarify aspects of the geology reported in Stahlecker’s manuscript, and to expand the geochronological work begun in 1977.

In September 1980, Butler, Drake, and Marshall revisited Puerta de Corral Quemado (with Stahlecker’s unpublished manuscript in hand) and collected additional rock samples for paleomagnetic and $^{40}\text{K} - ^{40}\text{Ar}$ study. The results of that trip are reported here. A 2,300 m thick composite paleomagnetic section, including the two sections collected in 1977, was obtained. This section correlates with the upper half of Stahlecker’s section, spanning his units 13 through 30 (see below) and includes four securely dated tuffs. We confirmed the identity of the tuff in our upper section of Marshall et al. (1979) as Stahlecker’s unit 29, but found that unit 8 in the lower section of Marshall et al. (1979) is actually Stahlecker’s unit 15. The unit identified as unit 15 by Marshall et al. (1979) cannot be securely correlated with a specific unit in Stahlecker’s section, although we believe that unit is correlative with Stahlecker’s unit 20.

Stratigraphic nomenclature of the late Tertiary sediments at Puerta de Corral Quemado and Chiquimil has had a confused history as reviewed by Marshall and Patterson (1981, pp. 14–15) and Bossi and Palma (1982, fig. 1). We follow the terminology used by Riggs and Patterson (1939) because it is the one which appears most frequently in paleontological literature.

The following abbreviations are used: FMNH, Field Museum of Natural History, Chicago; MACN, Museo Argentino de Ciencias Naturales “Bernardino Rivadavia,” Buenos Aires, Argentina; Ma, millions of years before present.

**PALEOMAGNETISM AND ROCK MAGNETISM**

Oriented samples were collected from 99 paleomagnetic sites (3 sample/site) in a 2300 m thick stratigraphic section at Puerta de Corral Quemado (fig. 1). This section was located on the west limb of a gently plunging anticline. Samples for paleomagnetic analysis were preferentially collected from claystones and siltstones rather than sandstones. In has generally been observed (e.g., Johnson et al. 1975) that finer-grained continental deposits yield more reliable paleomagnetic results.

Magnetic separates for thermomagnetic analysis were prepared from bulk samples collected at three stratigraphic levels. An example of the results of the thermomagnetic analyses is shown in figure 2. All thermomagnetic analyses were similar in indicating only a single Curie temperature of approximately 580°C. This observation indicates that magnetite ($\text{Fe}_3\text{O}_4$) is the dominant ferrimagnetic
mineral. The heating and cooling curves were very similar in all cases, suggesting absence of low temperature oxidation.

Single samples from 20 sites in the section were selected for study of acquisition of isothermal remanent magnetization (IRM). Typical results are illustrated in figure 3. IRM is acquired rapidly in magnetizing fields up to 300 millitesla (mT; 1 mT = 10 oe), but only minor amounts of IRM are acquired in higher intensity magnetizing fields. These observations are consistent with the thermomagnetic results indicating magnetite as the dominant ferrimagnetic mineral. The parameter δ is defined as (IRM(600mT) - IRM(300mT))/IRM (300mT) where IRM(H) is the IRM acquired in magnetizing field H (Butler 1982). This parameter is a measure of the ratio of high coercivity phases (such as hematite) to low coercivity phases (such as magnetite). Because it is advisable to avoid sediments which have suffered post-depositional oxidation with possible attendant secondary components and remanent magnetization, low values of δ are desirable. The δ values observed in the Puerta de Corral Quemado sediments are low for continental sedimentary rocks (Butler 1982). For all but one specimen, the δ values are <0.1, with an average δ value of 0.028. Thus, only minor amounts of high coercivity minerals such as hematite could be present in these rocks.

The natural remanent magnetism (NRM) intensities were strong, ranging from 5.2 \times 10^{-3} to 5.3 \times 10^{-1} A/m. Results of progressive alternating-field (AF) and thermal demagnetization of the NRM are illustrated in figures 4 and 5, respectively. In many cases, no systematic directional change was observed during either progressive AF or thermal demagnetization, and no significant secondary components are present in these samples. Where present (e.g., fig. 4b), secondary components were adequately erased by AF demagnetization to 20 mT peak field. No secondary components were erased by thermal demagnetization which were not also erased by AF demagnetization to 20 mT peak field. Thus, the blanket demagnetization treatment chosen was AF demagnetization at 20 mT. The primary NRM component has coercivity dominantly <80 mT and blocking temperature distribution dominantly <575°C. These observations indicate that the primary NRM is a depositional remanent magnetization (DRM) carried by the detrital magnetite.

Following AF demagnetization to 20 mT, the clustering of NRM directions for each site was excellent. All but four of the 99 sites show within-site clustering which is significant from random at the 95% confidence level (Watson 1956). For N = 3, this requires R >2.62. Given the uncomplicated nature of the NRM and the well-determined site mean directions, the resulting determinations of polarity of the primary NRM were in most cases unambiguous.

![Fig. 2. Strong-field thermomagnetic results on magnetic separate. Magnetizing field was 300 mT. Heating and cooling curves are indicated by arrows showing direction of temperature change. Sample chamber was evacuated then back-filled with argon gas. Heating and cooling rate was 15°C/min.](image)

![Fig. 3. Acquisition of isothermal remanent magnetization as a function of magnetizing field.](image)
Although the paleomagnetic samples were collected from only one limb of the plunging anticline, variations in structural attitude within this limb are sufficient to allow a fold test to be performed. Results of the fold test are tabulated in table 1 and illustrated in figure 6. Although the improvement in clustering of site mean vectors following structural correction is not visually dramatic, the increase in the k value produced by the structural correction is significant at the 99% confidence level (Watson 1956). Thus, the fold test indicates the anticipated result that the primary NRM is prefolding in origin.

An interesting feature of the distribution of site mean directions shown in figure 6 and tabulated in table 1 is that the mean direction after structural correction is deflected in a clockwise sense from the axial geocentric dipole field direction (declination = 0°, inclination = −45.9°). Although it is possible that this observation could indicate regional tectonic rotation, we believe such a conclusion would be premature. Sufficient structural data do not exist to allow application of a plunge correction, so the “structural correction” was done only about the local strike line. It is certainly possible that the clockwise deflection of the mean direction from the axial geocentric dipole direction is simply a result of the incomplete structural correc-
TABLE 1

<table>
<thead>
<tr>
<th></th>
<th>Inclination (°)</th>
<th>Declination (°)</th>
<th>N&lt;sup&gt;a&lt;/sup&gt;</th>
<th>R&lt;sup&gt;b&lt;/sup&gt;</th>
<th>k&lt;sup&gt;b&lt;/sup&gt;</th>
<th>α&lt;sub&gt;95%&lt;/sub&gt; (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before structural correction</td>
<td>38.0</td>
<td>7.8</td>
<td>99</td>
<td>83.0</td>
<td>5.81</td>
<td>6.4</td>
</tr>
<tr>
<td>After structural correction</td>
<td>46.9</td>
<td>26.6</td>
<td>99</td>
<td>89.4</td>
<td>10.22</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Note: In computing average direction, antipodes of reversed polarity sites are averaged with normal polarity sites.

<sup>a</sup> N = number of directions averaged.

<sup>b</sup> Statistical parameters of Fisher (1953).

The table presents averages of site mean directions before and after structural correction. The inclinations and declinations are given in degrees, along with statistical parameters.

![Fig. 6](image_url)

Fig. 6.—Equal area stereographic projections of site mean directions of NRM (a) before and (b) after structural correction. Squares indicate the average directions for the normal and reversed polarity directions. Circle of 95% confidence surrounds each mean direction.
ments, preventing post-depositional oxidation of the detrital magnetite or post-depositional precipitation of other magnetic phases. These conditions could in part account for the quality of the paleomagnetic data obtained from these continental sediments.

**POTASSIUM-ARGON AGE DETERMINATIONS**

Tuffs are abundant in the Corral Quemado section, especially in the upper part (above unit 14) of the section measured by Stahlecker (in Riggs and Patterson 1939; Marshall and Patterson 1981). These tuffs apparently originated from ash-flow eruptions in the adjacent Andean Cordillera, and some may prove to be identified with eruption events of nearby calderas (see Francis and Baker 1978; Francis et al. 1978). They vary from several meter thick coarse sands rich in biotite, glass, plagioclase, and sanidine to several centimeter thick water-worked sands and silts.

The primary deposition of these tuffs was in subaerial environments. Subsequent reworking by wind and water resulted in admixing of detrital material derived from nearby Precambrian and Paleozoic crystalline basement (Ruiz Huidobro 1972; Allmendinger et al. 1983; Jordan et al. 1983). Preliminary \(^{40}\)K - \(^{40}\)Ar age determinations on mineral separates from some of these tuffs yielded markedly discordant dates due to this contamination. Further study demonstrated that only mineral concentrates carefully hand-picked to remove detrital grains gave reproducible hence reliable, age estimates (see Marshall et al. 1979).

Mineral separates from two tuffs sampled in 1977 and reported by Marshall et al. (1979) yielded reliable age determinations permitting calibration of the upper and lower limits of the 2300 m thick section shown in figure 7. The lowest tuff sampled in our measured section is from unit 15 of Stahlecker (= unit 8 of Stahlecker in Marshall et al. 1979; Marshall and Patterson 1981). This is the most prominent tuffaceous unit in the section and consists of 3 m of coarse white crystal-rich sand overlain by 2.5 m of tan and 6 m of dark green tuffaceous sand. Sample LGM 3 is from the basal eolian sand, and LGM 2 is from the overlying tan sand. Biotite, plagioclase, and sanidine concentrates were dated from both samples, but only the three sanidine concentrates (KA 3307, 3307R1, 3307R2, see table 2) from LGM 2 yielded reproducible results. The average age of these three sanidine dates based on current decay constants is 6.70 ± 0.05 Ma (fig. 7).

The highest tuff sampled in the section is from unit 29 of Stahlecker (fig. 7), a 1 m thick tuffaceous sand. Mineral separates of biotite, plagioclase, and sanidine were dated (Marshall et al. 1979, table 1). Recalculation of the dates for two biotite (KA 3278, 3285), one plagioclase (KA 3438), and one sanidine (KA 3343) age using improved data reduction techniques gave an average age of 3.48 Ma (table 2). The date of 3.53 ± 0.04 Ma on the sanidine concentrate (KA 3343) is technically the best (fig. 7), and the biotite and plagioclase dates are concordant within their analytical errors. The concordant ages obtained for these three mineral separates suggests that this tuff, as opposed to those below it, was apparently uncontaminated by older detrital material.

In 1980, nine additional tuffs between units 15 and 29 were sampled. Six of these (LGM 213, 214, 216, 219, 220, 223) contained biotite and/or glass suitable for dating (table 2). Of these, only glass concentrates from LGM 216 and 220 yielded reproducible and technically precise dates. Two results (KA 4099, 4099R) from LGM 216 yielded an average age of 5.3 ± 0.2 Ma (fig. 7), and two others (KA 4368, 4368R) from LGM 220 yield an average age of 4.95 ± 0.14 Ma (fig. 7). All biotite dates proved unreliable due to contamination, and the other glasses gave imprecise results due to high concentrations of atmospheric \(^{40}\)Ar trapped in vesicles. LGM 216 apparently correlates with part of Stahlecker’s unit 23, and LGM 220 with part of his unit 24.

**DISCUSSION**

**Geochronology.**—The paleomagnetic, \(^{40}\)K - \(^{40}\)Ar, and paleontologic data are illustrated in stratigraphic context in figure 7. The magnetic polarity zonation determined from the paleomagnetic data is shown along with its correlation to the magnetic polarity time scale of Ness et al. (1980). Abundant siltstone layers are interbedded with the predominant sandstone in the bottom half of the section. Thus, paleomagnetic sampling in this part of the section was quite dense, and the resulting magnetic polarity zonation is defined with
Fig. 7.—Paleomagnetic, $^{40}$K–$^{40}$Ar, and paleontologic data as a function of stratigraphic position. Site average virtual geomagnetic pole (VGP) latitude, interpreted magnetic polarity column, and lithologic column are plotted against stratigraphic thickness. Solid symbols indicate sites with within-site clustering which is significant from random at the 95% confidence level while open symbols indicate sites with poorer within-site clustering. Black bars in polarity column indicate normal polarity, white bars indicate reversed polarity. Correlation of magnetic polarity zones with the magnetic polarity time scale of Ness, Levi, and Couch (1980) is illustrated at the right side of the diagram. The position of fossil specimens of Procyonidae in the section are shown.
TABLE 2
ANALYTICAL DATA FOR 40K–40Ar DATES OF MINERAL SEPARATES OF TUFFS FROM CORRAL QUEMADO, CATAMARCA PROVINCE, ARGENTINA, IN STRATIGRAPHIC ORDER (YOUNGEST TO OLDEST)

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Dated Material</th>
<th>Sample Weight (grams)</th>
<th>K (%)</th>
<th>40Ar a (× 10^-11 mole/gram)</th>
<th>40Ar a (%)</th>
<th>Age ± 2σ (Ma)</th>
<th>Collection Number (LGM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KA 3278</td>
<td>biotite</td>
<td>2.7520</td>
<td>4.281</td>
<td>2.59</td>
<td>9.6</td>
<td>3.49 ± .2</td>
<td>4A</td>
</tr>
<tr>
<td>KA 3285</td>
<td>biotite</td>
<td>1.3556</td>
<td>4.648</td>
<td>2.76</td>
<td>9.4</td>
<td>3.42 ± .6</td>
<td>4A</td>
</tr>
<tr>
<td>KA 3343</td>
<td>sanidine</td>
<td>4.6977</td>
<td>4.783</td>
<td>2.93</td>
<td>83.2</td>
<td>3.53 ± .04</td>
<td>4A</td>
</tr>
<tr>
<td>KA 3438</td>
<td>plagioclase</td>
<td>1.9678</td>
<td>.416</td>
<td>.25</td>
<td>4.9</td>
<td>3.46 ± .5</td>
<td>4A</td>
</tr>
<tr>
<td>KA 4392</td>
<td>glass</td>
<td>2.8786</td>
<td>4.323</td>
<td>4.61</td>
<td>6.2</td>
<td>6.1 ± 1.3</td>
<td>223</td>
</tr>
<tr>
<td>KA 4393</td>
<td>biotite</td>
<td>1.37</td>
<td>4.934</td>
<td>4.17</td>
<td>10.0</td>
<td>4.9 ± .4</td>
<td>223</td>
</tr>
<tr>
<td>KA 4368</td>
<td>glass</td>
<td>3.0822</td>
<td>4.445</td>
<td>3.77</td>
<td>31.6</td>
<td>4.88 ± .13</td>
<td>220</td>
</tr>
<tr>
<td>KA 4368R</td>
<td>glass</td>
<td>2.9131</td>
<td>4.445</td>
<td>3.88</td>
<td>23.4</td>
<td>5.02 ± .15</td>
<td>220</td>
</tr>
<tr>
<td>KA 4367</td>
<td>glass</td>
<td>1.2535</td>
<td>4.723</td>
<td>5.64</td>
<td>9.8</td>
<td>6.9 ± .5</td>
<td>219</td>
</tr>
<tr>
<td>KA 4099</td>
<td>glass</td>
<td>5.44</td>
<td>5.072</td>
<td>4.62</td>
<td>58.2</td>
<td>5.2 ± .3</td>
<td>216</td>
</tr>
<tr>
<td>KA 4099R ab</td>
<td>glass</td>
<td>3.0018</td>
<td>5.060</td>
<td>5.15</td>
<td>35.2</td>
<td>5.87 ± .3</td>
<td>216</td>
</tr>
<tr>
<td>KA 4099R 2</td>
<td>glass</td>
<td>2.58</td>
<td>5.060</td>
<td>4.77</td>
<td>61.7</td>
<td>5.4 ± .2</td>
<td>216</td>
</tr>
<tr>
<td>KA 4103</td>
<td>biotite</td>
<td>.5498</td>
<td>6.642</td>
<td>11.98</td>
<td>36.0</td>
<td>10.4 ± .2</td>
<td>216</td>
</tr>
<tr>
<td>KA 4095</td>
<td>biotite</td>
<td>.4418</td>
<td>6.540</td>
<td>6.97</td>
<td>8.5</td>
<td>6.14 ± 1.6</td>
<td>214</td>
</tr>
<tr>
<td>KA 4373</td>
<td>biotite</td>
<td>1.7327</td>
<td>6.351</td>
<td>28.66</td>
<td>76.0</td>
<td>25.1 ± 1.5</td>
<td>214</td>
</tr>
<tr>
<td>KA 4098</td>
<td>biotite</td>
<td>.3372</td>
<td>6.711</td>
<td>25.41</td>
<td>35.2</td>
<td>21.7 ± .6</td>
<td>213</td>
</tr>
<tr>
<td>KA 3307</td>
<td>sanidine</td>
<td>2.0359</td>
<td>9.477</td>
<td>11.07</td>
<td>91.2</td>
<td>6.73 ± .09</td>
<td>2</td>
</tr>
<tr>
<td>KA 3307 R 1</td>
<td>sanidine</td>
<td>2.0058</td>
<td>9.477</td>
<td>10.95</td>
<td>68.2</td>
<td>6.67 ± .12</td>
<td>2</td>
</tr>
<tr>
<td>KA 3307 R 2</td>
<td>biotite</td>
<td>3.3533</td>
<td>9.549</td>
<td>11.10</td>
<td>71.3</td>
<td>6.69 ± .09</td>
<td>2</td>
</tr>
</tbody>
</table>

Note.—Calculations are based on the radio-active decay constants for 40K = 4.962 × 10^-10 yr^-1 and λp + λn = 0.581 × 10^-10 yr^-1 and on the isotopic abundance 40K = 0.01167% of total K.

a Radiogenic 40Ar.

high fidelity. In the upper half of the section, however, the sampling density is generally lower with some significant gaps between paleomagnetic sites. This is a reflection of the lower abundance of siltstone interbeds. The resulting magnetic polarity zonation in the upper part of the section is correspondingly less well defined. It is fortunate that this portion of the section contains three tuff levels from which 40K–40Ar analyses have provided reliable age determinations (see above, fig. 7).

The correlation of the magnetic polarity zonation with the magnetic polarity time scale integrates the paleomagnetic and 40K–40Ar data. Both the pattern of polarity zonation and 40K–40Ar ages were used to accomplish this correlation. The correlation of polarity zones with polarity intervals of the magnetic polarity time scale is considerably more secure for the lower half of the section than for the upper half. To some degree this is a result of the fidelity with which the magnetic polarity zonation could be determined. Because the correlations of magnetic polarity zones with the magnetic polarity time scale intervals are firm in the lower portion of the section, these correlations are shown in figure 7 by solid lines. The less secure correlations in the upper part of the section are shown by dashed lines and were strongly influenced by the 40K–40Ar ages.

Two problems with the correlations shown in figure 7 are evident. Within the normal polarity zone is a thin reversed polarity zone. The normal zone is correlated with the older normal polarity interval of chron 5. No corresponding short-duration reversed polarity interval is present in the magnetic polarity time scale. It is possible that the high sediment accumulation rate in this section allowed recording of a short duration reversed polarity interval that is not included in the magnetic polarity time scale. The correlation also implies that the reversed polarity interval between the two older normal polarity events in the Gilbert epoch is not recorded in the magnetic polarity zonation. However, the sampling interval would appear to have been sufficient to anticipate having recorded this polarity interval. Despite these problems, the overall match of the magnetic polarity zonation with the magnetic polarity time scale is good. The goodness of the match can be ob-
served more easily in figure 8, where the magnetic polarity zonation is shown against a larger portion of the magnetic polarity time scale.

An effective evaluation of the consistency of the magnetostratigraphic and $^{40}$K–$^{40}$Ar data is a plot of the ages implied by the magnetostratigraphic correlation and the $^{40}$K–$^{40}$Ar age determinations against stratigraphic thickness (fig. 9). The internal consistency evident in figure 9 is to some degree forced because the $^{40}$K–$^{40}$Ar age determinations were used as guidance in the magnetostratigraphic correlations. However, the fact that the data are consistent with a simple constant sediment accumulation rate of 56 cm/1000 yr during deposition of this section provides confidence that the correlation of figure 7 is, in fact, correct. Any other correlation would imply major and repeated changes in sediment accumulation rate. We thus believe that the magnetostratigraphic and $^{40}$K–$^{40}$Ar data are providing accurate age determinations for this stratigraphic section.

Age of Formation Boundaries.—Stahlecker (in Riggs and Patterson 1939, fig. 1; Marshall and Patterson 1981, fig. 6) recognized five major mappable units in his Puerta de Corral Quemado profile; from oldest to youngest: the Calchaqui, Chiquimil B, Chiquimil A, Araucanense, and Corral Quemado Formations. Our measured section (fig. 7) includes the upper part of Chiquimil A, all of the Araucanense, and all except the very top of the Corral Quemado Formations. Correlations of our current section with that of Stahlecker are based on the secure identification of units 15 and 29 in both. Proportional dividers were used to extrapolate units from Stahlecker’s section into ours, using units 15 and 29 as reference points in this process. With this approach we were able to
place the following ages on formational boundaries: Chiquimil A-Araucanense 7.5 Ma, and Araucanense-Corral Quemado 6.4 Ma (fig. 7).

Stahlecker also made a detailed section at Chiquimil and in it recognized the same lower four formations that he recognized at Puerta de Corral Quemado. His Chiquimil profile apparently terminated below rocks and faunas that would correlate with the Corral Quemado Formation. Based on Stahlecker’s geological study and on a preliminary study of the fossils, Riggs and Patterson (1939, fig. 1) proposed a tentative correlation of the Chiquimil and Puerta de Corral Quemado sections. The geochronologic data presented here require modification of one important aspect of that correlation. The tuff from unit XIX at Chiquimil is confidently dated at 6.02 Ma (see Marshall et al. 1979) and that unit is placed by Riggs and Patterson (1939, fig. 1) in the middle part of their Araucanense Formation. This securely dated level correlates not with the middle part of the Araucanense Formation at Puerta de Corral Quemado as they suggest, but with the middle of unit 18 in the lower part of the Corral Quemado Formation. Thus, rocks and faunas from the upper half of the Araucanense Formation at Chiquimil correlate with those of the lower half of the Corral Quemado Formation at Puerta de Corral Quemado. This revised correlation clearly warrants a detailed reanalysis of the fossil mammal faunas from both localities.

Age of Fossil Procyonidae.—In the late Miocene a limited but important interchange of faunas between the Americas occurred (Simpson 1980). Members of the North American family Procyonidae (raccoons and their allies) dispersed to South America, and members of the South American ground sloth families Megalonychidae and Mylodontidae dispersed to North America. These dispersal events apparently resulted from members of each group being carried on rafts of vegetation that were broken away from banks of swollen rivers and ferried directly or by way of island chains across the marine water barrier that then separated the two Americas (Coney 1982). These animals, the “new island-hoppers” of G. G. Simpson (1950), represent the first participants in the Great American Faunal Interchange (sensu Webb 1976). Dispersal of these groups occurred prior to the emergence of the Panamanian land bridge at about 3.0 Ma (Marshall et al. 1979, 1982).

The earliest known Procyonidae in South America are of the genus Cyonasua from rocks of Huayquerian age in Catamarca Province, Argentina (Kraglievich and Olazábal 1959, table on p. 45). Numerous specimens were collected by early Argentine paleontologists from rocks of the Araucanense Formation in the Valle del Río Santa María at and near Chiquimil (fig. 1), but the stratigraphic levels from where they came were not recorded, and their positions within the geochronologic time framework here are not securely known. As summarized by Kraglievich and Reig (1954) and Kraglievich and Olazábal (1959) these specimens include: (1) the type of Cyonasua argentina Ameghino (1885, p. 19); (2) five specimens (MACN 6687, 6688, 6689, 6692, 8211) referred to Cyonasua cf. C. argentina; (3) the type of Cyonasua brevirostris (Moreno and Mercaret 1891, p. 235); and (4) the types of Amphinosua longirostris Rovereto (1914, p. 81) and Pachynasua robusta Rovereto (1914, p. 82), both regarded as junior synonyms of C. brevirostris (Kraglievich and Olazábal 1959).

The only Procyonidae from Catamarca with good stratigraphic control were obtained in 1926 by an expedition from the Field Museum (Riggs and Patterson 1939; Marshall et al. 1979; Marshall and Patterson 1981). Five specimens, two from Chiquimil and three from Puerta de Corral Quemado (fig. 1), were collected. The two specimens from Chiquimil include FMNH P14342 from unit XVIIIa and FMNH P14537 from unit XIX of the Araucanense Formation of Stahlecker in Riggs and Patterson (1939) and Marshall and Patterson (1981). Both specimens are referred to Cyonasua brevirostris by Tedford in Marshall et al. (1979). An average age of 6.02 Ma was obtained on three plagioclase (KA 3305, 3305R, 3390), and one sanidine (KA 3386) concentrate from a prominent tuff in unit XIX (Marshall et al. 1979). This date approximates the age of these specimens of Cyonasua at this locality.

The three specimens from Puerta de Corral Quemado include: (1) FMNH P14451 from unit 14 of the Araucanense Formation (fig. 7)
and referred to *Cyonasua* sp. by Tedford in Marshall et al. (1979); (2) FMNH P14397 from unit 16 or 17 of the Araucanense Formation (fig. 7) and identified as *Cyonasua* cf. *C. lutaria* by Tedford in Marshall et al. (1979) [the preceding specimens were incorrectly listed by Marshall et al. (1979, p. 276) as coming from the Corral Quemado Formation]; and (3) FMNH P14401 probably from unit 21 of the Corral Quemado Formation (fig. 7) and referred to *Chapalmalania* cf. *C. altaefrontis* by Kraglievich and Olazábal (1959, p. 9, 28). *Chapalmalania* is a bear-like procyonid and an apparent direct descendant of *Cyonasua* (Kraglievich and Olazábal 1959). FMNH P14401 is the specimen listed as *Cyonasua* nov. sp. by Riggs and Patterson (1939, p. 145). Our geochronologic data indicate the following ages for these specimens (see fig. 7)—7.0 to 7.5 Ma, 6.4 to 6.9 Ma, and 5.4 to 5.8 Ma, respectively. FMNH P14451 from unit 14 dated between 7.0 and 7.5 Ma is the oldest known representative of *Cyonasua* in South America, and FMNH P14401 from unit 21? dated between 5.4 and 5.8 Ma is the oldest known representative of *Chapalmalania*.

Age of the Huayquerian-Montehermosan Boundary.—The geochronologic data presented here permit approximate dating of the boundary between Huayquerian and Montehermosan land mammal age faunas at this locality. As summarized by Pascual and Odreaman Rivas (1973, chart opposite p. 318), Marshall and Patterson (1981), and Marshall et al. (1983), the Araucanense Formation at Puerta de Corral Quemado contains a mammal fauna assigned to the Huayquerian land mammal age, and the Corral Quemado Formation contains a fauna assigned to the Montehermosan land mammal age. The boundary between the Araucanense and Corral Quemado Formations thus approximates but does not necessarily represent the boundary between Huayquerian and Montehermosan land mammal age faunas at this locality. The boundary between these formations is securely dated at 6.4 Ma (fig. 7).

Rocks and faunas of Huayquerian age have also been dated by the 40K–40Ar method near San Carlos in Mendoza Province, west-central Argentina (see Marshall et al. in press). An age of 5.8 Ma was obtained on biotite separates from a tuff believed to be at the top of the Huayquerias Formation, namesake and type formation of the Huayquerian land mammal age (Simpson 1940). At this locality the Huayquerias Formation is discordantly overlain by the Tunuyan Formation (Dessanti 1946), which contains a mammal fauna assigned to the Montehermosan land mammal age. The boundary between the Huayquerias and Tunuyan Formations at San Carlos is thus 5.8 Ma or younger. The combined ages from San Carlos and from Puerta de Corral Quemado apparently bracket the Huayquerian-Montehermosan boundary between 5.8 and 6.4 Ma. Based on these dates we tentatively recognize an age of 6.0 Ma as the approximate boundary between these land mammal ages in Argentina.

**CONCLUSIONS**

Magnetostratigraphic and 40K–40Ar data on a 2300 m thick sequence of continental sediments at Puerta de Corral Quemado in Catamarca Province, NW Argentina permit calibration of land mammal faunas of Huayquerian and Montehermosan age. The time represented includes the interval from ~8.0 Ma to 3.5 Ma. The Araucanense Formation contains a mammal fauna of Huayquerian age, and the overlying Corral Quemado Formation contains a fauna of Montehermosan age. The age of the boundary between these formations is dated at 6.4 Ma, and this age is believed to approximate the boundary between the Huayquerian and Montehermosan land mammal ages at this locality. A specimen of *Cyonasua* from unit 14 (dated between 7.0 and 7.5 Ma) of the Araucanense Formation is the oldest known representative of the North American family Procyonidae in South America. This specimen represents the earliest known participant of the Great American Faunal Interchange on that continent.

In North America the earliest undoubted participant in this early phase of the Great American Faunal Interchange is represented by a specimen of the megalonychid ground sloth *Pliometenastes protistus* Hirschfeld and Webb (1968) from the Siphon Canal locality of the Mehrten Formation, Stanislaus County, California (Hirschfeld, 1981). This specimen was collected from 4 m below a tuff dated at 8.19 ±0.16 Ma (Wagner 1981).

Thus, the available geochronologic data document the occurrence of the earliest un-
doubted participants in the Great American Faunal Interchange in rocks of similar age in North America and South America. These new data further suggest that the beginning of the interchange may have been a synchronous event or nearly so, as proposed by Webb (1976) and not markedly diachronous as proposed by Marshall et al. (1979).

ACKNOWLEDGMENTS.—Funds for field work were provided by grant 1698 from the National Geographic Society, Washington, D.C. (LGM, RFB) and NSF Grant EAR-7909515 (LGM). The $^{40}$K–$^{40}$Ar dating was supported by NSF Grant EAR-73-00235 A01, formerly GA-40805 (GHC), and NSF Grants EAR-7909515, EAR-8300918, and EAR-8305243 (LGM). Processing paleomagnetic samples was supported by NSF Grants EAR-75-13571 and EAR-8115430 (RFB), and some of the paleomagnetic equipment was provided by a Cottrell Research Grant from the Research Corporation. Kathy Flanagan’s able assistance with the paleomagnetic analyses is gratefully acknowledged. The manuscript was improved by critical readings by John Obradovich and Steve May.

REFERENCES CITED


AMEGINO, F., 1885, Nuevos restos de mamíferos fósiles oligocenos, recogidos por el profesor Pedro Scalabrini y pertenecientes al Museo provincial de la ciudad de Paraná: Bol. Acad. Cienc. Córdoba, v. 8, p. 3–207.


——, DRAKE, R. E.; and CURTIS, G. H., in press, $^{40}$K–$^{40}$Ar age calibration of late Miocene-Pliocene mammal-bearing Huayquerias and Tunuyan Formations, Mendoza Province, Argentina: Jour. Paleont.


NESS, G.; LEVI, S.; and COUCH, R., 1980, Marine


