Calibration of the Great American Interchange

A radioisotope chronology for Late Tertiary interchange of terrestrial faunas between the Americas.

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Summary. From radioisotopic (potassium-argon) age determinations of tuffs and magnetostratigraphy of Late Tertiary mammal-bearing beds in Catamarca Province, northwest Argentina, refined estimates have been obtained for the durations and boundaries of beds of Chasicoan (Middle Miocene) through Chapadmalalan (Pliocene) age. An age of 9.0 million years is tentatively accepted for the Chasicoan-Huayquerian boundary, 5.0 million years for the Huayquerian-Montehermosan boundary, and 3.0 million years for the Montehermosan-Chapadmalalan boundary. Procyonids (raccoons and their allies), a group of North American origin, are first recorded in South America in a level immediately below a unit dated at 6.0 million years. Cricetine rodents of the tribe Sigmodontini are first recorded in South America in beds of Montehermosan age in Argentina. Ground sloths, a group of South American origin, first appear in North America in Early Hemphillian time in beds dated between 9.5 and 9.0 million years. The Panamanian land bridge was established by 3.0 million years ago, and an interchange of the terrestrial faunas was well under way by Late Blancan time (around 2.5 million years before present) in North America and by Chapadmalalan time in South America.

Throughout most, if not all, of the Tertiary period (65 million to about 2 million years ago) South America was an island continent (*1*). As a result of this long isolation, unique land mammal faunas developed and were dominated by autochthonous groups. The distinct character of these faunas and the absence of two-way intercontinental interchanges deters precise biostratigraphic correlations. The isolation of South America ended about 3 million years ago, when the Panamanian land bridge came into existence, uniting the two Americas. Thereafter the fossil record documents an intermingling of the long-separated North and South American faunas (*1, 2*).

A relative time scale for mammalian faunal succession within South America is now generally agreed upon (*3*), and beds and faunas of Early Oligocene to Middle Miocene age have now been partially calibrated in terms of a radioisotopic (^{40}K-^{40}Ar) time scale (*4*).

Rocks from two localities yielding rich Late Tertiary mammal faunas in the province of Catamarca, northwest Argentina, have given concordant radioisotopic and paleomagnetic results (Fig. 1). Diverse faunas of Huayquerian (Late Miocene) age have been collected from units XV to XX of the stratigraphic section of R. Stahlecker (*5*) from near Chiquimil (Entre Ríos) in the Valle de Santa María, Department of Santa María (Fig. 2). Faunas of Huayquerian and Montehermosan (Pliocene) age have been collected from units 14 to 17 and 18 to 32, respectively, of the stratigraphic section of Stahlecker (*5*) in the vicinity of Puerta de Corral Quemado, Department of Belén, nearly 100 kilometers to the southwest (Fig. 2). At these localities there are numerous airfall tuffs for potassium-argon dating and an abundance of clay layers suitable for paleomagnetic analyses. Stratigraphic levels at these localities were recorded for a large collection of fossil vertebrates in the Field Museum of Natural History, Chicago (*6*).

Stratigraphic terminology for the thick series of Late Tertiary beds in the Valle de Santa María has had a long and confused history, which has been summarized by Marshall and Patterson (*6*). Riggs and Patterson (*5*) recognized four formations in the Chiquimil area; these are, from oldest to youngest, the Calchaquí, Chiquimil B, Chiquimil A, and Araucanense. The first and last names were proposed by earlier workers and used in a restricted sense by Riggs and Patterson; Chiquimil B and Chiquimil A were proposed as new. The formations recognized by Riggs and Patterson were all poorly characterized and were based on an as yet unpublished manuscript on the geology of this area by Stahlecker, the expedition's geologist. A recent and detailed study of the geology of this valley is given by Ruiz Huidobro (*7*). He recognized and adequately characterized a number of formations, of which the San José, Loro Huasi, Las Arcas, and Andalhualá are approximate equivalents to the Calchaquí, Chiquimil B, Chiquimil A, and Araucanense of Riggs and Patterson.

At the Puerta de Corral Quemado locality Riggs and Patterson (*5*) recognized the same four formations as at Chiquimil, plus a younger (uppermost) formation, the Corral Quemado, which they first named. A tentative correlation of beds in the Chiquimil and Corral Quemado areas is given by Riggs and Patterson, and a revised correlation, based largely on data presented here, is given by Marshall and Patterson (*6*).

In this article we use the stratigraphic terminology of Riggs and Patterson (*5*) for the Late Tertiary beds in the Chiquimil and Puerta de Corral Quemado areas. The chronology and usage of South American land mammal ages follow Patterson and Pascual (*1*). The only modification is the recognition of a Chapadmalalan age, which Patterson and Pascual (*1*) and Pascual and Odreman Rivas (*3*) place in the upper part of the Montehermosan, following the reasonable recommendations to do so outlined by Simpson (*8*) and the fact that this age may be characterized by the first record in South America of numerous mammalian taxa of North American origin.

During May 1977, L.G.M., R.F.B., and R. Pascual visited the Chiquimil and

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Corral Quemado localities and collected rock samples for radioisotopic dating and paleomagnetic analyses. These dates and magnetostratigraphic data are the first to be obtained from strata associated with Late Tertiary (Late Miocene through Pliocene) land mammal faunas in Argentina. Such data permit calibration of boundaries and determination of the duration of hiatuses between Late Tertiary land mammal ages, as has been done for North America (*9-12*). These geochronologic data are combined with new and updated faunal analyses in an attempt to improve correlations of North and South American land mammal ages.

Potassium-Argon Age Determinations

Only two ^{40}K-^{40}Ar dates were previously available for the Late Tertiary mammal-bearing strata of South America. These dates, 5.5 and 6.4 million years before present (B.P.), were obtained from two samples of the basal tuff ("Toba 76") of the Umala Formation south of La Paz, Bolivia (*13*). The samples were collected 150 km apart, the former from near Ayo Ayo and the latter from near Pomata. Fossil mammals are reported from beds above and evidently conformable with this tuff (*14*). With one exception (*15*), the taxonomic identifications are preliminary, and the collections have not yet been adequately compared with type Argentine material. A tentative Montehermosan age for these local faunas has been suggested (*15*).

Samples of crystal-rich, vitric rhyodacite airfall or eolian tuffs associated with known mammal faunas of Huayquerian and Montehermosan age near Chiquimil and Corral Quemado (Fig. 1) were collected for ^{40}K-^{40}Ar dating (*16*). Biotite, plagioclase, and sanidine were separated, when possible and dated by the ^{40}K-^{40}Ar method by R.E.D. and G.H.C. (see Table 1.)

Thin sections of these tuff samples showed occasional detrital contamination of muscovite and fragments of gneissic material probably derived from Paleozoic or Precambrian basement, or both, appearing in nearby outcrops. This contamination explains the marked discordance between many of the mineral dates from the same tuff (Fig. 3). For this reason, the youngest dates for each tuff are considered most representative of its true age.

One tuff from unit 15, one from unit 29, and two from unit 8 of the stratigraphic section of Riggs and Patterson (*5*) from Corral Quemado were dated (Table 1). So far, only the tuff from unit 29 and the upper one from unit 8 have yielded reliable results. The other two have given mineral dates that appear to be too old, even for samples that were redated after handpicking of anomalous detrital grains.

Unit 29. Two biotite, two plagioclase, and one sanidine separate from unit 29 in the upper part of the Corral Quemado Formation were dated. Of these, the sanidine data (KA 3343) of 3.54 ± 0.03 million years B.P. is technically superior to and younger than either the biotite or the plagioclase dates. The two biotites (KA 3278 and 3285) gave dates of 3.55 ± 0.3 and 3.8 ± 0.25 million years B.P., respectively. The first plagioclase (KA 3342), dated at 4.8 ± 0.4 million years B.P., is significantly older than another handpicked plagioclase (KA 3438), which was dated at 3.8 ± 0.4 million years B.P., probably reflecting the presence of detrital feldspar. The best estimate for the age of this tuff is therefore 3.54 million years, given by the sanidine date. The dates for the two biotite and one plagioclase, although somewhat older, are concordant with the sanidine date within their analytical errors (Fig. 3).

Units 8 and 15. Biotite and plagioclase separates from a tuff in unit 15 and biotite, plagioclase, and sanidine separates from two tuffs in unit 8 in the middle part of the Corral Quemado section gave widely discordant results due to detrital contamination (Fig. 3). All of the biotite separates are believed to contain a metamorphic biotite component along with the conspicuous muscovite, and these dates must be regarded as too old.

Two plagioclase separates from the unit 15 tuff (KA 3304 and 3304R) gave respective dates of 7.9 ± 0.12 and 9.0 ± 0.5 million years B.P. Subsequently, a handpicked plagioclase (KA 3439) gave a younger date of 7.3 ± 0.1 million years B.P., indicating the presence of more detrital feldspar in the first two separates. Since plagioclase has a much lower potassium content than either biotite or sanidine, it is more affected by contamination; thus, even the youngest date of 7.3 million years B.P. must be considered a maximum age for this tuff.

A prominent tuff from unit 8, lying approximately 400 meters below the tuff of unit 15 (Fig. 2), was sampled at two levels because of the distinctive nature of the basal and upper parts of the tuff. Biotite, plagioclase, and sanidine were separated from both samples and dated. The results again were widely discordant. Three biotite dates (KA 3276, 3279, and 3279R), which ranged from 7.6 to 8.85 million years B.P., were disregarded for the same reason as before. Two plagioclases, one from each tuff,

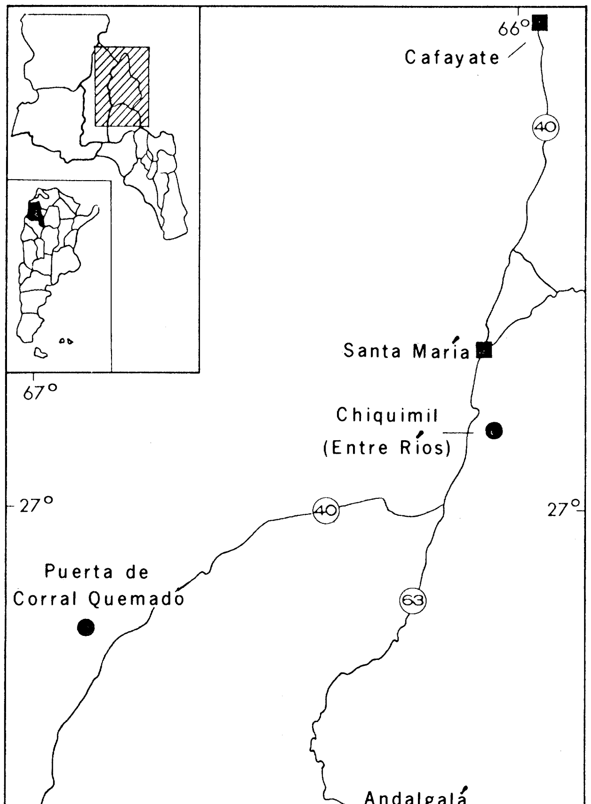

Fig. 1. Map of Catamarca Province, northwest Argentina, showing the Chiquimil and Puerta de Corral Quemado localities.

were redated after handpicking of detrital components. In each case the age dropped, from 9.1 to 7.9 million years (KA 3370R1 and 3370R2) in the upper tuff and from 9.3 to 8.72 million years (KA 3346 and 3346R) in the lower tuff, demonstrating the presence of an old feldspar component. Only the sanidine dates (KA 3307, 3307R1, and 3307R2) from the upper tuff with a mean of 6.68 ± 0.02 million years B.P. appear to give a reliable estimate of the age of the unit 8 tuff. Thus, all the plagioclase and biotite dates and the one sanidine date (KA 3345) from unit 8 must be rejected because of contamination. Furthermore, since the tuff from unit 15 lies stratigraphically above that from unit 8, the minimum date of 7.3 million years B.P. for the former appears somewhat too old.

Unit XIX. Only the tuff from unit XIX of the Araucanense of Riggs and Patterson was sampled at the Chiquimil locality (Fig. 1). Biotite, plagioclase, and sanidine were again separated for dating. The initial results for each mineral phase were concordant but differed significantly between phases. The mean of four biotite dates (KA 3277, 3212, 3212R, and 3280) was 9.3 ± 0.1 million years B.P., the mean of two sanidine dates (KA 3308 and 3308R) was 6.70 ± 0.01 million years B.P., and the mean of two plagioclase dates (KA 3305 and 3305R) was 6.0 ± 0.1 million years B.P. To resolve this discordance between minerals, another plagioclase and another sanidine separate were dated after handpicking of detrital grains. The sanidine (KA 3386) gave an age of 5.98 ± 0.05 million years, concordant with the plagioclase (KA 3390) age of 6.06 ± 0.07 million years. The mean of 6.02 ± 0.04 million years for KA 3386 and 3390 is accepted as the age of the unit XIX tuff in the Chiquimil section. In this tuff only plagioclase appeared to be free of contamination, since the first nonpicked separates gave essentially identical results, whereas the sanidine date fell from 6.7 to 6.0 million years B.P. only after removal of detrital grains (Fig. 3).

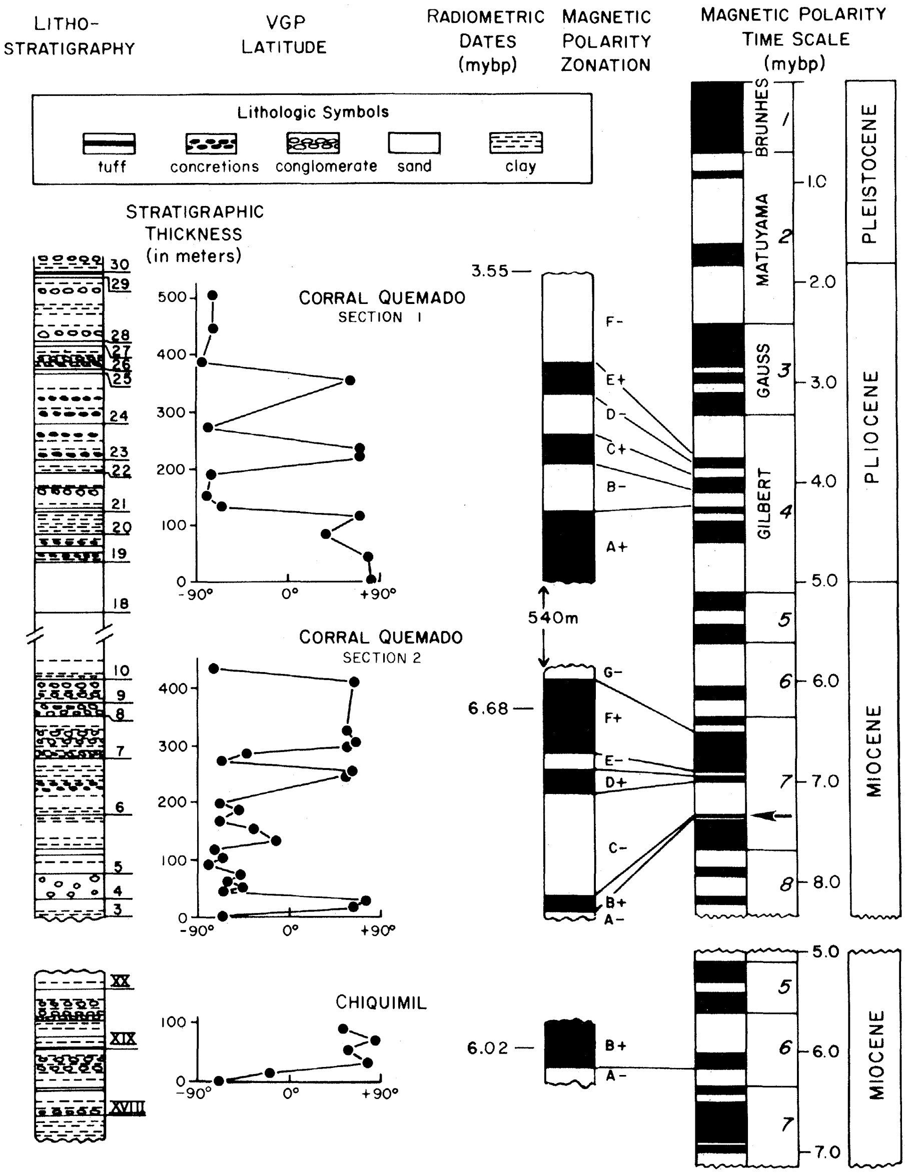

Fig. 2. Lithostratigraphy, magnetostratigraphy, and radioisotope dates for the Chiquimil and Corral Quemado localities. The partial lithostratigraphic columns are after Riggs and Patterson (*5*, figure 1), using their numberings for lithologic units. Corral Quemado sections are continuous, but the middle portion is not illustrated. Magnetozones in the polarity zonation column are labeled with plus signs for normal polarity and minus signs for reversed polarity. The magnetic polarity time scale follows LaBrecque *et al.* (*69*), with the addition of the short normal polarity interval (arrow) found in Iceland by Watkins and Walker (*70*). Numbers to the immediate right of the polarity time scale are epoch numbers. The geologic time scale follows Berggren and Van Couvering (*71*).

Magnetostratigraphy

Three oriented block samples suitable for paleomagnetic analyses (*17*) were collected (*18*) by R.F.B. and L.G.M. at each of 38 sites at Corral Quemado and six sites at Chiquimil (Fig. 2). Site average virtual geomagnetic pole (VGP) latitudes are shown in Fig. 2; positive VGP latitudes indicate normal polarity. The interpreted polarity zonation is shown adjacent to the VGP plots along with the radioisotope dates from the tuffs in the three sections. Tentative correlations of the magnetic polarity zones with the geomagnetic polarity time scale are also indicated. Radioisotope dates were used to indicate the region of the polarity time scale with which correlation should be attempted. Although the correlations are not unique and should be refined by future extension of the sections, the magnetostratigraphic data are consistent with and supportive of the radioisotope age determinations.

Corral Quemado section 2 (Fig. 2) exhibits the most convincing correlation with the polarity time scale. The 6.68 million year B.P. date from unit 8 near the top of this section constrains the polarity zonation to within epoch 7. With this initial confinement, the polarity zonation shows a strong correlation with the greater part of epoch 7.

Correlation of Corral Quemado section 1 (Fig. 2) with the polarity time scale is less certain. A tuff dated at 3.54 million years B.P. occurs within unit 29 at the top of this section. Given this constraint, the correlation of the normal polarity intervals in this section with the normal polarity events in the Gilbert epoch is preferred.

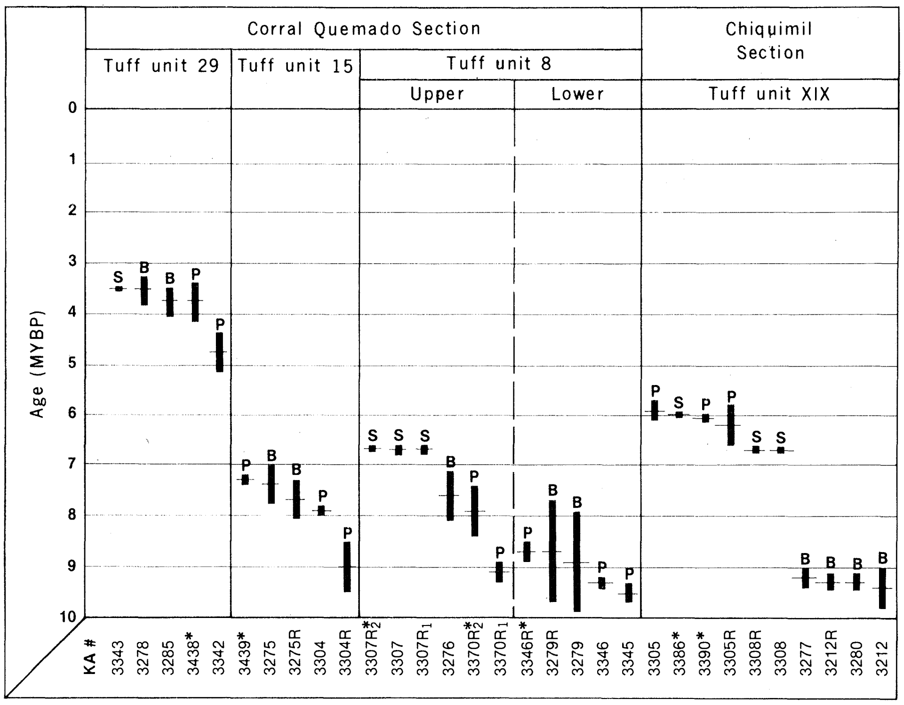

Fig. 3. Potassium-argon dates and analytical errors for biotite (*B*), plagioclase (*P*), and sanidine (*S*) separates. Samples handpicked to remove detrital grains are marked by an asterisk.

The sampled section at Chiquimil, which includes unit XIX dated at 6.02 million years B.P., is short and the proposed correlation (Fig. 2) with the base of epoch 6 of the polarity time scale is very tentative. This correlation is simply the most likely of the several possibilities and will be easy to test by further sampling.

The New Island Hoppers

Sometime during the Late Miocene a limited but important interchange of mammalian taxa between North and South America took place. Procyonids (raccoons and their allies), a group of North American origin, are first recorded in South America in beds of Huayquerian age, while members of the extinct South American ground sloth families Megalonychidae and Mylodontidae are first recorded in North America in Early Hemphillian time. It is now generally agreed (*2*, *19*) that these groups, the New Island Hoppers of Simpson (*19*), dispersed along island arcs before the appearance of the Panamanian land bridge in the Pliocene (around 3.0 million years B.P.; see below).

Cyonasua Group of Procyonids

The earliest and most generalized South American procyonid is *Cyonasua* (*20*), which represents or approximates the immigrant stock. The specimens of procyonids obtained by the Field Museum from Chiquimil and Corral Quemado were briefly mentioned by Riggs and Patterson (*5*), and most were referred to *Cyonasua brevirostris* (*21*). Restudy of the specimens by R.H.T. indicates that FMNH P14342 and P14537, from units XVIIIa and XIX, respectively, of the Araucanense near Chiquimil, are morphologically similar and resemble *C. brevirostris* as originally claimed.

The region near Chiquimil in the Valle de Santa María provided the type specimen of *C. brevirostris* and its synonyms (*22*), *Amphinasua longirostris* (*23*), and *Pachynasua robusta* (*23*). Numerous additional specimens of *Cyonasua* have been reported from the Araucanense in this area, although the exact units from which they were collected were not recorded (*20*-*29*). The Field Museum spec-

Table 1. Analytical data. Rock types are described in (*16*). Calculations are based on the radioactive decay constants $^{40}\mathrm{K}\lambda_\beta = 4.962 \times 10^{-10}$ year^{-1} and $\lambda^{40}\mathrm{K}^e + \lambda'^{40}\mathrm{K}^e = 0.581 \times 10^{-10}$ year^{-1} and on the isotopic abundance $^{40}\mathrm{K} = 0.01167$ percent of total K. For sample location see (*5*) and Fig. 2.

Sample number	Dated material	Sample weight (g)	K (%)	Radiogenic ^{40}Ar ($\times 10^{-11}$ mole/g)	Atmospheric ^{40}Ar (%)	Age ($\times 10^6$ years)
Corral Quemado: unit 29 of Corral Quemado Formation						
KA 3278	Biotite	2.75322	4.281	2.637	90.3	3.55 ± 0.3
KA 3285	Biotite	1.35560	4.648	3.084	89.6	3.8 ± 0.3
KA 3343	Sanidine	4.69771	4.783	2.939	16.6	3.54 ± 0.03
KA 3342	Plagioclase	3.77008	0.437	0.365	84.0	4.8 ± 0.4
KA 3438*	Plagioclase	1.96795	0.416	0.272	94.6	3.8 ± 0.4
Corral Quemado: unit 15 of Araucanense						
KA 3275	Biotite	1.05105	5.362	6.941	85.3	7.4 ± 0.4
KA 3304	Plagioclase	4.50055	0.598	0.819	61.2	7.9 ± 0.1
KA 3304R	Plagioclase	1.19357	0.598	0.931	71.6	9.0 ± 0.5
KA 3439*	Plagioclase	5.78810	0.676	0.857	57.8	7.3 ± 0.1
KA 3275R	Biotite	1.54439	5.362	0.712	84.9	7.65 ± 0.4
Corral Quemado: unit 8 of Chiquimil A						
KA 3276	Biotite	1.05942	5.991	7.914	88.5	7.6 ± 0.5
KA 3307	Sanidine	2.03594	9.477	11.048	8.8	6.70 ± 0.06
KA 3307R1	Sanidine	2.00584	9.477	10.971	31.7	6.66 ± 0.1
KA 3307R2*	Sanidine	3.3533	9.549	11.068	28.7	6.67 ± 0.04
KA 3370R1	Plagioclase	5.33648	0.340	0.536	61.3	9.1 ± 0.2
KA 3370R2*	Plagioclase	4.35474	0.264	0.361	83.3	7.9 ± 0.5
Corral Quemado: unit 8 (just below KA 3276, 3307, 3370R) of Chiquimil A						
KA 3279	Biotite	1.17351	6.061	9.324	90.8	8.9 ± 1.0
KA 3345	Sanidine	1.28803	9.001	14.911	61.9	9.5 ± 0.2
KA 3346	Plagioclase	4.59375	0.719	1.162	29.0	9.3 ± 0.1
KA 3346R*	Plagioclase	1.91959	0.709	1.075	66.5	8.7 ± 0.15
KA 3279R	Biotite	0.22902	6.061	9.13	91.3	8.7 ± 1.0
Chiquimil: unit XIX of Araucanense						
KA 3277	Biotite	1.84970	6.826	10.953	57.9	9.2 ± 0.2
KA 3212	Biotite	1.79458	6.796	11.044	60.9	9.4 ± 0.4
KA 3212R	Biotite	0.61562	6.796	10.926	62.8	9.3 ± 0.2
KA 3280	Biotite	1.35331	6.049	9.765	58.9	9.3 ± 0.15
KA 3308	Sanidine	4.22293	10.545	12.285	3.7	6.71 ± 0.05
KA 3308R	Sanidine	2.65988	10.545	12.248	20.5	6.69 ± 0.06
KA 3386*	Sanidine	3.97640	10.766	11.187	4.8	5.98 ± 0.05
KA 3305	Plagioclase	8.30366	0.400	0.408	67.0	5.9 ± 0.2
KA 3305R	Plagioclase	2.31491	0.400	0.428	86.5	6.2 ± 0.4
KA 3390*	Plagioclase	4.59688	0.4664	0.491	55.6	6.06 ± 0.07

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*Handpicked to remove detrital grains.

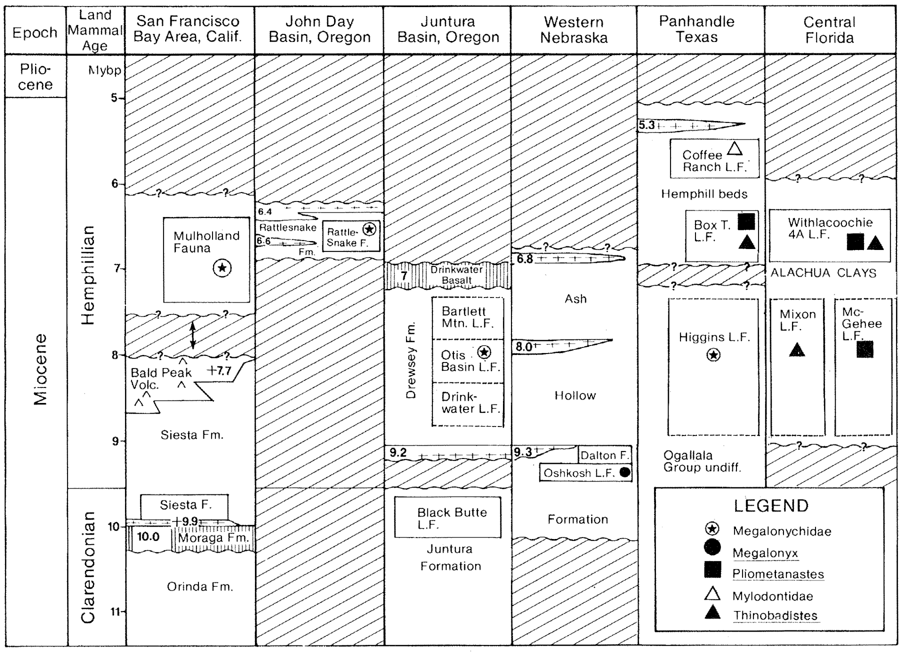

Fig. 4. Correlation of the sloth-bearing Miocene deposits in North America. Enclosure of faunal names in boxes indicates uncertainty regarding temporal position. Correlations are established by faunal similarity and calibrated by radioisotope and fission-track age determinations. Symbols show the distribution of sloth taxa in faunas at the rank indicated in the legend. Abbreviations: *F.*, Fauna; *L.F.*, Local Fauna: and *Fm.*, Formation.

imens may represent the earliest records of *Cyonasua* in South America, and their occurrence in or just below unit XIX, dated at 6.02 million years B.P., provides a minimal age for the arrival of procyonids into the South American continent.

Two specimens from the younger Corral Quemado Formation near Puerta de Corral Quemado (Fig. 1) are referable to *Cyonasua*. The first, FMNH P14451 from unit 14, is of a juvenile animal and is not further identifiable. The second, FMNH P14397 from unit 16 or 17, is a young adult whose size and morphology closely match the type of *Cyonasua lutaria* (*29*) from the Chapadmalal Formation, Buenos Aires Province, Argentina. The only apparent difference is that FMNH P14397 has a simple connate M_1 (first lower molar) paraconid rather than the more complex divided cuspid present in the type of *C. lutaria*. It differs from the Chiquimil specimens referred to *C. brevirostris* in having longer and more complex lower premolars bearing stronger anterior and posterior cuspids and having a shorter M_2 (second lower molar) than M_1. In these characters FMNH P14397 also compares with *Cyonasua groeberi* (*22*) from beds of Late Huayquerian or Montehermosan age at Las Playas, Córdoba, and it agrees further in having a very large canine, but this may be markedly sexually dimorphic as in other arctoids. *Cyonasua groeberi* also retains P_1 (first lower premolar) in the adult as in the smaller and otherwise more primitive *Cyonasua argentina*. This primitive character, combined with posteriorly widened, complex premolars and a bifid M_1 paraconid, gives *C. groeberi* a unique morphology.

Kraglievich and Olazábal (*24*) also note that in Argentine collections from Catamarca there is a form, smaller and more primitive than *C. brevirostris*, which they identified as *Cyonasua* cf. *C. argentina*.

A fragmentary lower jaw, FMNH P14401, collected between units 15 and 32 (probably from unit 21) of the Corral Quemado Formation, was discussed and figured (from a cast) by Kraglievich and Olazábal as *Chapalmalania* cf. *C. altaefrontis*. This specimen, listed as a new species by Riggs and Patterson (*5*), is the youngest procyonid obtained by the Field Museum. The difficulties of comparing the genoholotype of *Chapalmalania* [*C. orthognatha* (*26*), a premaxillary], the type of *C. altaefrontis* [(*24, 25*), a skull without mandible], and FMNH P14401 leaves the specific status of the latter in doubt and raises questions about the relationships of the named species. *Chapalmalania*, a giant bearlike procyonid (*28*), is known only from faunas of Montehermosan and Chapadmalalan age and occurs jointly with the youngest *Cyonasua, C. lutaria*. in the Chapadmalal Formation. *Chapalmalania* probably evolved in South America from *Cyonasua* or from a *Cyonasua*-like ancestor (*24*). *Cyonasua* and *Chapalmalania* are the only Tertiary genera of South American procyonids known (*20, 22*).

Earliest North American Ground Sloths

Rare although remarkably widespread remains of ground sloths of South American or Antillean origin first appear in Hemphillian (latest Miocene) deposits in North America. Three genera are represented: *Megalonyx* and *Pliometanastes* of the family Megalonychidae and *Thinobadistes* of the family Mylodontidae. Relatively complete specimens are virtually restricted to sinkhole fills of peninsular Florida, but the distinctive morphology of their bones and teeth make familial and generic assignments on single elements relatively secure.

The earliest records of sloths in North America occur in Early Hemphillian deposits scattered across the continent. These described occurrences can now be partially calibrated by the increasing number of radioisotope dates available for deposits that contain them (Fig. 4).

In the eastern San Francisco Bay area, Stirton (*30*) described megalonychid sloth remains as components of the Early Hemphillian Mulholland Fauna from rocks informally known as the Mulholland Formation; these rocks are younger than the Bald Peak volcanics, which interfinger with and overlie the Clarendonian-Hemphillian Siesta Formation. A basalt from the Bald Peak volcanics was dated at 7.7 million years B.P. (*31*); this gives a minimum age for the sloth occurrence, as the sample appears to be slightly altered. A tuff near the base of the Siesta Formation gave a date of approximately 10 million years B.P. (*31*).

In the John Day Basin of the Columbia Plateau, Sinclair (*32*) recorded a megalonychid phalanx in the Rattlesnake Formation, Grant County, Oregon. The associated fauna is compositionally similar to other well-known Early Hemphillian faunas of the adjacent Great Basin (such as the Rome, Thousand Creek, and Smith Valley faunas). The Rattlesnake Formation contains several tuffs that have yielded dates ranging from 6.4 to 6.6 million years B.P. (*33*). An earlier occurrence of sloths is documented in the nearby Juntura Basin, Harney County, Oregon. A small megalonychid proximal phalanx was found associated with the Otis Basin local fauna (*34*), from the Drewsey Formation. Within the Drewsey Formation, Shotwell (*34*) recognized a threefold faunal succession of compositionally similar Early Hemphillian assemblages. The Drewsey Formation conformably overlies the Welded Tuff of Devine Canyon (*35*), dated at 8.9 (*31*) and 9.15 (*36*) million years B.P. in nearby Drinkwater Pass. This thin but widespread tuff has been dated at other localities in Harney County, and the accepted average age is 9.2 ± 0.6 million years (*35*). The Drewsey Formation is disconformably overlain by the Drinkwater Basalt, dated at 6.9 ± 1.09 million years B.P. (*37*) from a locality in the Harney Basin southwest of the Juntura Basin. These dated volcanics thus bracket the Otis Basin megalonychid between 7 and 9 million years B.P.

Support for a first North American record of sloths close to 9 million years B.P. is provided by recent fission-track dating (*38*) of vitric tuffs interbedded with the upper part of the Ash Hollow Formation [*sensu* Breyer (*39*); Kimball Formation of Lugn (*40*)] of southwest Nebraska. *Megalonyx* has been recorded (*41*) at Oshkosh Quarry, Garden County, Nebraska, in rocks referred to the Kimball Formation. No tuffs occur in the Oshkosh section, but Breyer (*39*) indicates that this site is stratigraphically lower than the Dalton Quarry in nearby Greenwood Canyon, Cheyenne County, which is overlain by an ash yielding a date of 9.3 ± 0.8 million years B.P. (*38*). The top of the Ash Hollow Formation in this area is slightly younger than 7.0 million years, judging from relevant fission-track dates summarized by Boellstorff (*38*).

Early Hemphillian faunas of the southern Great Plains also contain rare sloth remains. In the superimposed faunal sequence in the Ogallala Group of Lipscomb County, Texas, and adjacent Ellis County, Oklahoma, megalonychids first occur in the Higgins Fauna (*42*) in unnamed rocks beneath the Hemphill beds (Fig. 4). *Pliometanastes* (*43*) and *Thinobadistes* occur jointly at Box T Quarry, Lipscomb County, in rocks interpreted as the base of the Hemphill beds. Higher in the same unit, the Coffee Ranch Quarry also contains mylodontid sloth remains (*42*) lying just below a vitric tuff dated at 5.3 ± 0.4 million years B.P. (*38*). The faunas from the Higgins and Box T localities are compositionally most similar to those from the Kimball of Nebraska.

Pliometanastes and *Thinobadistes* also occur jointly in Early Hemphillian beds in Florida, where they are found in deposits antedating the Late Miocene sea level lowering recognized there (*44*). *Pliometanastes* occurs in the McGehee Local Fauna, which contains estuarine vertebrates 90 to 100 feet above present sea level (*43*), indicating the position of the high Late Tertiary sea level on the tectonically stable Florida peninsula. *Thinobadistes* is also known from the Mixon bone bed (*45*), Levy County, Florida. Both the McGehee and Mixon local faunas are compositionally similar and contain taxa (such as *Osteoborus*, large *Aelurodon*, *Calippus*, *Yumaceras*, and *Aepycamelus*) that allow correlation with the Great Plains Early Hemphillian faunas. *Pliometanastes* and *Thinobadistes* occur in the estuarine Withlacoochie River 4A (*46*) near present sea level in deposits representing an accumulation during rising sea level following its Late Miocene low stand. Thus, the first appearance of sloths in Florida immediately antedates the period of low sea level identified on the Florida peninsula, which rules out the possibility that sea level lowering may have made possible the limited Neotropical exchange in Late Miocene time.

These data indicate that megalonychid sloths, close to *Megalonyx*, first appeared in North America near the beginning of Hemphillian time (9 to 9.5 million years ago, Fig. 4). *Pliometanastes* (*47*) appeared at about the same time as the first mylodontid, *Thinobadistes* (*48*), toward the end of the Early Hemphillian (7 to 8 million years ago, Fig. 4). *Pliometanastes* persisted into Late Hemphillian time, and the venerable *Megalonyx* continued until the close of the Pleistocene. The mylodontids seem to disappear during the Late Hemphillian and reappear (*Glossotherium*) in the Late Blancan (*49*) as a later immigrant from South America (Table 2).

Arrival of Sigmodontini Rodents in South America

The earliest recorded cricetid rodents of the tribe Sigmodontini (Hesperomyini) are thought to have been collected from what Bonaparte (*50*) referred to as the Limolitas Claras level of the sequence of Montehermosan age exposed in the cliff to the northwest of Farola de Monte Hermoso. This exposure is approximately 60 km southeast of Bahía Blanca, Buenos Aires Province. One of these and species from the slightly younger Chapadmalal Formation are specialized pastoral (grazing) forms that differ little from living species (*51, 52*). They are too advanced and diversified to be considered the first invaders of this group into South America. It is now believed (*51, 53*) that these rodents arrived earlier, possibly in or before the latest Miocene, by waif dispersal from North America. The Sigmodontini are now believed to have evolved in North America before 7.0 million years B.P. (*54*) long before their first recorded appearance in South America or before the inferred completion of the Panamanian land

Table 2. First records of South American immigrants in North America.

Age	Taxa	Fauna	Reference
Irvingtonian	*Didelphis*	Coleman IIA, Florida	(*62*)
Irvingtonian	*Pampatherium* (=*Chlamytherium*)	Coleman IIA, Florida	(*62*)
Early Irvingtonian	*Hydrochoerus*	Inglis IA, Florida	(*63*)
Early Irvingtonian	*Erethizon*	Inglis IA, Florida	(*63*)
Early Irvingtonian	*Eremotherium*	Inglis IA, Florida	(*63*)
Early Irvingtonian	*Nothrotheriops**	Vallecito Creek, California	(*11*)
Late Blancan	*Titanis*	Santa Fe River I, Florida	(*2, 46*)
Late Blancan	*Dasypus*	Haile XVA; Santa Fe River IA, Florida	(*49*)
Late Blancan	*Kraglievichia*	Santa Fe River IB; Haile XVA, Florida	(*49, 63*)
Late Blancan	*Glossotherium* (=*Paramylodon*)	Haile XVA, Santa Fe River I, Florida; Cita Canyon (~ 2.5 million years B.P.), Texas	(*10, 49*)
Late Blancan	*Glyptotherium*	Cita Canyon (~ 2.5 million years B.P.) and Mount Blanco, Texas	(*10, 64*)
Late Blancan	*Neochoerus*	111 Ranch, Flat Tire Fauna, Arizona	(*65*)
Late Blancan	*Coendu*†	Wolf Ranch, San Pedro Valley, Arizona	(*9*)
Early Hemphillian	*Thinobadistes*	Mixon's Bone Bed, Florida	(*66*)
Early Hemphillian	*Pliometanastes*	McGehee Farm, Florida	(*43*)
Early Hemphillian	*Megalonyx*	Oshkosh, Nebraska	(*41*)

*Generic arrangement follows Paula Couto (*67*). A Late Blancan specimen, possibly referable to this genus, has been reported (*59*). †Frazier (*68*) refers these same specimens to *Erethizon*.

bridge. The earliest known Sigmodontini are two species of *Calomys* from the medial Hemphillian (≈ 6.7 million years B.P.) White Cone Local Fauna from the upper member of the Bidahochi Formation, Arizona (*54*).

Interchange Across the Panamanian Land Bridge

Establishment of the Panamanian land bridge sometime in the latest Tertiary (around 3.0 million years B.P.) provided a direct dry land connection between the two Americas. Across this passage occurred an extensive interchange of terrestrial faunas.

The beginning of this interchange in South America is marked by the first record of an abundance of mammals of North American origin in the Chapadmalal Formation, in the southeast corner of Buenos Aires Province. These include a mustelid, *Conepatus* (*55*), a tayassuid, *Argyrohyus* (*56*), and four genera (*Akodon*, *Graomys*, *Reithrodon*, and a new genus) of Sigmodontini rodents (*51, 53*). A marked increase in mammals of North American origin occurs between the Chapadmalalan and the Uquian, in which 18 genera are recorded for the first time (*57*). Ten immigrant genera are first recorded in the Ensenadan (*1, 58*) and 24 in the Lujanian (*1, 58*).

A large contingent of terrestrial vertebrates of South American origin are first recorded in North America in beds of Late Blancan age dated around 2.5 million years B.P. (Table 2). These include *Neochoerus*, *Coendu*, *Glyptotherium*, *Glossotherium*, *Kraglievichia*, and *Dasypus* among the mammals, and the phororhacoid groundbird, *Titanis*. Numerous other South American mammals, including *Nothrotheriops* (*59*), *Eremotherium, Erethizon, Hydrochoerus, Pampatherium*, and *Didelphis*, are recorded slightly later in the Irvingtonian (Table 2).

Revised Chronology of North and South American Land Mammal Ages

The radioisotopic and magnetostratigraphic data from the Chiquimil and Corral Quemado localities permit refined estimates of the durations and boundaries of faunas of Huayquerian and Montehermosan age (Fig. 5). The revised chronology of the North and South American land mammal ages presented in Fig. 5 is based on available radioisotopic, magnetostratigraphic, and biostratigraphic data, which in all cases are concordant and complementary.

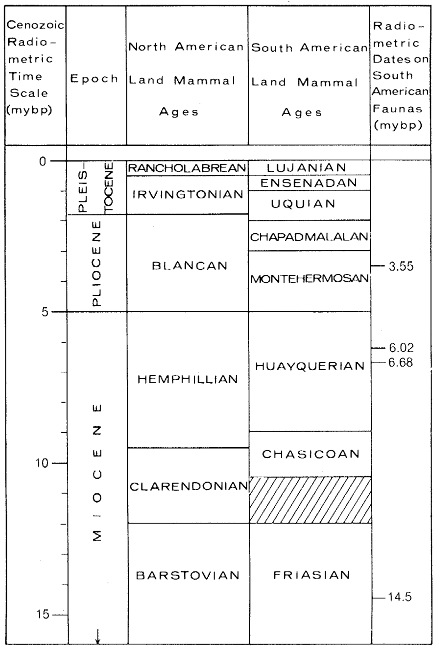

Fig. 5. Late Cenozoic radioisotope time scale and chronostratigraphy, showing approximate correlations of North and South American land mammal ages based on new data presented in this article. The geologic time scale follows Berggren and Van Couvering (*71*). The Friasian date is from Marshall *et al.* (*4*). The chronology of North American land mammal ages was compiled by R.H.T.

Accepted ^{40}K-^{40}Ar dates of 6.02 and 6.68 million years B.P. were obtained on tuffs directly associated with Huayquerian faunas (*3, 5, 6*). Fossils assignable to the Huayquerian land mammal age are abundant in unit XVII of the Chiquimil section, some 75 m below the tuff from unit XIX dated at 6.02 million years B.P. (*6*). Thus, the base of the Huayquerian at that locality is somewhat older than 6.02 million years. Accepting an age of 14.5 million years for the type Friasian (Middle Miocene) (*4*) and the existence of a paleontological hiatus between the known Friasian and the temporally restricted Chasicoan, we propose that the Chasicoan-Huayquerian boundary be tentatively placed at about 9.0 million years B.P. (Fig. 5).

The 3.54-million-year date from unit 29 near the top of the Corral Quemado Formation, which has yielded a Montehermosan fauna (*3, 6*), provides a minimum age for the Montehermosan at that locality. In turn, the magnetostratigraphic data (Fig. 2) indicate that the Corral Quemado fauna occurs at least within the middle part of the Gilbert epoch and provide a maximum age of around 4.4 million years. These dates, coupled with the dates of 5.5 and 6.4 million years B.P. for the basal tuff of the Umala Formation of Bolivia and the conformable occurrence of that tuff below a bed containing a fauna tentatively regarded as Montehermosan in age, favor placement of the boundary between known Montehermosan and known Huayquerian at around 5.0 million years B.P. (Fig. 5).

Refinement of the boundary for known Montehermosan and known Chapadmalalan is based on the 3.54-million-year date for unit 29 of the Corral Quemado Formation and on biostratigraphic data. The virtually synchronous appearance of seven South American genera in North America in beds dated around 2.5 million years B.P. favors the existence of the Panamanian land bridge by that time. If the beginning of the extensive faunal interchange in the Pliocene between North and South America indicates temporal synchronization, there is strong evidence for approximate equivalence of Late Blancan with Chapadmalalan. Furthermore, the first record of Sigmodontini rodents of North American origin in the Montehermosan of Argentina (*50*), coupled with the report (*3*) that the faunas from the Chapadmalal Formation and the Montehermosan are remarkably similar, favors placement of the boundary for known Chapadmalalan and known Montehermosan at around 3.0 million years B.P. As cricetines are unknown from the Corral Quemado Formation, and if their absence is not attributable to sampling error, the Monte Hermoso formation (that is, type Montehermosan fauna) might be younger than 3.54 million years and thus lie within the uppermost part of the Montehermosan land mammal age as here recognized.

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measured with a Reynolds-type mass spectrometer by the isotope dilution technique. Mineral contents and descriptions of the samples, based on thin section and binocular microscope study, are as follows.

Tuff from unit 15 (Corral Quemado): loosely compacted, crystal (15 to 20 percent), vitric dacite tuff; biotite, plagioclase, and minor amounts of hornblende present in fine white ash matrix; little or no quartz and sanidine present; detrital contamination containing plagioclase.

Upper tuff from unit 8 (Corral Quemado): eolian crystal/dominated (75 percent) vitric dacite tuff; biotite, sanidine, and plagioclase abundant; minor amounts of hornblende present; minor quartz, large euhedral sphene, apatite, and magnetite; no detrital contamination visible in thin section.

Lower tuff from unit 8 (Corral Quemado): composite vitric, crystal dacite tuff; white devitrified pumice fragments embedded in tan matrix of crystals and glass; biotite, plagioclase, and sanidine present; minor amounts of hornblende, large apatite, and quartz; no detrital contamination visible in thin sections.

Tuff from unit 29 (Corral Quemado): fine, loosely compacted crystal (25 percent), vitric rhyolite tuff; plagioclase, sanidine, quartz, biotite, and minor amounts of hornblende present; minor andesite and pumice fragments.

Tuff from unit XIX (Chiquimil): eolian crystal (60 percent), vitric rhyolite tuff; biotite, plagioclase, sanidine, quartz, minor hornblende, and apatite present in white tuffaceous matrix; minor detrital muscovite crystals, and composite clasts with intergrown muscovite, quartz, and plagioclase.

17. Remanent magnetization was measured by R.F.B. on a cryogenic magnetometer (Superconducting Technology C-102); alternating-field demagnetization was performed with a Schonstedt GSD-1 demagnetizer. The intensity of the natural remanent magnetism (NRM) ranged from 5×10^{-6} to 5×10^{-4} gauss. The alternating-field demagnetization to a peak field of 150 oersteds successfully removed the small viscous secondary components. Within-site clustering of NRM vectors following magnetic cleaning was excellent (R/N typically > 0.96), and unambiguous determination of the polarity of the primary depositional remanence was possible for all sites.
18. Sampling was biased toward clay-stone and siltstone layers, which were found to be more reliable paleomagnetic recorders than coarser sediments. As a result, some sampling intervals are rather large in regions where sandstone is the dominant lithology. Preliminary analyses of polished sections indicate that the dominant ferromagnetic mineral in these sediments is detrital magnetite.
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