Reports

Calibration of the Beginning of the Age of Mammals in Patagonia

Abstract. *Beds of the Rio Chico Formation containing the earliest known land mammals in Patagonia, southern Argentina, were calibrated by potassium-argon age determinations and paleomagnetic polarity data. The Riochican land mammal age encompasses the middle and late Paleocene and corresponds in time with Torrejonian and Tiffanian land mammal faunas in North America.*

Knowledge of the beginning of the Age of Mammals in Patagonia, South America, is based on faunas from the Rio Chico Formation in east-central Chubut province, southern Argentina (*1*, *2*). These faunas provide the earliest recognized South American land mammal age, the Riochican, which is conventionally regarded as late Paleocene in age (*3*, *4*). We report the first radioisotopic age determinations and paleomagnetic data which bear directly upon the age of these earliest known land mammal faunas in Patagonia.

The marine Salamanca Formation (*5*) underlies the terrestrial Rio Chico Formation in which the oldest described fossil mammals in the Argentine succession occur (*1*, *2*). Basalt flows are intercalated between the late Cretaceous Bajo Barreal and early Paleocene Salamanca formations along the upper course of the Rio Chico, just east of Lago Colhué-Huapí. Whole rock samples of two olivine-rich flows were dated by the ^{40}K-^{40}Ar method by R.E.D. and G.H.C. The first sample was collected 2 km east of Estancia La Angostura (also known as Puesto de Williams) on the south side of the Rio Chico (Fig. 1). The basalt caps the Bajo Barreal and is regarded (*6*) as the base of the Salamanca Formation. This basalt occurs 50 to 55 m stratigraphically above (*7*) a fossil level containing remains of the sauropod dinosaur *Argyrosaurus superbus* (*8*) and the hadrosaur *Secernosaurus koerneri* (*9*). This sample (KA 3575) gave a date of 64.0 ± 0.8 million years ago (*10*).

The second sample was collected from a basalt flow 6 km east of the Estancia La Angostura on the north side of the Rio Chico (Fig. 1). The basalt is overlain by 12 m of red beds that are overlain by 21 m of green beds. At 33 m above the basalt, at the top of the green beds, remains of oysters and shark teeth occur. A sample of this basalt (KA 3576) yielded a date of 62.8 ± 0.8 million years ago (*11*). The dates of the two samples provide basal ages for the Salamanca Formation at these localities.

Studies of planktic foraminifera (*12*) indicate a late Danian (early Paleocene) age for the Salamanca Formation. This age is supported by a ^{40}K-^{40}Ar date of 61 ± 5 million years obtained (*13*) on a sample of a vitric tuff from the upper Hansen Member of the Salamanca Formation at Cañadón Hondo (Fig. 1).

The Banco Negro Inferior from the lower Bustamente Member of the Salamanca Formation is predominantly a black bentonitic shale (*14*). When present, it generally attains a thickness of 1 to 5 m and has a 10-cm bed of fine white tuff (*6*) containing remains of turtles, crocodiles, silicified wood (*6*, *15*), and the oldest mammals reported from Argentina (*16*).

Simpson (*17*), on the basis of the work of McCartney (*18*), included the Banco Negro Inferior in the Salamanca Formation. Feruglio (*6*) considered it to be the base of the Rio Chico Formation, and it has been so considered by most investigators. However, because of the similar lithology between the Banco Negro Inferior and the beds below it and a marked change in the sedimentation above the

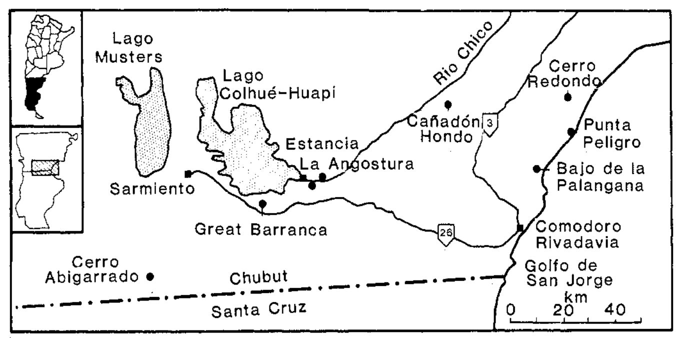

Fig. 1. Map of central Patagonia, southern Argentina.

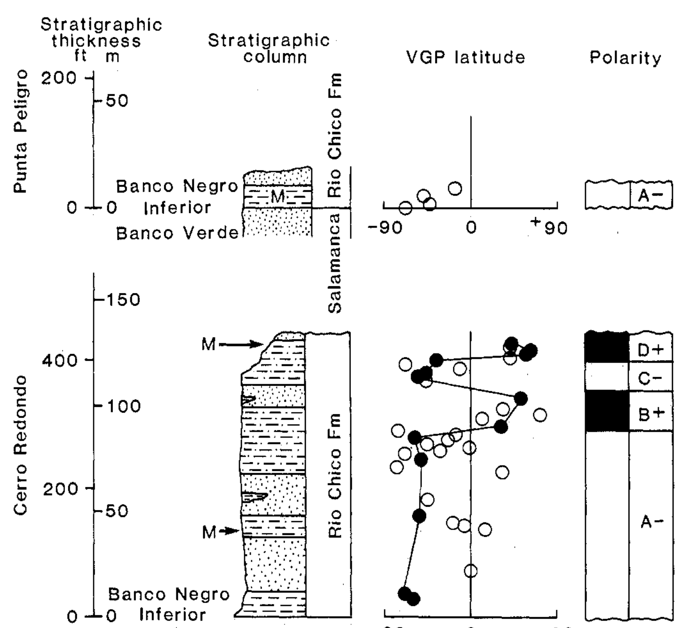

Fig. 2. Lithostratigraphy, magnetostratigraphy, and mammal-bearing horizons for sections at Punta Peligro and Cerro Redondo. In the stratigraphic column, the dot pattern indicates sandstone, the dot-dash pattern siltstone, and the dash pattern claystone; *M* indicates levels yielding fossil mammals. Mean virtual geomagnetic pole (*VGP*) latitude after alternating-field demagnetization is shown for both sites. Closed data points (●) indicate sites at which clustering of natural remanent magnetization vectors are significant from selection from a random population at the 95 percent confidence level; open data points (○) designate sites with poorer clustering. Positive VGP latitudes indicate normal polarity and are shown by black bars; negative VGP latitudes are reversed polarity and are shown by white bars (*27*).

0036-8075/81/0403-0043$00.50/0

Banco Negro Inferior, Andreis, Mazzoni, and Spalletti (*14*) included it in the Hansen Member of the Salamanca Formation. They recognized the marked change in sedimentation as an erosional unconformity between the Banco Negro Inferior and the Rio Chico Formation. From our observations at Cerro Redondo, Punta Peligro, and Cerro Abigarrado, we recognize the Banco Negro Inferior as the basal bed of the Rio Chico Formation.

Simpson (*19*) formerly applied the name Rio Chico Formation to the mammal-bearing beds above the Salamanca Formation and below the Sarmiento Group (*20*). Two members of the Rio Chico Formation are recognized. The lower Las Violetas Member is characterized by epiclastic and pyroclastic gray-yellow sediments with paleosol levels. The upper Visser Member is identified by the feldspathic nature of its sandstones and conglomerates, gray-green interbedded bentonites, fossil vertebrates, and tree trunks. The top of the Visser Member is difficult to define because the contact is at times transitional with the Sarmiento Group (*21*). Fossil mammals are abundant and well known from the Sarmiento Group (*20*), and the oldest known fauna, the Casamayor, is conventionally regarded as early Eocene in age (*4*).

Samples for paleomagnetic analysis were collected (*22*) from 35 sites in a 140-m section of the Visser Member of the Rio Chico Formation on the southeast slope of Cerro Redondo (Fig. 1). A 5-m section with four paleomagnetic sites was collected at Punta Peligro (Fig. 1). The results of the natural remanent magnetization (*23*) show that the Banco Negro Inferior is of reversed polarity at both Punta Peligro and Cerro Redondo (Fig. 2), and this reversed polarity zone encompasses approximately the lower 80 m of the Rio Chico section at Cerro Redondo. Above this thick basal zone of reversed polarity are two zones of normal polarity that are separated by a 15-m zone of reversed polarity. We correlate the two zones of normal polarity with magnetic anomalies 25 and 26 chrons (*24*) of the magnetic polarity time scale (*25*) from the following evidence. (i) Radioisotope dates corroborate a late Danian age for the Salamanca Formation. The late Danian includes magnetic anomaly 27 chron (*25, 26*) (Fig. 3). Thus, none of the polarity zones in the Cerro Redondo section can be as old as anomaly 27 chron. (ii) Our field observations indicate no significant unconformity between the Salamanca and Rio Chico formations at Cerro Redondo. These observations and the demonstrated late Danian age for the Salamanca Formation require that the Salamancan-Riochican boundary be placed near the Danian-Thanetian boundary (~ 62.0 million years ago) (Fig. 3). (iii) Given these age constraints, the magnetic polarity sequence observed at Cerro Redondo correlates with the magnetic polarity time scale in the interval from above anomaly 27 chron into anomaly 25 chron (Fig. 3). The implied age range of the Rio Chico Formation at Cerro Redondo thus encompasses middle and late Paleocene, and corresponds in time with Torrejonian and Tiffanian land mammal age faunas in North America (Fig. 3).

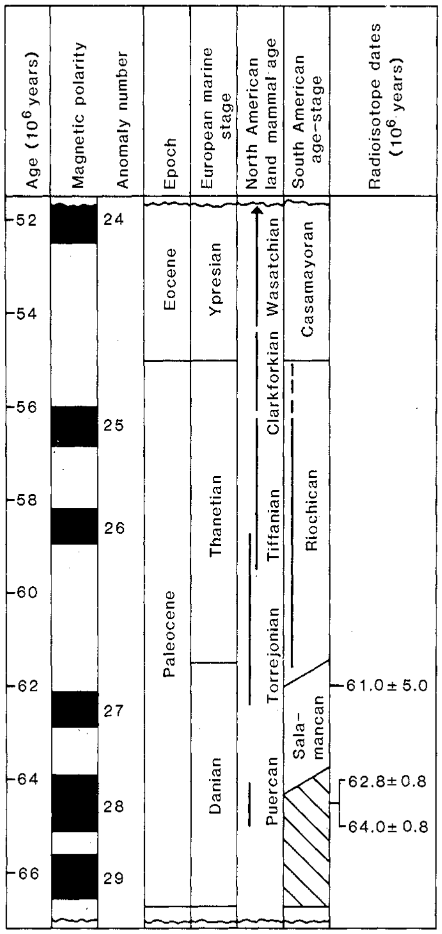

Fig. 3. Correlation of earliest Tertiary North and South American land mammal ages, and European and South American marine stages. Magnetic polarity time scale is after Ness, Levi, and Couch (*25*) with additional modifications of Butler, Gingerich, and Lindsay (*26*). European marine stage boundaries are after Hardenbol and Berggren (*28*) modified to incorporate a revised ^{40}K decay constant. Vertical bars adjacent to Puercan and Torrejonian indicate local stratigraphic limits of mammal faunas in the San Juan Basin (*29*). Local stratigraphic limits of Tiffanian, Clarkforkian, and Wasatchian mammal faunas in the Clark's Fork Basin (*26*) are shown by vertical bars. Vertical bar adjacent to Riochican indicates local stratigraphic limits of Riochican mammals at Cerro Redondo and Punta Peligro. The proposed correlations of South American ages–stages are based on data in this report.

Fossil mammals have been reported from six local faunas at four localities in the Rio Chico Formation (*1, 2, 17*): Bajo de la Palangana (two levels), Cañadón Hondo, Cerro Redondo (two levels) (Fig. 2), and Pan de Azúcar. Simpson (*17*) arranged these local faunas into faunal zones based on their relative ages, as judged by the stage of evolution of the known taxa. These include the *Carodnia* faunal zone (lower faunas from Bajo de la Palangana and Cerro Redondo), the *Kibenikhoria* faunal zone (fauna from Cañadón Hondo), and the *Ernestokokenia* faunal zone (upper fauna of Bajo de la Palangana). The upper local fauna from Cerro Redondo and that from Pan de Azúcar could not be confidently assigned to any of these zones due to the small sample sizes of the known faunas.

The upper Riochican local fauna from Bajo de la Palangana contains typical Casamayoran species (*21*). Many taxa in this local fauna occur in both typical Riochican and Casamayoran faunas, indicating that there is little time difference between late Riochican (that is, the uppermost fauna from Bajo de la Palangana) and early Casamayoran. This latest known Riochican local fauna occurs in the uppermost beds of the Rio Chico Formation, which are overlain by Casamayoran beds of the Sarmiento Group. The exposures at Cerro Redondo terminate below this contact, suggesting that latest Riochican time is not recorded in that section. Because of the lack of geochronologic calibration of latest Riochican, it is convenient to recognize the Riochican-Casamayoran boundary as the boundary between the Paleocene and Eocene epochs (Fig. 3).

The revised chronology in Fig. 3 is based on available radioisotopic, magnetostratigraphic, and biostratigraphic data, which in all cases are concordant and complementary. These geochronologic data verify and refine the middle to late Paleocene age range for Riochican land mammal faunas in Patagonia as suggested by Simpson (*2*).

LARRY G. MARSHALL
Department of Geology, Field Museum of Natural History, Chicago, Illinois 60605
ROBERT F. BUTLER
Department of Geosciences, University of Arizona, Tucson 85721
ROBERT E. DRAKE
GARNISS H. CURTIS
Department of Geology and Geophysics, University of California, Berkeley 94720

References and Notes

1. G. G. Simpson, *Am. Mus. Novit.* **793**, 1 (1935).
2. ———, *Am. Mus. Novit. Bull.* **91**, 1 (1948).
3. B. Patterson and R. Pascual, in *Evolution, Mammals and Southern Continents*, A. Keast *et al.*, Eds. (State Univ. of New York Press, Albany, 1972).
4. L. G. Marshall, R. Pascual, G. H. Curtis, R. E. Drake, *Science* **195**, 1325 (1977); L. G. Marshall and R. Pascual, *Obra Centenario Museo La Plata* **5**, 11 (1978).
5. This lithostratigraphic unit is based on the designation "Salamancanéen" of H. von Ihering, *An. Mus. Nac. Buenos Aires* **2**, 195 (1903).
6. E. Feruglio, *Minist. Indep. Commer. Nac. Div. Gen. Yacimientos Pet. Fiscales* **2** (1949).
7. A stratigraphic section showing the basalt ("manto de roca magmática básica") and fossil level is given in figure 157 (*6*, p. 243).
8. R. Lydekker, *An. Mus. La Plata Paleontol.* **2** (1893).
9. M. K. Brett-Surman, *Nature (London)* **277**, 561 (1979).
10. Analytical data include: sample weight = 4.263 g; percent K = 0.915; radiogenic ^{40}Ar = 10.3 $\times 10^{-11}$ mole/g; percent atmospheric ^{40}Ar = 19.0. Calculations are based on radioactive decay constants $^{40}K\lambda_{\beta} = 4.962 \times 10^{-10}$ year^{-1} and $\lambda^{40}K^{e} + \lambda'^{40}K^{e} = 0.581 \times 10^{-10}$ year^{-1} and on the isotopic abundance ^{40}K = 0.01167 percent of total K.
11. Analytical data include: sample weight = 4.365 g; percent K = 0.995; radiogenic ^{40}Ar = 11.0 $\times 10^{-11}$ mole/g; percent atmospheric ^{40}Ar = 18.0.
12. A. Bertels, *Rev. Esp. Micropaleontol.* **7**, 429 (1975); *Ameghiniana* **16**, 273 (1979).
13. R. R. Andreis, *Obra Centenario Museo La Plata* **4**, 82 (1977).
14. ———, M. M. Mazzoni, L. A. Spalletti, *Rev. Asoc. Geol. Argent.* **30**, 85 (1975).
15. R. Pascual and O. E. Odreman Rivas, *Ameghiniana* **8**, 376 (1971).
16. Three specimens of mammal were collected by R.F.B., L.G.M., M. C. McKenna, and W. D. Turnbull in January 1979 from the Banco Negro Inferior, about 1 km southwest of Punta Peligro (Fig. 1). These include two pelvic fragments (MLP 79-I-19-1 and 79-I-19-2) and a fragment of a right mandible with alveoli of the last two molars and part of the angle of the jaw (MLP 79-I-19-3). This locality was again visited in February 1979 by L.G.M., E. Herrera, and students at the Universidad de La Patagonia (UNP), Comodoro Rivadavia, during which time an isolated tooth (UNP 79-II-18-1) of a mammal was found. These specimens will be studied under the direction of R. Pascual, Museo de La Plata. The oldest known mammals in South America are from the Laguna Umayo local fauna from the Vilquechico Formation near Lake Titicaca, southern Peru (*30*). The same rocks, mapped as Late Cretaceous (*31*), have yielded dinosaur eggs (*32*) and Late Cretaceous charophytes (*30*). This earliest known land mammal fauna in South America is thus regarded as Late Cretaceous, although some workers, for example, L. Van Valen and R. S. Sloan [*Evol. Theory* **2**, 49 (1977)], have assigned it to the Paleocene. Mammal faunas of Riochican age are also known from Itaboraí, Brazil (*21*), and faunas of possible Riochican age have recently been reported from the provinces of Salta and Jujuy in northwestern Argentina (*21*).
17. G. G. Simpson, *Am. Mus. Novit.* **818**, 7 (1935).
18. G. C. McCartney, *ibid.* **630**, 15 (1933).
19. G. G. Simpson, *ibid.* **644**, 11 (1933).
20. E. Feruglio, *Bol. Inf. Pet. Yacimientos Pet. Fiscales* **171**, 1 (1938).
21. L. G. Marshall, R. Hoffstetter, R. Pascual, in *Cenozoic Mammals; Their Temporal Record, Biostratigraphy and Biochronology* (Univ. of California Press, Berkeley, in press).
22. Sampling techniques were similar to those of N. M. Johnson, N. D. Opdyke, E. H. Lindsay, *Geol. Soc. Am. Bull.* **86**, 5 (1975).
23. Natural remanent magnetization (NRM) was measured by R.F.B. on an ScT C-102 cryogenic magnetometer; alternating-field demagnetization was done with a Schonstedt GSD-1 demagnetizer. Intensities of NRM were low (geometric mean ~ 1×10^{-6} gauss). Progressive demagnetization studies indicated that, in most cases, secondary components of magnetization could be erased by alternating-field demagnetization at 200-Oe peak field. After measurement of NRM, all samples were demagnetized at 100 Oe and 200-Oe peak field, with remaining NRM measured after each demagnetization. Site average directions were calculated by the technique of R. A. Fisher [*Proc. Roy. Soc. London Ser. A* **217**, 295 (1953)], and these directions were used to compute the virtual geomagnetic pole latitudes. Both the cleaned NRM direction after 200-Oe alternating-field demagnetization and the motion of the NRM vector during the progressive demagnetization are used in interpreting the polarity of the stable NRM. Clustering of the NRM vectors following the alternating-field demagnetization to 200-Oe peak field was tested by the technique of G. S. Watson [*Mon. Not. R. Astron. Soc. Geophys.* **1** (Suppl.), 160 (1956)] to determine whether the grouping was significantly removed from selection from a random population at the 95 percent confidence level. Sites passing this test were given more weight in the interpretations of polarity.
24. Time intervals of the magnetic polarity time scale are referred to by attaching the suffix chron [*Geology* **7**, 578 (1979)].
25. G. Ness, S. Levi, R. Couch, *Rev. Geophys. Space Phys.* **18**, 753 (1980).
26. R. F. Butler, P. D. Gingerich, E. H. Lindsay, *J. Geol.*, in press.
27. Polarity zones from this study are designated by the prefix "Visser" after the geographic location Puerto Visser. The basal polarity zone in the sections shown in Fig. 3 would thus be designated Visser A−. This nomenclature is in keeping with recommendations regarding magnetostratigraphic nomenclature described in (*24*).
28. J. Hardenbol and W. A. Berggren, in *Contributions to the Geological Time Scale*, G. B. Cohee, M. F. Glaessner, H. D. Hedberg, Eds. (American Association of Petroleum Geologists, Tulsa, Okla., 1978).
29. E. H. Lindsay, R. F. Butler, N. M. Johnson, *Am. J. Sci.*, in press.
30. L. Grambast, L. Martínez, M. Mattauer, L. Thaler, *C. R. Acad. Sci. Ser. D* **264**, 707 (1967); B. Sigé, *ibid.* **273**, 2479 (1971); J. Y. Crochet, *ibid.* **288**, 1457 (1979); B. Sigé, *Bull. Mus. Nat. Hist. Nat. Sci. Terre* **19**, 375 (1972).
31. J. A. Portugal, *Bull. Am. Assoc. Pet. Geol.* **58**, 982 (1974).
32. B. Sigé, *C. R. Acad. Sci.* **267**, 1495 (1968).

33. We thank M. C. McKenna and W. D. Turnbull for assistance in the field and R. Pascual, R. Haskin, L. Taylor, Y. Tomida, and L. Van Valen for assorted help. Field funds were provided by grant 1943 from the National Geographic Society, Washington, D.C., to L.G.M. and R.F.B.; logistic support was given by AMOCO Argentina Oil Company; ^{40}K-^{40}Ar dating was supported by NSF grant EAR 73-00235 A01 to G.H.C. and grant EAR 7909515 to L.G.M.; and processing of paleomagnetic samples was supported by NSF grant EAR 7803326 to R.F.B.

10 July 1980; revised 24 November 1980

Discovery of Natural Gain Amplification in the 10-Micrometer Carbon Dioxide Laser Bands on Mars: A Natural Laser

Abstract. *Fully resolved intensity profiles of various lines in the carbon dioxide band at 10.4 micrometers have been measured on Mars with an infrared heterodyne spectrometer. Analysis of the line shapes shows that the Mars atmosphere exhibits positive gain in these lines. The detection of natural optical gain amplification enables identification of these lines as a definite natural laser.*

Since their invention some 25 years ago, optical lasers have become nearly ubiquitous tools in the laboratory and in everyday life. Despite this abundance of man-made lasers, no definite naturally occurring lasers have been reported, even though the extreme variety of physical and chemical environments of extraterrestrial objects argues that natural lasers should exist (*1*). Natural microwave amplifiers (masers) are abundant in interstellar clouds and some circumstellar shells, primarily among the rotational level populations of certain molecules (OH, SiO, H_2O), and are all characterized by the property $h\nu \leqslant kT$, where $h\nu$ is the energy of a light quantum, k is Boltzmann's constant, and T is the kinetic temperature. However, optical lasers are characteristic of electronic or vibrational transitions, for which $h\nu \gg kT$. Many examples of natural nonthermal optical emission have been found, such as the infrared and ultraviolet auroras or the day glows of Earth, Jupiter, Mars, and Venus, but it has never been established that a population inversion exists for any of these emissions. The relative populations of the two molecular levels must be inverted for gain amplification—the essence of lasing—to occur. We report here the discovery of a population inversion and natural gain amplification in the 10.4-μm CO_2 laser bands on Mars, representing to our knowledge the first definite identification of a natural infrared laser.

The observations were made with the Goddard infrared heterodyne spectrometer (*2*) during January to April 1980, when the planet was near opposition. The beam size (half-power beam width) was 1.7 arc seconds and the disk of Mars was ~ 13.8 arc seconds in diameter, providing good spatial resolution on the planet. Fully resolved atmospheric line profiles were measured at various locations on the disk, including many individual rotational-vibrational lines in both the 10.4-μm ($00^{\circ}1$–$[10^{\circ}0, 02^{\circ}0]_{I}$) and 9.4-μm ($00^{\circ}1$–$[10^{\circ}0, 02^{\circ}0]_{II}$) bands. We report here some results obtained from analysis of several measurements of the 10.33-μm R8 line at 967.7072 cm^{-1}.

The intensity profiles were measured simultaneously at 25-MHz (0.0008 cm^{-1}) resolution with 64 consecutive channels and at 5-MHz (0.00016 cm^{-1}) resolution with a second bank of 64 consecutive channels. All 128 channels were recorded simultaneously, thereby eliminating registration errors and drift. Absolute intensity calibration and removal of terrestrial atmospheric lines was achieved by use of lunar comparison spectra, measured nearly simultaneously and scaled to the appropriate air mass.

Fully resolved intensity profiles of the

0036-8075/81/0403-0045$00.50/0