STRATIGRAPHY OF THE RIO FRIAS FORMATION (MIOCENE), ALONG THE ALTO RIO CISNES, AISEN, CHILE

LARRY G. MARSHALL Institute of Human Origins, 2453 Ridge Road, Berkeley, California 94709, USA

PATRICIA SALINAS Museo Nacional de Historia Natural, Sección de Geología, Casilla 787, Santiago, Chile

ABSTRACT

The type area of the Río Frías Formation is along the Alto Río Cisnes, Aisén, southern Chile (44°34'-39'S; 71°13'-15'W). Two lithologic units of the Río Frías Formation are recognized. The lower mammal-bearing unit (*ca.* 131 m) consists of dacitic and rhyolitic tuffs, tuffites, siltstones, and fine to medium grained sands. The upper, unfossiliferous unit (*ca.* 75 m) consists of conglomerates composed principally of volcanic clasts (andesites, rhyolites, granites, diorites) in a tuffaceous matrix, and alternating levels of well stratified, laminated and weakly cross-bedded orange-brown sands. In places, the upper conglomerate-sand unit is deeply channeled into the underlying mammal-bearing tuffite-sand unit, and its deposition may correlate with the maximum phase of the Quechua Orogeny (*ca.* 9 Ma). The Río Frías Formation was deposited by high energy fluvial systems. It rests in angular unconformity on massive dacites and andesites of the Early Cretaceous age Ñirehuao Formation. The fossils from the lower unit represent the type fauna of the Friasian Land Mammal Age, long regarded as Middle Miocene (15-12 Ma). However, an Ar-Ar date of *ca.* 17 Ma from near the base of this unit and knowledge of fossil marsupials indicate that these rocks and faunas are temporally equivalent to the Santa Cruz Formation (= Santacrucian Land Mammal Age, 18-15 Ma) in southern Argentina and are thus late Early Miocene in age.

Key words: Río Frías Formation, Friasian, Santacrucian and Colloncuran Land Mammal Ages, Miocene, Chile.

RESUMEN

El área tipo de la Formación Río Frías se ubica a lo largo del río Cisnes, Aisén, sur de Chile (44°34-39'S; 71°13-15'W). Se reconocen dos unidades litológicas en esta formación. La unidad inferior (*ca.* 131 m), caracterizada por la presencia de abundantes fósiles, consiste en tobas dacíticas y riolíticas, tufitas, limolitas y areniscas de grano fino a medio. La unidad superior (*ca.* 75 m), carente de fósiles, consiste en conglomerados con clastos principalmente volcánicos (andesitas, riolitas, granitos, dioritas) en una matriz tobácea alternados con areniscas bien estratificadas y laminadas, y areniscas pardo-anaranjadas con estratificación cruzada débil. Localmente, la unidad superior presenta paleocanales labrados en la unidad inferior y su depositación puede correlacionarse con la fase principal de la orogénesis Quechua (*ca.* 9 Ma). La Formación Río Frías fue depositada por sistemas fluviales de alta energía. Se dispone, en discordancia angular, sobre dacitas y andesitas macizas de la Formación Ñirehuao del Cretácico Inferior. Los fósiles de la unidad inferior corresponden a la fauna tipo de Edad-mamífero Friasense, durante largo tiempo considerada del Mioceno Medio (15-12 Ma); sin embargo, una edad Ar-Ar de *ca.* 17 Ma, obtenida cerca de la base de la unidad, y el actual conocimiento de los marsupiales fósiles de la formación, indican que estas rocas y su fauna son equivalentes en el tiempo a la Formación Santa Cruz (= Edad-mamífero Santacrucense, 18-15 Ma), de la parte alta del Mioceno temprano.

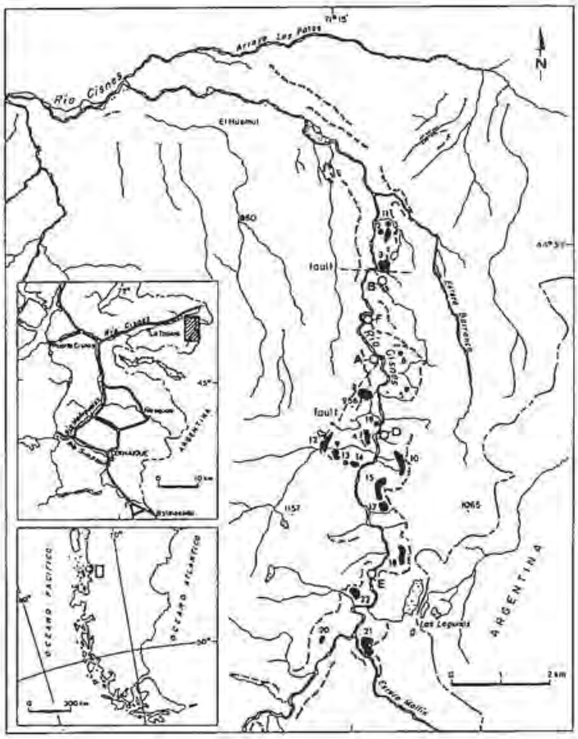
Palabras claves: Formación Río Frías, Edades-mamífero Friasense, Santacrucense y Colloncurense, Mioceno, Chile.

INTRODUCTION

The fossil record of land mammals in South America is sufficiently well known that vertebrate paleontologists have long used it to subdivide geologic time. The occurrence of unique associations of taxa that are inferred to have existed during a restricted interval of time has resulted in the recognition of discrete faunal-time units called Land Mammal Ages. These ages were established on the basis of knowledge of stage of evolution of the taxa, on their time of first and/or last appearance in the fossil record, and on changing faunal associations through time.

The type rocks and fauna of the Friasian Land Mammal Age (long regarded as Middle Miocene) are from the Río Frías Formation along the Alto Río Cisnes, Aisén, southern Chile (Text-Fig. 1). Despite its importance as a type fauna only a small and fragmentary collection of fossils was made from this area in the late 1890's. Consequently, its precise affinities with faunas of similar age elsewhere in South America, particularly Argentina, remained virtually undocumented.

In view of this situation an extensive geological-paleontological program was undertaken to study the type Friasian rocks and fauna along the Alto Río Cisnes, and to secure a large collection of fossil mammals for the Museo Nacional de Historia Natural, Santiago. Provided as a result of this program are: 1. a description of the geology of the Río Frías Formation along the Alto Río Cisnes; 2. a discussion of the historical conceptual and operational development of the Friasian Land Mammal Age; 3. a reevaluation of the age of reputed Friasian rocks and local faunas elsewhere in Chile and Argentina; 4. a new age assessment of the type Río Frías Formation and the type Friasian Land Mammal Age fauna; and 5. a revised definition of the Río Frías and Santa Cruz formations in Chile and adjacent Argentina.



Text-Fig. 1. Map of Alto Río Cisnes, Aisén, southern Chile, showing localities (numbers) where stratigraphic sections were taken and where fossil vertebrates were collected, and sites (capital letters) of important geological observations. Based on Hoja Arroyo Los Patos (4430-7100), No. 85, scale 1:50,000, Instituto Geográfico Militar de Chile, 1985 edition.

ABBREVIATIONS

The following abbreviations are used: LMA. Land Mammal Age; Loc. Locality; Ma. megaannum or millions of years ago, a point in time; Myr, millions of years, a duration of time.

LOCATION AND PREVIOUS STUDIES

The study area is along an 8 km stretch of the headwaters of the Río Cisnes (44°34-39'S, 71°13-15'W), 11-16 km southeast of the Estancia Río Cisnes, Aisén, southern Chile. Here the Alto Río Cisnes drains south to north from 0.5-3.0 km west of the Argentina-Chile border (Text-Fig. 1).

This area was discovered during the austral summer of 1897-98 by Santiago Roth, a Swiss immigrant to Argentina who was employed by F.P. Moreno, director of the Museo de La Plata, to survey the Argentina-Chile frontier in Patagonia. Roth (1908) believed that the area was in Argentina and that the small river along which he collected fossils was the Río Frías. Subsequent surveys stemming from the 1902 boundary agreement between Chile and Argentina showed that the 'Río Frías' of Roth is in fact the headwater of the Río Cisnes which drains into the Pacific Ocean and is thus in Chile. Maps showing this area were subsequently published by Feruglio (1950, Fig. 266) and Ramos (1981, Fig. 12).

Roth spent only a few days in this area and made a small collection of fossil mammals now deposited in the Museo de La Plata. Ameghino (1906, p. 503) published a preliminary identification of Roth's fauna and proposed for it the 'Etage Friaséen' (*i.e.* Friasian LMA) which he believed was younger in age than faunas from the Santacrucian LMA in southern Argentina:

"Friaséen. Dépots d'eau douce du Río Frías dans l'intérieur de la Patagonie avec des débris de *Protypotherium, Pachyrucos [sic], Astrapotherium, Nesodon,* melés á des débris de Toxodontidae, d'un Macrauchénidé voisin de *Scalabrinitherium,* un Mylodontidé voisin de *Scelidotherium,* etc...".

The first paper with observations on the geology was published by Roth (1908, p. 119-120):

"Ein ganz besonders guter Aufschuss befindet sich etwa nördlich vom Lago Fontana, da wo der Río Frías in scharfer Biegung in die grosse Ebene hinaustritt. In 770 m meereshöhe habe ich in einer Lehmschicht Reste von *Astrapotherium* gefunden. Etwa 250 m höher ist eine Sandsteinbank, die sehr reich an Säugetierresten ist und noch ungefähr 100 m höher ist ein anderer Aufschluss, wo ebenfalls solche vorhanden sind. Die beiden letzten Stellen sind auf Taf XVII [*nec* X] mit a bezeichnet. Hier habe ich unter anderem Zähne von *Homalodontotherium* und *Nesodon*, sowie Panzerstücke von *Propalaehoplophorus* gefunden, welche Gattungen charakteristische Typen der Santa Cruz-Fauna bilden. Ferner fand ich einen Schädel der Gattung *Theosodon* und Kieferstücke von *Protypotherium*, die sowohl in der Santa Cruz wie in der Paraná-Stufe vorkommen. Auch einen Oberkiefer von *Toxodontherium (Eutrigonodon)* und den hinteren Teil eines Schädels von *Scelidotherium* habe ich hier ausgegraben. Diese beiden Gattungen kommen in der Paraná-Stufe sehr häufig vor, sind aber bis jetzt in den Santa Cruz-Schichten noch nicht gefunden worden. Offenbar beherbergen diese Schichten die vermissten Formen, die den übergang von der Santa Cruz- sur Paraná-Fauna binden. Leider konnte ich an diese sehr interessanten Stellen nur im Vorübergehen Sammlungen machen. Die Schichtenserie hat hier eine Mächtigkeit von über 500 m. Im unteren Teil sind die Schichten in ihrer Lagerung gestört, während sie im oberen ihre ursprüngliche Lage bewahrt haben".

Roth (1908, p. 145) applied the name "Río Frías Stufe" to this fossiliferous rock unit.

Years later, Roth (1920, p. 161-162; 1925, p. 173-174) provided additional observations on the geology and vertebrate paleontology of this area. He noted (1925, p. 173) that his fossiliferous 'Río Frías-Stufe' rested on beds of red sandstone (capas de formación de arenisca roja = Ñirehuao Formation, see below). The lower fossil level (770 m above sea level) is formed by silty sediments. The middle fossil level consists of a grey tuffite and the upper fossil level of a sandy loess. The sediments between the middle and upper fossil levels are concordant. Above the upper fossil level are conglomerate terraces and sandstones with silty levels which do not contain fossils. He concluded that the mammal-bearing sediments and overlying conglomerates and sands are horizontal, and together attain a thickness of over 500 m.

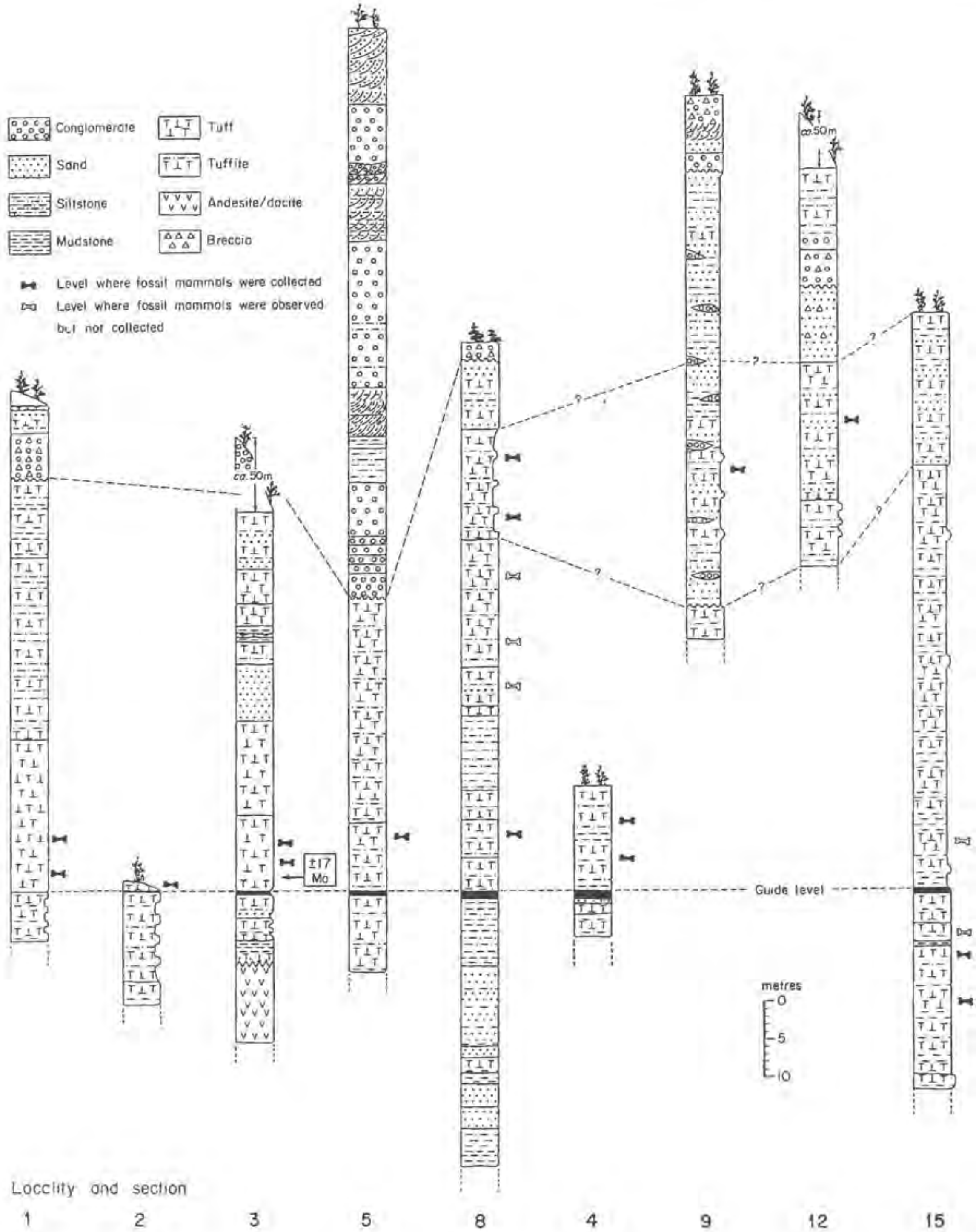
Roth also modified some observations he made in his 1908 paper with regard to the fossils. He noted (1920, p. 161) that *Astrapotherium* came not from the lower level but from a level 300 m above it; he made no distinction between the middle and upper fossil levels (*sensu* 1908), but lumped the taxa of the two into an upper fossil level and noted that the lower level included remains of Notohippidae, Leontiniidae, and (1925, p. 174) *Astraponotus.*

As stated by Hoffstetter (*in* Hoffstetter *et al.*, 1957, p. 134), contradictions exist between Roth's 1908 paper and those published in 1920 and 1925. Whether the latter two papers really included justified emmendations or whether there were confusions in Roth's field notes or memory is not clear. Subsequent authors (*e.g.* Feruglio, 1949, p. 187) were aware of these problems and choose to follow Roth's 1908 work because it was the first published on his field studies and for this reason could be potentially the most accurate.

The first and only detailed systematic study of the Roth collection was made by Kraglievich (1930, p. 132-137). Because there was no stratigraphic data with the fossils, he could not place these in the three fossil level context noted by Roth (1908). Consequently, all were described under the homogeneous heading 'Yacimientos de Río Frías'. Kraglievich recognized the following taxa: *Astrapotherium* sp., *Homalodontotherium* sp., *Adinotherium* sp., *Nesodon* sp., *Prototrigodon rothi* n. gen. n. sp., *Theosodon* aff. *gracilis, Protypotherium* sp., *Pachyrucos [sic]* sp., *Tachytypotherium* sp., *Eusigmomys? friasensis* n. sp., Rodentia incertae sedis, *Prozaëdyus* sp., *Propalaehoplophorus* sp., and *Megathericulus friasensis* n. sp.

Cabrera (1940) redescribed *Prototrigodon rothi* Kraglievich 1930 and erected a new species of *Astrapotherium, A. hesperinum.*

Bondesio *et al.* (1980) provided a revised generic



Text-Fig. 2. Measured stratigraphic sections of Río Frías Formation along Alto Río Cisnes. Section numbers correspond to locality numbers in Text-Fig. 1. Sections are presented in an order, from left to right, which corresponds approximately to their north to south position along the Alto Río Cisnes. A description of lithologies is presented in Appendix 1.

list for the 'Río Frías' fauna which included: *Prozaedius* sp., *?Propalaehoplophorus* sp., *?Palaehoplophorus* sp., *Megathericulus* sp., *Neonematherium* sp., *Theosodon* sp., *Phoenixauchenia* sp., *Homalodotherium* sp., *Eutypotherium* sp., *Protypotherium* sp., *Pachyrukhos* sp., *Nesodon* sp., *Prototrigodon* sp., *Adinotherium* sp., *Astrapotherium* sp., *?Eusigmomys* sp., and *Simplimus* sp.

Vucetich (1984) reviewed Friasian age rodents and assigned *Eusigmomys? friasensis* Kraglievich 1930 to *Alloiomys*.

The only published geological observations subsequent to Roth (1908, 1920, 1925) are by Ploszkiewicz and Ramos (1977, p. 220-221) and Ramos (1981, p. 67-70) who formally applied the name Río Frías Formation to Roth's 'Río Frías-Stufe'. Within the Río Frías Formation as defined by Ramos (1981) are included both the lower tuffite-sand which yielded the fossil mammals and the upper unfossiliferous conglomerate-sands mentioned first by Roth in 1925.

PRESENT STUDY

In 1987 a geological-paleontological program was initiated to undertake a detailed study of the type Río Frías Formation and its type Friasian LMA fauna along the Alto Río Cisnes. Field studies were carried out in December 1987 and January-February 1989 under the auspices of the Museo Nacional de Historia Natural, Santiago. The authors made a study of the geology, one (LGM) collected volcanic rock samples for radioisotopic dating by C. Swisher at the Institute of Human Origins Geochronology Center, Berkeley; J. J. Flynn (Field Museum of Natural History, Chicago) collected rock samples for paleomagnetic analysis; and fossil vertebrates were collected and their stratigraphic context recorded for systematic and biostratigraphic studies by R. Madden (Duke University), R. Cifelli (University of Oklahoma) and A. Walton (Southern Methodist University).

During the course of this study, over 500 specimens of fossil vertebrates, mostly mammals, were collected from 21 localities along the Alto Río Cisnes (Text-Fig. 1). At nine of these localities (1, 2, 3, 4, 5, 8, 9, 12, 15) detailed stratigraphic sections were made, at two (3, 8), rock samples were collected for magnetostratigraphic study, and at one (3) rock samples were collected for radioisotopic ($^{40}Ar/^{39}Ar$) dating.

This is the second in a series of papers which will be published on aspects of the geology, geochronology and vertebrate paleontology of this important area; the first was on fossil Marsupialia (Marshall, 1990).

STRATIGRAPHY

The Río Frías Formation forms the cliffs along both sides of the Alto Río Cisnes; it rests in angular unconformity on the Ñirehuao Formation and its top is represented by the present erosion surface.

The Ñirehuao Formation is exposed on the erosional plane above and on both sides of the river and forms the divide along the Argentina-Chile border (see Ramos, 1981, Fig. 12). Within the valley large exposures occur at Sites E and F (Text-Fig. 1; Pl. 2, Fig. 1).

Samples from the base of Section 3 (Text-Fig. 2; Appendix I) show that these rocks are primarily massive dacites and andesites, and are accordingly referable to the Arroyo La Bolsa Member of Ramos (1981, p. 52).

Ramos (1981, p. 55, Tabla 3) reported $^{40}K/^{40}Ar$ dates of 135 ± 10, 117 ± 10 and 110 ± 10 Ma on rock samples from three localities of the Ñirehuao Formation in Argentina. He further noted that an isochron of 115 ± 5 Ma was obtained for these dates which indicates an Early Cretaceous (Upper Barremian-Aptian) age.

Along the Alto Río Cisnes the base of the Ñirehuao Formation is not exposed, but its top is marked by an angular unconformity which separates it from the overlying Río Frías Formation. This contact is clearly seen at Loc. 3 (Pl. 2, Fig. 4) and Site A (Pl. 2, Fig. 3) where abundant weathered clasts of the Ñirehuao Formation occur within the lower 1.5 m of the Río Frías Formation.

In the base of Section 3 a narrow reddish aureole occurs along the contact of the Ñirehuao and Río

Frías formations produced by an intrusive which caused a low grade metamorphism. Rocks in this part of the section have altered minerals associated, in part, with the adjacent fault at Site B (Text-Fig. 1).

A period of uplift called the Quechua Phase is apparently responsible for the erosion surface and paleotopographic relief of the Ñirehuao Formation onto which was later deposited the Río Frías Formation (Ploszkiewicz and Ramos, 1977, p. 225; Ramos, 1981, p. 83).

RIO FRIAS FORMATION

DEFINITION

The Río Frías Formation, conceptually and operationally, dates from Roth (1908, p. 145) who applied the name 'Río Frías-Stufe' to the rock unit along the Alto Rio Cisnes (*nec* Río Frías) in which he found fossil mammals assigned by Ameghino (1906) to the 'Etage Friaséen'. Roth also noted that his 'Río Frías-Stufe' yielded fossil mammals at Río Fénix, Río Guenguel and Laguna Blanca (= Lago Blanco) in adjacent Argentina (Ramos, 1981, p. 67; Riccardi and Rolleri, 1980, p. 1250).

Kraglievich (1930) recognized a 'Formación Friaseana' and included in this definition the term 'ciclos faunísticos' to specify faunal content. As noted by Ramos (1981, p. 68), Kraglievich's 'Formación Friaseana' represents a biostratigraphic (faunal-rock) term (*sensu* Simpson, 1971, p. 284) and not a lithostratigraphic (rock) unit.

Simpson (1940) proposed the term 'Friasian Group' and within it included a 'Friasian Formation'. He thus used these terms in a strict lithostratigraphic sense.

Ramos (1976, p. A60) applied the name Formación Frías to the fossiliferous rock unit described by Roth (1908) along the Alto Río Cisnes and noted that it also occurs in the valley of Arroyo Gato just north of Lago Fontana in Argentina. Ramos credits Kraglievich (1930) with this name, although as noted above and by Ramos (1981, p. 68) this is not technically correct.

The name Río Frías Formation was first formally applied by Ploszkiewicz and Ramos (1977, p. 220) to Roth's (1908) 'Río Frías-Stufe', and the first detailed description of this formation is provided by Ramos (1981, p. 67-70). The type section of Ramos (1981, p. 69, Fig. 12) is on the west side of the Alto Río Cisnes and extends in a southwest direction from the river just south of Loc. 4 (this study) to the south of Loc. 9 (Text-Fig. 1). He selected this as the type section because it was the largest and the upper part included the fossils collected by Roth.

The description of the type section is as follows:

"Está integrado por una sucesión horizontal a subhorizontal de limos castaños amarillentos, con intercalaciones de areniscas arcillosas deleznables, con considerable participación tobácea, que hacia arriba presenta una serie de bancos de tufitas y cineritas de color blanquecino. El perfil se completa con la presencia de conglomerados aglutinados por una matriz tufítica, con clastos de andesita, hornfels, etc., de hasta 5 cm de diámetro medio, con los que remata la secuencia sedimentaria. El espesor total aflorante es de 280 metros" (Ramos, 1981, p. 68).

Ploszkiewicz and Ramos (1977, p. 220-221, Fig. on p. 210) and Ramos (1981, p. 69, map) recorded exposures of this formation in adjacent Argentina in the region of the Sierra de Payaniyeu, along both sides of the Río Apeleg between the junction of the Río Apeleg Chico and Río Apeleg Grande, along both sides of the Río Apeleg Chico near Puesto Alvistur, in Arroyo León and Arroyo Huemul, along the south side of Arroyo Gato across from Estancia Arroyo Victoria, in the area of Estancia La Esperanza southeast of Cerro Pedrero, and along the north side of Arroyo Seco.

As a technicality it is important to note that in the original description of his 'Río Frías-Stufe', Roth (1908) mentioned only the lower mammal-bearing tuffite-sand unit, while the upper unfossiliferous conglomerate-sand unit was first mentioned in his 1925 paper. In both papers (1908, 1925) he mentions that the total thickness of his 'Río Frías-Stufe' is *ca.* 500 m, demonstrating that Roth originally (1908) included the upper conglomerate-sand unit in his conceptual definition of this rock unit. Yet, if the authors follow what was actually published then the Río Frías Formation of Ploszkiewicz and Ramos (1977) and Ramos (1981) represents the 'Río Frías-Stufe' *sensu* Roth (1925), while the Río Frías Formation *sensu* Roth (1908) represents only the lower mammal-bearing tuffite-sand unit. In view of these details the authorship and date of publication of the Río Frías Formation as: Roth (1908, p. 145) as emended by Ramos (1981, p. 67-70) is here formally recognized. During the course of this study it was observed that an erosional unconformity separates the lower mammal-bearing tuffite-sand unit from the overlying unfossiliferous conglomerate-sand unit. Accordingly, these units are discussed separately below.

LOWER MAMMAL-BEARING TUFFITE-SAND UNIT

This unit consists of dacitic and rhyolitic tuffs, tuffites, siltstones, and fine to medium sands which are principally white, light brown and/or orange in color. The sediments are generally well stratified, poorly consolidated and horizontal to subhorizontal, dipping *ca.* 3° to the north.

Correlation of these sediments was facilitated by a **guide level**: a 0.5-1.0 m thick vitroclastic white tuff of high porosity (Text-Fig. 2; Pl. 1, Fig. 5; Pl. 2, Figs. 2-5; Pl. 3, Figs. 5-6). It is continuous from Locs. 5 and 8 south to Loc. 15, and is well developed in Sections 5, 8, 4 and 15 (Text-Fig. 2). At Site A (Pl. 2, Fig. 3) on the west side of the river about 1 km south of Loc. 8 (Text-Fig. 1), the **guide level** occurs within the upper meter of a *ca.* 10 m thick sequence of light orange tuffites which form 3 or 4 erosion resistant levels. Above these resistant levels is a white tuff and below is the Ñirehuao Formation. This same sequence forms the base of Section 3 where the **guide level** occurs within the upper meter of the erosion resistant level (Text-Fig. 2; Pl. 2, Fig. 5). Site A thus provides the 'key' for correlating the **guide level** from Section 3 to Sections 5 and 8 located about 2.5 km further south. The **guide level** is not evident in Sections 1 and 2, although the lower light orange tuffite with erosion resistant levels overlain by a white tuff is the same as in the base of Section 3. Section 2 is a slump block of the base of the Section 1 cliff.

Sections 9 and 12 do not include the **guide level** and for this reason their correlation with the other sections is not readily apparent. The upper part of Section 8 is tentatively correlated with the lower part of Section 9 (Text-Fig. 2) for the following reasons. First, using a hand level to site from Section 8 to 9 it was found that the upper fossil level of 8 (see below) and the fossil level at 9 are at the same elevation. Second, evidence of faulting between Sections 8 and 9 was not observed. And third, the sediments of both are predominantly orange-brown sands with several erosion resistant levels.

The stratigraphic position of Section 12 is the least constrained because tentative correlation is possible only with Section 9 which also lacks the **guide level**. Using a hand level, it was observed that the base of the conglomerate unit in Section 9 corresponds to the lower *ca.* 10 m of Section 12. A fault extending in a S-SW direction between Locs. 9 and 12 was also recognized, although due to vegetation cover the presence of this structure between these two localities could not be established. Furthermore, it could not be confirmed if this was a strike-slip or reversed fault. However, the 18 m fossil-bearing unit and the 10 m above it at Loc. 12 are predominantly orange-brown sands as at Loc. 9. For this reason, and based on the hand level observations, it is supposed that the top *ca.* 25 m of Section 8, the lower part of Section 9, and the lower *ca.* 28 m of Section 12 are stratigraphically equivalent. These same orange-brown sands also form the upper *ca.* 20 m of Section 15 (Text-Fig. 2).

There are two principal fossil and lithologic levels in the tuffite-sand unit. The lower includes fossils collected from *ca.* 10 m above the **guide level** at Locs. 1, 2, 3, 5, 8 and 4, and within *ca.* 20 m below the **guide level** at Loc. 15 (Text-Fig. 2). At most of these localities the fossils derive from a white tuff and the majority of fossils (*ca.* 99%) were collected from this level. The upper level occurs in orange-brown sands at Locs. 8, 9 and 12 (Text-Fig. 2). The only section in which fossils from both levels are recorded is 8 where they are separated by a stratigraphic distance of *ca.* 40 m; the fossils from the upper level are typically cream to tan in color, while the fossils from the lower level are typically black.

The sediments within Section 8 are concordant, suggesting that there was no major time break between the lower and upper fossil levels. In fact, the only evidence observed of an erosional unconformity within the lower mammal-bearing tuffite-sand unit is in the base of Section 9 where the overlying orange-brown sands are channeled into the lower *ca.* 4 m of white to grey tuffites.

A $^{40}Ar/^{39}Ar$ date of *ca.* 17 Ma (Flynn *et al.*, 1989) was obtained on plagioclase crystals from the white tuff located about 1 m above the **guide level** in Section 3. This age dates directly the lower fossil level and indicates that it is late Early Miocene and within the early part of the Santacrucian LMA (Text-Fig. 4).

The maximum stratigraphic thickness of the mammal-bearing tuffite-sand unit occurs at Section 8 (106 m), while at Section 9 it may attain on additional 25 m. These data suggest a total observed thickness of *ca.* 131 m for this lower unit.

Section 8 best exemplifies this unit because it is the thickest, the **guide level** is well developed, the two fossil levels are present, it was probably sampled by Roth (see below), and it is near the type section of the Río Frías Formation of Ramos (1981). The lower fossil level at Loc. 8 may be regarded as the type 'Etage Friaséen' (*sensu stricto*) of Ameghino (1906).

UPPER UNFOSSILIFEROUS CONGLOMERATE-SAND UNIT

The lower mammal-bearing tuffite-sand unit is separated by an erosional unconformity from the upper unfossiliferous conglomerate-sand unit. The latter consists principally of conglomerates composed mainly of volcanic clasts (andesites, rhyolites, granites, diorites) in a tuffaceous matrix (Pl. 3, Fig. 1) and alternating levels of well stratified, laminated and weakly cross-bedded orange-brown sands (Pl. 3, Fig. 2). This unit is present in Sections 1 (Pl. 2, Fig. 6), 3, 5, 8 9 (Pl. 1, Fig. 6) and 12 (Text-Fig. 2; Appendix 1), and attains a maximum observed thickness of *ca.* 75 m in Section 5 where the conglomerate-sand sequence is repeated three times.

In Section 5 the lower conglomerate level is *ca.* 8 m thick and the clasts are well stratified. The lower *ca.* 4 m has a grey-brown matrix, while the upper *ca.* 4 m has an orange-brown matrix. The relative position of the different colored matrix changes randomly within this *ca.* 8 m unit along the cliff. The orange-brown matrix apparently derives its color from the basement Ñirehuao Formation which in places weathers to a dark orange (*i.e.* at Site E and just north of Loc. 12; Text-Fig. 1).

In Section 9 are *ca.* 10 m of conglomerates (Pl. 1, Fig. 6). The lower *ca.* 4 m has an orange-brown matrix while the upper *ca.* 6 m has a yellow-grey matrix. The two levels are separated by an erosional unconformity.

In Section 1 the *ca.* 6 m conglomerate has a grey matrix; the same is true for the *ca.* 2 m conglomerate in Section 8.

Of the measured sections, channeling of the upper conglomerate-sand unit into the lower tuffite-sand unit is most evident at the south end of the Loc. 5 cliff where the conglomerates cut to within *ca.* 39 m above the **guide level**. At the south end of the Loc. 10 cliff are also seen broad and extensive conglomerate (grey matrix) channels (Pl. 1, Fig. 4; Pl. 3, Figs. 3-4).

At the north end of the Loc. 15 cliff a large conglomerate (grey matrix) channel cuts to within *ca.* 5 m of the **guide level** (Pl. 3, Fig. 6). About 50 m further south is a broader channel filled with well stratified orange-brown sands which resemble the upper sand unit in Section 5; it cuts to within *ca.* 15 m of the **guide level**.

However, the most extensive channeling was observed at Site D (Pl. 3, Fig. 5), a large cliff on the east side of the river across from Loc. 4 (Text-Fig. 1). The north side of the cliff consists of the lower tuffite-sand unit with the **guide level** located *ca.* 18 m from the top and *ca.* 25 above the level of the river. The south side of the cliff is an enormous channel which begins *ca.* 4 m above river level with 2-3 m of stratified conglomerates (brown-orange matrix) followed by *ca.* 35 m of poorly sorted and weakly stratified sands, pebbles and conglomerates in a grey tuffaceous matrix. This channel cuts *ca.* 20 m below the **guide level**; it can be followed laterally southward along the cliff and river (Pl. 1, Fig. 5), becoming shallower and occurring above the **guide level**. Given the total observed stratified thickness of *ca.* 131 m for the lower tuffite-sand unit (see above), the channeling at this site resulted in removal of *ca.* 114 m of the lower mammal-bearing sediments.

The observed channeling thus begins with a 3-4 m conglomerate in which the clasts show some stratification and the matrix is orange-brown or grey-brown in color. In places channels cut deeply into the underlying fossil unit, nearing its contact with the Ñirehuao Formation. In Section 5 are observed three distinct conglomerate levels which alternate with three levels of stratified sands, demonstrating the existence of at least six primary erosional events. It was not possible for the authors to equate channels at each site or locality with the units in Section 5.

DEPOSITIONAL ENVIRONMENT

The sediments of the Río Frías Formation were deposited in a high energy continental fluvial environment. The lower tuffite-sand unit contains neither paleosoils nor significant breaks in deposition, suggesting that it represents a continuous sedimentary sequence that accumulated during a restricted interval of time. The sediments become coarser toward the top where they are represented by poorly sorted sands with pebble lenses. This indicates an increase in energy transport from bottom to top. A significant increase in energy transport is evidence by the beginning of the upper conglomerate-sand unit which contains large clasts channeled deeply into the underlying tuffite-sand unit. Within this upper unit are evidenced at least three periods of exceedingly high energy transport (3 conglomerate levels) which alternate with three periods of decreased energy transport (3 sand levels).

STRUCTURE

The authors observed evidence of two distinct faults or fault zones which are related to the 'Fractura Apeleg' in adjacent Argentina (see Ploszkiewicz and Ramos, 1977, Fig. 3; Ramos, 1981, Fig. 14). The first is visible at Site B, the canyon south of Loc. 3 (Text-Fig. 1); the fault runs in an east-west direction and produced deformation of the tuffite-sand unit such that the lower erosion resistant level is inclined at an angle ca. 60°. The second extends in a S-SW direction along the south side of Site A toward Locs. 9 and 12 (Text-Fig. 1) and is responsible for the deformation of sediments at Site A (Pl. 2, Fig. 3)

COMMENTS ON ROTH (1908, 1920, 1925)

Roth's papers (1908, 1920, 1925) on the geology and vertebrate paleontology of the Alto Río Cisnes have long been the subject of debate. During the course of this study the authors were able to clarify some of these controversies and identify others. Some of the observations made in the present contribution are based on facts and others on inferences.

As fact, it is known that Roth approached the Alto Río Cisnes from the north or northwest after his visit to Loma Baguales (Roth, 1925). The first fossil vertebrates at the north end of the Alto Río Cisnes valley occur at Locs. 1, 2, 3 and 11 (Text-Fig. 1). It is therefore inferred that one of these localities was also found by Roth and represents the lower level from which he collected fossils. He mentions (1908, p. 119) that this level occurs 770 m above sea level. On the topographic map Arroyo Los Patos (4430-7100, No. 85, scale 1:50.000, Instituto Geográfico Militar de Chile, 1985 edition) the base of Locs. 1, 2, 3 and 11 correspond approximately to the 800 m contour, while a point on the river (which is relatively flat-lying in this area) about 1.5 km N-NE of Loc.1 has an elevation of 765 m. This inference is thus supported by elevation data. Also, Roth (1925) mentions that his lower fossil level is 300 m up stream from the mouth of the Alto Río Cisnes valley. This distance approximates the position of Locs. 1, 2, 3 and 11 (Text-Fig. 1).

As fact, it is known that Roth followed the Alto Río Cisnes south to at least Locs. 8 and 9 (Text-Fig. 1) because he published a photo of these and identified present Loc. 9 with an 'a' (Roth, 1908, Pl. 17). Roth (1908, p. 119) also indicated that his 'a' locality included both his middle and upper fossil levels. The authors believe that Roth erroneously labeled as 'a' their Loc. 9 when in fact the locality where he collected his fossils is their 8. This inference stems from the following facts. First, Loc. 8 is the largest and most fossiliferous cliff along this area of the Alto Río Cisnes. Because of its size and ease of access it was the first locality the authors prospected in this area and they believe that Roth did the same. Loc. 9 is less prominent, is not readily visible from the Río Cisnes, and access is difficult due to extensive tree cover and topography. Second, Loc. 9 is virtually unfossiliferous and only one fossil from the middle part of the section was recovered. Only a few bone fragments were observed and no evidence to indicate the presence of two fossil levels was found. On the other hand, two distinct fossil levels occur at Loc. 8: one just above the **guide level** here mentioned and another *ca.* 40 m higher in the section (Text-Fig. 2). Roth (1925, p. 173) noted that the fossils from his middle level came from a grey tuffite while those from his upper level came from a sandy loess; this agrees with the authors' observations of the lithology of these levels. Locs. 8 and 9 are side-by-side in the center of Roth's (1908, Pl. 17) photo. This feature and the fact that the photo was published 10 years after Roth's field work apparently led to an error in labelling.

As fact, it is known that Roth's geological observations were based on use of an altimeter. The 250 m which he recorded between his lower and middle fossil levels means 250 m higher in elevation and not in stratigraphic position. As shown on the topographic map Arroyo Los Patos, the base of Section 8 lies close to the 850 m contour while the first fossil level is *ca.* 40 m higher. Thus, the elevation difference between the lower fossil level of Loc. 8 (Roth's middle level?) and Locs. 1, 2, 3 and 11 (Roth's lower fossil level?) is only *ca.* 120 m and not 250 m as recorded by Roth. The authors have no explanation for this discrepancy other than possible problems with Roth's altimeter or that he may simply have estimated the distance and not used his altimeter.

As fact, it was possible for the authors to demonstrate that the fossils from Locs. 1, 2, 3 and from the lower fossil level at Loc. 8 come from *ca.* 10 m above the **guide level** (Text-Fig. 2; Appendix 1). Therefore, fossils from these localities are from the same stratigraphic level and apparently include Roth's lower and middle fossil levels. There is thus clear evidence for only two distinct fossil levels: a lower one near the **guide level** which includes Roth's lower and middle fossil levels, and one *ca.* 40 m stratigraphically higher which apparently represents Roth's upper fossil level.

Roth (1908) recorded that the 'Río Frías-Stufe' attained a thickness of over 500 m, while Ramos (1981, p. 68) found a total thickness of only 280 m. The present study confirms the observations of Ramos.

CONCEPTUAL AND OPERATIONAL DEVELOPMENT OF THE FRIASIAN LAND MAMMAL AGE

The first fauna to be described from rocks which would later be included in the Friasian LMA are by Roth (1898). He collected mammals in 1895-1896 from what he called 'Tobas del Collón Curá' (p. 156) near Arroyo Pichipicúm-Leufú in Río Negro Province, Argentina, and believed that they were Santacrucian in age. Roth (1898) also noted the existence of a similar age fauna from the headwaters of the Río Senguerr.

Florentino Ameghino (1904) described fossils collected by his brother Carlos in 1901-1902 from Laguna Blanca and Río Fénix (Text-Fig. 3). Faunal lists were published by Ameghino (1906, p. 268), a brief description of the geology is provided by Roth (1908, p. 119), and many of the fossils were subsequently figured by Rovereto (1914). Two fossil horizons were observed at Laguna Blanca, although most of the fauna came from the lowest (Feruglio, 1949, p. 185; González, 1967, p. 53).

Ameghino (1906, p. 235, 493-498, 503) applied and rectricted the term 'Etage Friaséen' to the as yet undescribed fauna collected by Roth in 1897-1898 from the Alto Río Cisnes (*nec* Río Frías). The 'Friaséen' was used by Ameghino to distinguish this local fauna which appeared to be slightly younger or more advanced in its stage of evolution than that from the Santa Cruz Formation (*i.e.* Santacrucense or Santacrucian LMA) of southern Argentina.

Roth (1920, p. 164) proposed the term Mayoense for the fossil mammal levels near the headwater of the Río Mayo (type locality and fauna) and in the region of Laguna Blanca (Text-Fig. 3). He also recognized a slightly older 'Piso Friasense' and included in it the faunas from the Alto Río Cisnes (*nec* Río Frías), Río Guenguel, Río Senguerr and Río Fénix (Text-Fig. 3).

Groeber (1929) applied the term Colloncurense to the fauna from the 'Tobas del Collón Curá' (= Collón Curá Formation) described by Roth (1898) because he believed that it was younger than that of the Santa Cruz Formation and hence warranted a different age name. He also believed that the Santacrucense and Colloncurense are separated by his second Andean tectonic phase. In Groeber's concept of Colloncurense he included the Friasense (*i.e.* Colloncurense + Friasense = Colloncurense of Groeber; see Pascual and Odreman Rivas, 1973, p. 306).

The first and only synthetic revision of Friasian faunas is by Kraglievich (1930) and our present concept of a Friasian LMA stems primarily from this study. He described all the fossils collected by Roth from the Alto Río Cisnes (*nec* Río Frías), Río Huemules, Río Senguerr, Río Guenguel, Laguna Blanca and Río Fénix, and recognized a 'Formación Friasiana' with three 'horizontes terrestres': from oldest to youngest-Colloncurense Groeber 1929, Friasense Ameghino 1906 and Mayoense Roth 1920 which he regarded as representing succesive stages of faunal evolution between Santacrucian and Chasicoan (p. 151). In the Colloncurense he included only the fauna from the

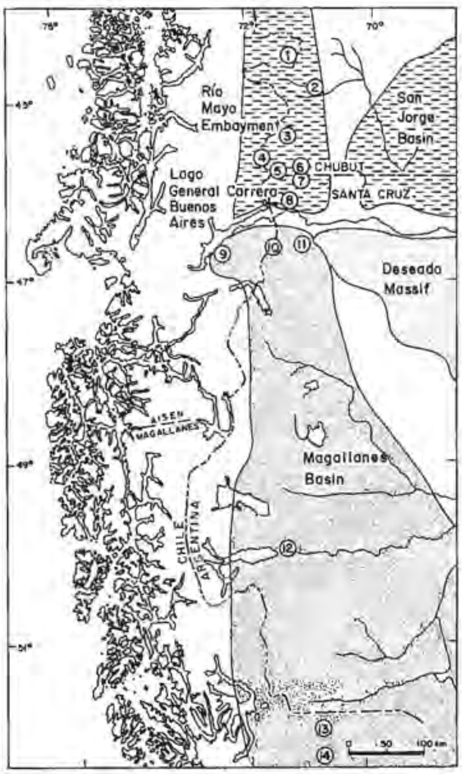


FIG. 3. Map showing distribution of Río Frías and Santa Cruz formations in southern Chile and adjacent Argentina. Based on Riccardi and Rolleri (1980, Fig. on p. 1.281) and Ramos (1982, Fig. 4; 1989, Fig. 1). Localities: 1. Alto Río Cisnes(= Río Frías); 2. Alto Río Senguerr; 3. Alto Río Mayo; 4. Cerro Galera; 5. Río Huemules; 6. Laguna Blanca (=Lago Blanco); 7. Río Guenguel; 8. Río Fénix; 9. Pampa Castillo; 10. Río Zeballos; 11. Meseta Buenos Aires; 12. Karaikén; 13. Laguna Blanca; 14. Laguna del Toro.

Collón Curá Formation; the Friasense included the fauna from the Alto Río Cisnes and the lower fossil level from Laguna Blanca (Feruglio, 1949, p. 186; González, 1967, p. 53); while the Mayoense "included parts of the sediments from the rivers Huemules, Guenguel and Fénix and upper fossil level of Laguna Blanca" (p. 150-151). The fauna from the Río Senguerr "is similar to that of the Santa Cruz" (p. 150), and he inferred that it may be similar in age to the Colloncurense but did not include it in that age. Later, Kraglievich (1934) specifically stated that he excluded the Colloncurense and Río Senguerr faunas from the Friasense because they were more closely related to those from the Santacrucense.

This arrangement was modified by Simpson (1940) who recognized a 'Friasian Group' with three 'continental formations': from oldest to youngest- Colloncurense, Friasense and Mayoense of which the first and last were recognized only provisionally.

An excellent discussion of the history of Friasian up to this time is provided by Feruglio (1949, p. 182-191, 218-226, 310-328, 341).

Hoffstetter (*in* Hoffstetter *et al.*, 1957, p. 135) proposed a possible modification of the scheme of Kraglievich (1930) by suggesting that the term Friasiano be used to include only the Friasense and Mayoense, although this was not followed by subsequent workers. As noted by Hoffstetter (*in* Hoffstetter *et al.*, 1957), terminology for the Friasian has been chaotic and inconsistent, and terms such as Friasense, Friaseano, Friasiano, Friaseana and Friasean have been called (in different combinations) a group, formation, 'horizonte' and/or 'piso'. The terms have been used in chronostratigraphic (time-rock), lithostratrigraphic (rock), geochronologic (time) and biostratigraphic (fauna-rock) context and in some cases usage is neither specified nor evident. These problems have been discussed by Simpson (1971), Pascual *et al.* (1965), and Pascual and Odreman Rivas (1971, 1973).

As a result of these studies a consensus was reached in the early 1970's regarding usage and content of a Friasian LMA. The Friasian (Friasense in Spanish) was regarded as a Land Mammal Age *sensu* Evernden *et al.* (1964), a faunal unit that encompassed Late Miocene time (*i.e.* Patterson and Pascual, 1972). Its content essentially followed Kraglievich (1930) with regard to succession of local faunas, although separate subage names (Colloncurense, Friasense, Mayoense) were not formally recognized but were often used, as in this study, at convenience.

But consensus is not necessarily truth, and it has long been recognized that the Friasian LMA had problems which stemmed from its conceptual and operational history.

As discussed above, the type fauna of this LMA is based on the small and fragmentary collection of fossil mammals made by Roth from the Río Frías Formation, along the Alto Río Cisnes. Conceptually, the Friasian includes faunas that are slightly more progressive in their stage of evolution than those from the Santa Cruz Formation (Santacrucian LMA) of southern Argentina, located 600-800 km S-SE of the Alto Río Cisnes, and less progressive than those from the lower Vivero Member of the Arroyo Chasicó Formation (*i. e.* Chasicoan LMA; see Marshall *et al.*, 1983) in southwest Buenos Aires Province, Argentina, located about 1,200 km northeast of the Alto Río Cisnes. Yet, faunas which 'fit' this concept are principally known from the Collón Curá Formation (Colloncurense) in Río Negro and Neuquén Provinces, located 400-800 km N-NE of the Alto Río Cisnes. Of all known Friasian faunas (*sensu* Bondesio *et al.*, 1980) that from the Collón Curá Formation is the most taxonomically diverse and best studied, and for this reason has come to serve as the operational basis of a Friasian LMA. As a result, there is secure paleontological evidence based on this Argentine fauna to support the existence of a distinct LMA between Santacrucian and Chasicoan. However, the fragmentary faunas (Friasense, Mayoense) from the Río Frías Formation (*sensu* Riccardi and Rolleri, 1980) have not been recollected for the past 90 years and their age relative to that from the Collón Curá Formation has never been firmly documented. This stems from the fact that the scattered local faunas from the Río Frías Formation are poorly known and in need of systematic revision. Furthermore, there were no radioisotopic ages on volcanic rocks associated with these local faunas. Thus, the absolute and relative ages of these local faunas within the concept of a Friasian LMA have long been assumed but never securely demonstrated. For these historical reasons some workers have questioned the validity of both a Friasian age and its rock and faunal content (see below).

RELATIVE AND ABSOLUTE AGE OF FRIASIAN ROCKS AND LOCAL FAUNAS

Our knowledge of the age of the Río Frías Formation and Friasian LMA has changed considerably during the past 20 years.

Around 1970 (*i.e.* Pascual and Odreman Rivas, 1971, 1973; Patterson and Pascual, 1972) the Friasian LMA was by consensus regarded as Late Miocene and the Santacrucian LMA as Middle Miocene (Text-Fig. 4). Within the Friasian were included, from oldest to youngest, the Colloncurense, Friasense and Mayoense. The Friasense included the fauna from the Alto Río Cisnes (*nec* Río Frías) and was regarded as Middle Friasian.

The only radioisotope (K-Ar) date then available for the entire mammal-bearing Cenozoic of South America was 21.7 ± 0.3 Ma for a plagioclase concentrate of a tuff from the Santa Cruz Formation along the Río Gallegos in southern Argentina (Evernden *et al.*, 1964, p. 170). Based on the geological time scale available at that time, this date corresponded with the Middle Miocene Burdigalian Stage in Europe and corroborated a Middle Miocene age for the Santa Cruz Formation and Santacrucian LMA. This K-Ar date indirectly favored a Late Miocene age for Friasian faunas.

Yet, Pascual (*in* Patterson and Pascual, 1972, p. 251) questioned the validity of a Friaisian age and inferred that at least some local faunas placed in it may prove to be Late Santacrucian. This position was noted earlier by Pascual *et al.* (1965, p. 177).

The first K-Ar dates for a Friasian local fauna were published by Marshall *et al.* (1977) on mineral concentrates from the Miembro Ignimbrítico Pilcaniyeu (*sensu* Rabassa, 1978) of the type Collón Curá Formation on the west bank of the Río Collón Curá, Neuquén Province. This ignimbrite occurs directly below the principal mammal-bearing tuffite at this locality which represents the type fauna of the Collón Curá Formation and Colloncurense (*sensu* Groeber, 1929 as emended by Kraglievich, 1930). Four dates were obtained: two on biotite (14.0 ± 0.3, 14.1 ± 0.3 Ma) and two on plagioclase (14.4 ± 0.3, 15.4 ± 0.3 Ma) concentrates. Rabassa (1978, p. 741) reported another date of 15 Ma (but no analytical data) on a biotite concentrate from the same ignimbrite 2 km east of Pilcaniyeu and assigned (*sensu* Pascual and Odreman Rivas, 1971) the 'Colloncurense' fauna to the 'Santacrucense-Friasense'. These dates collectively indicated that the Friasian was of Middle Miocene age (*i.e.* 16-12 Ma;Marshall *et al.*, 1977). Because the dates were on the Collón Curá Formation (*i.e.* Colloncurense) which according to Kraglievich (1930) and Pascual and Odreman Rivas (1971, 1973) represented Early Friasian time, the age of the Friasense (*i.e.* Río Frías Formation along the Alto Río Cisnes) which was regarded as younger than the Colloncurense would have to be approximately 14-13 Ma (*i.e.* Middle Friasian time) and the still younger Mayoense would represent Late Friasian time (about 13-12 Ma).

Marshall *et al.* (1977) also reported a K-Ar date of 18.5 ± 0.2 Ma on a whole rock tuff from the Santa Cruz Formation at Monte León. This and the 21.7 Ma date reported by Evernden *et al.* (1964) from the Río Gallegos indicated that the greater part, if not all, of the coastal Santa Cruz Formation was of Early Miocene age.

These K-Ar dates thus indicated that Friasian and Santacrucian were older than previously recognized. In addition, Marshall and Pascual (1978, p. 21) cautioned that because Santacrucian faunas from Lago Pueyrredón may be younger than those from the coastal Santa Cruz localities (*fide* Scott, 1932) it is possible "that the faunas from Santa Cruz and Collón Curá could overlap in time..."

Charrier *et al.* (1978, 1979) published K-Ar dates from the Meseta Buenos Aires; one of them was on a basalt (16.0 ± 0.5 Ma) which capped the Friasian age Río Zeballos Group (*sensu* Ugarte, 1956). Ugarte's age assignment was followed by Charrier *et al.* (1979, p. 438; 'Friasian deposits = Formación Río Zeballos' caption to Fig. 2) who concluded:

> "The continental conglomeratic unit, considered a lateral equivalent of the Friasian Stage, is assigned to the late Oligocene-early Miocene interval because of its position below the 16.0 m.y.-old basalts and above the Eocene-lower Oligocene Marine Sandstones. The same age is therefore assigned to the Friasian Stage. This age does not agree with the age (between 16 and 12 m.y....) deduced for the same stage by Marshall and others (1977, Fig. 1), but does agree with the ages deduced by Evernden and others (1964) and Marshall and others (1977) for the Santacrucian Land-Mammal Stage. It should be noted that along the Argentine-Chile border between Lat. 45°S and Lat. 47°S, there are no lithologic criteria to differentiate the Friasian from the Santacrucian deposits. Considering that the stratigraphic position of the Santacrucian deposits in the region of Pueyrredón Lake (Riggi, 1957) is similar to that of the Friasian deposits in the region of Meseta Buenos Aires, it is highly probable that both stages are of the same age".

The conclusions of Charrier *et al.* (1979) are further supported by comments presented by Pascual *(in* Ugarte, 1956, p. 213) on fossil mammals from the Cerro Boleadoras Formation of the Río Zeballos Group at Cerro Boleadoras, just south of Lago Buenos Aires:

"En lo que respecta al nivel geológico de donde fueron exhumados estos restos, parece que se trata de uno más moderno que el Santacrucense típico. Nos hace sospechar esto el tamaño más grande del *Prepotherium* que el de las especies conocidas del Santacrucense. En nuestras colecciones (del Museo de La Plata) existen algunos restos de una especie de este género que proviene de la zona del Río Frías, localidad típica del Friasense... El resto del material *[Propalaehoplophorus* sp., *Nesodon* sp., *Astrapotherium magnum]* es común al Santacrucense."

Ramos (1982, 1989) and Riccardi and Rolleri (1980) show that the 'Patagoniano' marine beds which conformably underly the Río Zeballos of Ugarte (1956), and the Guadal Formation which conformably underlies the Galera Formation (*sensu* Niemeyer *et al.*, 1984) south of Lago General Carrera, represent the marine Centinela (Late Oligocene to possibly Early Miocene) and continental Santa Cruz formations, respectively. Ramos (1982, p. 42) noted that deposition of the Santa Cruz Formation is associated with a magmatic phase responsible for the intrusion of the Fitz Roy Granite which yielded a K-Ar date of 18 ± 10 Ma.

William Zinsmeister (written commun. , 1985) reported that biotite concentrates from two tuff samples between the Centinela and Santa Cruz formations at and near Estancia Quién Sabe, Lago Argentino, yielded dates of 18.8 ± 0.4 and 19.4 ± 0.4 Ma, respectively (samples run by Dr. K.A. Foland, Ohio State University). These dates collectively suggest that the base of the Santa Cruz Formation and Santacrucian LMA along the southern Cordillera between Argentina and Chile is 19-18 Ma. The lowest fossil level of the Santa Cruz Formation in this area is called the 'Notohipidense horizon' and is regarded as Early Santacrucian (Marshall, 1976; Marshall and Pascual, 1977, 1978; Marshall *et al.*, 1983).

Bondesio *et al.* (1980) review Friasian faunas and discuss those of the Collón Curá Formation within the geological context of Rabassa (1975, 1978). In this study they provide the following observations:

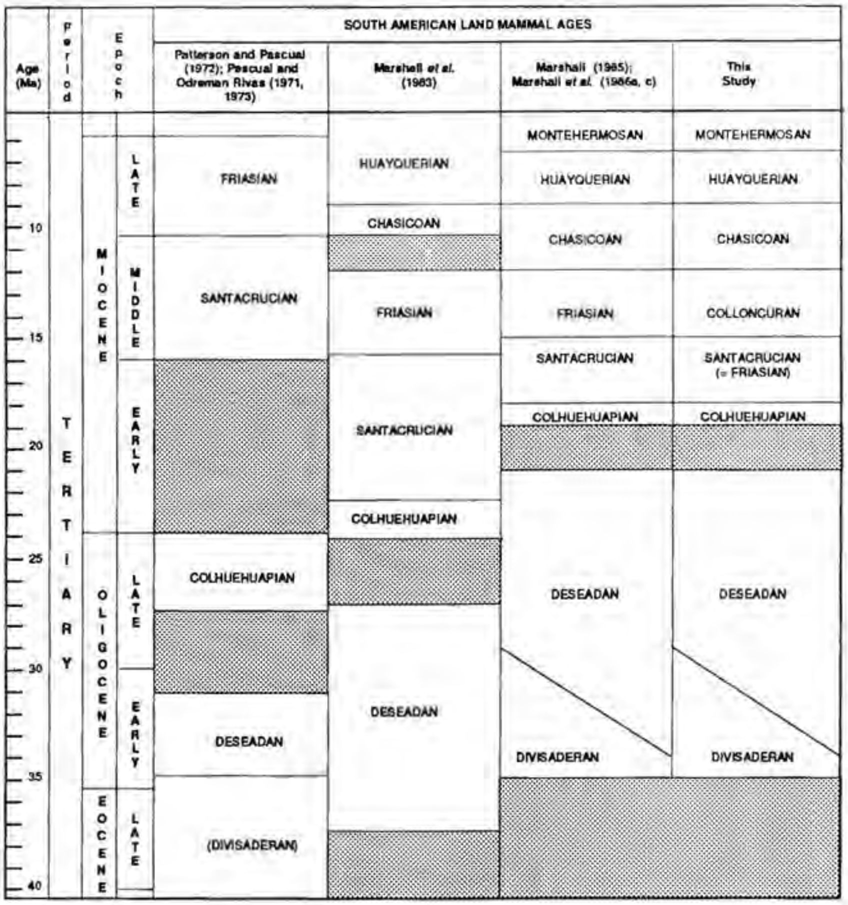
(1) "Los mamíferos del 'Etage Astrapothericuléen'... y del 'Etage Notohippidéen'... de la Meseta del Lago Buenos Aires y del este del Lago Argentino, respectivamente, presentan un estado evolutivo transicional entre aquéllos de las Edades-mamífero Colhuehuapense y Santacrucence..." "Muy probablemente aquellos mamíferos mencionados precedentemente, que Roth (1920: 161 y 1925:173-174) exhumara de la base de los sedimentos terciarios del Río Frías corresponden a esos elementos transicionales... Recordemos que de esta misma secuencia y por sobre estos niveles, concordantemente, se encuentran aquéllos que fueron base del 'étage Friaséen' de Ameghino y de nuestra Edad-mamífero Friasense' (p. 87).

(2) "... la mayoría de los vertebrados exhumados de la Formación Collón Curá lo fueron de los niveles superiores de la Ignimbrita... esto es, del Miembro Tobáceo Las Bayas;... otros vertebrados taxonómicamente vinculados a los anteriores, pero de un grado evolutivo más avanzado, provienen de otras unidades litológicamente diferentes y relativamente más modernas. El conjunto de todos estos registros son los que fundamentaron la Edad-mamífero Friasense... En consecuencia, es lógico inferir que tanto la parte superior de la Formación Collón-Curá (Miembro Tobáceo Las Bayas) como las demás formaciones mamalíferas de la Edad-mamífero Friasense cronológicamente posteriores... representan un tiempo geológico que debe extenderse hasta épocas más recientes. Luego, la Edad-mamífero friasense muy probablemente abarcó hasta parte del Mioceno tardío, regionalmente representado por las sefitas superiores de la Formación Collón-Curá" (p. 93).

(3) "... la Edad-mamífero Friasense está representada por una serie de unidades formacionales distintas y portadoras de mamíferos fósiles que testimonian sucesivas comunidades que cubrieron un lapso del tiempo geológico que en sus inicios se vincula con la Edad-mamífero Santacrucense y en sus fines con la Edad-mamífero Chasiquense...Los mamíferos hallados por Rabassa... por debajo del Miembro Ignimbrítico Pilcaniyeu no son de taxa exclusivos friasenses, por lo que no es descartable que el Miembro Tobáceo Caruhué... pueda representar parte de la Edad-mamífero Santacrucense" (p. 93-94).

(4) "...recordemos que los mamíferos de la Formación Collón-Curá de la localidad tipo y de Pilcaniyeu Viejo provienen en su mayoría del Miembro Tobáceo Las Bayas, es decir del tercio superior, por arriba del Miembro Ignimbrítico Pilcaniyeu. Estos mamíferos acusan un grado evolutivo más avanzado que aquéllos de la Edad-mamífero Santacrucense, pero un estado aún posterior lo testimonian aquéllos hallados en los sedimentos mayormente areniscosos de la Laguna Blanca, río Fénix, río Frías, río Guenguel, río Huemules y arroyo Challa. No es improbable, pues, que éstos sean correlacionables con la parte sefítica más superior de la Formación Collón Curá de ciertos lugares..., hasta el momento estéril" (p. 95).

Riccardi and Rolleri (1980, p. 1246-1250) provide an overview of Cordilleran geology in southern Patagonia and give an extended description of the Río Frías Formation (*sensu* Ramos, 1976; Ploszkiewicz and Ramos, 1977: *i.e.* sediments extending from south of Lago Buenos Aires north along the Andean Cordillera of Chubut Province). Stratigraphic equivalents include the Cerro Boleadoras and Río Correntoso formations of the Río Zeballos Group (Ugarte, 1956) and Río Mayo and Pedregoso formations (González, 1967) in Argentina, and the upper part of the Mesa Guadal Formation and the Galera Formation (Skarmeta, 1976, 1978; Skarmeta and Charrier, 1976) in Chile. Within the Río Frías Formation are included the Friasian fossil localities at Alto Río Mayo, Laguna Blanca, Alto Río Senguerr, Río Huemules, Río Fénix, Río Guenguel and Alto Río Cisnes (*nec* Río Frías). This is the first time that the name Río Frías Formation is formally applied to all of these



Text-Fig. 4. Chronology of Miocene South American Land Mammal Ages as proposed by various workers. Shading denotes hiatuses in knowledge of land mammal faunas. Geologic time scale follows Berggren *et al.* (1985).

localities although some (see above) were originally included by Roth (1908, 1920, 1925) in his 'Río Frías Stufe'.

In their analysis of the age of the Río Frías Formation Riccardi and Rolleri (1980, p. 1249) note that the K-Ar dates on the ignimbrite from the Collón Curá Formation presented by Marshall *et al.* (1977) and Rabassa (1978) are from below the Colloncurense mammal level and that the younger Friasense (and by extrapolation the Río Frías Formation) is probably of Late Miocene or perhaps Early Pliocene age. They thus suggested equating the Río Frías Formation with the upper part of the Collón Curá Formation which at that time inferred an age of approximately 13-12 Ma.

González (1967) applied the name Río Mayo Formation to a 700-800 m thick section of tuffs and tuffites with occasional conglomeratic benches located north of Lago Buenos Aires, southwest Chubut Province, Argentina, which included the Alto Río Mayo, Río Huemules and Laguna Blanca local faunas of Roth (1920, p. 164), as well as those from the Río Guenguel, Río Fénix and Río Senguerr. Concordantly overlying the Río Mayo Formation are 400 m of polymictic conglomerates which he named the Pedregoso Formation. The conglomerates thin toward the east; they occur in the areas of Río Fénix and Loma Baguales (Roth, 1908) but are absent at Río Mayo and Laguna Blanca (González, 1967, p. 55). González (1967) assigned the Río Mayo Formation to the Miocene and Pedregoso Formation to the Pliocene.

In Chile, Skarmeta (1976) named the Galera Formation which he recognized was a stratigraphic equivalent to both the Río Mayo and Pedregoso formations of González (1967). Skarmeta (p. 77, 79) included within the Galera Formation rocks containing fossils described by Roth (1908) from the Alto Río

Cisnes in Chile and those described by Ameghino (1906) and Roth (1908) from Laguna Blanca in Argentina. He also noted (p. 75) that in Argentina exposures of these deposits occur sporadically from the Río Chubut to the Río Santa Cruz. Specifically, he identified exposures along the Río Mayo, on the west side of the Meseta Guenguel, and on the high part of the Pampa de Chalía.

Riccardi and Rolleri (1980, p. 1250) recognized that at least the two upper formations (*i.e.* Cerro Boleadoras and Río Correntoso) of the Río Zeballos Group of Ugarte (1956) are stratigraphic equivalents of the Galera, Río Mayo and Pedregoso formations. Skarmeta and Charrier (1976, p. 278) further correlated the Galera Formation with the conglomerates in the upper part of the Mayoense in the Fénix region, and with the Río Mayo and Pedregoso formations in Río Mayo. These same conglomerates occur to the south of the village Lago Blanco and the south of the Estancia Valle Huemules (Skarmeta, 1976, p. 80). Ramos (1976, p. A60) also recognized that his 'Frías Formation' was a stratigraphic equivalent of the Galera Formation of Skarmeta (1976).

Riccardi and Rolleri (1980, p. 1250) concluded that the Río Frías Formation is lithologically very similar to the three members of the Santa Cruz Formation described by Furque (1973) at Lago Argentino. In their Cuadro III, they show the Galera, Río Frías and Santa Cruz formations as age (and stratigraphic?) equivalents extending from Early Miocene to Early Pliocene.

Ramos (1981, p. 70) correlated the lower mammal-bearing tuffite-sand unit of the Río Frías Formation with the Río Mayo Formation of González (1967) and the upper unfossiliferous conglomerate-sand unit with González's Pedregoso Formation which he noted was less well developed in the Río Frías Formation. Ramos (1981, p. 70) also noted that the Galera Formation of Skarmeta (1976) was similar in lithology and depositional environment to the Río Frías Formation. Following Pascual *et al.* (1978), Ramos concluded (p. 70) that the Río Frías Formation was 15-11 Ma (Middle Miocene) in age.

Niemeyer *et al.* (1984, p. 48) assigned their Galera Formation an Early to Middle Miocene age following Charrier *et al.* (1979), and correlated it with rocks containing fossil mammals described by Roth (1908) and Ameghino (1906) at Laguna Blanca, the Río Frías Formation along the Alto Río Cisnes (Ramos, 1976), the Mayoense of Kraglievich (1930) and the Río Zeballos Group of Ugarte (1956). They noted that further south, the Galera Formation is similar to the continental levels studied by Riggi (1957) in the region of Lago Posadas which contains a Santacrucian age fauna. Further south near Lago Cardiel, Ramos (1982) recognized the Santa Cruz Formation (which correlates with the Galera Formation) and concordantly below it the marine Centinela Formation (which is an equivalent of the Guadal Formation). These geological studies are further supported by the paleontological observations of Pascual *et al.* (1984, p. 551) who caution:

> "...it is not improbable that the lower part of the mammal units assigned to the Friasian age... could represent the Santacrucian age..."

The only group of mammals from Friasian faunas in Argentina and Chile which have been reviewed subsequent to the work of Kraglievich (1930) are the rodents (Vucetich, 1984). Vucetich's concept of Friasian follows Pascual and Odreman Rivas (1971) and her usage of Río Frías Formation follows Riccardi and Rolleri (1980).

Data presented by Vucetich (1984) were tabulated (Table 1) to see if local faunas from the Río Frías Formation showed closer taxonomic affinity with those from the Santa Cruz or Collón Curá formations. She recognized 16 species referable to 13 genera. Seven species *(Massoiamys obliquus, Eocardia robusta, E. robertoi, Matiamys elegans, Megastus elongatus, Prolagostomus rosendoi, Pliolagostomus friasensis)* are recorded only from the Collón Curá Formation; one *(Disteiromys gracilis)* is known only from Laguna Blanca; one *(Cardiomys? andinus)* is a *nomen dubium* from Río Guenguel; one *(Cardiomys? huemulensis* is a *nomen dubium* from Río Huemules; one *(Eusigmomys oppositus)*, based on a lost type that was never figured, is from Río Fénix; and one *(Simplimus indivisus)* is based on an isolated tooth now lost from Laguna Blanca and another isolated tooth from Laguna Blanca or Río Fénix. Thus, 12 of the 16 species are of no chronostratigraphic value because they are site specific, and four of the nine taxa reported from localities of the Río Frías Formation *(Cardiomys? andinus, C.? huemulensis, Eusigmomys oppositus, Simplimus indivisus)* are either *nomina dubia* or *nomina vana*.

The remaining four taxa are recorded (some tentatively) from multiple localities and are therefore of potential value for correlation and age inference. *Alloiomys friasensis* is represented by a partial skull from the Collón Curá Formation and an isolated fourth premola from the Alto Río Cisnes; *Stichomys regularis*, a Santacrucian species, is tentatively reported from Río Senguerr; *Neoreomys australis*, a Santacrucian species, is tentatively reported at Río Senguerr and Río Guenguel; and *Prolagostomus pusillus* occurs at Río Senguerr and in the Santa Cruz Formation. Thus, the only evidence to suggest age affinity between the Collón Curá and Río Frías formations is the co-occurrence of *Alloiomys friasensis* (represented by an isolated tooth at Alto Río Cisnes) and *Prolagostomus pusillus* (represented by an isolated tooth at Río Senguerr). In contrast, the one locality of the Río Frías Formation represented by multiple taxa and for which age inference appears permissible is Río Senguerr which has three species *(Stichomys* cf. *regularis, Neoreomys* cf. *australis, Prolagostomus pusillus)* known also in the Santa Cruz Formation. Thus the data of Vucetich (1984) favor only a Santacrucian age for Río Senguerr, while data supporting age affinity of the Río Frías and Collón Curá formations are based solely on two isolated teeth.

Knowledge of the age and content of Friasian up to about this time is summarized by Marshall *et al.* (1983; see Text-Fig. 4). Several papers which report new K-Ar dates on Miocene land mammal faunas were published subsequently and these constrain Friasian time.

The first involved a geochronologic study of the Araucanense and Corral Quemado formations in Catamarca Province, northwest Argentina which respectively include land mammal faunas of Huayquerian and Montehermosan age (Butler *et al.*, 1984; Text-Fig. 4). A 2,300 m magnetostratigraphic section with four K-Ar dated tuff levels extended from about 8.0-3.5 Ma. The 6.4 Ma contact between the Araucanense and Corral Quemado formations approximates the boundary in this area between Huayquerian and Montehermosan LMA faunas. Furthermore, Marshall *et al.* (1986b) report a date of 5.8 Ma on a biotite concentrate of a tuff that is believed to be from the top of the Huayquerias Formation (name-sake and type formation of the Huayquerian LMA) near San Carlos, Mendoza Province, Argentina. Here the Huayquerian Formation is discordantly overlain by the Tunuyán Formation which contains a mammal fauna of Montehermosan age. The combined ages from San Carlos (5.8 Ma) and Catamarca (6.4 Ma) apparently bracket the Huayquerian-Montehermosan boundary at about

TABLE 1. DISTRIBUTION OF FRIASIAN AGE RODENTS IN ARGENTINA AND CHILE

Taxon	Recorded Occurrence		
	Santa Cruz Formation	Río Frías Formation	Collón Curá Formation
Massoiamys obliquus			x
Matiamys elegans			x
Megastus elongatus			x
Eocardia robusta			x
Eocardia robertoi			x
Pliolagostomus friasensis			x
Prolagostomus rosendoi			x
Prolagostomus pusillus	x	Río Senguerr	
Stichomys regularis	x	Río Senguerr?	
Neoreomys australis	x	Río Senguerr? + Río Guenguel?	
Disteiromys gracilis		Laguna Blanca	
Cardiomys? andinus		Río Guenguel	
Cardiomys? huemulensis		Río Huemules	
Eusigmomys oppositus		Río Félix	
Simplimus indivisus		Laguna Blanca + Río Frías?	
Alloiomys friasensis		Alto Río Cisnes	x

x, present

(Data based on Vucetich, 1984)

6 Ma (Text-Fig. 4).

The Huayquerian and Chasicoan boundary is estimated on knowledge that Huayquerian faunas in Catamarca are from the part of the section dated approximately 8 Ma, and faunas of Chasicoan age (see Pascual and Odreman Rivas, 1973, chart opposite p. 318) are known from the lower part of the Chiquimil Formation in this area. The Huayquerian-Chasicoan boundary is thus older than 8 Ma, and 9 Ma is a reasonable estimate (Marshall, 1985, p. 63; Text-Fig. 4).

These studies show that the Huayquerian LMA spans from about 9-6 Ma and is thus Late Miocene (Text-Fig. 4). There are no K-Ar dates available for Chasicoan rocks, yet the faunas clearly predate Huayquerian and postdate Friasian time. For reasons discussed by Marshall (1985, p. 63) the Friasian-Chasicoan boundary is estimated to be about 12 Ma. This age is consistent with the K-Ar dates of 15.4-14.0 Ma on the Pilcaniyeu Ignimbrite of the Collón Curá Formation which as of 1985 were believed to date an Early Friasian (Colloncurense) fauna. Thus, the K-Ar dates available up to this time document that land mammal faunas of Huayquerian and Chasicoan age are Late Miocene, and Friasian is Middle Miocene (Text-Fig. 4).

Several papers which constrain the base of Friasian time were published in 1985 and 1986. The most relevant was by Marshall *et al.* (1986a) who report new radioisotopic dates and a paleomagnetic section of the Santa Cruz Formation. Only the technically 'good' dates are mentioned here. From Karaikén near Lago Argentino were obtained three dates on plagioclase concentrates from rhyolite pebbles which average 16.7 ± 0.2 Ma; and a fission track date of 15.7 ± 1.8 Ma was obtained on six zircon grains from the lowest tuff sampled. From Monte León are reported seven K-Ar dates on glass, biotite and plagioclase concentrates which range from 19.9 ± 1.2 - 16.5 ± 0.4 Ma (one of the dates was reported earlier by Marshall *et al.* 1977). The most precise of these is a date of 17.3 ± 0.3 Ma from a tuff low in the section and from tuffs higher in the section are dates on glass and plagioclase concentrates which average 17.0 ± 0.5 Ma. Thus, the Santa Cruz Formation at Monte León appears to be bracketed between 17.3-17.0 Ma. A K-Ar date of 16.0 ± 0.8 Ma was also obtained on a glass concentrate of a tuff from Rincón del Buque.

The above K-Ar dates (two on plagioclase, three on glass) collectively indicate an overall age of about 17.3-16.0 Ma for the Santa Cruz Formation. These new dates also indicate that two previously reported dates (21.7 ± 0.3 Ma, Evernden *et al.*, 1964; 18.5 ± 0.2 Ma, Marshall *et al.*, 1977) were too old due to probable contamination. Furthermore, the magnetostratigraphic section from Monte León is dominantly, if not entirely, of reversed polarity and given the dates of 17.3-17.0 Ma on mineral concentrates from this locality, it most likely correlates with chron 5Cr which ranges from 17.5-17.0 Ma (Berggren *et al.*, 1985).

These new geochronologic data, along with the 15.4-14.0 dates on the Collón Curá Formation, thus indicated that the Santacrucian LMA ranged from about 18-15 Ma, encompassed the upper part of Early Miocene and lower part of Middle Miocene time, and was younger than believed by previous workers (Text-Fig. 4).

The younger age assignement for the Santacrucian LMA was corroborated by K-Ar dates on a Deseadan (conventionally regarded as Early Oligocene; Patterson and Pascual, 1972; Text-Fig; 4), fauna at Scarritt Pocket, Chubut Province, Argentina. Marshall *et al.* (1986c) present 18 K-Ar dates on basalts and mineral concentrates of tuffs which bracket this local fauna, and demonstrate that it occurs between 23.4 ± 1.0 - 21. 0 ± 1.0 Ma, and is thus lower Early Miocene in age. This study complements that of MacFadden *et al.* (1985) who, based on paleomagnetic and K-Ar data of the Deseadan age Salla Beds of Bolivia, report that it extends from about 28.5 - 24.0 Ma and is thus Late Oligocene to possibly earliest Miocene. Naeser *et al.* (1987) published three fission-track (34.5 ± 4.0, 24.2 ± 3.6, 23.5 ± 2.2 Ma) and four ^{40}K-^{40}Ar (biotite: 28.0 ± 0.9, 27.2 ± 0.9, 27.9 ± 0.9, 25.1 ± 0.7 Ma) dates from four ash levels in the lower part of the Salla Beds and conclude that the principal fossil horizons range from 27-24 Ma while the complete section ranges from about 28-22 Ma. They concluded that the age of these beds is Late Oligocene-Early Miocene. These conclusions are consistent with those of Hayashida and Danhara (1985) who report four fission track dates (27.2 ± 1.6, 25.0 ± 1.5, 26.1 ± 1.9, 24.0 ± 1.5 Ma) on zircons from an unspecified level(s) in the Salla Beds.

A consequence of these radioisotopic studies is that they constrain the Colhuehuapian LMA (conventionally regarded as Late Oligocene; Patterson and Pascual, 1972; Text-Fig. 4) within the 21-18 Ma hiatus between Deseadan and Santacrucian. Because Colhuehuapian faunas show closer taxonomic similarity with Santacrucian than with Deseadan faunas, it was regarded by Marshall (1985) and Marshall *et al.* (1986a, c) as possibly ranging from 19-18 Ma. This assignment must be ragarded as tentative, because no geochronologic data are yet available for Colhuehuapian age rocks and faunas.

The only radioisotopic dates published on Argentina Miocene age faunas subsequent to the above studies are by Bown *et al.* (1988) who report fission track ages of 16.6 ± 1.5 Ma on a tuff from the Pinturas Formation associated with the *Astrapothericulus* beds (Pinturas local fauna) of Ameghino (1906) which represents an Early Santacrucian local fauna (Marshall, 1976, p. 1140), and an age of 15.8 ± 2.5 Ma on a tuff located 20 m above a Late Colhuehuapian local fauna from the Trelew beds at Gaimán.

DISCUSSION

The work on the Río Frías Formation along the Alto Río Cisnes shows that these rocks and faunas are temporally equivalent to the Santa Cruz Formation and Santacrucian LMA in southern Argentina. This age assignment is based on three facts. First are the observations on the regional geology suggesting equivalence of Santacrucian and Friasian deposits summarized above (*e.g.* Charrier *et al.*, 1979). Second, Marshall (1990) described marsupials collected during 1987 and 1989 field seasons and showed that of the 12 species represented, 10 were indistinguishable from taxa known from the Santa Cruz Formation of Argentina. In addition, three of these taxa (*Pichipilus halleuxi*, *Pitheculites rothi*, *Parabderites bicrispatus*) show special affinity with the Early Santacrucian fauna at Karaikén near Lago Argentino (*i.e.* 'Notohipidense horizon' of Ameghino; see Marshall and Pascual, 1977). And third, a $^{40}Ar/^{39}Ar$ date of *ca.* 17 Ma on plagioclase from the lower mammal-bearing unit is consistent with a Santacrucian age (*sensu* Marshall *et al.*, 1986a). The Ar/Ar date and study of marsupials are thus complementary. This age assignment applies specifically to the lower fossiliferous tuffite-sand unit. Refinement of the age of this local fauna within Santacrucian time must await completion of ongoing magnetostratigraphic studies, systematic and biostratigraphic study of the rest of the fauna, and additional radioisotopic dates. Deposition of the upper unfossiliferous conglomerate-sand unit may correlate with the period of maximum deformation and hence exceptionally high energy transport of the Quechua uplift Phase (*ca.* 9 Ma) and could be Late Miocene (see below).

As a result of this new age determination for the type Río Frías Formation and Alto Río Cisnes local fauna, the Friasense (*s.s.*) of Ameghino (1906) is older (not younger) than the Colloncurense and represents a junior synonym of the Santacrucian LMA which has priority based on date of publication. In view of this, the authors follow the recommendations of Marshall (1990) and use the Colloncuran LMA of Groeber (1929; but *sensu* Kraglievich, 1930) in place of Friasian (*sensu* Pascual and Odreman Rivas, 1971, 1973; Patterson and Pascual, 1972; Text-Fig. 4). The type fauna from the Miembro Tobáceo Las Bayas of the Collón Curá Formation at Pilcaniyeu Viejo, Río Negro Province (Bondesio *et al.*, 1980), occurs above the Miembro Ignimbrítico Pilcaniyeu which has K-Ar dates ranging from 15.4-14.0 Ma, and based on these dates and knowledge of the fauna is securely of post-Santacrucian and pre-Chasicoan aspect. It is the best sampled, most taxonomically diverse, and only local fauna associated with K-Ar dates which fits the concept of 'Friasian' as conceived by earlier works.

Placement of other classic 'Friasian' local faunas (*i.e.* Laguna Blanca, Río Senguerr, Río Guenguel, Río Huemules, Río Fénix, Río Mayo) within the emmended land mammal age sequence presented here (Text-Fig. 4) is unclear. Based on reassessment of the rodent faunas described by Vucetich (1984, see above), it appears that at least the Río Senguerr local fauna is also Santacrucian, an observation supported by Kraglievich (1930, p. 150). Given the fact that all these local faunas occur in the Río Frías Formation it is possible that most or all may prove to be Santacrucian. However, the authors realize that rocks presently mapped as the Río Frías Formation could be time transgressive and potentially include land mammal faunas older and/or younger than Santacrucian. Yet, the only secure solution to resolving the relative and absolute ages of these local faunas is to undertake studies as done along the Alto Río Cisnes which involves recollection of faunas and radioisotopic dating of rocks.

The results of this interdisciplinary geological-paleontological study of the type Río Frías Formation and type Friasian LMA thus permits refinement of the age of these rocks and faunas. As shown above, this study requires modification of aspects of the LMA sequence as conceived by earlier workers; yet, it represents only one of many such changes made in this sequence during the past 14 years. These changes are a direct result of new radioisotopic (K-Ar, Ar/Ar, fission track) age determinations and/or magnetostratigraphic study of rocks associated with these land mammal age faunas.

This study has also permitted clarification of controversial aspects of nomenclature of Miocene continental rock units in the area of Lago General Carrera-Buenos Aires along the Argentina-Chile border. Based principally on knowledge of the regional geology as summarized by Ramos (1982, 1989), the following was recognized:

The continental Santa Cruz Formation conformably overlies the marine Centinela Formation and its stratigraphic equivalents (*i.e.* 'lower marine fossil level' at Meseta Buenos Aires of Charrier *et al.*, 1978, 1979; 'Patagoniano' of Ugarte, 1956; 'Segundo Nivel Marino con *Ostrea*' and Guadal Formation of Niemeyer *et al.*, 1984) and includes the 'Friasian deposits = Formación Río Zeballos' at Meseta Buenos Aires of Charrier *et al.* (1979), the Río Zeballos Group of Ugarte (1956), the Galera Formation south of Lago General Carrera of Niemeyer *et al.* (1984), and the Palomares Formation in Magallanes Region where fossil mammals of Santacrucian age have been collected at Laguna Blanca (*Nematherium birdi;* Simpson, 1941) and Laguna del Toro (*Astrapotherium magnum;* Hemmer, 1935) (Text-Fig. 3).

The Río Frías Formation includes continental rocks containing Santacrucian faunas which have a sporadic and discontinuous distribution in small valleys and depressions (Ramos, 1981, p. 83) north of Lago General Carrera-Buenos Aires and includes the Río Mayo and Pedregoso formations of González (1967) and the Galera Formation north of Lago General Carrera of Skameta (1976) and Niemeyer *et al.* (1984).

The stratigraphic thickness of the Santa Cruz Formation south of Lago General Carrera-Buenos Aires is considerably thicker than the Río Frías Formation to the north (see Ramos, 1989, p. 890). The Santa Cruz Formation was deposited in the Magallanes Basin and the Río Frías Formation in the Río Mayo Embayment along the western edge of the San Jorge Basin (*sensu* Ramos, 1989, Fig. 1). These depositional basins are separated by the western end of the Deseado Massif which corresponds to the east-west axis of Lago General Carrera-Buenos Aires (Text-Fig. 3).

Both the Santa Cruz and Río Frías formations were deposited by high energy fluvial systems and sediments were derived from uplift of the Cordillera to the west. This uplift phase is called Quechua (Charrier and Malumian, 1975; Ramos, 1981, p. 83) which was responsible for initiation of deposition of the Río Frías Formation and for uplift to present height of the Patagonian Cordillera (Ramos, 1981, p. 83). It also initiated deposition of the Santa Cruz Formation (Malumian and Ramos, 1984; Ramos, 1989) which accompanied regression of the Centinela Formation epicontinental sea. The Quechua phase thus began *ca.* 18 Ma, although the period of maximum uplift and deformation apparently occurred about 9 Ma (Malumian and Ramos, 1984; Ramos, 1989, p. 899). The latter date may correspond with deposition of the upper unfossiliferous conglomerate-sand unit of the Río Frías Formation.

The above timing of deposition events suggests that the last uplift phase of the southern Cordillera began *ca.* 18 Ma, although the southern Andes did not attain sufficient height to produce a rain shadow effect by blocking moisture laden Pacific winds until somewhat later. As noted by Patterson and Pascual (1972), and Pascual *et al.* (1965), the first evidence of a rain shadow effect is seen in 'Friasian' faunas where a change occurs from savanna-woodlands to pampas. Based on the time scale of LMA's presented here (Text-Fig. 4), this rain shadow effect apparently became operative about 15 Ma which currently represents the Santacrucian-Colloncuran boundary.

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ADDENDUM

Additional studies which support the age, stratigraphic and rock nomenclature conclusions presented in this paper are as follows. Wyss *et al.* (1987) reported a Santacrucian age land mammal fauna from Pampa Castillo, south of Lago General Carrera (= Galera Formation of Niemeyer *et al.*, 1984). Barrio *et al.* (1984) informed about Santacrucian mammals from numerous localities in what they call the Santa Cruz Formation (which conformably overlies the marine Centinela Formation) at the Meseta del Lago Buenos Aires and along the southwest edge of the Deseado Massif. González and Vilela (1966) mapped Santacrucense along Long. 70°W to the west of Lago Musters in Chubut Province, Argentina. They noted (p. 196) that about 20 km west of the confluence of the ríos Mayo and Senguerr the Santacrucense (= Río Mayo Formation of González, 1967) conformably overlies the marine Patagoniense. A similar relationship of Santacrucense conformably overlying marine Patagoniense is reported at Pampa de Castillo north of the Río Deseado in northernmost Santa Cruz Province (Feruglio, 1936; Bordas, 1939). Ameghino (1906, p. 267, Fig. 61) earlier equated the continental rocks at Pampa de Castillo with those of the ríos Fénix, Guenguel and Mayo (see Feruglio, 1949, p. 182). Thus, the Río Frías Formation apparently extended eastward to the Atlantic coast between Lago Musters and the northern edge of the Deseado Massif as approximated by the Río Deseado. In this area the Río Frías Formation conformably overlies the marine Patagoniense which appears to be temporally equivalent to the Centinela Formation in the Magallanes Basin.

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APPENDIX 1. STRATIGRAPHIC SECTIONS AT FOSSIL MAMMAL LOCALITIES

Description of stratigraphic sections at localities 1, 2, 3, 5, 8, 4, 9, 12 and 15 (Text-Fig. 2). The section and locality number are the same to facilitate reference and are listed below in the preceding order which is their approximate north to south position along the Alto Río Cisnes (Text-Fig. 1).

Section 1

Top	:	Top of cliff
2.0 m	:	Soil
0.5 m	:	Tuff, color black, very weathered, poorly consolidated. Under microscope are visible unwelded pyroclastic fragments and many pores (sample 45)
3.0 m	:	Sandy tuffites, color brown to orange
6.0 m	:	Conglomerates and breccias in loosely consolidated grey tuffaceous matrix; matrix supported clasts, poorly sorted, range from 0.1- 1m; clasts are principally volcanic (andesites, rhyolites, granites and diorites)
--------	:	Erosional unconformity (clearly seen on south side of cliff)
10.5 m	:	Tuffites and mudstones, color whitish to light brown
24.0 m	:	Tuffites and siltstones, color whitish to brown
20.0 m	:	Tuffs, color whitish, massive: fossil mammals collected *in situ* and as float from lower *ca.*10 m. Under microscope it corresponds principally to a fine grained crystal tuff, poorly consolidated; composed of crystal fragments of hornblende and plagioclase in a weakly welded vitroclastic matrix containing lithic and pumice fragments (sample 41)
6.0 m	:	Tuffites, color white to light orange, well stratified with 3-4 erosion resistant levels. Based on correlation with Section 3, **guide level** occurs within upper meter of this unit, but is here absent
Base	:	Covered by recent alluvium
72.0 m	:	Total thickness of exposed section

Section 2

Top	:	Top of slump block
0.5 m	:	Tuff, color whitish, fossil mammals collected *in situ* and as float from this unit
12.0 m	:	Tuffites, color white to light orange, well stratified with 3-4 erosion resistant levels. Based on correlation with Section 3 **guide level** occurs within upper meter of this unit, but is here absent
3.0 m	:	Tuffites, color light orange
Base	:	Covered by recent alluvium
15.5 m	:	Total thickness of exposed section

Section 3

Top	:	Top of section; an additional *ca.* 50 m to top of cliff covered by soil and vegetation. Abundance of numerous volcanic clasts of various sizes within soil on scree slope below this level indicates presence of a conglomerate-breccia unit above this point which is apparently same as in uppermost part of Section 1 (Tex-Fig. 2)
7.5 m	:	Sandy tuffites, color white to brown
4.5 m	:	Tuff, color white to brown, loosely compacted, slightly stratified. Under microscope it represents a vitric tuff with rhyolitic crystals which vary in size from 0.2-1.0 mm and includes crystal fragments of plagioclase, hornblende and quartz with abundant elongate (up to 1.0 mm) pumice 'shards' and pores; glass in both pumice 'shards' and matrix devitrified, resulting in development of chlorite and kaolinite (sample 39)
3.0 m	:	Tuff, color orange, with altered plagioclase. Under microscope it represents a crystal tuff of dacitic composition (sample 38).
1.0 m	:	Mudstone, color brown
0.5 m	:	Tuffites, color whitish to light brown
0.5 m	:	Mudstone, color white to brown, loosely consolidated
3.0 m	:	Tuffites, color white to green, very fine texture
7.5 m	:	Sands with some larger volcanic clasts, color brown to green
12.5 m	:	Tuffs, color white, massive in upper 2-3 m, slight stratification. Under microscope the tuff (sample 33) contains dacitic crystals which range in size from 0.5-1.0 mm; a large fraction of crystals of plagioclase, hornblende and biotite, fine pumice 'shards', and relatively thick vitroclastic materials semi-welded and devitrified
10.0 m	:	Tuffs, color white, massive; altered minerals; Ar/Ar date of *ca.* 17 Ma on plagioclase; fossil mammals collected *in situ* and as float from this unit. Under microscope a fine grained crystal tuff, similar to sample 33 (above), but with higher proportion of crystals and pumice; matrix contains thick vitroclastic fragments (sample 32)
3.5 m	:	Tuffites and some sand, color white to light brown; **guide level** (a fine white tuff) occurs in upper meter of this unit within an erosion resistant layer. Under microscope a fine vitric tuff with scarce fresh crystals of plagioclase (*ca.* 0.5 mm in diameter), small fragments of volcanic rock and quartz in a slightly devitrified vitroclastic matrix beige to green in color (samples 30, 31)
3.0 m	:	Tuffites, white to orange, well stratified with 2-3 erosion resistant layers. Under microscope it is composed of tuff and pumice fragment in a fine grained recrystallized vitroclastic matrix which includes fragments of plagioclase, biotite and quartz probably derived from a fine grained ash (sample 29)
1.5 m	:	Siltstones, color brown to green
1.5 m	:	Tuffites, color yellowish; in base of unit are abundant clasts from underlying formation
--------	:	Angular unconformity
ca. 10.0 m	:	Dacites and andesites, color dark grey-greenish-red, massive Ñirehuao Formation. Under microscope it corresponds to a fluidal dacitic and andesitic tuff, with partly devitrified groundmass. Dacitic tuff composed of pumice and crystal material in welded vitroclastic matrix with irregular fluidal bands; crystals include plagioclase, potassium feldspars and relict biotite;

lithic fragments include fluidal pilotaxic andesites and pumice (sample 16A). Andesitic tuff has porphyritic texture with scarce clasts of plagioclase and relicts of mafic chlorite in pilotaxitic groundmass composed principally of microlitic plagioclase with chloritic and argillaceous alteration (sample 16C)

Base : Level of river

69.5 m : Total thickness of exposed section

Section 5

Top : Top of cliff

10.0 m : Fine grained sands, color brown to orange, well stratified with fine laminations; weakly cross-bedded

10.5 m : Conglomerates in grey tuffaceous matrix; clasts, as in units below this level, are principally volcanic (andesites, rhyolites, granites and diorites); clasts smaller in base of unit larger toward top; basal part shows weak cross-bedding

7.5 m : Fine grained sands, siltstones and mudstones, color brown, well stratified with fine laminations; weakly cross-bedded.

19.5 : Conglomerates in a grey tuffaceous matrix with several levels of massive siltstones, unstratified

8.0 m : Mudstones, color whitish brown, well stratified with fine laminations; weakly cross-bedded

4.5 m : Siltstones, whitish grey, well stratified

7.0 m : Conglomerates in grey tuffaceous matrix, unstratified

8.0 m : Conglomerates distinctly stratified in poorly sorted tuffaceous siltstone matrix, brown to orange in upper part, brown to grey in lower part; clasts vary in shape from semiangular to round, and in size from a few mm to 1 m

------- : Erosional unconformity (clearly seen on south side of cliff)

30.0 m : Tuffites, color white to grey, well lithified

9.0 m : Tuffites, color whitish, fossil mammals collected *in situ* and as a float in upper 3 m which has irregular black stains

0.5 m : Tuff, color white, soft due to presence of much water; **guide level**

10.0 m : Tuffites, color whitish

Base : Covered by recent alluvium

124.5 m : Total thickness of exposed section

Section 8

Top : Top of cliff

ca. 2.0 m : Conglomerates and breccias in grey sand-pebble tuffaceous matrix; clasts unstratified

------- : Erosional unconformity

9.0 m : Fine grained sands with some tuffites, color brown

14.5 m : Tuffites, color orange, well stratified with 3-4 erosion resistant levels; fossil mammals collected *in situ* and as float from this unit (skull of toxodont collected 3 m above base), bones typically tan to cream in color; this is the upper fossil level of Loc. 8

17.0 m : Tuffites, color brown. Under microscope it corresponds to a tuffaceous sandstone with crystals of quartz and plagioclase (0.1-0.5 mm) in an ash and clay matrix (sample 23). Some bones of mammals observed *in situ*, but none collected

5.0 m : Tuffaceous sandstones, color brown. Under microscope it contains crystals, and lithic and pumice fragments in an altered vitroclastic matrix with clay and chlorite (sample 22). Bones of fossil mammals observed *in situ*, but none collected

1.0 m : Tuffite, color brown. Under microscope are seen crystals of quartz and plagioclase, and scarce lithic (0.2-0.8 mm) and glass fragments in devitrified matrix (sample 21)

10.0 m : Mudstones, color brown. Under microscope it corresponds to either a very fine tuff or very fine grained sedimentary rock; scarce fragments of quartz in ash-clay matrix (sample 20)

4.0 m : Tuffites, color white. Under microscope it corresponds principally to a rhyolitic tuff; numerous crystal fragments of plagioclase, anfibole, quartz and pumice; subrounded fragments of igneous rocks; vitroclastic matrix containing many pores due to devitrification and alteration of minerals to clay and chlorite (sample 18)

5.0 m : Tuffites, color light brown. Under microscope it corresponds principally to an ash, weakly consolidated; some small lithic fragments and pumice in vitroclastic matrix (sample 19). Abundant fossil mammals collected *in situ* and as float from this unit, bones typically black in color; this is the lower fossil level of Loc. 8

4.5 m : Tuffites, color brown

1.0 m : Very fine tuff, color white, soft due to presence of much water; **guide level.** Under microscope it corresponds to a vitroclastic tuff with crystals of plagioclase; high porosity (sample 16)

9.0 m : Mudstones and siltstones, color brown

10.5 m : Fine grained sands, color greenish-brown

1.5 m : Fine grained sands, color green

2.0 m : Tuffites, color greenish-brown. Under microscope it represents a weathered ash; small crystals of plagioclase in vitroclastic matrix (sample 12)

1.5 m : Siltstones, color brown

3.0 m : Fine grained sands, color greenish, unconsolidated

4.5 m : Mudstones below grading upward to siltstones, color greenish

Base : Covered by recent alluvium; level of river

108.0 m : Total thickness of exposed section

Section 9

Top : Top of cliff

6.0 m : Conglomerate-breccia in poorly sorted sandy matrix; clasts, which vary in size from 1-20 cm, are principally volcanic (andesites, rhyolites, granites and diorites); in base of unit matrix yellowish in color, well stratified, weakly cross-bedded in places, clasts generally small and oriented parallel to stratification, many contact each other; toward top of unit matrix grey in color, clasts larger and unstratified

-------	:	Erosional unconformity
4.0 m	:	Conglomerates and poorly sorted sands and siltstones, matrix brown to orange in color; distinct horizontal stratification; clasts larger in base, pebbly and sandy toward top
-------	:	Erosional unconformity
57.5 m	:	Poorly sorted sands and some tuffites, color light brown to orange; numerous pebble lenses, sharp changes in lithology laterally, poorly consolidated; lower *ca.* 25 m principally brown to orange in color, typified by 3-4 resistant levels which vary in thickness from 0.5-1.0 m, discontinuous laterally, much channeling; upper 32.5 m light brown in color, sediments predominately sands, better stratified and consolidated, little or no channeling. Only fossil collected was partial skull of a toxodont 18 m above base
-------	:	Erosional unconformity
4.0 m	:	Tuffites, color white to grey; overlying sediments distinctly channeled into it
Base	:	Level of tributary of Alto Río Cisnes
71.5 m	:	Total thickness of exposed section

Section 12

Top	:	Top of section; an additional *ca.* 50 m to top of cliff covered by soil and vegetation, with abundant volcanic clasts of various sizes within soil level indicating presence of one or more conglomerate units above this point
10.5 m	:	Tuffites, greenish white; gradual transition exits between this unit and underlying conglomerate-breccia
5.0 m	:	Conglomerate-breccia in orange sandy matrix; matrix supported clasts vary in size from a few mm to 20 cm; no evidence of stratification
-------	:	Disconformity
10.0 m	:	Sands, color orange, poorly sorted with some large angular volcanic clasts
18.0 m	:	Sandy tuffites, color brown to orange. Fossil mammals collected *in situ* and as float from this unit
9.0 m	:	Tuffites and clays, color whitish brown; sediments show little compaction, several erosion resistent levels occur toward top.
Base	:	Covered by recent alluvium
52.5 m	:	Total thickness of exposed section

Section 4

Top	:	Top of cliff
14.0 m	:	Tuffites with mudstone and siltstone levels, color brown to green. Fossil mammals collected *in situ* and as float, especially from middle of unit
1.0 m	:	Fine tuff, color white; **guide level**
0.5 m	:	Mudstone, color whitish, mottled green and brown
1.5 m	:	Tuffite, color green
3.0 m	:	Tuffite, color brown to pink
Base	:	Section continues downward
20.0 m	:	Total thickness of measured section

Section 15

Top	:	Top of cliff
20.0 m	:	Tuffites with coarse sands and pebbles, color brown to orange
56.0 m	:	Tuffites, color predominantely whitish with some brown to pink levels; 3 erosion resistant levels. Fossil mammals observed *in situ* throughout unit, but none complete enough to warrant collection.
0.5 m	:	Fine tuff, color white; **guide level**
4.0 m	:	Tuffites, color varies from white-pink to green; sediments compact
2.5 m	:	Tuffites and siltstones, color pink toward top, bright red toward bottom. Fossil mammals observed *in situ*, but none complete enough to warrant collection
0.5 m	:	Tuffite and siltstone, color yellow-orange
17.0 m	:	Tuffite, color whitish in upper part, light brown in lower part; fossil mammals collected *in situ* and as float from upper 12 m.
2.0 m	:	Tuffite, color whitish, mottled green and red; erosion resistant level
Base	:	Level of river
102.5 m	:	Total thickness of exposed section

PLATE 1

Figures

1 Looking east toward Loc. 11. Note erosion resistant level in base of cliff.

2 Looking east toward Loc. 1. Note erosion resistant level in base of cliff.

3 Looking south toward Loc. 5.

4 Looking northeast toward Loc. 10. Note large channel (ch) of conglomerate-sand unit int un-derlying tuffite-sand unit in upper right corner of cliff.

5 Looking east-southeast from Loc. 4 toward Loc. 15 (cliff in upper right corner). Note channeling (ch) of conglomerate-sand unit into lower tuffite-sand unit and position of guide level (g.l.).

6 View of Loc. 9 from tributary of Río Cisnes. Note conglomerate-sand unit (c.s.) at top of cliff.

PLATE 1

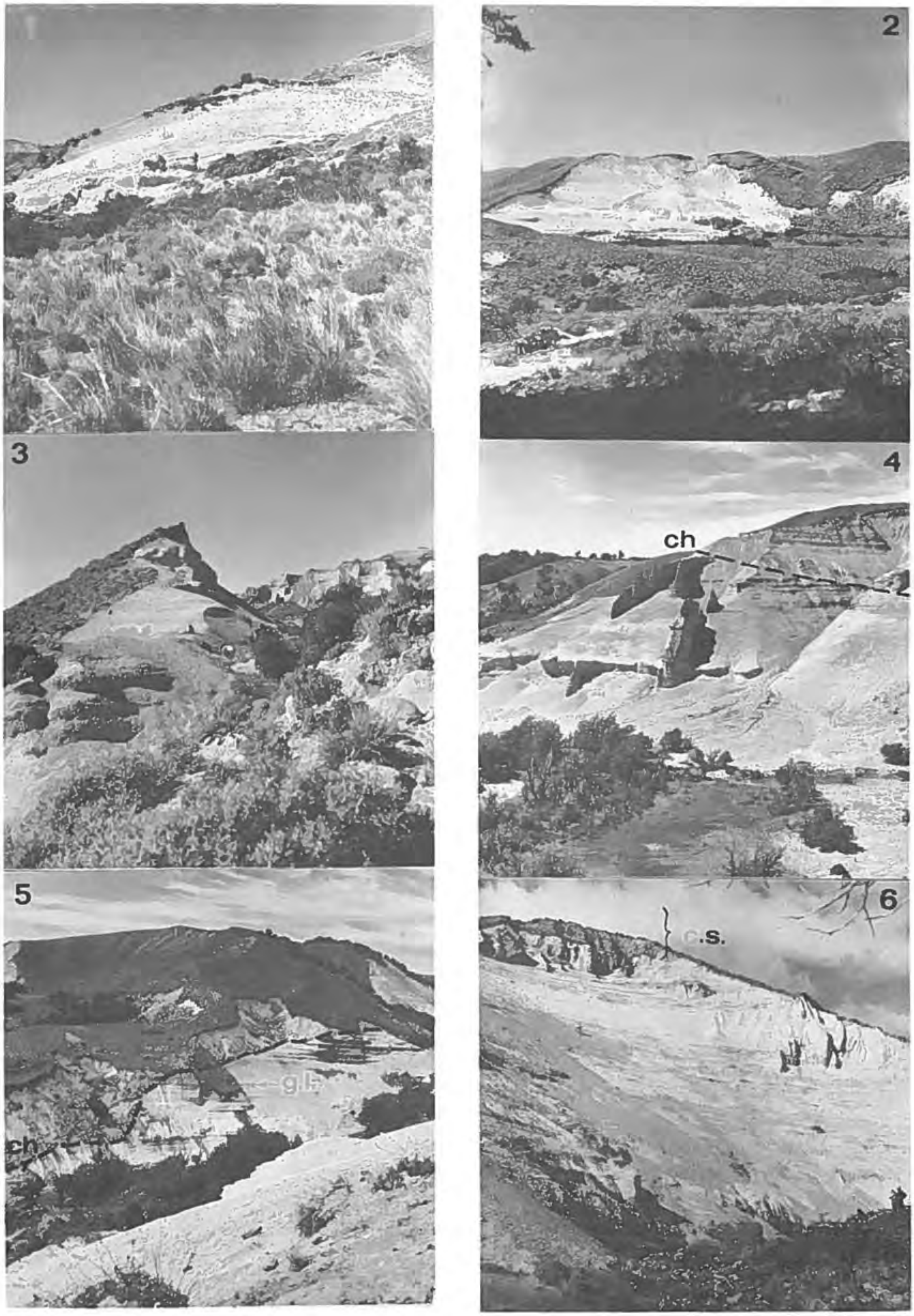

PLATE 2

Figures

1 Looking north toward Site F with Ñirehuao Formation in foreground and Loc. 5 at center top.

2 Photo showing **guide level** (g.l.) *in situ* and in slump block.

3 Looking west toward Site A showing lower erosion resistant unit, **guide level** (g.l.) and white tuff unit. Deformation of sediments are associated with adjacent fault (see Text-Fig. 1).

4 Looking north toward Loc. 3. Note Ñirehuao Formation in base of cliff and erosion resistant unit above with **guide level** (g.l.).

5 Close up view of erosion resistant unit in Fig. 4, showing **guide level** (g.l.).

6 Looking south-southeast toward Loc. 1. Note erosion resistant unit in base of cliff and conglomerate-sand channel (ch) at top.

PLATE 2

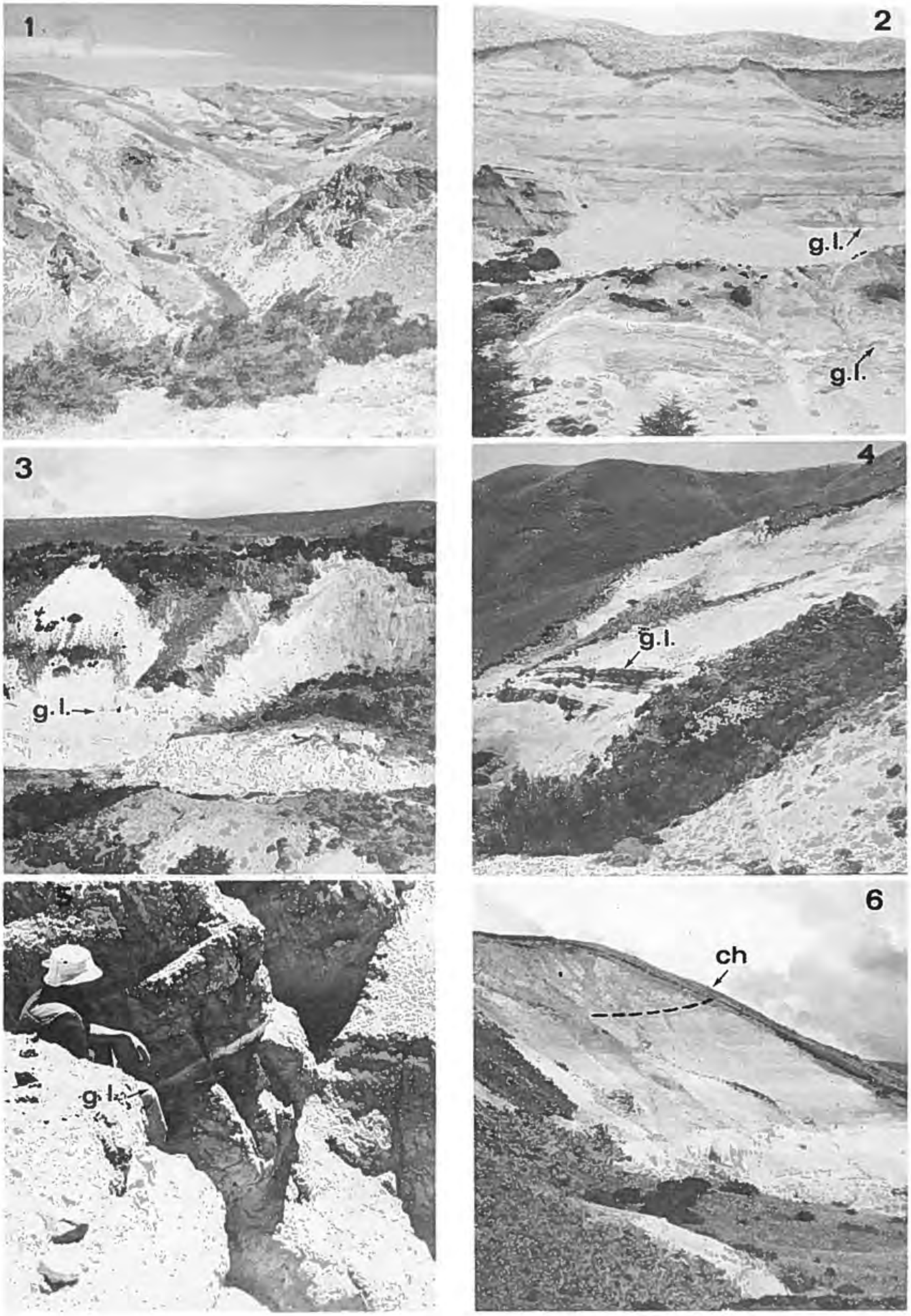

PLATE 3

Figures

1 Close up view of top of Section 5 cliff showing upper conglomerate level and subjacent stratified sand unit.

2 Close up view of stratified sand unit in upper part of Section 5.

3 Looking south toward Loc. 10. Note channeling (ch) of conglomerate-sand unit into underlying tuffite-sand unit.

4 Close up view of base of channeling at south end of Loc. 10.

5 Looking northeast toward Site D cliff. Note position of **guide level** (g.l.) and large conglomerate-sand channel (ch).

6 Looking east toward north end of Loc. 15 cliff. Note position of **guide level** (g.l.) and conglomerate-sand channel (ch).

PLATE 3