CENOZOIC ANDEAN PALEOENVIRONMENTS AND TECTONIC HISTORY: EVIDENCE FROM FOSSIL MAMMALS

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INTRODUCTION

Fossil mammals have long been one of the most useful tools for establishing the age of Cenozoic terrestrial sequences, particularly in those that cannot be dated radioisotopically. Mammals also are key sources of data for understanding evolution, documenting faunal change through time, and assessing environmental transformations. In contrast, tectonic studies typically have relied on geophysical, structural, and geochemical data to constrain deformation and uplift histories. For almost 200 years, knowledge of South American fossil mammals has been derived almost exclusively from the remarkable, but gap-riddled record from Patagonia and other Argentine lowland, high-latitude sites. But broader availability of data from the tropics and tectonically-active regions are required to understand continent-wide or Andean patterns and their possible causal processes. Similarly, a precise and reliable terrestrial geochronology, integrating magnetostratigraphic and radioisotopic calibration with the biochronology of South American Land Mammal "Ages" (SALMAs), had not been available until very recently[1]—this is an essential prerequisite to accurately determining timing and duration of events *throughout* the continent (e.g. refs. 1-4), and employing data from fossil mammals in more extensive tectonic, paleoecologic or evolutionary analyses. As Andean fossil mammal discoveries continue increasing, integrating paleontological data with those typically used in tectonic analyses can yield new or deeper insights into both.

South America has long been considered a model system for studying "evolution in isolation," as the continent was basically an island from its final split from Africa during Gondwana fragmentation by 80 Ma, until its reconnection to North America ~3.5 Ma. By the mid-1900s, G.G. Simpson had developed a "3-stratum" concept of South American Cenozoic mammal evolution and environmental change during isolation, and it remains a reasonable basic summary today. There is growing evidence, however, of much greater complexity in the geological connections and the biotic interchanges than had been believed, and that Cenozoic faunas record and responded in more complicated ways than had been envisioned to both global and regional biogeographic, climatic, tectonic, sea level, ecological, and environmental changes (e.g., refs. 1, 4-6).

CONCLUSIONS

This paper focuses on review of paleoenvironmental and tectonic inferences derived from recent analyses of Andean mammal faunas, emphasizing those from Chile. In broad terms, South American environments were largely forested across the entire continent in the early Cenozoic, with two subsequent phases of widespread habitat change during the middle (Eo-Olig.; earliest global appearance of widespread open, grassland/woodland habitats) and late (Plio-Pleist.; glacial-interglacial oscillations, increased aridity, pulsed shifts of grassland-forest biomes, and major faunal reorganization and extinctions as part of the Great American Biotic Interchange ["GABI"] following the final formation of the Isthmus of Panama connecting North and South America) Cenozoic. These phases appear to have marked relatively rapid transformations, likely in response to more global rather than regional causes, although the key driving-forces, duration, and "tempo" or rate of change are still being clarified. The large-scale faunal provinciality observed today, in which there is marked "endemism" (species restricted to certain regions) and differentiation (tropical biotas share very few species or genera with high-latitude faunas, and montane assemblages differ markedly from lowland faunas) due to climatic and elevational gradients and barriers, existed by the middle to late Miocene[3]. New data from Andean and foreland sequences suggests that regional or continent-wide provinciality may have been present earlier, by the Eocene and perhaps even within the earliest parts of the Cenozoic[2,4-6]. Our current knowledge, greatly enhanced by discovery of the first South American assemblages of transitional Eo-Oligocene age (Andean [1-2,4,7-18]) also suggests that the evolutionary events of "stratum 2" (dispersal of rodents and primates to South America, "modernization" of mammal groups and entire mammalian communities, and appearance of first extensive grassland habitats [in South America only]) occurred rapidly, by the earliest Oligocene. These changes almost certainly were caused by dramatic geological, climatic, and environmental changes that occurred across the Eocene/Oligocene boundary (~34 Ma) interval.

Periodically, smaller-scale changes were superimposed on the large-scale transformations, including several mid-Cenozoic episodes of poleward expansion of forested habitats as late as the middle Miocene (indicated by presence of obligate humid forest-dwelling primates as far south as 50° in southern Patagonia) and expansion and contraction of major epicontinental seaways along the Andean foreland during the Eocene and Miocene. Of particular note is that Andean data are crucial to resolving the age and extent of some of these smaller-scale fluctuations, as well as testing models for the effects of larger-scale changes.

Exceptionally diverse or important Tertiary mammal faunas from the Andean highlands are now known from Chile, Bolivia, Colombia, Ecuador and elsewhere. These range in age across the early Paleocene (Tiupampa, Bolivia[19-21]), Eocene-Oligocene boundary interval (Tinguiririca, Chile; part of a series of sites in the Abanico Formation of central Chile spanning the Eocene-middle Miocene[1-2,4,7-18, 22-25]), early Oligocene (Salla, Bolivia[13,26-29]; with other important Miocene-Pliocene sites elsewhere in the Bolivian Altiplano), early Miocene (Pampa Castillo, Patagonian Chile[30]; Chucal, Altiplano, Chile[31-34]), and middle Miocene (LaVenta, Colombia[3,35-36]). In contrast to most lowland temperate sequences, some of these are precisely dated because of their Andean setting and associated abundance of volcaniclastics. A few others, especially in Bolivia[14,27,37-38] and Colombia[3,35], include paleobotanical, sedimentological and stable isotope evidence complementing mammal-based paleoenvironmental inferences.

Discussion will present exemplar "case-studies" of published and in-progress work on key regions and conclusions. Perhaps the best-sampled temporal interval in the Andes is now the early-middle Miocene (~20-11 Ma), with important Andean assemblages complementing the classical record from foreland and coastal

Argentina now known from southern Chile (47°S) to north-central Colombia (3°N), a range of some 50° of latitude. At the southern extreme, the diverse, late early Miocene (Santacrucian SALMA, ~16-17.5 Ma) Pampa Castillo fauna[30] of Chile is the westernmost high latitude mammal fauna known from South America, and its similarity to coastal Santacrucian faunas suggest similar habitats[39] (increasing aridity, extensive grasslands) across all of Patagonia. The mammal fauna transitionally overlies fossiliferous marine strata, documenting the NW-most extent and last significant incursion of Patagonian early Miocene Atlantic epicontinental seaways, and constrains initiation of uplift in this region by 16 Ma in response to tectonic events associated with the nearby Chile Margin Triple Junction.

At the northernmost extreme, the tropical LaVenta fauna[3,35-36] (13.5-11.8 Ma) documents marked provinciality (similar to modern systems in sharp "icehouse" latitudinal climatic gradients) by the middle Miocene, presence of extensive and varied forest biotopes throughout (rather than the expansive savanna grasslands inferred in previous studies), and environmental regimes of high rainfall (>1,500-2,000 mm/yr) and low seasonal aridity. The fauna and associated geochronologic studies also provide new insights into Andean tectonics, including dramatic basin subsidence shortly before 13.5 Ma, a short and rapid phase of uplift and volcanism in the Central Cordillera at about 12.9 Ma coincident with initiation of uplift in the Eastern Cordillera at 12.9 Ma (completed by 11.9 Ma) and major depositional changes in the intervening Magdalena basin, and some of the fastest sediment accumulation rates observed in any tectonic setting. Significant global and regional plate tectonic and sea level changes may be coincident with, and related to, the major changes in the terrestrial system beginning at 12.9-11.8 Ma.

Intervening Andean Miocene sequences occur throughout southern-central Chile (Abanico Formation of Ríos Maipo, Las Leñas, Teno, and Upeo[22,24]; and equivalents at Lonquimay[40] and Laguna del Laja [newly discovered by the author and colleagues]), the first mammal assemblage from the Chilean Altiplano (Chucal, Santacrucian? SALMA[31-34]), and others from the Bolivian Altiplano[37] and Ecuador[3]. The 4,500 m high Chucal site better constrains the age of the strata, timing of deformation, and initiation of major uplift in the Chilean Altiplano. Preliminary study suggests that this region probably was already an intermontane basin, but not yet extremely high, with a mixed habitat of grasslands and significant riparian regions flanked by forests and woodlands. An unusual hoofed herbivore group (mesotheres) are abundant and diverse here and in the Bolivian Altiplano, but rare elsewhere (Patagonia, LaVenta), while chinchilline rodents (a montane group today) appear to originate within this Andean region, 10-15 million years before they appear elsewhere. Miocene Altiplano faunas (Chile and Bolivia) are similar compositionally, but differ from contemporaneous faunas in both the low-latitude tropics (Colombia) and the high-latitudes (Patagonia)—these patterns may be due to marked regional provinciality in the Miocene, which in turn may be the result of significant global climate changes, Andean tectonics, and associated paleoenvironmental changes[3-4].

Some of the most interesting Andean data are derived from a growing array of sites in unusual (relative to standard mammal-preserving environments) volcaniclastic deposits of central Chile. The first assemblage discovered in this sequence, the Tinguiririca Fauna[1-2,4,7-18, 22-25], documents a new earliest Oligocene biochronologic interval, suggests some faunal provinciality by the Oligocene or earlier, dramatically alters understanding of the age and tectonic history of a large Andean lithosome (Abanico Formation; part of Darwin's "Porfiritica"), includes the oldest South American rodent (indicating origin from African ancestry and Eocene transoceanic dispersal), and yields key insights into environmental change in South America around the E/O boundary. Paleoenvironmental analyses reveal some non-analog aspects of middle Cenozoic South American localities, that a relatively dry habitat was present at Tinguiririca, and that the most dramatic shift in Cenozoic South American paleoecology and paleoenvironment occurred by the earliest Oligocene. The data provide compelling indications that open habitat, grassland/woodland environments flourished 15-20 million years earlier in South America than on other continents, likely related to the E/O boundary and earliest Oligocene climatic "deterioration", and associated paleoenvironmental events. The younger fauna from Salla, Bolivia[14,26-29] complements this record of change, and documents some intracontinental provinciality by the early Oligocene.

The series of other mid-Cenozoic localities in central Chile represent at least 6 temporal intervals, and are just beginning to be studied in similar detail to Tinguiririca. For example, the Las Leñas fauna[22] documents monkeys in the Colhuehuapian (20 Ma) of the Andes, in addition to Colhuehuapian and Santacrucian primates previously reported from higher latitudes, supporting one or more early-middle Miocene climatic ameliorations and poleward spread of major forested habitats (New World monkeys are limited to tropical, forested environments). Further analysis of the Las Leñas/Cachapoal area has yielded a new regional model of early Cenozoic extensional tectonics followed by later compression, inversion and uplift[25]. Radioisotopic and biochronologic data suggest that deposition began by the earliest Oligocene, more likely within the Eocene, and that compression and uplift postdated the middle Miocene[23,25]. Similar thrusting has been documented in the Abanico Formation along the Río Tinguiririca valley well to the south, although it is of uncertain timing relative to that farther northward[2,9,11-12,41-43].

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