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Stratigraphy and Magnetostratigraphic/Faunal Constraints for the Age of Sauropod Embryo-Bearing Rocks in the Neuquén Group (Late Cretaceous, Neuquén Province, Argentina)

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ABSTRACT

The stratigraphy and age of a sauropod nesting ground containing the first definitive embryonic remains of sauropods preserved inside their eggs is analyzed. The fossil locality, called Auca Mahuevo, occurs in the Anacleto Member of the Río Colorado Formation in Neuquén Province, Argentina. The 5 m thick interval of overbank mudstones containing the fossilized eggs and embryos occurs near the middle of a 35 m sequence of thin, fluvial, concretionary sandstones and thicker units of silty sandstone. Flooding of shallow stream channels deposited overbank silt and mud on the eggs, killing the embryos and initiating the process of fossilization. Egg fragments containing patches of fossilized integument were found as float weathering out of the mudstone on local flats. Complete eggs containing embryonic bones and teeth were quarried from a steep ridge where the mudstone was exposed.

Twelve paleomagnetic samples collected throughout the lower 30 m of the section establish the presence of a Reverse geomagnetic polarity interval. This constitutes the first magnetostratigraphic characterization for this part of the Río Colorado Formation and for the late Cretaceous sequence of formations that comprise the Neuquén Group. Biochronologic age estimates for the Río Colorado fauna combined with the Reverse polarity determinations for the fossiliferous sediments in the Anacleto Member argue for an age younger than the long

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Cretaceous C34 Normal, which ends at the upper boundary of the Sartonian and older than the late Campanian. The Reverse interval containing the fossils at Auca Mahuevo is therefore considered to be early or middle Campanian in age, most likely correlative with C33R between 83.5 and 79.5 Ma.

INTRODUCTION

Chiappe et al. (1998) reported the first unequivocal embryonic remains of sauropod dinosaurs from a late Cretaceous nesting ground called Auca Mahuevo in the Neuquén Basin of Patagonia, Argentina (fig. 1). These unique fossils also represent the only known nonavian dinosaur embryos from Gondwana, and some contain large patches of fossilized skin casts—the first definitive integument reported for any embryonic nonavian dinosaurs.

Here, we describe and discuss the stratigraphic context in which these fossils were found, including the regional geology, the local lithostratigraphy, the basic sedimentology, the local magnetostratigraphy, and the magnetostratigraphic implications for the age of the fossils.

REGIONAL GEOLOGY AND PALEONTOLOGY

Auca Mahuevo occurs in the Anacleto Member of the Río Colorado Formation (fig. 2). The Anacleto Member, which is composed predominantly of fluvial sandstones, siltstones, and mudstones, overlies the Bajo de la Carpa Member, which contains coarser-grained sandstones and conglomerates in the area under study.

The formation has produced one of the most important late Cretaceous vertebrate faunas from South America. Abundant remains are known for ornithischian and saurischian dinosaurs, including titanosaurids, carcharadontosaurids, and basal birds, as well as primitive snakes and crocodylomorphs (Bonaparte, 1991).

The Río Colorado Formation has been considered the uppermost of three cycles of continental deposition that took place during the late Cretaceous. These three fining-upward sequences, the Río Limay, Río Neuquén, and Río Colorado formations (listed from oldest to youngest) together compose the Neuquén Group. The Neuquén Group varies in thickness from 500–1300 m (Cazau and Uliana, 1973) across the Neuquén Basin. Its contact with the underlying Rayoso Group is unconformable and a major seismic marker within the basin (Vergani et al., 1995; Macellari, 1988; Ramos, 1981; Cazau and Uliana, 1973). The upper limit of the Río Colorado Formation is poorly defined. It is usually considered to be conformable (e.g., Ramos, 1981, but see Bonaparte, 1991, for a different opinion) with the formations of the overlying Malargüe Group (Loncoche, Allen, and Jagüel formations) where these are represented in different sectors of the basin.

Auca Mahuevo, which today lies about 120 km northwest of the city of Neuquén, was situated in the central-northwest portion of the Neuquén Basin during the deposition of the Río Colorado Formation. The Neuquén Basin developed throughout the Mesozoic-Cenozoic (Uliana and Biddle, 1987, 1988; Vergani et al., 1995). Its early evolution was tectonically controlled by stress regimes related to the breakup of Gondwana and associated rifting in the South Atlantic. Later, regimes related to subduction along the southwestern paleomargin of South America and, finally, the uplift of the southern Andes played the dominant roles in determining the basin's development (Vergani et al., 1995; Uliana et al., 1989).

In the late Jurassic, the basin underwent significant compression, which created a ridge in its southwest sector. This paleo-high apparently influenced the location of the major depocenters during the late Cretaceous. Neuquén Group isopachs trace the outline of this earlier ''Huincul'' ridge as a band where the sequence is only 500 m thick. Auca Mahuevo lies in the basin to the north of this ridge, where the Neuquén Group is almost 1000 m thick (Cazau and Uliana, 1973: fig. 4).

During the late Cretaceous, tectonic control in the Neuquén Basin switched from South Atlantic extension to western subduction. The Neuquén Basin was dominantly a foreland basin developing east of the subduction zone (Pindell and Tabbutt, 1995).

Fig. 1. Index map showing the location of Auca Mahuevo in Neuquén Province, Argentina.

This period constituted the second greatest period of subsidence in the basin's history (Manceda and Figueroa, 1995: fig. 3).

Evidence for repeated marine transgression and regression is recorded throughout the Cretaceous of the Neuquén Basin. Each cycle represents a Pacific incursion, except that which closed the Cretaceous and brought the first Atlantic invertebrates into the basin (Bertels, 1969; Ramos, 1981). Matching the pattern of these events to the Vail curves for eustatic sea level (Reyment and Morner, 1977) has been largely unsuccessful (Malumían and Ramos, 1984; Macellari, 1988). The lack of temporal constraint and the difficulty in distinguishing local tectonic causes from global eustatic cycles has inhibited interpretation of these patterns.

LOCAL LITHOSTRATIGRAPHY

The section within the Anacleto Member of the Río Colorado Formation, which contains the fossilized sauropod eggs and embryos, consists predominantly of 35 m of pale reddish brown silty sandstone punctuated by several thin gray to greenish gray micaceous sandstones (fig. 3). The base of the local section is dominated by fine to medium grained sandstones and silty sandstones. The contact with the underlying Bajo de la Carpa Member is not exposed locally; however, that member is exposed in underlying escarpments about 10 km to the west. The fossil embryos are restricted to a 5-m thick interval of pale reddish brown mudstone situated near the middle of the local section. Near the middle of the mudstone is a light gray micaceous sandstone containing abundant clasts of biotite and muscovite. The mudstone contains numerous, irregular vein-like and nodular zones of greenish mudstone that appear to result from diagenetic alteration. Some of the nodular zones of alteration contain crystalline nuclei, apparently composed of celestine. Root traces are rarely preserved; however, the mudstone contains abundant, small-scale slickensides that often exhibit clear striations due to gouging. These slickensides usually are confined within the mudstone and only rarely offset contacts at the top or bottom of a bed. The uppermost meter or two of this mudstone contains abundant nodules of bluish gray celestine; however, it is difficult to find these nodules in place. The fossiliferous mudstone is easily traceable across several square kilometers of flats and low ridges in the field area.

Above the fossiliferous mudstone the section becomes more sandy, with fewer, thinner beds of dark reddish brown and greenish gray mudstone. The only other vertebrate fossils found so far consist of isolated sauropod vertebrae from a light gray sandstone about 4 m above the mudstone containing the fossilized eggs and embryos. Exposures of the Anacleto Member continue upward for about 50 m above the top of the section shown in figure 3 to the exposed base of the Allen Formation in the main escarpment about 1 km to the east.

SAUROPOD EGGS AND EMBRYOS

Clusters of egg chunks and shell fragments litter the surface of the ground where the mudstone is exposed on the flats (fig. 4). There, at least 195 clusters of eggs are exposed on the surface within an area of ap-

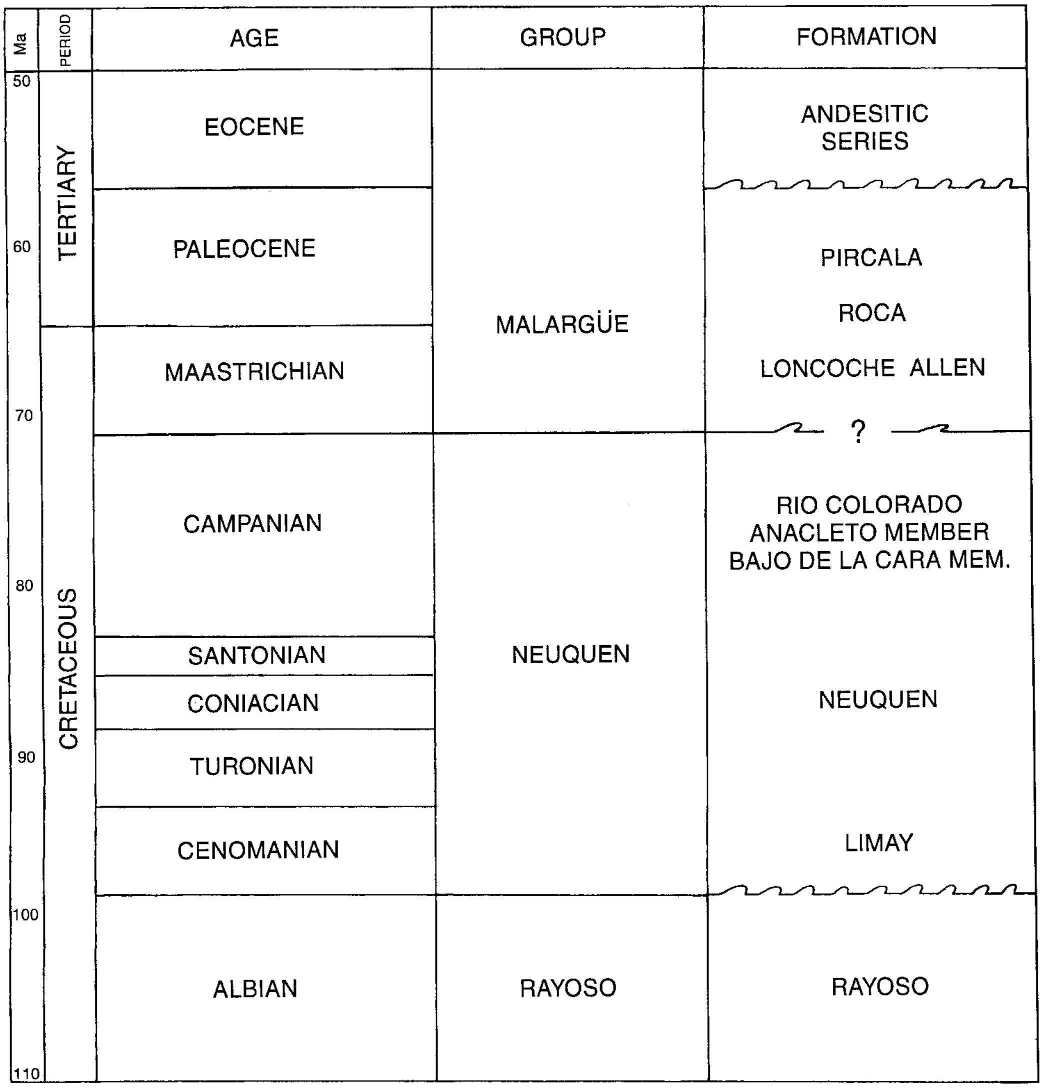

Fig. 2. Correlation chart showing the stratigraphic relationship of the Río Colorado Formation to other Mesozoic formations in the Neuquén Basin, based on Vergani et al., 1995: fig. 2.

proximately 20,000 m^2. It is primarily in these clusters on the flats that fossilized egg fragments were collected that contained the patches of fossilized skin. The skin casts are composed of carbonate containing clay and quartz (Chiappe et al., 1998). Fossilized bones are not common in these egg fragments.

The mudstone can be traced along low east-west trending ridges for about 1 km to the west of these flats where one quarry along the northernmost ridge produced numerous more or less complete eggs—12 to 15 cm in diameter—containing embryonic bones and teeth (fig. 5). These remains probably belong to titanosaur sauropods based on the shape of the 2-mm-long, peglike teeth and the inclination of wear facets on some teeth (Chiappe et al., 1998). Embryos are very abundant in the eggs from the quarry. Nearly every egg exposed contained embryonic remains. Fossilized embryonic remains are far more abundant than the number that would be expected to have died from the nat-

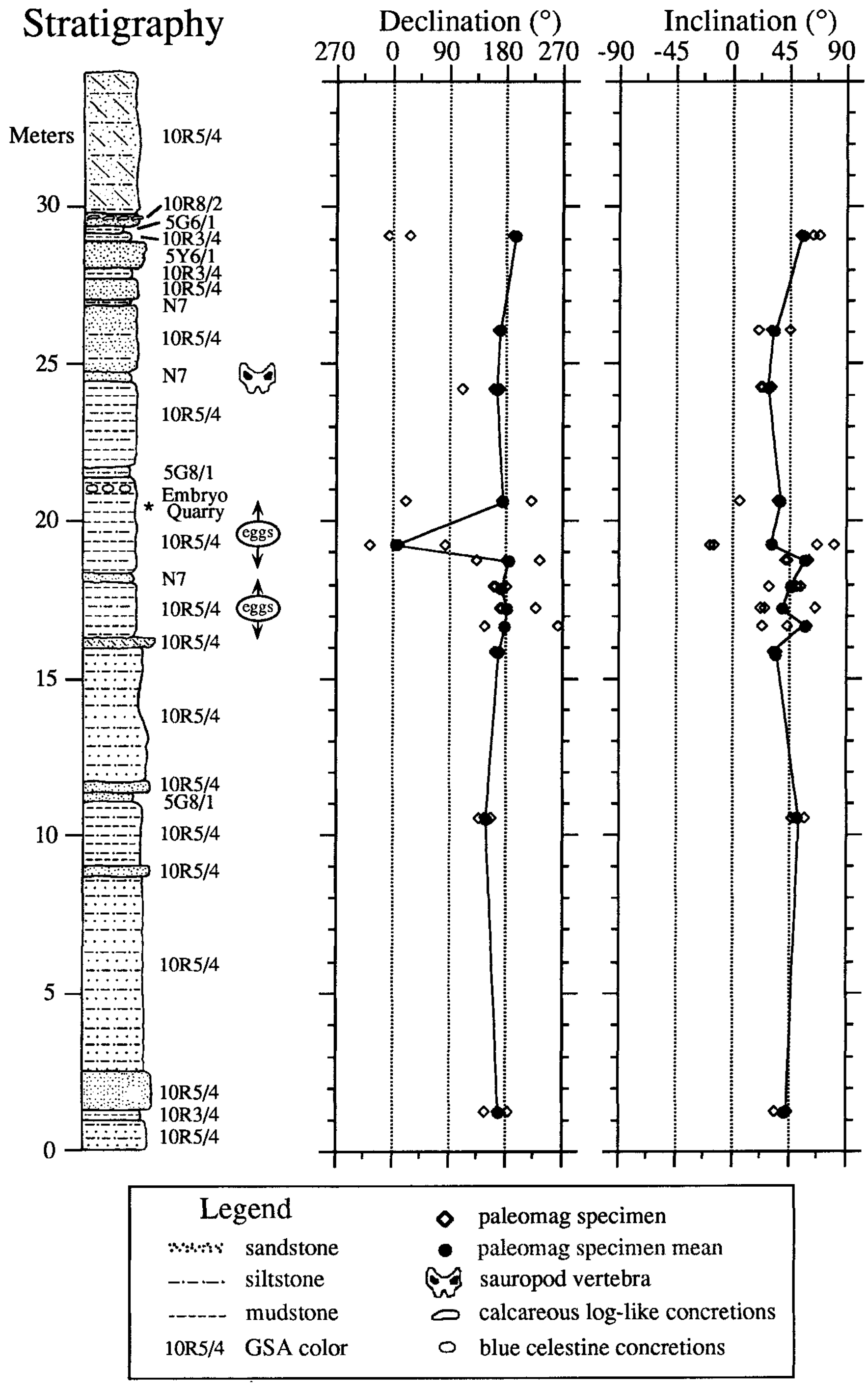

Fig. 3. Stratigraphic section of a part of the Anacleto Member in the Río Colorado Formation exposed at Auca Mahuevo, showing position of egg-bearing mudstone and magnetostratigraphic samples with geomagnetic polarity determinations.

Fig. 4. Fragments of eggs and egg shell weathering out on the flats where the fossiliferous mudstone is exposed. Pencil is about 14 cm long.

ural rate of embryonic mortality. Interestingly, the eggs from this hillside quarry have not yet preserved definitive patches of fossilized skin casts, and the bed containing the eggs is relatively thin, less than 2 m thick.

The thin sandstone units preserved in the section are occasionally cross-bedded or flatbedded and are interpreted to represent the infilling of shallow stream channels no more than a meter or two deep. The siltstones and mudstones, including the unit that contains the eggs and embryos, are interpreted to represent adjacent overbank deposits. The high concentration of fossilized embryonic remains in the eggs from the quarry suggests that entire clutches may have been buried by a natural disaster, such as a flood. One such event presumably killed the embryos located at the quarry site and initiated the process of fossilization. The eggs and embryos are exclusively preserved in the thickest and finest-grained overbank sediments in the section. It could be that the dinosaurs preferentially chose this area away from active channels to lay their eggs, or it could be that eggs laid near active channels were simply not preserved. Although eggs do weather out in clusters on the flats, it has not yet been rigorously established whether these represent true nests or random accumulations.

The section at Auca Mahuevo is distinctly finer grained than that of the underlying sandstones and conglomerates of the Bajo de la Carpa. Clearly, the local section of the Anacleto at Auca Mahuevo represents a more distal and lower-gradient portion of a floodplain than that existing in the area during Bajo de la Carpa deposition.

PREVIOUS AGE ESTIMATES FOR THE RIO COLORADO FORMATION

Age estimates for the Río Colorado Formation have varied from Coniacian to Cam-

Fig. 5. Collectors excavating cluster of more or less complete sauropod eggs from quarry. Eggs are about 12–15 cm in diameter.

panian. No radioisotopic or paleomagnetic data have previously existed for the Neuquén Group. Age estimates for formations within the Neuquén Group have been based on constraining the age of the group as a whole, using the ages of over- and underlying strata. The Río Colorado Formation has been assigned the youngest age within this range because it is the stratigraphically highest formation in the group.

Traditionally, the Neuquén Group has been given a Cenomanian-Campanian age, with the Río Colorado assigned to the Campanian (Digregorio and Uliana, 1979; Macellari, 1988; Vergani et al., 1995). The basal age resulted from the unconformity at the lower contact of the Neuquén Group being correlated with an Albian-earliest Cenomanian pulse of tectonic activity (Cazau and Uliana, 1973; Vergani et al., 1995). At the top, the Cretaceous/Tertiary boundary was placed in the Roca Formation (which lies above the Allen + Jagüel formations or the Loncoche Formation) based primarily on micropaleotological evidence.

Biostratigraphic analyses of the ostracod fauna from the Allen Formation have suggested a late Maastrichtian age for its ''upper member'' (Ballent, 1980). The decapod fauna primarily from the Jagüel and Roca formations indicate a Maastrichtian-Danian age for these formations, with the K-T boundary falling within or at the base of the Roca Formation depending on the location of a section within the basin (Feldmann et al., 1995). These results agree with a study of ostracods and planktonic foraminifera from the Jagüel and Roca formations at the type locality of the Roca, which indicate an early Danian age (Bertels, 1969). Further, a middle Maastrichtian age was assigned to the upper Jagüel Formation by Bertels (1978), who also suggested a possible equivalence between the Allen Formation and the lower Jagüel. She considered the lower Jagüel (and thus possibly the Allen) Formation to be early Maastrichtian. However, a new palynologic study cited as personal communication in Heredia and Salgado (1999) has concluded that an earlier, middle Campanian age is more appropriate for strata from near the middle of the Allen Formation. This would restrict the upper boundary of the Río Colorado Formation to middle or early Campanian. Following these arguments, as well as others indicating that the entire Malargüe Group ranges from early Maastrichtian to Danian, the immediately underlying Río Colorado Formation could be no younger than middle Campanian.

Bonaparte (1991) made a biostratigraphic argument for an earlier, Coniacian, age for the Río Colorado based on comparisons of its fauna with that of the Los Alamitos Formation. The Los Alamitos Fauna has almost no taxa in common with the Río Colorado. It has been assigned a Campanian-earliest Maastrichtian age (Andreis, 1987; Bonaparte, 1991). Bonaparte (1991) concluded that the Los Alamitos Fauna, with its abundant fossil mammals, is younger than that of the Río Colorado, from which no mammals are known. However, the age of the Los Alamitos, as well as the stratigraphic relationships between the Los Alamitos and the Río Colorado formations, are uncertain.

Ramos (1981) also assigned a Coniacian age to the Río Colorado based on an argument pertaining to the lower limit of the Neuquén Group. He suggested that the original Cenomanian age given to the ''intercretaceous'' movements was incorrect. Ramos (1981) surmised that, based on more recent studies of Andean orogenesis, a pre-Cenomanian date for this tectonism could be more appropriate. Under this scenario, the Neuquén Group would have been deposited during the Albian-Coniacian. Nonetheless, Ramos (1981) presented the traditional dates on his map of the region. Bonaparte (1991), as well as others including Chiappe and Calvo (1994), followed Ramos' (1981) suggestion, presenting a Coniacian or Coniacian-Santonian age for the Río Colorado.

Further, there is no consensus on how much time is missing at the unconformity underlying the Neuquén Group, regardless of whether it is considered Cenomanian (the traditional date) or earlier (Ramos, 1981). For Riccardi (1987) the hiatus extended from early Cenomanian and lasted until the Coniacian, thus the Neuquén Group was deposited more quickly. Other authors have treated the sedimentation to be almost continuous (Guilsano and Legaretta in Macellari, 1988). However, with the exception of Ramos (1981) all authors have considered the Neuquén Group to be constrained within a post-Albian to pre-Maastrichtian interval (Digregorio and Uliana, 1979; Vergani et al., 1995).

MAGNETOSTRATIGRAPHY AND ITS IMPLICATIONS FOR AGE

In an attempt to constrain the age of the fossil-bearing horizons, 12 oriented paleomagnetic block samples were collected from intervals of fine-grained sediment in the Auca Mahuevo section. Three came from the lower portion of the section underlying the fossiliferous mudstone, six from different levels within the fossiliferous mudstone, and three from above this mudstone (fig. 6). The samples consisted of grayish-red to reddish-brown mudstones, siltstones, and fine-grained sandstones. Sampling intervals were determined by the stratigraphic distribution of finegrained units and varied from approximately 10 m in the lower part of the section to less than a meter within the middle fossil-bearing unit (fig. 3).

In the laboratory at the Berkeley Geochronology Center, each block sample was cut into three or more specimens, each about 6 cm^3 in size, using a fluted carbide-edged band saw blade. The specimens were then housed in a magnetically shielded room prior to and during all phases of analysis. Results are summarized in figs. 3 and 6. Following NRM measurements, the specimens were thermally demagnetized in a modified ASC TD-48 thermal specimen demagnetizer in 15

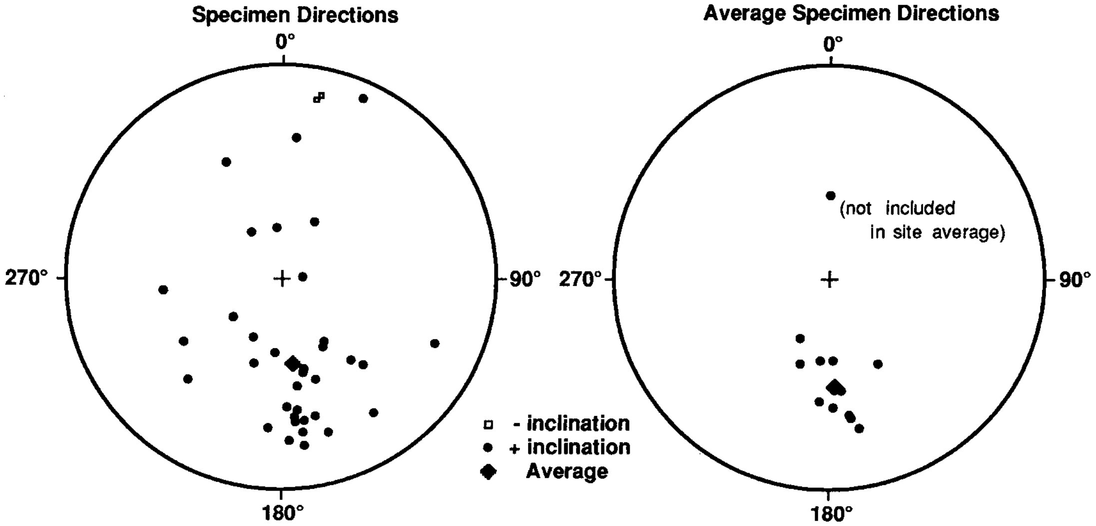

Fig. 6. Diagram showing stereoplots of specimen directions and average specimen direction for paleomagnetic samples from Anacleto Member at Auca Mahuevo section illustrated in figure 3.

to 20 temperature increments from 130 to 620°C. At each temperature increment, magnetic directions of the specimens were determined using a 2G Enterprise Cryogenic Magnetometer, with the data collected by a Macintosh Computer using software developed in house.

All samples indicated various amounts of present-field Normal polarity overprint that is attributed here to goethite (an iron oxyhydroxide that has a Curie Point of 120°) formed during near-surface weathering. Thermal demagnetization at 130°C removed 18% (specimen APM-8 at the 29 m level of the section) to 68% (specimen APM-B at the 1 m level) of the NRM intensity, suggesting a wide range in the amount of goethite present in the samples. Samples that showed little indication of present-field Normal overprint, such as APM-7 at the 26 m level and APM-4 at the 16 m level, gave well-clustered mean Reverse specimen directions. These directions were easily characterized by least square line fits of the vector endpoints and/or averaging clusters of measured directions obtained from a sequential series of thermal demagnetization steps. In contrast, samples such as APM 1 at the 17 m level or 8 show strong persistent Normal overprints that were not effectively (and in some cases incompletely) removed until temperatures above 400°C. Characterization of primary magnetic directions in those samples with persistent Normal overprints proved difficult, due to incomplete thermal cleaning. Directions of these samples were based on the furthest measured sequential point away from the NRM direction that was acquired during sequential demagnetization prior to the specimen becoming magnetically unstable. Mean directions from specimens of these samples show greater scatter owing to different ratios of mixing between the two magnetic components. The difference in the two demagnetization behaviors can be attributed to slight differences in initial mineralogy (and grain size), as well as variable near-surface alteration in the Recent Normal polarity environment. None of the specimens, however, gave stable Normal directions at high temperature.

Characteristics of the thermal demagnetization histories, including stable paleomagnetic directions measured above 580°C and IRM experiments on specimens with various demagnetization behaviors, indicate all measured samples exhibit Reverse polarity, apparently residing in hematite. Although the formation of hematite in red beds is commonly considered to have occurred soon after burial, no independent reversal or fold tests were possible in the short, flat-lying

Auca Mahuevo section that might have helped constrain the timing of its formation and magnetization.

Our preliminary results document the presence of an interval of Reverse polarity in the Auca Mahuevo section. This has important implications for restricting the age of the fossils. Given the previous assessment that the Río Colorado is post-Albian, the Reverse character of these sediments indicates that the fossils must be younger than Santonian. This is because the long chron of Normal polarity C34N extends to the upper boundary of the Santonian at about 83.5 Ma (Gradstein et al., 1995). Consequently, if the Río Colorado is accepted as middle Campanian or older, based on biochronologic comparisons (especially Heredia and Salgado, 1999) then the interval of Reverse polarity must represent C33R of the early or early-middle Campanian, between 79.5 and 83.5 Ma (Gradstein et al., 1995). Extension of the magnetostratigraphy at Auca Mahuevo will be required to define the upper and lower limits of the Reverse interval.

CONCLUSIONS

The sauropod embryos from Auca Mahuevo were probably laid by titanosaurs on a low-gradient floodplain that occupied the central-northwest Neuquén Basin sometime during the Campanian between 79.5 and 83.5 Ma. Their demise resulted from the flooding of shallow stream channels that buried the eggs in overbank silt and mud, which initiated the process of fossilization. The Reverse geomagnetic polarity of the sediments helps constrain the age and has important implications for the study of late Cretaceous, South American, vertebrate faunas and floras because the Río Colorado Formation and the Neuquén Group as a whole contain the richest assemblage of South American dinosaurs and other terrestrial vertebrates yet discovered.

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