Palaeogeography, Palaeoclimatology, Palaeoecology 482 (2017) 83–102

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Preservation of titanosaur egg clutches in Upper Cretaceous cumulative palaeosols (Los Llanos Formation, La Rioja, Argentina)

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ARTICLE INFO

Article history:
Received 12 February 2017
Received in revised form 20 May 2017
Accepted 30 May 2017
Available online 1 June 2017

Keywords:
Titanosaur egg clutches
Cumulative palaeosols
Semiarid palaeoenvironment
Late Cretaceous
Los Llanos Formation
La Rioja - Argentina

ABSTRACT

Studies of the palaeobiology of titanosaur eggs are significantly more common than studies of titanosaur-egg-bearing strata. Nevertheless, the latter provide significant insight into palaeoenvironmental conditions associated with the egg-laying behaviour. This study examines titanosaur-egg-bearing strata of the Upper Cretaceous Los Llanos Formation (La Rioja, Argentina) and relates them to the laying and preservation of titanosaur egg clutches. Los Llanos Formation is a predominantly sandstone succession throughout represented by palaeosol profiles. Five titanosaur egg clutches were recovered from the Bw horizon of an Inceptisol profile. This palaeosol type, named Tama pedotype, constitutes 69% of the entire succession, by thickness. Rare planar, and undulating lamination and cross stratification, quartz-grain surface microtextures and ventifacts are indicative of the interaction of fluvial-aeolian processes of sedimentation during accumulation of the parent material on the distal part of a coalescent alluvial fan system (*bajada*). Highly abundant root traces, reddish colour, clay coatings and calcium carbonate nodules testify that the Tama pedotype had abundant vegetation cover, and was developed in well-drained conditions under the influence of a semiarid climate regime. Palaeosol horizons with exaggerated thickness and diffuse boundaries indicate a cumulative pedotype, whereby the soil developed in response to continuous accretion via on-going sedimentary processes.

Morphological features of eggshells suggest that titanosaurs dug holes in the topographic surface to lay eggs. Thus, palaeosols seem to have been putative areas for the laying of titanosaur eggs. Actually, it is uncommon for palaeosols to constitute sites for the preservation of eggs, since soils typically develop in response to long episodes of weathering. However, cumulative palaeosols can provide ideal conditions for egg burial and preservation. In cumulative soils, the residence time of an object within the weatherable thickness of a soil is reduced to $<10^3$ years, thereby significantly increasing the long-term preservation potential of eggs.

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1. Introduction

Studies providing details of the taxonomy, palaeobiology and palaeoecology of titanosaur eggs and nesting sites are numerous (e.g., Carpenter et al., 1994; Hirsch, 2001; Chiappe et al., 2004, 2005; Grellet-Tinner et al., 2006; Salgado et al., 2009; Grigorescu et al., 2010; Vila et al., 2010; Fiorelli et al., 2012; García et al., 2015; Hechenleitner et al., 2015, 2016). By contrast, studies focused on palaeoenvironmental aspects of titanosaur egg-bearing strata are not common (for a synthesis see Paik et al., 2012). These studies indicate that egg-bearing strata are dominantly represented by fluvial floodplain, distal alluvial-fan, coastal and inland interdune palaeoenvironments (Tandon et al., 1995; López-Martinez et al., 2000; Chiappe et al., 2004; Díaz-Molina et al., 2007; Saneyoshi et al., 2008; Kim et al., 2009; Liang et al., 2009; Paik et al., 2012; García et al., 2015; Hechenleitner et al., 2016). In some sedimentary successions where in situ eggs have been found, some described aspects of the egg-bearing strata are indicative of palaeosols: the concentration of calcareous nodules, the presence of mottles, rhizoliths, bioturbation, a red-brown colour, and the general absence of primary sedimentary structures (Tandon et al., 1995; López-Martinez et al., 2000; Kim et al., 2009; Hechenleitner et al., 2016). Actually, some articles describe titanosaur eggs preserved in

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http://dx.doi.org/10.1016/j.palaeo.2017.05.034
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palaeosols (Sander et al., 1998; Van Itterbeeck et al., 2004, 2005; Paik et al., 2004; Bojar et al., 2005), though very few articles consider the aspects of such palaeosols in detail (Cojan et al., 2003). In other cases, where palaeosol profiles contain titanosaur eggs, authors have asserted that the eggs were buried by sedimentary processes and that the pedogenesis occurred later (Liang et al., 2009; Grigorescu et al., 2010).

This article seeks to resolve four general research questions: (i) Are titanosaur-egg-bearing strata commonly associated with palaeosols? (ii) Was the pedogenesis later than or contemporaneous to the egg laying? (iii) What conditions allowed the laying and the preservation of eggs of titanosaurs in palaeosols? (iv) What palaeosol types are most likely associated to the preservation of eggs of titanosaurs?

Los Llanos Formation, which is exposed near the locality of Tama (La Rioja, Argentina) (Fig. 1), is an Upper Cretaceous sandstone unit where palaeosol profiles occur throughout the succession. In situ egg clutches of titanosaurs were found in this formation (Fig. 2) for which it is possible study and reconstruct the paleoenvironmental conditions that allowed the laying of the eggs and their preservation into the sedimentary record.

With the goal of contributing to the understanding of titanosaur nesting palaeontological sites, this study (i) interprets the palaeoenvironmental conditions that enable the generation of the palaeosols that contain the titanosaur eggs, and (ii) examines the circumstances that permitted the preservation of egg clutches within the palaeosols. Results help to clarify the preferred palaeoenvironmental conditions that titanosaurs selected to lay eggs, and which influenced their preservation into the geological record.

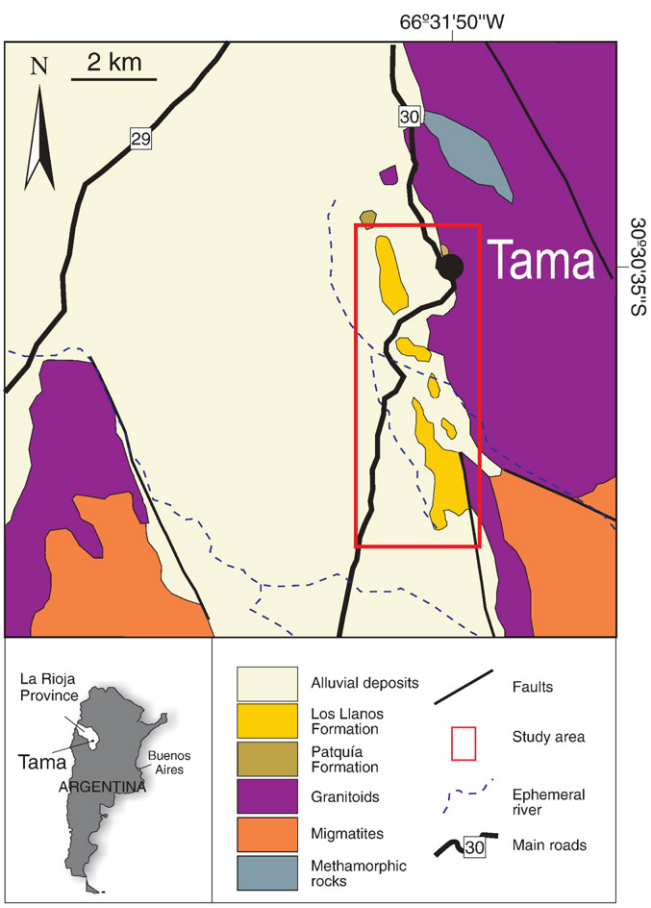

Fig. 1. Location of the study area and distribution of the main geological units. Granitoid complexes cropping out to the east of exposures of Los Llanos Formation are the possible source of the sandstone of this unit. Data simplified from geological map of Limarino and Poma (2008).

2. Geological and stratigraphic setting

Los Llanos Formation is exposed in small outcrops (2–20 km^2) in the central-east region of La Rioja province, Western Argentina (Fig. 1). However, seismic and drilling data indicate a larger spatial extent beneath Quaternary deposits and a thickness up to 290 m (Fisher et al., 2002; Vujovich et al., 2007). The study area is located southwest of the small town of Tama (Fig. 1). Here, Los Llanos Formation crops out as a *c.* 70 m-thick succession (Fig. 2). The base of this unit is characterised by a near-flat but erosional surface. Along a 3 km-long, north-south oriented transect this basal surface caps two stratigraphic units: (i) a cross-stratified and planar-laminated sandstone (the Carboniferous-to-Permian Patquía Formation); (ii) an Ordovician leucogranite. In this area Los Llanos Formation dips 3° towards the WNW and is unconformably overlain by a horizontally bedded, Neogene or Quaternary coarse-grained sandstone and conglomerate (Fig. 2). Los Llanos Formation contains freshwater ostracods and charophytes (Carignano et al., 2013), articulated remains of the three dinosaur clades (ornithischians, sauropods and theropods) (Hechenleitner et al., 2014), turtles, notosuchian crocodyliforms (Fiorelli et al., 2016) and titanosaur eggs preserved in situ (Hechenleitner et al., 2016). Collectively, the palaeontological record indicates an Upper Cretaceous age for this unit.

At the studied locality, deposits of Los Llanos Formation are characterised dominantly (79% of succession) by pale reddish orange, moderately sorted, medium- and fine-grained sandstone with <2% granule and small pebble clasts (Fig. 2). Additionally, pebbly sandstone and muddy sandstone also occur (14 and 7% of succession, respectively). Beds with high calcium carbonate content are particularly common in the lower part of the succession. Primary sedimentary structures are near absent: only in few places are sets of faint traces of medium-scale cross-stratification and planar lamination observed. Within the structureless sandstone deposits, rhizoliths, carbonate nodules and mottles are all abundant (Fig. 2); these features indicate the presence of numerous vertically stacked palaeosol profiles. Previous detailed sedimentological and stratigraphic studies of Los Llanos Formation interpreted this sedimentary succession to be of braided alluvial origin, characterised by intense pedogenesis (Ezpeleta et al., 2006).

3. Methods

We measured a stratigraphic log of all the exposed section of Los Llanos Formation in an area of 12 km^2 to the southwest of the town of Tama (Figs. 1 and 2). Palaeosol profiles dominate throughout the entire sedimentary succession; few primary sedimentary structures are preserved. Exposure conditions permitted detail examination of *c.* 65% of the succession. In the field, palaeosols were distinguished according to the following characteristics: presence and distribution of root traces, colour, abundance and size of calcareous nodules, style of mottle development and type of horizon development. Field estimations of abundance of calcium carbonate and boundary distinctness, and topography of the palaeosol horizons were made using the recommendations of Retallack (2001) and Schoeneberger et al. (2012). The deposits were differentiated based on the presence of sedimentary structures. Twenty-seven palaeosol profiles were examined and recorded in the detailed logs. These were divided into two pedotypes (Retallack, 1994): Tama and Colozacán pedotypes. The Tama pedotype is the one that contains the egg clutches and is therefore described in more detail herein than the Colozacán pedotype. Compositional features of clasts >20 mm across were determined in the field on 1 m^2 exposed surfaces of three pebbly sandstone beds. Thirty-two fresh sandstone samples of palaeosol profiles were collected from different portions of the succession (see Fig. 2) for laboratory geochemical and micromorphological analyses. Major oxides and trace elements of

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