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Triassic vertebrate footprints in the southern Paraná Basin

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ABSTRACT - The central region of the Rio Grande do Sul state has become increasingly important due to the discoveries of fossils from the Triassic, which along with the establishment of the proposed Quarta Colônia Geopark can transform the region into one of the most important for paleontological research, education and tourism in Brazil. Fossilized footprints and tracks of vertebrates were found in this region only recently, particularly in the locality known as Predebon Site (Alemoa Member, Santa Maria Formation), Municipality of São João do Polêsine. The fine texture of the rock allowed the preservation of trace fossils in detail, making them valuable to the knowledge of the producing organisms and the genesis of the deposits. The outcrop displays facies related to temporary lacustrine bodies and ephemeral river channels. Among the sites with fossil footprints in the Paraná Basin, the Predebon Site presents the best quality of preservation and the greatest diversity, with nine morphotypes. The ichnospecies *Rhynchosauroides retroversipes* and *Dicynodontipus protherioides*, described from specimens of this outcrop, are unprecedented for science and are unknown in any other location. The site is classified as a geosite with national relevance to scientific and educational purposes. Furthermore, it was considered of high fragility and high risk of degradation due to agricultural activities. However, the prospects for conservation of geosites in this region are encouraging. The CONDESUS Quarta Colônia, a non-profit legal entity under private law, has as priorities the implementation of the paleontological park and the creation of mechanisms for conservation of sites under threat.

Key words: Geopark proposal; Quarta Colônia; Triassic; ichnofossils; vertebrates; Paraná Basin.

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INTRODUCTION

The Quarta Colônia, located in the central region of Rio Grande do Sul State, includes the municipalities of Agudo, Dona Francisca, Faxinal do Soturno, Ivorá, Nova Palma, Pinhal Grande, Restinga Seca, São João do Polêsine and Silveira Martins. This region has become increasingly important to science in recent years due to the frequent discoveries made in rocks of the Triassic period. Adding to this, the establishment of the Quarta Colônia Geopark as proposed by the Geological Survey of Brazil (CPRM) with the support of the Consortium for Sustainable Development of the Quarta Colônia (Consórcio de Desenvolvimento Sustentável da Quarta Colônia) (CONDESUS - Quarta Colônia) could transform the region into one of the most important for research and paleontological tourism in Brazil.

The fossils from the region of Quarta Colônia are very diverse, and among them are some of the oldest dinosaurs and advanced cynodonts related to the origin of mammals. Although osteological records are being studied in Rio Grande do Sul for over a century (*e.g.* Holz & De Ros, 2000), only recently were found fossilized footprints and tracks of vertebrates, especially in the area known as Predebon Site (Azevedo *et al.*, 1999; Silva *et al.*, 2007; 2008a; 2008b; 2008c), beyond invertebrate traces (Netto, 2007). The fine texture of the rock allowed the preservation of morphological details of trace fossils (Fig. 1), which makes them valuable for identifying the trackmakers and to a better understanding about the genesis of the

layers. Moreover, most of tetrapods recorded in this lithostratigraphic unit consists in medium to large animals (*e.g.* Holz & De Ros, 2000), but most of the footprints from the Predebon Site were produced by small animals. Thus, their study is important for the knowledge of these animals, providing information on functional morphology and life habits of the trackmakers.

Figure 1 – Sample with fossil footprints from Predebon Site, Quarta Colônia, RS. Photo: Rafael Costa da Silva.

The Vertebrate Paleoichnology is an area that has greatly progressed in recent decades, and the discovery of trace fossils increasingly provide more information about the behavior, biomechanics and life habits of animals that produced them. Through the trace fossils is possible to obtain the record of animals that didn't had their skeletons preserved in the fossil record and a better understanding of their geographical and stratigraphic distribution, beyond information about the physical properties of sedimentary deposits, such as plasticity and water content.

LOCATION

The Predebon Site (Figs. 2 and 3), geographic coordinates 29º38'29"S - 53º26'52" W, is placed in the municipality of São João do Polêsine, Rio Grande do Sul State, region of Quarta Colônia. It is located on private land easily accessed from the paved road RS-149 and visiting point is near the road. Arriving from Porto Alegre or Santa Maria the site can be accessed along highway BR-287. The outcrop is located approximately 2.6 km south of the city of São João do Polêsine.

Figure 2 – General view of Predebon Site, Quarta Colônia, RS. Photo: Rafael Costa da Silva.

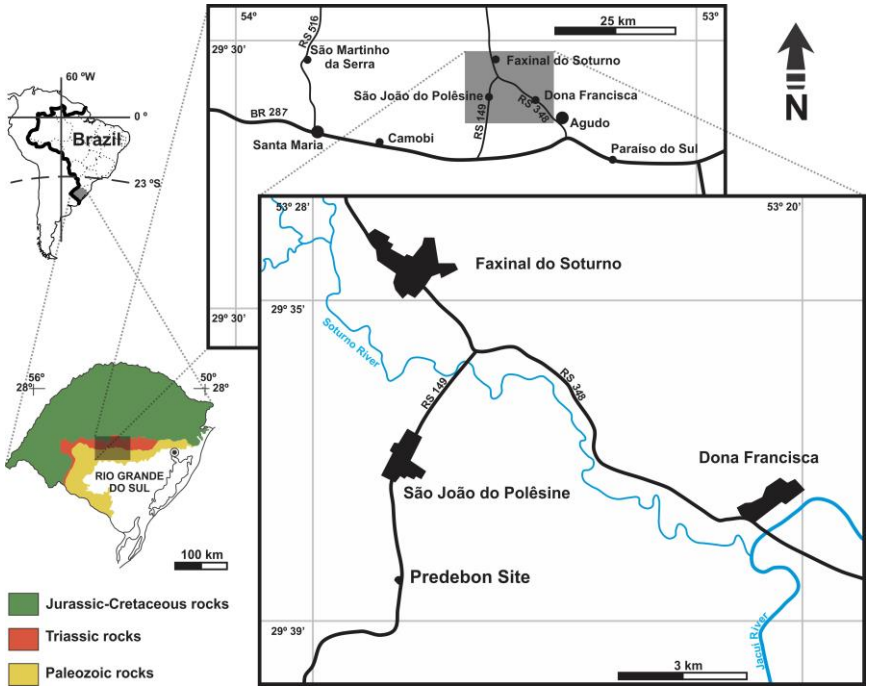

Figure 3 – Location of the Fossiliferous Predebon Site, RS.

SITE DESCRIPTION

Geological Context

The Paraná Basin shows a large horizontal extension (over 1.400.000 km²), occurring in the Southern, Midwest and Southeastern Brazil as well as in Argentina, Uruguay and Paraguay. The basin was filled with an over 7 km thick sedimentary and igneous succession of rocks, formed from the Upper Ordovician to Lower Cretaceous (Schneider *et al.*, 1974; Milani *et al.*, 1994). The Triassic section in the Paraná Basin was stratigraphically positioned by Milani (2002) in the Gondwana I and II supersequences. The Triassic deposits comprised in these two supersequences are represented by the Sanga do Cabral, Santa Maria and Caturrita formations of the Rosario do Sul Group and were deposited in fluvial, lacustrine and eolian environments.

The ages assigned to the Santa Maria and Caturrita formations are generally based on vertebrate biostratigraphy and are controversial. The outcrops are discontinuous due to the pronounced cover in the region, where few exposures show more than several meters, which reduces the amount of available data and complicating stratigraphic correlations. According to Scherer *et al.* (2000) and Rubert & Schultz (2004), the Santa Maria and Caturrita formations correspond to the Ladinian-Eonorian sequence. According to

Milani (2000), these deposits are included in the Gondwana II supersequence, which is spread in time between the Middle and Late Triassic. However, Lucas (1998, 2001) and Lucas and Heckert (2002) have dated the upper portion of the Alemoa Member and Caturrita Formation as Carnian. According to Langer (2005), the upper portion of the Alemoa Member and the base of the Caturrita Formation can be tentatively correlated to the Ischigualasto Formation (Carnian) of ~~in~~ Argentina, but some faunal associations of the Caturrita Formation seem to correspond to the post-Ischigualastian (Norian age?). Anyway, the Carnian age (between 215 and ~ 229 Ma) is admitted to the upper portion of the member Alemoa, where the Predebon Site is placed.

The Triassic rocks of Rio Grande do Sul were also studied by Zerfass *et al.* (2003) in the context of the Sequence Stratigraphy and divided into two second order depositional sequences: Sanga do Cabral Supersequence (equivalent to the Sanga do Cabral Formation) and Santa Maria Supersequence (equivalent to the Santa Maria and Caturrita formations and the Mata Sandstone by Faccini, 1989). The first would have been deposited by ephemeral river systems of low sinuosity, possibly during the late Induan. The Santa Maria supersequence include low sinuosity rivers, lakes and deltas and can be divided into three sequences of third order: Santa Maria 1 (Ladinian), Santa Maria 2 (Eonorian to Carnian) and Santa Maria 3 (possibly Retic to Lower Jurassic) (Zerfass *et al.*, 2003).

Description of the Predebon Site

The Predebon Site has about 100 m of extension and six meters high and relates to a cutoff carried out for the construction of a reservoir. The studied section corresponds to the upper portion of the Alemoa Member of Santa Maria Formation, near the contact with Caturrita Formation (see Figs. 4 and 5). Overall, the outcrop shows sedimentary facies association related to deposits of temporary lacustrine bodies and ephemeral fluvial channels (Zerfass, 2007).

The outcrop has four distinct facies (Fig. 4 and 5):

(1) massive reddish mudstone containing calciferous nodules and fossils of Rhynchosauria (Facies1);

(2) whitish or reddish fine sandstone with tabular geometry, usually massive, with calciferous nodules on the top of the layer and trace fossils of invertebrates, mainly *Skolithos* isp. (Facies 2);

(3) massive reddish fine sandstone with tabular geometry, with horizontal lamination in the top of the layer and dense bioturbation, mainly *Skolithos* isp. (Facies 3);

(4) reddish to orange fine sandstone with horizontal lamination, forming lenses of a few meters long and about 30 cm in thickness, with invertebrate trace fossils (*Skolithos* isp. *Arenicolites* and isp.), vertebrate fossils and footprints. This facies also presents desiccation cracks and fluidization structures (Facies 4).

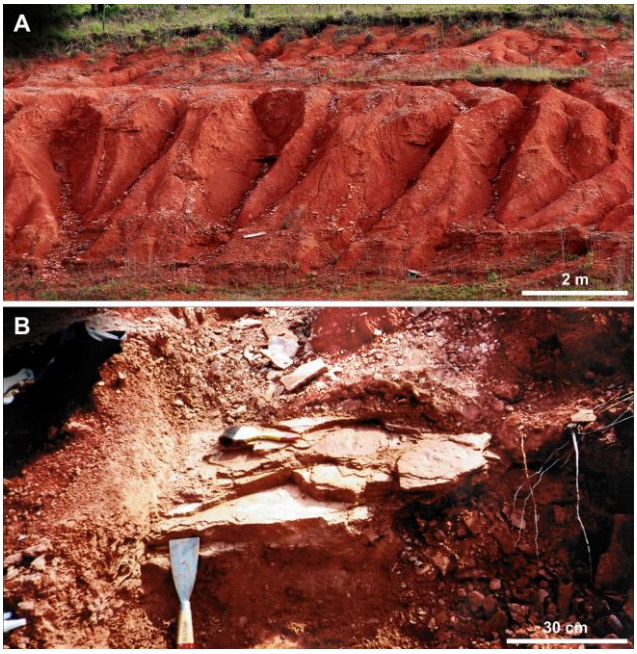

Figure 4 – A) Detailed view of the outcrop, showing the distribution of mudstone and sandstone facies; Photo: Rafael Costa da Silva. **B)** Detail of sandstone lenses. Photo: Jorge Ferigolo.

The facies 2 and 3 occur intercalated in the facies 1 in the lower portion of the outcrop whereas facies 4 occurs interbedded in facies 1 in the upper portion. The faciological interpretations for the rocks of the upper portion of the Santa Maria Formation have been controversial and some different interpretations can be found in the literature. For example, the mudstones are traditionally interpreted as lacustrine water bodies (*e.g.* Faccini, 1989; Zerfass *et al.*, 2003), while the lenticular layers represented by facies 4 could correspond to small channel resulting from events of subaerial exposure. Another hypothesis suggests that this sequence could be formed by a fluvial system with meandering to stable channels, where the described facies association correspond to overbank deposits; paleosoils levels can also occur. The tabular sandstones correspond to major channels as small lenses sandstone are interpreted as crevasse splay deposits (*e.g.* Fonseca & Scherer, 1998; Schultz *et al.*, 2000).

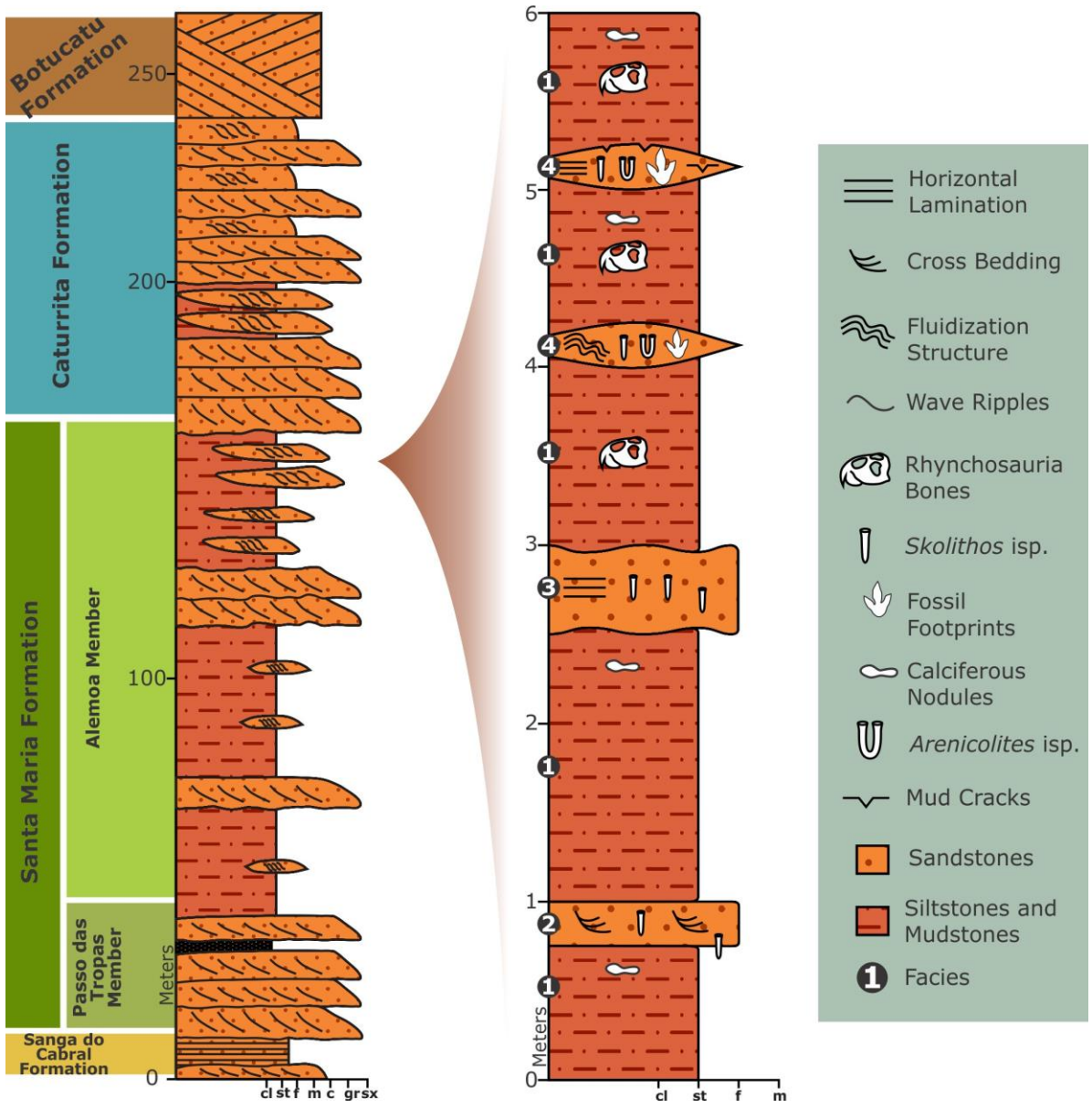

Figure 5 – Compound section of the Santa Maria and Caturrita formations and detailed section of Predebon outcrop.

More than 30 samples from the Predebon Site containing trace fossils of invertebrates and vertebrates, collected between 2002 and 2005 are deposited in the paleontological collection of the Museum of Natural Sciences (Museu de Ciências Naturais) of the Zoobotanical Foundation of Rio Grande do Sul (Fundação Zoobotânica do Rio Grande do Sul), in Porto Alegre.

The fossil footprints from Predebon Site

According to Silva *et al.* (2007; 2008a; 2008b; 2008c), nine morphotypes of footprints have been described from the Predebon Site: *Rhynchosauroides* isp., *Rhynchosauroides retroversipes*, *Rhynchosauroides?* isp., drag marks of autopodia, *Dicynodontipus* isp., *Dicynodontipus prothérioides*, theromorphoid footprints *Incertae sedis*, dinosaur footprints indet. and *Grallator*? isp.

The trackmaker of *Rhynchosauroides retroversipes* (Fig.6) was a lacertoid and quadruped tetrapod, with primitive autopodia, sprawling gait and a long tail; the feet were rotated posteriorly and laterally (Silva *et al.*, 2008b). With arboreal adaptations, this animal had an ineffective locomotion on the ground, although it could reach higher speeds over short distances with bipedal posture. The whole of footprints studied, including *Rhynchosauroides retroversipes*, *Rhynchosauroides* isp., half-swimming traces and *Rhynchosauroides*? isp., can be attributed to lacertoid animals, possibly sphenodontids, whose skeletons are found in the Caturrita Formation, superimposed to the Santa Maria Formation.

Figure 6 – Reconstruction of the trackmaker of *Rhynchosauroides retroversipes*, Sítio Predebon, RS. Drawnig: Renata Cunha.

The trackmaker of *Dicynodontipus protherioides* corresponds to a quadrupedal cursorial animal, with alternate walking but little lateral flexion of the spine. The gait was erect and the autopodia palmigrade/ plantigrade to semipalmigrade/ semiplantigrade, without long and sharp claws and with phalangeal and plantar/palmar pads. The tracks were produced with alternate gait and with the tail touching the ground (Silva *et al.*, 2008c). The studied footprints, including *Dicynodontipus protherioides* and *Dicynodontipus* isp., may be attributed to advanced small cynodonts, possibly trithelodontids, whose skeletons are found in Santa Maria and Caturrita formations. The tracks identified as dinosaur footprints indet. and *Grallator*? isp. were attributed to basal dinosaurs. The genera *Staurikosaurus*, *Saturnalia* and *Sacisaurus*, from the Alemoa-Caturrita sequence, would be morphologically close to the trackmaker (Silva *et al.*, 2008a).

Morphological features allowed to know behavioral details of the trackmakers, such as swimming activity, the possible occasional bipedalism and climbing behavior in *Rhynchosauroides retroversipes*, besides alternate gait and drag of the tail, typical of basal amniotes, in the non-mammalian cynodonts producers of *Dicynodontipus protherioides*. The preservation of the footprints of the Predebon Site was influenced by the presence and depth of a water sheet during its production and subsequent subaerial exposure, and was classified into five categories: underwater tracks, semi-aquatic tracks, semi-terrestrial tracks, wet substrate tracks and damp substrate tracks (Silva *et al.*, 2007). The degree of subaerial exposure increases from first to last. The footprints in wet and damp substrate provided the best preservation. The presence of small temporary channels in seasonal climate, where the tracks were produced, implies in a deeper water column in the central part of the channel and more shallow next to the edges, both subject to a gradual drying. The deeper regions could have generated underwater and semi-aquatic tracks, while those closer to the margins and more subject to subaerial exposure would have caused other preservational forms. These data constitute the basis for the reconstruction of the trackmakers, their habits and relationship with the paleoenvironment (Fig. 7).

SYNOPSIS ON THE ORIGIN, GEOLOGICAL EVOLUTION AND IMPORTANCE OF THE SITE

During the Triassic, continental depositional systems evolved in the southern Paraná Basin, leaving as record the Rosario do Sul Group (*sensu* Andreis *et al.*, 1980). An important biocenose settled down in the region, leaving the fossil record of vertebrates and conifers (*e.g.* Holz & De Ros, 2000). Subsequently, the first movements related to the fragmentation of Gondwana resulted in the elevation of parts of the basin, which led to an erosional stage which continued until the Middle Jurassic (Milani *et al.*, 1994).

Among the sites with fossils footprints in the Paraná Basin, the Predebon Site shows the highest quality of preservation and also the greatest diversity (Silva *et al.*, 2007; 2008a; 2008b; 2008c). The ichnospecies *Rhynchosauroides retroversipes* and *Dicynodontipus protherioides*, described from specimens of this outcrop, were until then unknown for the science, and are not recorded in any other location. The occurrences of dinosaur tracks of the Santa Maria Formation are unique in the Triassic of the Rio Grande do Sul State and correspond to the oldest in Brazil.

The association of several morphological types of footprints in the same outcrop of the Santa Maria Formation allowed the identification of a complex ichnocoenosis, comprising at least two kinds of sphenodontians, cynodonts and dinosaurs, showing a different paleofaunistic composition from that known to the top of Alemoa Member through the fossilized skeletons. Curiously, this ichnocoenosis shows the presence of a paleofauna similar to that found in the

Caturrita Formation, showing that the fossils tracks can anticipate the record of body fossil (*e.g.* Lockley 1991; Sarjeant, 1988) and supplement the information supplied by them.

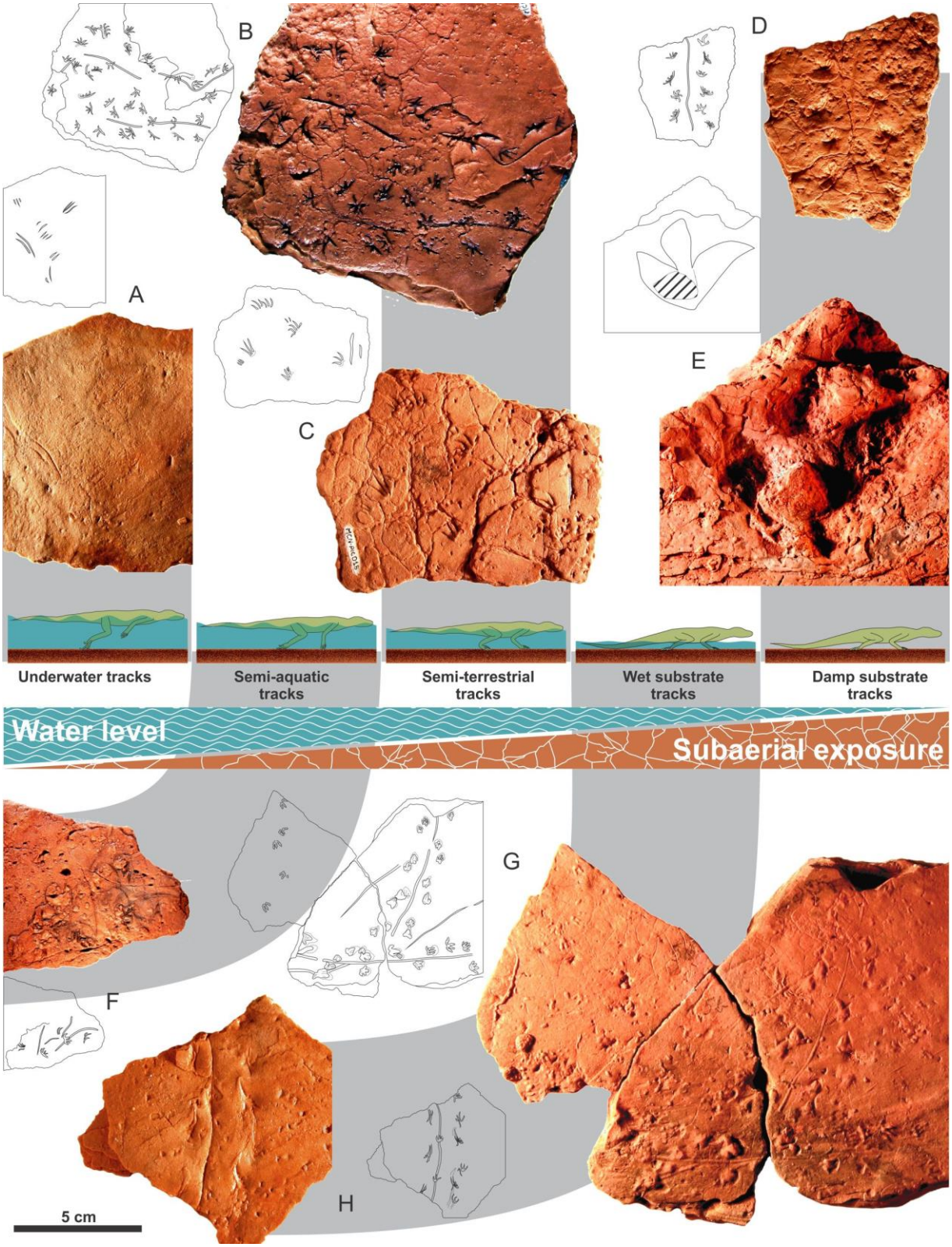

Figure 7 – Relationship between the preservation of the tracks from the Predebon Site, the water content of the substrate when the tracks were produced and subsequent subaerial exposure. **A, F** = swimming traces of sphenodontians; **B, C, D, H** = sphenodontian footprints; **E** = dinosaur footprint; **G** = cinodont footprints. Photos: Rafael Costa da Silva.

However, there are still unresolved questions and gaps to be filled and further studies and the discovery of new specimens could give a more complete knowledge of the ichnocoenosis from Southern Brazil. There is also a possibility of new findings in the Santa Maria Formation, not only in the Predebon Site, but also in other faciologically similar sites that occur in the same region, although previous surveys have shown negative results.

PROTECTION PROCEDURES

During 2009, the Geological Survey of Brazil-CPRM performed the geological mapping of the Quarta Colônia area at 1:100.000 scale. The survey was accompanied by an inventory of its most important geosites. During this work, the Predebon site was classified as a site of national importance with possible scientific and educational use. Furthermore, the site was considered fragile and at high risk of degradation due to agricultural activities conducted in the surroundings and the removal of sedimentary material. However, the perspectives of conservation of geosites in the region are quite encouraging. Additionally, the Predebon Site is stable for at least 10 years and its preservational situation is much better than many of the triassic sites of the Rio Grande do Sul State, which often have significant levels of weathering.

Local communities are mobilized through the Consortium for Sustainable Development of the Quarta Colônia (Consórcio de Desenvolvimento Sustentável da Quarta Colônia) (CONDESUS - Quarta Colônia) in order to develop a Paleontological Park, with a Support Center for Paleontological Research (Centro de Apoio à Pesquisa Paleontológica - CAPPA) and three museological units in major fossiliferous sites. The first module of CAPPA, located in São João do Polêsine, has already been built and opened. Furthermore, following the proposal for the creation of a geopark. (Quarta Colônia Geopark) presented by CPRM, the CONDESUS - Quarta Colônia intends to submit an application dossier to UNESCO seeking its approval for the Global Geoparks Network under the auspices of this international institution.

According to the criteria established by the Global Geoparks Network, the Quarta Colônia Geopark proposal fulfills its basic requirements. Among them stands out (i) presence of paleontological sites of scientific and pedagogical importance, (ii) potential for sustainable development of local communities through geotourism and (iii) the existence of an infrastructure that will enable the creation of mechanisms aiming the preservation of its rich geological heritage. No less important is the involvement of local communities which, through the CONDESUS-Quarta Colônia, are holding many relevant initiatives, demonstrating its strong interest in the consolidation of the Geopark.

The CONDESUS-Quarta Colônia, a non-profit legal entity under private law, has among its basic principles: a) the conservation of ecosystem biodiversity, b) promote sustainable development in their areas of coverage, c) promote scientific research, education and permanent monitoring.

With the implementation of the Paleontological Park, one of the priorities of CONDESUS will be the creation of mechanisms for conservation of the most endangered sites, such as the Predebon Site.

The implementation of important projects of research and surveying of natural and cultural heritage of the Quarta Colônia can be highlighted during the administration of CONDESUS, such as a Flora and Fauna Inventory and a Survey of the Buildings of Historical Interest.

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SUMMARIZED *CURRICULUM VITAE* OF THE AUTHORS

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