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Systematic and taphonomic insights of fossilized feathers: A new occurrence from the Oligocene of Taubaté Basin (SE, Brazil)

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ABSTRACT

Feathers are rare in the fossil record because they have a low fossilization potential. Despite their palaeobiological significance, they also provide important palaeoecological and taphonomic information. Here, we report a new occurrence of three isolated feathers from the shales of the Oligocene Tremembé Formation (Taubaté Basin, SE Brazil). Their possible taxonomic affinities and taphonomic features are also discussed. Analyses identified the specimens as representatives of two pennaceous morphotypes (*i.e.*, a contour and a rectrice feather). Both are preserved as carbonized traces, although, due taphonomic processes, they show different degrees of preservation. Since the Tremembé Formation is responsible for the most diverse record of Cenozoic birds, and because water-adapted birds (*e.g.*, anseriformes and phoenicopteriformes) occur in this unit, it is highly possible that these feathers belonged to these aquatic taxa. Further investigations should concentrate on geochemical and microscopic techniques in order to reveal additional taxonomic and paleoecological features currently unknown in Paleogene birds of Brazil.

1. Introduction

Feathers are considered the most intriguing features of living birds, since they are involved in diverse roles such as intraspecific communication, protection, and display (Lucas and Stettenheim, 1972). They exhibit a large array of morphologies, sizes and colors, ranging from small downy feathers to big pennaceous rectrices and remiges (Proctor and Lynch, 1993), with a plethora of hues, varying from brown, black, blue, green and red, among others (Hill and McGraw, 2006). Feather coloration shows close affinity to environmental and climatic conditions in which birds dwell, providing camouflage and protection against radiation and parasite load (Shawkey and Hill, 2004; Hill and Mcgraw, 2006). These color patterns may have evolved early in the Dinosauria clade, however, their initial functions, such as display and interspecific signaling, are still debated (Ruxton and Stevens, 2015).

In a timespan of approximately 50 Ma, birds emerged and diversified into many groups during the Mesozoic (252-66 Ma) (Xu et al., 2014; Brusatte et al., 2015). Molecular and fossil evidence indicates that the most diverse group, the Neornithes, started to diverge in the late Mesozoic (Jarvis et al., 2014; Claramunt and Cracraft, 2015) with an explosive rate of diversification only occurring early in the Cenozoic (Prum et al., 2015). In addition, it is suggested that tropical Neoaves, especially in the Amazon, diversified late in the Quaternary in the last 3 Ma (Ribas et al., 2011).

During the Paleogene (ca. 66 - 23 Ma), several geological events in the southern hemisphere allowed the emergence of new land areas (Rea et al., 1990; Hoorn et al., 2010). The isolation and occupation of new niches favored speciation (Hoorn et al., 2010) especially among the avifauna, which diversified into many groups well-adapted to these new spaces, such as the case of the *Terra-Firme* Forest birds (Brumfield and Capparella, 1996; Hedges et al., 1996; Ribas et al., 2011, 2012; Jetz et al., 2012). Consequently, several Neornithes become endemic (James, 2005; Mayr et al., 2011a; Ribas et al., 2011, 2012), and then spread throughout the world (Claramunt and Cracraft, 2015).

Represented by diverse taxa, Cenozoic Era fossil birds appear in several sedimentary deposits in Brazil, occurring in the Paleocene of the São José de Itaboraí Basin (Alvarenga, 1983, 1985b; Baird and

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Vickers-Rich, 1997; Alvarenga, 2010), the Oligocene of the Taubaté Basin (Alvarenga, 1982, 1985a, 1988, 1990, 1993, 1995, 1999; Mayr et al., 2011a, 2011b), the Mio-Pliocene of the Acre and Pirabas basins (Ackerman, 1964; Alvarenga and Guilherme, 2003; Bandeira et al., 2015), and Quaternary deposits of Bahia, Minas Gerais and Rio Grande do Sul (Alvarenga, 1998; Alvarenga and Olson, 2004; Lopes et al., 2006; Alvarenga, 2007; Alvarenga et al., 2008; Hsiou, 2009). Among these deposits, the largest record (8 species) is in the Tremembé Formation (Taubaté Basin) (Alvarenga, 1982, 1985a, 1988, 1990, 1993, 1995, 1999, Olson and Alvarenga, 2002; Mayr et al., 2011b), although few feathers have been described to date (Shufeldt, 1916; Santos, 1950; Alvarenga, 1988).

Compared to other fossils (*e.g.*, bones), feather records are rare since they are delicate and rarely preserve during the process of diagenesis (Davis and Briggs, 1995). Their preservation occurs mainly as carbonized traces, but they are also found as iron oxide-hydroxide compounds, impressions (external molds), or inclusions in ambers and coprolites (Wetmore, 1943; Davis and Briggs, 1995; Mckellar et al., 2011; McNamara, 2013; Vitek et al., 2013). In Brazil, feathers are generally preserved as impressions, carbonized traces, and iron oxide-hydroxides residues (Prado et al., 2016).

The taphonomy of feathers has been explored in detail by forensic scientists, and categorization of their microstructures can lead to taxonomic identifications of birds to the family level (Dove and Koch, 2011). Although isolated feathers are not a diagnostic feature of new taxa, in some deposits, they can indicate the presence of animals whose bones were not yet found. In some cases, they help with the identification of new bird specimens, such as the case of *Archaeopteryx* sp. (Wellnhofer, 2010) and the polemic bird *Praeornis sharovi* (Rautian, 1978). In addition, their presence allow inferences about dinosaur paleobiology when bone evidence is absent (Davis and Briggs, 1995).

Two previous reports (Shufeldt, 1616; Santos, 1950) of feathers found in the Tremembé rocks did not address taphonomic and systematic issues. In addition, bird bones were firstly unearthed in the late 1970's, however, the recovery occurred in the absence of feathers, representing an unusual event that needs clarifications.

Here, we report a new occurrence of fossilized feathers from the Oligocene *Konservat-Lagerstätte* the Tremembé Formation (Taubaté Basin), southeastern Brazil. Their systematics is briefly addressed and their taphonomy extensively discussed, enabling for the first time the recognition of the taphonomic processes that acted on vertebrate soft tissues of this unit.

1.1. Geologic setting

The Taubaté Basin in southeastern Brazil (Fig. 1) is an elongate rift basin with an estimated extension of 2.400 km^2, within which is found several cities of the Paraíba Valley, São Paulo state (Riccomini, 1989; Carvalho et al., 2011). This geologic unit integrates the Continental Rift of Southeastern Brazil (CRSB), formed during the reactivation of the Precambrian shear zones in the Late Mesozoic to Early Cenozoic, in a strike-slip fault system with deposits of approximately 850 m maximum of thickness (Marques, 1990; Carvalho et al., 2011; Cogné et al., 2011, 2013; Franco-Magalhães et al., 2014). In this basin, six depocenters (sub-basins), separated by three structural highs have been identified through seismic profiles. The Tremembé Formation layers only occur in the three deepest sub-basins (Marques, 1990; Cogné et al., 2013).

Generated in *playa-lake* and lacustrine environments, the Tremembé Formation is composed of siliciclastic sediments dominated by smectitic clays and papyraceous bituminous shales with interdigitating layers of sandstones (Riccomini, 1989; Riccomini et al., 1996). The analysis of the mammalian fauna (Paula-Couto and Mezzalira, 1971) and palynomorphs from the Tremembé layers (Lima et al., 1985) have yielded a Late Oligocene age (Chattian Stage, ~25 Ma).

The presence of organic matter, clay minerals and bitumen (*e.g.*, smectite, kaolinite and kerogen) suggests the presence of hot and humid tropical forests during most of the time of deposition (Loureiro and Cardoso, 1987, 1990; Brandt-Neto et al., 1991; Riccomini et al., 1996; Chagas et al., 2009; Mendonça-Filho et al., 2010).

The fine sediments of the Tremembé Formation were laid down in a swampy lake surrounded by a rich vegetation (Duarte & Mardarim-de-Lacerda, 1992; Mandarim-de-Lacerda and Bernardes-de-Oliveira, 1999; Veiga, 2009). The biota is represented by diversified fossils of mammals, reptiles, birds, fishes, arthropods, plants and several types of ichnotaxons (Ferreira, 1974; Fernandes et al., 1987; Chiappe, 1988; Carvalho and Fernandes, 1989; Martins-Neto, 1998; Malabarba, 2000; Bernardes-de-oliveira et al., 2002a, 2002b; Olson and Alvarenga, 2002; Melo et al., 2007; Veiga, 2009; Ribeiro, 2010; Mayr et al., 2011a; Bergue et al., 2015a, 2015b). While younger in age, the high quality of its fossils is comparable to the Eocene Messel Shale Pit fossils (Franzen, 1985), as soft tissues of different groups of organisms, such as plants and vertebrates, were exquisitely preserved (Prado et al., 2015).

2. Materials and methods

Two feathers from the Taubaté Basin were identified, following the terminology of Lucas and Stettenheim, 1972, Sick (1984) and Proctor and Lynch (1993) and described according to Prado et al. (2016). The fossils occur in a grayish shale of the Tremembé Formation, in the "*Sociedade Extrativa Santa Fé*" quarry in the city of Tremembé in São Paulo state. All feathers are deposited in the Palaeontological Collection of the Laboratory of Systematic Palaeontology, Institute of Geosciences, University of São Paulo (São Paulo). The specimens received the numbers GP/2E-8125, GP/2E-8126, and GP/2E-8127. Measurements and comparisons of specifics portions, such as barbs and rachis, were made to assist morphological identifications (Table 1). Microscopic images and measurements were made using caliper, a millimeter-scale stand with Canon EOS REBEL T3, a Carl Zeiss stereomicroscope with AxioCam ICC3 image capturing system, and AxioVision LE software.

3. Results

3.1. Systematic Palaeontology

Infra-division Maniraptora Gauthier 1986

Class Aves Linnaeus 1758

Infraclass Neognathae Pycraft 1900

Family *Incertae sedis*

(Fig. 2, A – C)

Material: GP/2E-8125 (Fig. 2, A).
Horizon: Grey shales, upper part of the Tremembé Formation.
Age: Paleogene, Oligocene (Chattian, ~25 Ma).
Description: An incomplete feather composed only by the mid portion, presenting a black hue. The presence of barbs and barbules are seen (Fig. 2, D). Barbicels are not present and rachis can not be noted by its preservation.
Measurements: See Table 1.
Remarks: The identification of this specimen is difficult, but it resembles morphologically extant contour feathers. On the extant pennaceous feathers, the distal portion is characterized by vanes