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Supplementary information

Pterosaur melanosomes support signalling functions for early feathers

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Contents

1. Supporting text.

1.1. Origin of the specimen.

The specimen is believed to have been originally poached from an undetermined outcrop of the Early Cretaceous Crato Formation (Araripe Basin, north-eastern Brazil) and then resided in private collections in Europe for an unknown period of time. The specimen was deposited by its private owner at the Royal Belgian Institute of Natural Sciences (RBINS) through the French fossil preparation company Eldonia in 2020. The Brazilian authorities were contacted immediately and the specimen is now part of the collections of the Museum of Earth Sciences, Rio de Janeiro (collection number: MCT.R.1884). Negotiations between the RBINS, Eldonia and Brazilian authorities led to the official physical repatriation of the specimen to Brazil in early February 2022. The specimen was incompletely prepared when it arrived at Eldonia. Preliminary preparation under the supervision of FE allows us to certify that this specimen is not a composite and that restorations prior to its arrival at RBINS are limited to standard consolidation procedures.

1.2. Geological background.

The specimen is hosted within grey laminated limestones and was probably excavated from the Nova Olinda Member of the Crato Formation (Fm). This member is located at the base of the formation; all specimens of *Tupandactylus imperator* described thus far have been recovered from here[1–4]. The vertebrate assemblage in the Nova Olinda Member includes well preserved fish[5–8], bird feathers[9–15], lizards[16–19], anurans[20–23] , turtles[24–28] and rare crocodilians[29–32]. The member also preserves abundant arthropods[33, 34], arachnids[35], crustaceans[36] and plants, including early angiosperms[37, 38].

The deposits of the Crato Fm consist of a mixture of siliciclastic deposits and laminated limestones[39]. The Nova Olinda Member is a laminated unit that for most of its vertical thickness (ca. 13 m) comprises pale carbonate-rich and dark carbonate-poor laminae[3]. This composition indicates deposition in a stratified water body characterized by a persistent thermocline or chemocline. The preservation of fossil soft tissues probably reflects (at least in part) low oxygen conditions in bottom waters. The geochemistry, sedimentology and palaeontology of the sediments indicate deposition in a brackish, restricted environment (not open marine) close to shore, probably a lagoon[39–40].

1.3. Description of the specimen.

Systematic Palaeontology.

Pterosauria Kaup, 1834
Pterodactyloidea Plieninger, 1901
Tapejaridae Kellner, 1989
Tapejarinae Kellner, 1989
Tupandactylus Kellner & Campos, 2007
Tupandactylus cf. *imperator* (Campos & Kellner, 1997)

Description and identification.

Specimen MCT.R.1884 comprises the posterior portion of the cranium and the remains of a soft tissue cranial crest, spanning five separate slabs. The specimen is in left lateral aspect, with most bones compacted. The absence of the anterior portion of the cranium is unlikely to represent an artefact of preservation. Instead, it was probably lost during excavation by quarry workers, as indicated by clean cuts (presumably saw cuts) through the bones in the anterior part of the cranium and by no obvious disarticulation around articulation sutures, which would be expected if the cranium disarticulated naturally from the rest of the carcass.

Of the cranium, parts of the orbit and nasoantorbital fenestra are still visible (Extended Data Figs. 1, 4a). Although only the dorsal part is preserved, the orbit appears rather small with an inverted pear geometry. The dorsal margin of the nasoantorbital fenestra is set more dorsally than the dorsal margin of the orbit. Orbit and nasoantorbital fenestra are separated by a thin lacrimal process. Two long bony processes extend posteriorly, supporting a soft tissue cranial crest that spans ca. 0.3 m^2 (465 mm high x 588 mm long). The occipital process is robust and extends posterodorsally from the back of the skull. Its ventral margin is straight, forming an angle of ca. 130° with the dorsal margin of the nasoantorbital fenestra; its dorsal margin is markedly concave. Only the posterior portion of the premaxillary bony crest is preserved as small rods, which seem to form a transition between the ossified base of the premaxillary crest and the soft tissue crest. These bony rods have been reported in the holotypes of *T. imperator*[41] and *T. navigans*[42]. The premaxillary bony crest extends as a postpremaxillary process that is about 20% longer (but more slender) than the parietal crest and is poorly preserved as a trabecular meshwork. The postpremaxillary process forms an angle of ca. 80° with the dorsal margin of the nasoantorbital fenestra and its posterior part has a distinct ventral arch.

The soft tissue cranial crest is the most complete known for *Tupandactylus*. The crest of MCT.R.1884 is similar to another described specimen of *Tupandactylus*[4], with a convex dorsoposterior margin. It comprises parallel fibres that run oblique to the occipital crest between the dorsal margin of the cranium and occipital crest. These parallel fibres are similar to the fibres described in other *Tupandactylus* specimens[1, 4]. Along the occipital process, the crest locally shows monofilaments and branched integumentary structures, here identified as feathers (see Main Text). Similar monofilaments are known from the mandibular ramus of *Tupandactylus*[4] (reported as 'probable pycnofibres'), but have not been reported in association with a cranial crest previously. Overall, the cranial crest of this specimen closely resembles that of the tapejarid pterodactyloid *Tupandactylus* from the Crato Fm of the Araripe Basin[1]. Synapomorphic characters include the presence of a spine-like and slightly caudally-inclined postpremaxillary process and of a long (only slightly shorter than the postpremaxillary process) and caudally-oriented occipital crest[1, 4, 43]. As in previous specimens of *Tupandactylus*[1, 4, 42], no obvious sutures are present, indicating that the specimen was probably an adult.

The maximum extension of the occipital process of MCT.R.1884 cannot be inferred from the known specimens of *Tapejara wellnhoferi*[44], from the Santana Fm of the Araripe Basin, but it was obviously much shorter than in *T. imperator*. Further, our specimen differs from *T. wellnhoferi* whereby the orbit of the latter lies slightly below the dorsal margin of the nasoantorbital fenestra[43]. The occipital process of the tapejarid *Sinopterus dongi* differs from that of *T. imperator* in morphology and size[4, 45]. *Tupandactylus navigans*, also from the Crato Formation, lacks an occipital process and has a more vertically-inclined postpremaxillary process[42]. The specimen described in the present paper differs from the four other *T. imperator* specimens described from the Crato Formation whereby its occipital crest is more dorsally inclined and by the concave dorsal margin of the occipital crest[4]; the soft-tissue supracranial crest is narrower antero-posteriorly than that of the other *T. imperator* specimens. Such morphological variation is not unexpected and is implied in sexual selection[46]. We therefore tentatively refer this specimen to *Tupandactylus* cf. *imperator*, pending further evidence on the intraspecific variability of the cranial crest in this taxon.

1.4. Soft tissue anatomy.

In addition to the monofilaments and branched feathers associated with the occipital process (and that are described in detail in the main text), the cranial crest exhibits two types of fibrous integumentary structures. First, numerous sub-parallel, light to dark brown fibres (100–150 µm wide and up to ca. 300 mm long (Fig. 1a, Extended data Figs. 1, 4)) are widespread across the cranial crest. Those elongate fibres are well defined in the posteroventral part of the crest. They are faint or not evident in the anterodorsal part of the crest, where only a thick, black layer, possibly representing decayed organic matter, is present. Most of these fibres are mutually parallel, aligned with the sagittal axis ventrally and curved dorsally. Ventrally, a series of ca. 100 striking dark brown structures, each 600–900 µm wide, are aligned close to, but isolated from, the occipital process by a 20 mm to 30 mm-wide zone that lacks soft tissues (save faint fibre impressions). Each dark brown structure gives rise to a series of these sub-parallel dark brown fibres (usually ca. five) (Extended Data Fig. 4a–c). The crest of *T. imperator* described in Pinheiro et al. (2011) also exhibits similar fibres, but those in MCT.R.1884 show a striking curvature.

Locally, the dorsal part of the crest displays wrinkles. Those are thin (ca. 0.3 mm wide), mutually parallel and tightly packed. In the posterior part of the crest, those structures are preserved as external moulds (Extended Data Fig. 4e, f) and run perpendicular to the main set of brown fibres that emerge from the ventral part of the crest. Those wrinkles are especially visible in the posterodorsal part of the crest (Extended Data Fig. 4e, f).

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