Oldest cingulate skulls provide congruence between morphological and molecular scenarios of armadillo evolution

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The cingulates of the mammalian order Xenarthra present a typical case of disagreement between molecular and morphological phylogenetic studies. We report here the discovery of two new skulls from the Late Oligocene Salla Beds of Bolivia (approx. 26 Ma), which are the oldest known well-preserved cranial remains of the group. A new taxon is described: Kuntinaru boliviensis gen. et sp. nov. A phylogenetic analysis clusters K. boliviensis together with the armadillo subfamily Tolypeutinae. These skulls document an early spotty occurrence for the Tolypeutinae at 26 Ma, in agreement with the temporal predictions of previous molecular studies. The fossil record of tolypeutines is now characterized by a unique occurrence in the Late Oligocene, and a subsequent 12 Myr lack in the fossil record. It is noteworthy that the tolypeutines remain decidedly marginal in the Late Paleogene and Early Neogene deposits, whereas other cingulate groups diversify. Also, the anatomical phylogenetic analysis herein, which includes K. boliviensis, is congruent with recent molecular phylogenetic analyses. Kuntinaru boliviensis is the oldest confident calibration point available for the whole Cingulata.

Keywords: Palaeogene; Tolypeutinae; Bolivia; phylogeny; fossil record; calibration point

1. INTRODUCTION

The extant Xenarthra constitute one of the four recently recognized major clades of extant placental mammals [1,2], but also the only living testimony of the great endemic evolution undergone by placental mammals in South America. The Xenarthra gather the extant sloths, anteaters and armadillos, and a large number of much diversified fossil taxa. As such, the group offers a unique opportunity to use evidence from both molecular and morpho-palaeontological data to reveal a part of this very peculiar history.

Until now, however, these two approaches have worked largely apart from each other and resulted in some conflicts regarding the phylogeny of xenarthrans. A typical case is evident in the phylogeny of the diverse Cingulata (e.g. [3,4]), which contains not only the modest current representatives of armadillos, but also a great diversity of fossil armadillos and the herbivorous pampatheres and glyptodonts [5,6]. As well as pure phylogenetic disagreements, the dispute concerns temporal predictions made by molecular studies on the time divergences of various clades and their effective recognition in the fossil record, which generally occurs much later. The scarcity of the Palaeogene fossil record of cingulates is certainly a major reason for this incongruence. It consists only of very rare cranial bones, a few isolated scutes and postcranial elements (e.g. [7–9]). The first well-preserved skulls and skeletons allowing extensive anatomical descriptions are only known from the Early Miocene Santacrucian South American Land Mammal Ages (SALMA), around 16–17 Ma [10,11].

The Late Oligocene Deseadan Salla Beds of Bolivia have yielded one of the richest South American Palaeogene mammal faunas, dated around 25–26 Ma [12]. We provide here the description of two new well-preserved cingulate skulls from this locality. The two specimens constitute, together with an undescribed peltephilid skull from the same locality [13], the oldest well-preserved cranial remains from Cingulata (and Xenarthra as a whole).

These skulls document an early spotty occurrence for the Tolypeutinae at 26 Ma, in agreement with the temporal estimates made by previous molecular studies [14]. The fossil record of tolypeutines is, however, still characterized by a great rarity of remains in the Late Palaeogene and Early Neogene, with this new unique occurrence in the Late Oligocene and a subsequent 12 Myr lack in the fossil record. Moreover, the cladistic analysis we performed including this new taxon provides interesting congruence with molecular studies on the phylogenetic relationships within the Cingulata. This discovery also allows the establishment of the oldest confident calibration point available for the whole Cingulata.
2. RESULTS

(a) Description and comparison

Xenarthra Cope, 1889.
Cingulata Illiger, 1811.
Dasypodidae Gray, 1821.
Tolypeutinae Gray, 1865.

Kuntinaru gen. nov.

Kuntinaru boliviensis sp. nov.

Synonymy: Dasypodidae cf. Prozaedyus and/or Proeutatus sp. [15].

Holotype: MNHN-SAL 1024, skull missing the apex of the rostrum, but preserving most of the left tooth row, and all of the posterior half of cranium, except the zygomatic arches (figure 1a–e), collected by one of us (C.M.).

Paratype: MNHN-SAL 3, skull missing the apex of the rostrum but preserving the six posterior teeth on both sides, the orbitotemporal fossae and the anterior half of the auditory region (figure 1f,g), collected by R. Hoffstetter.

Locality: Salla, Department of La Paz, Bolivia.

Distribution: Desedral SALMA, Late Oligocene.

Etymology: Kuntinaru, ‘ghost’ in Aymara, the native spoken language in Salla, refers to the ghost-like isolated occurrence of this taxon and the subsequent 12 Myr absence of the tolypeutines in the fossil record. Boliviensis is for the occurrence of this taxon in Bolivia.

Diagnosis (both genus and species, for monotypy): Kuntinaru is a member of the Tolypeutinae because it exhibits the following tolypeutine apomorphies: a vertical anterior edge of the orbit and a surface anterior to the postglenoid foramen elongated antero-posteriorly, not delimited posteriorly by a line continuous with the lateral edge of the zygomatic arch; Kuntinaru differs from all armadillos by the presence of a thick crest anterolateral to the middle-ear cavity; differs from extant tolypeutines in possessing the following plesiomorph features: an infraorbital foramen approximated to the anterior root of the zygomatic arch and a well-marked orbital muscular crest; differs from Cabassous and Priodontes in possessing the following plesiormorph features: a distinct antorbital depression and crest for nasolabialis muscle insertion, and a stylomasoid foramen medial to the paroccipital process of petrosal and not postomedial; differs from the early-diverging euphractine Prozaedyus by the tolypeutines apomorphies cited above and in possessing the

Figure 1. Kuntinaru boliviensis gen and sp. nov. Detailed views of the cranial anatomy. (a–e) MNHN-SAL 1024, respectively, (a) dorsal, (b) ventral, (c) rostral, (d) zoom on auditory region and (e) left lateral views. (f) Ventral and (g) dorsal views of MNHN-SAL 3. Abbreviations: gl.surf., elongated glenoid surface; inf.f., infraorbital foramen; ent.pt., entopterygoid crests in line with the tooth rows; sc., dermal scutes of the cephalic shield; sph.f.cr., crest anteroventral to the sphenorbital fissure; vert.edg., vertical anterior edge of the orbit.
following plesiomorph features: straight entopterygoid crests in line with the tooth rows, and posterior part of the palate flat; differs from earlier-diverging cingulates like Peltephillus and Stegotheirium in exhibiting notably the following apomorphies uniting tolypeutines, eupractines and glyptodontoids (in addition to the tolypeutine apomorphies already mentioned above): a sinuous and glyptodontoids (in addition to the tolypeutine

region is damaged (i.e. distorted) in *Kuntinaru*, but remnants of such a crest are clearly present.

While flattened, we observed that the glenoid surface in *Kuntinaru* is barely longer than it is wide, but clearly less elongated than in *Cabassous*, *Tolypeutes* and *Priodontes* (figure 1d). It is also different from *Euphractus*, *Chaetophractus*, *Dasypus* and *Euteius*, in which glenoid width is greater than its length. Anterior to the post-glenoid foramen, the glenoid surface of *Euphractus*, *Chaetophractus*, *Dasypus* and *Euteius* is delimited backwards by a low crest continuous with the lateral edge of the zygomatic arch. Such a crest is absent in *Kuntinaru* and extant tolypeutines.

The auditory region of *Kuntinaru* is very well preserved and delivers a wealth of anatomical information that is detailed and illustrated in the electronic supplementary material, S1 and S2. Among the observations made therein, it can be pointed out here that *Kuntinaru* presents an overall auditory region especially reminiscent of *Tolypeutes*: a likely absence of a well-ossified bulla, like, notably, in tolypeutines and dasyopodines; an elongated epitympanic wing on the petrosal, greatly resembling *Tolypeutes*, *Cabassous* and the glyptodontoids; a well-marked crest bordering laterally the postglenoid foramen as in *Tolypeutes*; and a wide and shallow epitympanic recess as in *Tolypeutes* and *Priodontes*. However, the two latter characters could unfortunately not be checked in many armadillos and should therefore be considered here as suggestive rather than definite support for exclusive resemblance of the auditory region of *Kuntinaru* with that of some tolypeutines.

(b) Phylogenetic analysis

A cladistic analysis comprising 22 taxa and 125 characters has been performed in order to explore the phylogenetic relationships of *Kuntinaru* and armadillos; 112 characters come from Gaudin & Wible [4], 17 of which have been slightly modified; 13 characters are new. The taxonomic sample is the same as Gaudin & Wible [4], with the addition of *Kuntinaru*. The character list and data matrix can be consulted in the electronic supplementary material, S1. The analysis has been performed with TNT [16], with the traditional search option, 100 replications and the tree bisection reconnection swapping algorithm.

The analysis resulted in four most parsimonious cladograms of 455 steps. The indices of the present cladograms are very similar to those of Gaudin & Wible [4]: consistency index = 0.42 and retention index = 0.54. The strict consensus (462 steps, consistency index = 0.41, retention index = 0.53) is presented in figure 2.

The Cingulata (clade A) are monophyletic. The earliest-diverging cingulate is *Peltephillus*. Within the immediate less inclusive cingulate clade B, the dasyopodines (clade C; sensu [21]) are monophyletic. They constitute the sister taxa of clade D, gathering the tolypeutines, eupractines, *(Proeutatus*, *Euteius* and the glyptodont *Propalaeohoplophorus*.

In the orbitotemporal fossa, *Kuntinaru* exhibits a ridge continuous with the posterior edge of the sphenoidal fissure anteroventrally, like extant tolypeutines. This ridge defines the lateral wall of a deep gutter running forward up to the sphenopalatine foramen (figure 1e). This
3. DISCUSSION AND IMPLICATIONS

(a) The phylogeny of the Cingulata

The phylogenetic analysis supports the monophyly of the extant Tolypeutinae and Kuntinaru as an early-diverging tolypeutine. Given the pattern of relationships obtained for the Tolypeutinae, we could consider the clade clustering the three extant genera as crown tolypeutine and Kuntinaru as a stem tolypeutine. However, we rather favour a total-group concept [23], the common practice in Cingulata, and therefore classify Kuntinaru as a member of the Tolypeutinae. The monophyly of the Tolypeutinae is also clearly supported by molecular studies [3,14,24,25], and by recent analyses including postcranial morphology [26,27]. The previous analysis of Gaudin & Wible [4] based on craniodental morphology argued the Tolypeutinae may form a paraphyletic assemblage at the base of the Euphractinae–Glyptodontoida clade. New characters provide here unambiguous support for the monophyly of the tolypeutines. Particularly, the results of the analysis highlight a progressive modification of the facial region just anterior to the orbit in the Tolypeutinae (see data matrix, character list, character distribution and Bremer support values in the electronic supplementary material, S1).

The analysis supports Cabassous as being more closely related to Priodontes than to Tolypeutes, which is in contradiction to the molecular hypotheses that instead cluster Cabassous with Tolypeutes [3,14,24,25]. Nevertheless, the clade Cabassous–Priodontes is strongly supported not only by characters of the whole cranial anatomy (Bremer support value > 5), but also by a dataset comprised of a large number of postcranial characters [26]. Möller-Krull et al. argued that ‘it is possible that morphologically based cladistic reconstructions might have been confounded by the highly derived morphology of Tolypeutes’ (p. 2580 in [3]). However, the present cladistic analysis clearly shows that Cabassous and Priodontes share a high number of derived morphological characters not present in Tolypeutes, which displays rather plesiomorphic features.
Actually, considering only the extant genera on the strict consensus cladogram obtained here, the pattern is very close to the one hypothesized by a recent series of molecular phylogenetic studies [3,14,24,25,28]. In both patterns, Dasypus is the earliest-diverging extant genus, the extant tolypeutines and extant euphractines form a distinct clade (clade D), the extant tolypeutines are monophyletic (clade F), and Euphractus, Chaetophractus and Zaedyus are united in a clade (clade J) that does not include Chlamyphorus. A recent molecular analysis [3] supported Chlamyphorus as being closer to the tolypeutines than to the extant euphractines. If our morphological analysis indeed locates Chlamyphorus farther than usual from the extant euphractines [4,29], it nevertheless still supports closer relationships of this genus with extant euphractines than with tolypeutines. This relationship is especially evidenced by the shared derived configuration of the posterior part of the palate in Chlamyphorus, Zaedyus, Euphractus and Chaetophractus (and fossil relatives). Obviously, more molecular and morphological investigations are needed to resolve this contradiction. Our analysis also supports a clade allying the Euphractinae and Glyptodontoidea, as in two recent morphological analyses [4,29]. As in these works, the Santacrucian Prozaedyus constitutes the earliest-diverging member of this clade, and the Eututini constitute a polyphyletic assemblage with Proceutatus as the sister taxon of the Glyptodontoidea. The main difference with the Gaudin & Wible [4] study concerns the earlier divergence of Chlamyphorus in our analysis.

It is worth mentioning that it is the first time that a cladistic analysis based on morphology mirrors so much the results of molecular studies [3,14,24,25,28], a fact that gives credence to the phylogenetic conclusions.

(b) The fossil record and the dating of evolutionary events in Cingulata

In agreement with molecular studies [14], the present result implies that the Tolypteutinae as a whole may have differentiated at least 26 Myr ago and diverged before this date from the euphractines and the fossil glyptodontoids. Kantinaru from Salla constitutes the unique referral to Tolypteutinae from this period. Conversely, referrals to the Euphractinae and the Glyptodontoidea are known in various Oligocene localities [7,30,31], and are even registered in the Late Eocene Mustans and Casamayoran SALMA [7,9,32,33]. Moreover, the Glyptodontoidea may be present as early as the Late Paleocene, as tarsal remains from the Brazilian locality of Itaboraí have been referred (although with doubts) to the group [34]. In any case, referrals to the Glyptodontoidea and Euphractinae trace their presence back to at least the Casamayoran, 36 Ma [17]. From this, a major problem occurs relative to the emergence of the Glyptodontoidea. In the present analysis, and in others [4,27], the glyptodontoids are located as an apical group nested within the euphractines. Their occurrence in the fossil record at least 36 Myr ago thus argues for a much older origin for the Euphractinae–Glyptodontoidea clade, and for the entire cingulate radiation. This latter point is not confirmed by the Paleocene and Eocene fossil record of cingulates, which, to date, is very defective. Actually, a divergence between the Euphractinae–Glyptodontoidea and the Tolypteutinae at a time much earlier than 36 Ma is also in disagreement with the molecular estimates for the divergence of Euphractinae/Tolypteutinae ranging between 37 and 29 Ma [14]. A solution may be that the Glyptodontoidea occupy a more basal position on the cingulate phylogenetic tree. On this point, the Bremer support values may be indicative. The position of the Glyptodontoidea as an apical group among the Euphractinae is not very strongly supported. All nodes within clade H have a Bremer support value of 1 or 2. However, their presence in a common clade H with the Euphractinae is strongly supported (Bremer support value = 5). More investigations and new fossil discoveries will drive our understanding of the evolution of the Glyptodontoidea, and we hope this will resolve the incongruence between the phylogenies, fossil record and dating estimates. As such, ancient DNA studies could constitute a powerful approach to better reconstruct the phylogenetic position of this remarkable group, as has been already done with extinct ground sloths [35,36].

The recent molecular studies dated the emergence of the Tolypteutinae around the Early Oligocene, at the latest before 29 Ma [14]. However, until the present study, no tolypeutine fossil was known before the Middle Miocene (12–14 Ma; [37]). This, therefore, implied a huge ghost lineage of at least 15 Myr. Further, immediately younger remains recognized as Tolypteutinae were described from Early Pliocene deposits (i.e. not before 5.3 Ma [21]). By supporting the Late Oligocene Kantinaru as an early-diverging tolypeutine, the present analysis argues that the tolypeutines are known by a unique occurrence in the Late Oligocene, and are there-after characterized by a subsequent 12 Myr lack in the fossil record. The fact that tolypeutines remain marginal in the Late Paleogene and Early Neogene deposits, whereas other groups diversify, recalls in some way the pattern called ‘dead clade walking’ [38], a term usually specifically applied to those taxa presenting survival without recovery after mass extinction. This absence could, however, simply result from a poor knowledge of the characteristic features that allow tolypeutines to be distinguished from other fossil cingulates (e.g. unrecognized scutes). Meanwhile, in the Miocene, the euphractines and glyptodontoids are relatively abundant in the fossil record. This hiatus in the tolypeutine fossil record may also be due to some peculiar ecological factors incompatible with the preservation of their skeletal remains.

The discovery of these new Oligocene cingulate skulls points out how patchy is our knowledge of early cingulate evolution, as is the case for all xenarthrans, and, above all, how spotty is their fossil record. In this context, the description of Kantinaru remains is of crucial importance. Indeed, Kantinaru constitutes the only Paleogene armadillo taxon with such completeness—it preserves the most complete cranial skeleton of any Palaeogene cingulate—that was placed in a phylogenetic context. Its recognition as an early-diverging tolypeutine now confers to it the role of the oldest and best existing calibration point for molecular analyses among cingulates.

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