Skull of *Minotaurasaurus ramachandrani*, a new Cretaceous ankylosaur from the Gobi Desert

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A new genus and species of ankylosaurid, a dinosaur from the Upper Cretaceous of the Gobi Desert has been described. It shows characters typical of many Late Cretaceous ankylosaurs. The new specimen is a virtually complete skull with both hemimandibles preserved intact with the predentary. This skull has been subjected to almost no crushing or shearing. It has an equilateral, triangular-shaped skull when viewed dorsally and large, highly ornamented narial osteoderms, which give the skull a bull-like appearance with flaring nostrils. Braincase features are more primitive than those of the other Gobi Desert ankylosaurs.

Keywords: Ankylosaur, cranium, Cretaceous, Dinosauria.

Systematic paleontology
Order: Ankylosauria
Family: Ankylosauridae

Minotaurasaurus new genus

Holotype. INBR21004, Victor Valley Museum, Apple Valley Rd. Apple Valley, California, 92308. A skull with complete lower jaws and predentary.

Etymology. The gerenic name means 'man–bull reptile', in Latin, in reference to the bull-like appearance of the skull, similar to the Minotaur of Greek mythology.

Holotype locality. The skull was originally purchased by V. S. Ramachandran and displayed at the Victor Valley Museum, California, USA. The only stratigraphic information that we have is the matrix around the specimen. This indicates a location in the Gobi Desert of either Mongolia or China. It is expected that the stratigraphic position for the skull will eventually be discovered when additional specimens are found.

Diagnosis. As for the species.

Minotaurasaurus ramachandrani new species

Etymology. (Latin) for V. S. Ramachandran, paleontology patron who made sure that this skull was described and made available to science.

Diagnosis. Skull with large, horizontally elliptical external nares situated terminally; external nares rimmed laterally and posteriorly by well-developed osteoderm, anteriorly rimmed by thin, triangular osteoderm fused on premaxilla; foramina for premaxillary and maxillary sinuses housed within external nares; premaxillary part of snout broad; occipital condyle poorly developed as in *Saichania*, directed ventrally; exoccipitals low, separated from skull roof by a gap, dorsal part near supraoccipital curved anterodorsally; quadrate nearly vertical, with distal articular condyle situated at the level between posterior rim of skull and posterior rim of orbit, quadrate head not fused to paroccipital process; skull roof not overhanging occiput; maxillary shelf well-developed and wide to below middle of orbit; premaxilla forms anterior rim of palatal vacuity, separating maxillae from vomer, as in *Pinacosaurus*; premaxillary beak wider than the distance between the last maxillary tooth; pterygoid body almost horizontal, not vertical as in *Tarchia*, *Saichania* and most ankylosaurids; teeth similar to *Pinacosaurus* with weakly developed cingulum.

Skull roof (Figure 1) – Remodelled surface bone prohibits any description of the skull roof with regard to sutural boundaries. Dorsally, the skull is longer than wide (excluding the squamosal horns) and is almost subtrapezoidal due to the extreme lateral flaring of the external

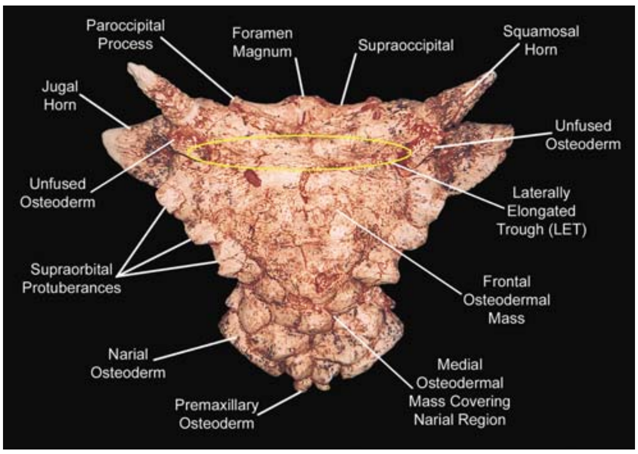

Figure 1. Skull roof.

*For correspondence. (e-mail: cliff@westernpaleolabs.com) nares (Figure 1), giving the snout a 'pinched' or constricted look mid-length. The supraorbital protuberances (Figure 1) are prominent both caudolaterally and anterolaterally. The widest point of the skull roof is formed by the squamosal horns which are more gracile and tapering than seen in any other ankylosaurid. The skull has an arching profile that reaches its zenith well rostral to the orbits, when seen in lateral view with the maxillary tooth row horizontal. The nuchal rim is smaller and reduced compared to *Tarchia* and *Saichania*.

The surface of the skull is extensively remodelled mostly as pyramid-shaped ornamentation, except across the skull roof posterior to the level of the orbits (Figure 1). Computed tomography (CT) reveals that the nodes on the skull surface are not osteoderms fused to the skull surface, but extensively remodelled bone (Figure 2 *c* and *d*, arrows). That the most 'fused cranial armor' of ankylosaurs is the remodelled surface bone was first proposed by Coombs[1] and has been supported by recent work[2,3]. The cranial ornamentation is roughly bi-symmetrically arranged on the skull, especially near the lateral margins of the dorsal surface.

As in *Pinacosaurus* and *Saichania*, there are two laterally projecting, sharp-keeled, supraorbital ornamentations over the orbit in the specimen, and a similar structure in the vicinity of the prefrontal (Figures 1 and 3). In *Tarchia*, these structures project dorsally more than laterally, whereas in *Ankylosaurus* these supraorbital ornamentations have coossified with the squamosal 'horn' into a single structure that extends along the dorso-lateral surface of the skull[4]. In all of these ankylosaurs and this specimen, the sharp-keeled structures do not project abruptly from the skull, but are continuous with the bones surrounding the orbit. As a result, with the posteriorly widening of the skull, the orbit actually faces slightly anteriorly and lateroventrally in the specimen (Figure 3). The supraorbital ornamentation is imbricated in all three taxa, so that the anterior edge of one overlaps the posterior edge of the preceding. A few osteoderms are present, which appear to be only partially fused. One pair is located on the skull roof just anterior of the squamosal horns (Figure 1). Another is a single osteoderm on the left jugal horn (Figure 4). A single unfused pair is located below the orbits (Figure 3) and appears to be unique to the specimen.

The central portion of the skull roof, at the level of the posterior rim of the orbit, is depressed into a laterally elongated trough (Figure 1, oval). This feature does not appear to be due to crushing as evidenced by CT data (Figure 2 *e*, arrow). The bone in this region is not remodelled (Figure 1), except at the lateral margins. A similar trough lacking ornamentation also occurs in *Pinacosaurus* and *Tarchia*. The orbit in the specimen is tear drop-shaped (Figure 1) with the tapered end of the tear shape pointing anteriorly. This differs from *Tarchia* which has circular orbits and *Saichania* which are subcircular. Significant features of the specimen are those created by the dermal ossifications in the nasal region of the skull (Figures 1 and 5). The narial osteoderms are large and highly ornamented to the extent that they create a flared look, projecting anteriorly and laterally, giving the skull a bull-like appearance. The specimen exhibits narial apertures

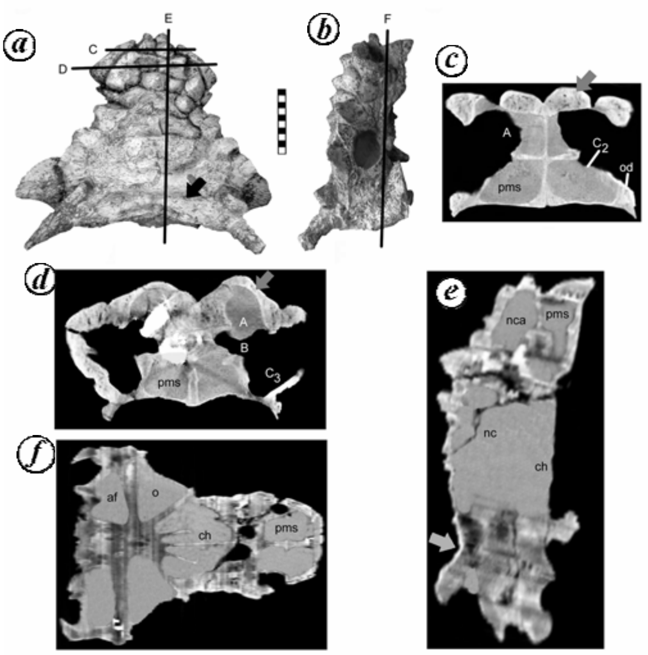

Figure 2. Computer tomography of the *Minotaurasaurus* skull. Reference images of skull in dorsal (***a***) and lateral views (***b***). Arrow shows the location of the longitudinal or transverse trough. ***c***, Section across premaxilla showing development of ornamentation as remodelled bone (arrow), and thin osteoderm (od) covering the premaxilla below the external narial cavity. Note expanded sinus chamber into the premaxillae (pms). Apertures A and C2 of Hill *et al.*[5] denoted. ***d***, Section through posterior portion of external nares showing premaxillary sinus, and apertures A, B and C3 (which is a fossa). ***e***, Sagittal section showing the cross-section of the trough (arrow), choana (ch), nasal cavity (nca), narial chamber (nc) and premaxillary sinus (ps). ***f***, Horizontal section showing the premaxillary sinus (pms), orbit (o) and adductor fossa (af).

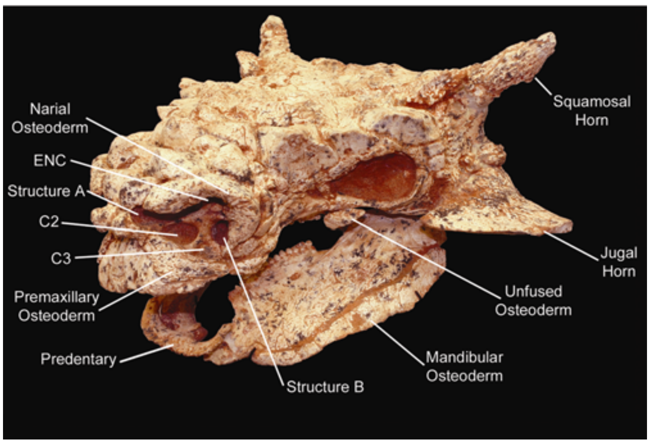

Figure 3. Antero lateral view of skull.

and recesses similar to those seen in *Pinacosaurus grangeri*, IGM 100/1014 and an undescribed juvenile *Pinacosaurus* skull cast. While these skulls exhibit variation of these apertures and recesses, skulls of the specimen most clearly resemble those of the *Pinacosaurus* skull cast and face rostrally. The narial region has three apertures and a shallow fossa within a larger structure, here termed the external nasal cavity (Figure 3). The external nasal cavity is bound by a single osteoderm (Figure 5), rather than two as seen in *Pinacosaurus*. The dorsal-

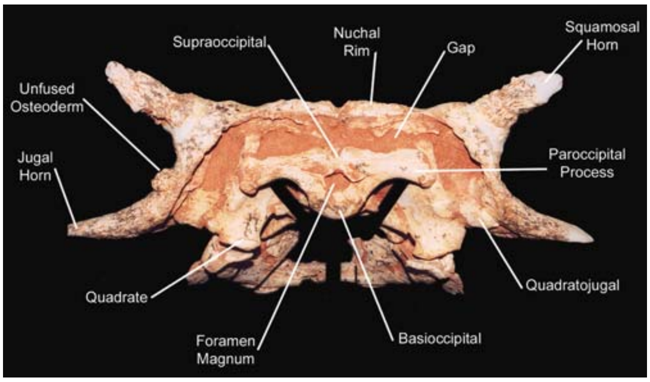

Figure 4.

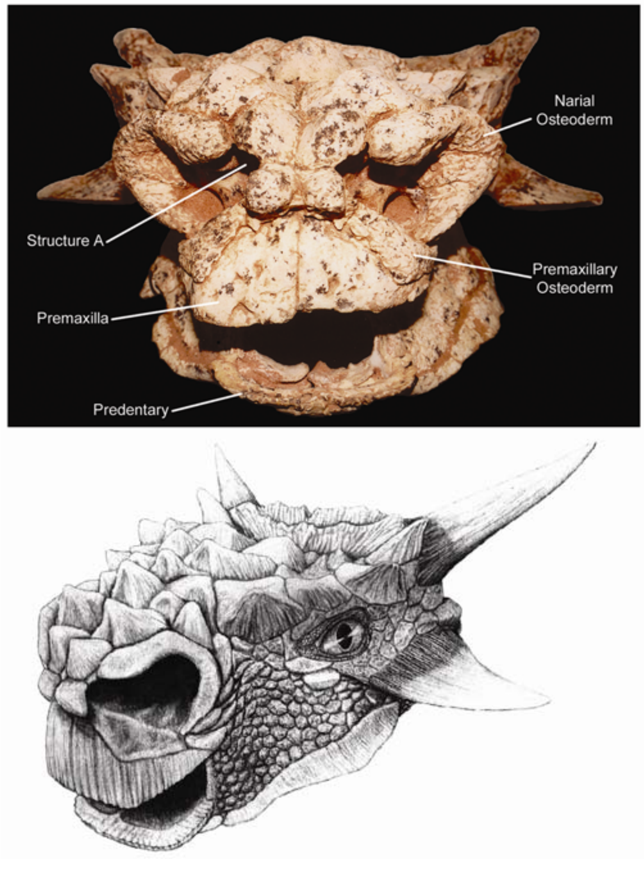

Figure 5.

most aperture, which is the largest of the three, is the external nares into the nasal chamber contained within the muzzle. The right and left external nares are divided by a thin, discontinuous, midline septum as revealed by CT (Figure 2). Below the external nares are a pair of elliptical apertures separated by a wide bar of bone and a shallow fossa. Structure 'B' (Figure 3) is a well-marked, round fossa. It is located caudolaterally fully within the premaxilla, as is seen in *Pinacosaurus*. It corresponds to aperture B of Hill *et al.*[5], and the anterior one to aperture C2. Aperture C1 of Hill *et al.*[5] is absent. CT reveals that aperture B opens into the posterior portion of the premaxillary sinus, and not into the maxillary sinus. Aperture C2 opens in about the middle of the premaxillary sinus. The shallow fossa may correspond to aperture C3 of Hill *et al.*[5]. However, it does not pierce into the premaxilla.

The premaxillary beak surface is partially covered by secondary dermal ossifications (Figures 3 and 5), which is the exception with most of the Asian ankylosaurs. The premaxilla has an inverted, thin, triangular osteoderm coossified to it along the ventral margin of the narial opening. As seen by CT, the structure is an osteoderm and not remodelled bone (Figure 2 *c*). In contrast, outgrowths of the premaxilla (Figure 1) are seen as a pair of nipple-shaped structures which project anteriorly from the nasal processes. This feature is seen to a lesser extent in *P. grangeri*, IGM 100/1014 described by Hill *et al.*[5]. The tomial (ventral) ridge of the left premaxilla is incomplete (Figures 3 and 5). The palatal portions of the premaxillae in the specimen and *Pinacosaurus* are unusual in that they change shape from anterior to posterior, resulting in a sharp premaxillary beak. Anteriorly, they are flat to slightly concave (i.e. arched dorsally), and posteriorly are convex. This convexity occurs in the region anterior to the vomers. The premaxilla forms the anterior-most border of the palatal vacuity as in *Pinacosaurus*, excluding the maxilla from the vomer, but unlike *Saichania*. In lateral view, processes of the premaxilla obscure the rostral-most maxillary teeth (Figure 3). The two apertures, B and C2, within the external nasal cavity open into the premaxillary sinus, which fills almost the entire premaxilla. In horizontal cross-section, CT reveals the chamber to be subrectangular (Figure 2 *f*). In vertical cross-section the premaxilla is subtriangular anteriorly and almost square within the external nasal cavity (Figure 2 *c*). The sinus does not extend into the nasal process of the premaxilla as it does in *Ankylosaurus*[4].

Palate (Figure 6)

The premaxillary palate is wider than long, not parallel-sided, but somewhat angled; wider posteriorly, narrower anteriorly and squared-off at the rostral edge. It exhibits a ventrally convex premaxillary palate. The ventral surface of the skull is dominated by a large choanal recess. This recess is bounded by the pterygoids posteriorly, the maxillae and ectopterygoids laterally and the premaxilla anteriorly. The vomer and pterygoids, which have a pterygoid foramen, form a narrow, sheet-like palatal keel. One clear suture can be discerned on both the left and right sides, between the vomer and the pterygoids (Figure 6). The vomers are fused along their midline. They extend ventrally well beyond the level of the maxillary tooth crowns, and are visible in lateral profile of the skull. This is not the case in most ankylosaurids, where the vomer does not extend below the teeth. Dorsally, as revealed by CT, the vomers and ventral extension of the nasals do not form a complete sagittal partition dividing the nasal chamber in half as it does in *Euoplocephalus*[6]. *Pinacosaurus* also does not have a complete partition.

The epipterygoid is a small, triangular structure forming the anterior half of the ventrolaterally projecting pterygoid processes or flange; it separates the pterygoid from the maxilla. The main body of the pterygoids is near horizontal, rather than vertical or even slightly overturned as seen in most ankylosaurids. As a result the interpterygoid vacuity is visible in palatal view. Anteriorly, the vomer has an overlapping suture on the lateral surface of the anterior or vomerine process of the pterygoid. Dorsally, as revealed by CT, the vomerine processes meet and are fused, but remain separate along their ventral margin. In this, the specimen differs from other ankylosaurids where the pterygoids typically meet and sometimes fuse (e.g. *Ankylosaurus*) along their midline. Posteriorly, the pterygoid meets the basisphenoid anterior to the basitubera and extends laterally around the small basipterygoid process, as seen by CT. The quadrate process is short and deep, and projects posterolaterally from near the level of the basipterygoid process. The articular surface of the quadrate is less steeply angled and flatter than what is seen in *Tarchia*. The pterygoid–quadrate articulation is more flattened in the specimen than *Saichania*, but is similar to *Tarchia*.

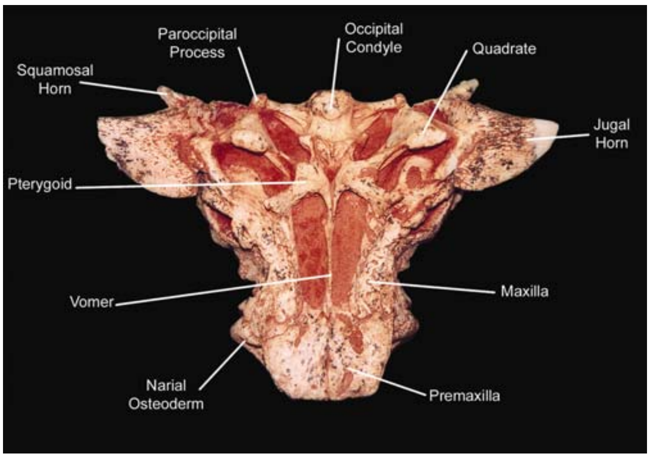

Figure 6.

Occipital region and braincase (Figures 4 and 6)

The basioccipital region is well preserved. The occipital condyle is heart-shaped and faces ventrally from the plane of the maxillary tooth rows. As with most ankylosaurids, it lacks a neck. Most of the cranial foramina are not visible on the skull of the specimen, except for those near the anteroventral base of the paroccipital process. The foramina visible include, from anterior to posterior, the fenestra ovalis, fenestra miotica and hypoglossus (XII) fenestra. The vidian canal is prominent in the CT. Regrettably, contrast between the matrix infilling of the brain cavity and the surrounding bone is not good enough to allow detailed interpretation of the finer details within the braincase. When viewed dorsally, the occipital condyle of the specimen is almost entirely obscured by the paroccipital processes, which themselves are entirely visible and not obscured by any overhang of the skull roof (Figure 1). The braincases of *Tarchia* and *Saichania* are entirely obscured by the skull roof when viewed dorsally. The occiput of *Minotaurasaurus* is low and rectangular, and much wider transversely than it is high. The paroccipital processes do not extend far enough laterally to make contact with the medial edge of the squamosal horn (Figure 4). Instead, they fall well short of contact by some 3 cm, which is a feature unique to this genus. In both *Tarchia* and *Saichania*, the paroccipital processes are hooked and extend laterally all the way to the medial edge of the squamosal horn. The basisphenoid and basioccipital are fused together, although the suture can be seen in CT. The sutural area is expanded as a ridge as in most ankylosaurs, marking the insertion for the rectus capitis and longus capitis. In most ankylosaurs, the prominent development of this insertion ridge suggests that these are major muscles in the neck of ankylosaurs.

Looking at a posterior view of the skull (Figures 1, 4 and 6), the nearly perfect bilateral symmetry and lack of crushing of both the left and right jugal horns provide evidence that the jugal horns thrust more laterally than ventrally, unlike in other ankylosaurs such as *Tarchia* and *Saichania*.

The maxillary tooth rows are deeply inset (emarginated) from the lateral edge of the skull. The maxillary shelf lateral to the tooth row is broad and extends beneath the middle of the orbit as in most ankylosaurids; it is extremely wide anteriorly and narrows posteriorly in *Saichania*. The width between the posterior-most maxillary teeth is less than the premaxillary beak width (Figure 6) as in *Euoplocephalus*, but unlike in *Pinacosaurus* and *Saichania*, it is equal to the width in *Tarchia* and *Ankylosaurus.*

Mandibles (Figures 7 and 8)

Both hemimandibles are preserved along with the slender predentary. They were separated during preparation from the skull and are in good condition showing little plastic distortion. The cheek tooth row is inset deeply, as is typical of the ankylosaurids. The right mandible is nearly complete with only little damage to the anterior symphysis grove that receives the predentary, starting about 3 cm behind. The posterior processes of the articular and surangular are incomplete on the right mandible. The symphysis for the predentary on the right mandible is complete with no crushing and should be used when making comparisons with other specimens. The left mandible is also nearly complete. The symphysis for the predentary which is crushed has been restored short. The posterior processes of the articular and surangular are complete on the left mandible and should be used when making comparisons with other specimens.

Ventrolaterally, there is a long, narrow osteoderm partially fused to the mandible along the lateral edge (Figures 7 and 8). This osteoderm does not extend dorsally onto the lateral surface as it does in *Saichania*. These osteoderms extend nearly the entire length of the mandible rostrocaudially, which differs from both *Tarchia* and *Saichania*, in which the hemimandible covers only about half the length of the mandible. The right mandibular osteoderm is missing approximately 5 cm of bone from the middle.

Figure 7. Dorsal view of mandibles and predentary.

The tooth row retains the primitive position along the margins of the dentary. However, to compensate for the inset of the maxillary teeth, the mandibles are canted so as to put the teeth into occlusion with the maxillary teeth. This canting of the mandibles is synapomorphic for ankylosaurids more derived than *Cedarpelta* and explains the apparent dorsally arced tooth row commonly reported for ankylosaurids[7,8]. The lateral surface of the mandible shows a roughened texture of the bone surface along the ventral half; the dorsal half is smooth. When the mandibles are in occlusion, the boundary between the smooth and the textured surfaces is opposite the lateral edge of the maxillary shelf and thus marks the position of the cheeks on the lower jaws. The coronoid process is low, but does extend to the level of the teeth. Medially, a small coronoid is present at the anterior base of the process, immediately posterior to the last dentary tooth. A small coronoid is also present in *Ankylosaurus*[4], whereas it is significantly larger relative to the mandible in *Tarchia* and *Euoplocephalus*.

Predentary (Figures 7 and 9)

The predentary is slender and bracket-shaped and resembles that of *Pinacosaurus*, and so is more gracile than in *Tarchia*, but not as much as in *Euoplocephalus*. In cross-section, it is subtriangular. The dorsal or occlusal surface is flat and bears numerous nutrient foramina to serve the ramphotheca. These foramina pierce through to the anteroventral surface to a network of vascular grooves. The predentary is proportionally larger in the specimen than *Tarchia*, along with being broader front to back. The midline projection on the triturating surface is less pronounced in the specimen than *Tarchia*.

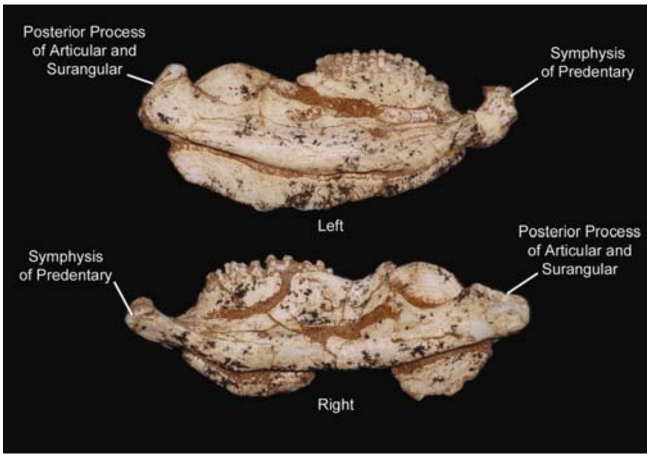

Figure 8. Medical view of hemi mandibles.

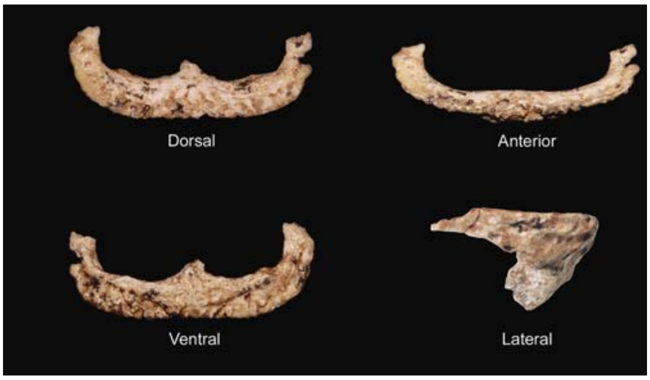

Figure 9. Predentary.

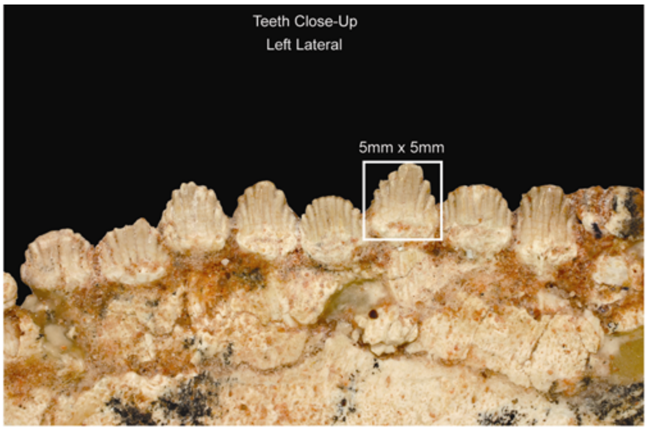

Figure 10. Close-up of teeth.

Teeth (Figure 10)

The teeth are leaf-shaped, with each one bearing vertical striations dividing the crown surface into eight cusps. There are a total of 17 teeth and alveoli in the left maxilla, 16 in the right, and 15 in the left dentary and 16 in the right. The maxillary teeth are up to 25% larger than the dentary teeth. The crowns of the teeth are variable, with some being swollen. Swollen teeth, have a weakly developed cingulum, which is best developed on the labial side of the dentary teeth. A few of the teeth show apical wear, which is unusual for ankylosaurids, where wear is typically on the crown face[7].

A few key measurements allow us to extrapolate the length of *Minotaurasaurus*. The maximum length of the skull is 30 cm. Maximum width of the skull measured from the jugal horns is 43 cm. Distance between the squamosal horns is 34.2 cm. Total length of right hemimandible is 22.5 cm. Width of predentary is 10.3 cm. These measurements lead us to conclude that *Minotaurasaurus* grew to a length of at least 4.2 m. The unfused osteoderms may indicate an animal not quite fully grown and therfore likely that larger individuals will be discovered.

Conclusion

This new specimen increases the diversity of East Asian ankylosaurids. The osteologic manifestation of cranial ornamentation in *Minotaurasaurus* has more surface relief throughout the skull than any of the other known members of this family. This ornamentation has developed in spite of the fact that features of this new genus are more primitive than what is seen in other members of the family. This is yet another example of the degree to which ornamentation has developed within this group and with time we will no doubt see specimens discovered that will push the envelope of this development. Regrettably, the provenance for the specimen is poor. However, we believe that the specimen is too important not to be described. The skull shows an interesting blend of characters that are also seen in *Saichania* and *Pinacosaurus*. A phylogenetic study of ankylosaurs is currently under way, which will elaborate upon the relationship of *Minotaurasaurus*.

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