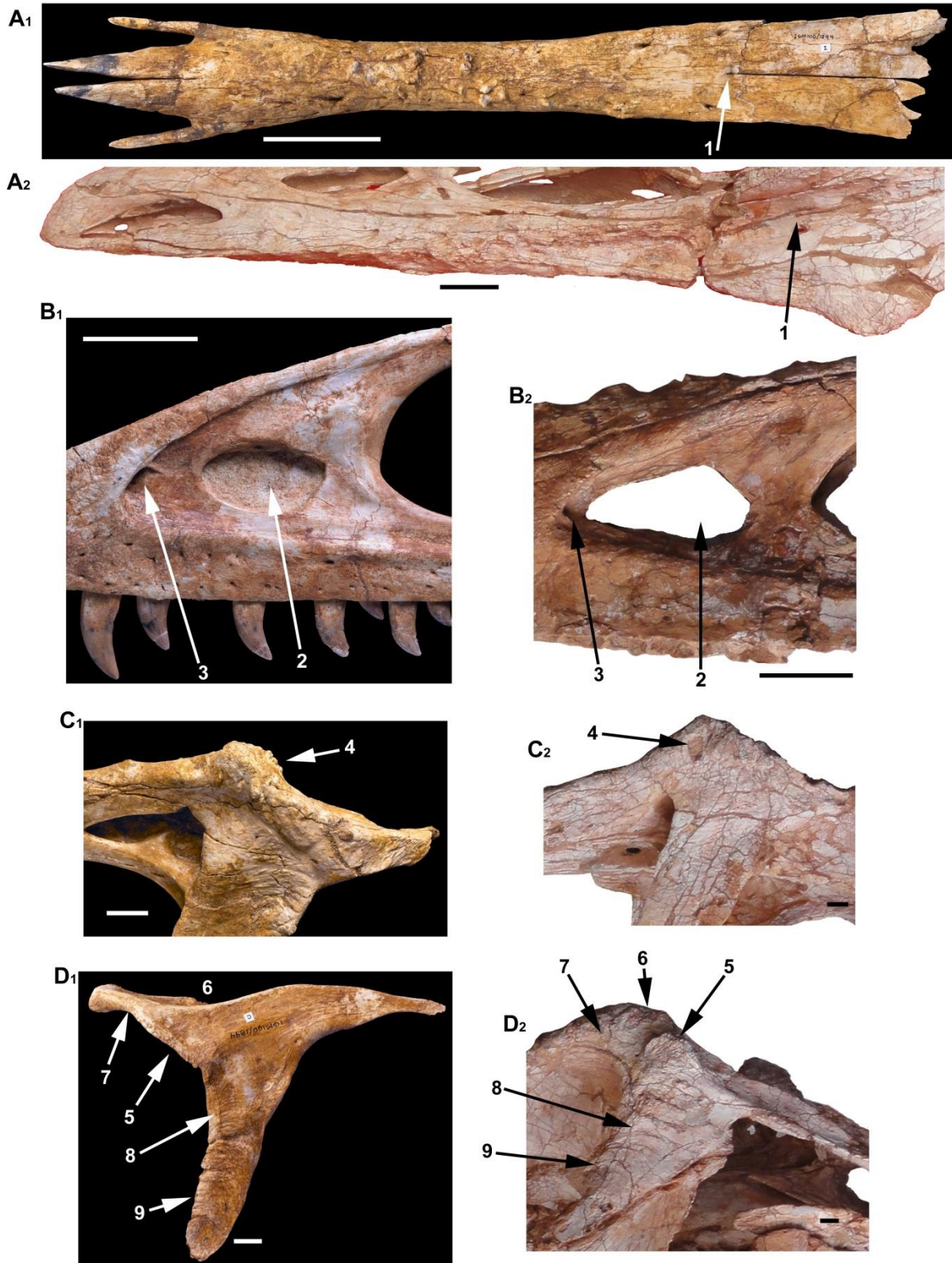
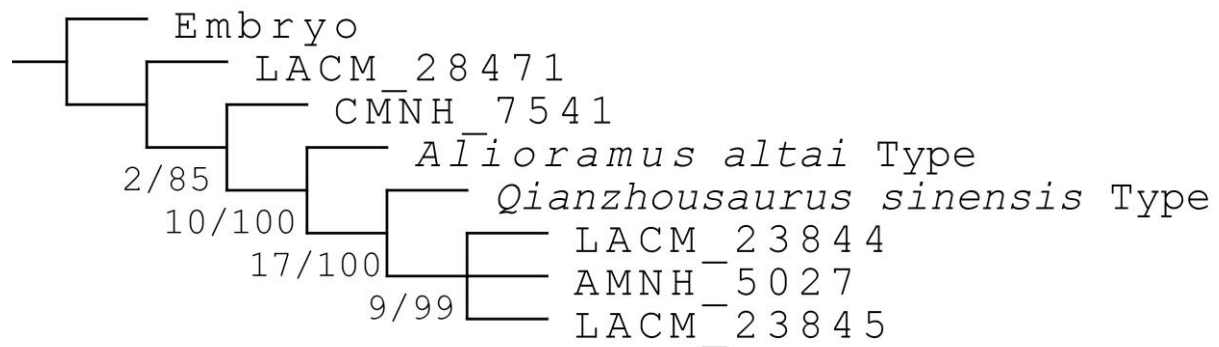




Supplementary Figure 1. Comparisons of the holotypes of *Alioramus altai* and *Qianzhousaurus sinensis* illustrating selected features that exhibit a more mature condition

in *Qianzhousaurus*. Photographs of *Alioramus altai* on the left (denoted by subscript 1) and those of *Qianzhousaurus sinensis* on the right (denoted by subscript 2). (a) Nasals in dorsal view with arrow 1 denoting the anterior end of the open suture (note that the line in front of this arrow, discontinuous with the suture, is a crack). (b) Maxillae in lateral view with arrow 2 denoting the more anteriorly placed maxillary fenestra of *Qianzhousaurus* and arrow 3 denoting the more rounded (less slit-like) promaxillary fenestra of *Qianzhousaurus*. (c) Lacrimals in lateral view with arrow 4 denoting the larger, more swollen, and more overhanging cornual process of *Qianzhousaurus*. (d) Postorbitals in lateral view with arrow 5 indicating the larger and more swollen postorbital horn of *Qianzhousaurus*, arrow 6 the convex (compared to horizontal or slightly concave) dorsal border of the bone of *Qianzhousaurus*, arrow 7 the shorter and deeper anterior process of *Qianzhousaurus*, arrow 8 the anteroposteriorly broader ventral process of *Qianzhousaurus*, and arrow 9 the incipient subocular process of *Qianzhousaurus*. Scale bars in A-B equal 5 cm and C-D equal 1 cm. All photos of *Alioramus altai* were taken by Mick Ellison (American Museum of Natural History).



Supplementary Figure 2. Ontogenetic tree indicating the relative maturity of the *Qianzhousaurus sinensis* holotype. Strict consensus of two most parsimonious trees from the ontogenetic analysis (97 steps, consistency index=0.948, retention index=0.967). Numbers next to nodes denote Bremer supports/jackknife (absolute frequencies, 36% character removal probability, 1000 replicates). See Supplementary Note 2 for more details on this analysis.



Supplementary Figure 3. Supplementary phylogenetic analysis of long-snouted tyrannosauroids. Strict consensus phylogeny when *Qianzhousaurus sinensis* is included in the phylogenetic dataset of Loewen et al. (see Supplementary Note 3). Numbers next to nodes are jackknife support values (absolute frequencies, 1000 replicates, 36% character removal probability).

Supplementary Table 1. Measurements (in mm) of cervical vertebrae of the *Qianzhousaurus sinensis* holotype.

	Length	width	Height (posterior articular end)	Neural canal	
				width	height
intercentrum	19.4	55.5			
axis	54.5				
3	48.8	41.2 (posterior articular end)			
4	55.8	39	51.8	16.7	21.5
6	86.7	61			
7	88.1	66.5	67.1	21.1	20.7
8	91.5	57.7			
9	85.1	58.9			
10	78.9	56.9			

Supplementary Table 2. Measurements of the anterior dorsal vertebrae (in mm) of the *Qianzhousaurus sinensis* holotype.

	length	Posterior articular end width
1 st dorsal	65.5	55.8
2	68.4	53.6
3	69.8	54.1
4	75.1	57.7

Supplementary Table 3. Measurements of pneumatic foramina on the cervical and dorsal vertebrae (in mm) of the *Qianzhousaurus sinensis* holotype.

	length	depth
Cervical 2	24.8 (11.8)	17.9 (7.3)
3	3.9	3.9
4	24 (15.3)	18.9 (11.3)
6	49.2 (24.8)	25.7 (15.2)
7	51.3 (32.5)	28.9(18.3)
8	48.9(24.2)	27.8 (11.8)
9	41.2 (23.0)	31.6(11.9)
10	34.9(16.1)	24.1(11.0)
Dorsal 1	24.5(11.4)	16.6(7.4)
2	18.3	11.7
3	19.0	7.9
4	16.3	7.2

Supplementary Table 4. Measurements of the caudal vertebrae (in mm) of the *Qianzhousaurus sinensis* holotype.

Anterior caudals	length
1 (partial)	74.5
2	85.1
3	96.1
4	94.1
5	94.1
6	98.5
7	52.7
Mid-posterior caudals	
1	54.9
2	96.7
3	102.7
4	100.9
5	97.5
6	97.6
7	88.3
8	84.7
9	80.4
10	75.2
11	68.3

Supplementary Table 5. Measurements of the appendicular skeleton (in mm) of the *Qianzhousaurus sinensis* holotype.

Femur: proximodistal length 700 mm

Tibia: proximodistal length 760 mm

Astragalus: proximodistal length 245 mm

Calcaneum: proximodistal length 70 mm

Metatarsal I: proximodistal length 75 mm

Metatarsal III: distal end mediolateral width 55 mm, anteroposterior length 46 mm

Metatarsal IV: distal end mediolateral width 56 mm, anteroposterior length 47 mm

Supplementary Table 6. Data used in linear regression of femur length vs. skull length.

TAXON	SPECIMEN	FEMUR LENGTH (mm)	SKULL LENGTH (mm)
<i>Albertosaurus sarcophagus</i>	TMP 1981.10.1	940	890
<i>Albertosaurus sarcophagus</i>	TMP 1985.98.1	750	720
<i>Daspletosaurus torosus</i>	FM PR308 (AMNH 5434)	940	1118
<i>Daspletosaurus</i> sp.	MOR 590	865	895
<i>Gorgosaurus libratus</i>	AMNH 5458	1025	990
<i>Gorgosaurus libratus</i>	NMC 2120	1030	970
<i>Gorgosaurus libratus</i>	ROM 1247	765	782
<i>Gorgosaurus libratus</i>	TMP 91.36.500	645	670
<i>Gorgosaurus libratus</i>	TMP 94.12.602	920	870
<i>Gorgosaurus libratus</i>	TMP 99.33.1	765	700
<i>Gorgosaurus libratus</i>	USNM 12814 (AMNH 5428)	860	820
<i>Gorgosaurus libratus</i>	AMNH 5664	700	678
<i>Gorgosaurus</i> sp.	MOR 1153	460	525
<i>Tarbosaurus baatar</i>	MPC-D107/0 2	1120	1220
<i>Tarbosaurus baatar</i>	MPC-D107/0 3	990	1100

<i>Tarbosaurus baatar</i>	PIN 551-3	970	1130
<i>Tarbosaurus baatar</i>	PIN 552-2	560	502
<i>Tarbosaurus baatar</i>	ZPAL MgD-1/3	700	740
<i>Tyrannosaurus rex</i>	BHI 3033 (Stan)	1350	1360
<i>Tyrannosaurus rex</i>	FMNH PR2081 (Sue)	1321	1530
<i>Tyrannosaurus rex</i>	MOR 555	1280	1500
<i>Tyrannosaurus rex</i>	RTMP 81.6.1 (Black Beauty)	1210	1160

Supplementary Note 1

We conducted a linear regression of skull length vs. femur length for several tyrannosaurid specimens, in order to gauge whether the holotypes of *Qianzhousaurus sinensis* and *Alioramus altai* have longer than expected skull lengths for their femur lengths (which is a proxy for body size). If this is the case, then this is evidence that long-snouted tyrannosaurids have a unique body plan compared to other taxa, and provides further support that the long-snouted taxa are not juveniles of previously known tyrannosaurids such as *Tarbosaurus*. Brusatte et al.¹ reported the results of a similar procedure in which they plotted by hand the position of the *A. altai* holotype on the skull vs. femur length plot of Currie². However, no statistical analysis or confidence intervals were presented, because the original data used by Currie² were not available to the authors.

Here, we utilize a dataset of tyrannosaurid skull and femur lengths from Williams et al.³, which derived from the Currie² dataset. This dataset includes 22 tyrannosaurid specimens for which both of these measures are available. In this dataset, total skull length is measured in lateral view from the anterior edge of the premaxilla to the posterior tip of the paroccipital process. The dataset includes a broad sample of albertosaurine (*Albertosaurus*, *Gorgosaurus*) and tyrannosaurine (*Daspletosaurus*, *Tarbosaurus*, *Tyrannosaurus*) specimens. The dataset was log transformed and subjected to linear regression analysis in PAST v. 2.17 and 95% confidence intervals were calculated. There is a highly significant relationship between skull and femur lengths (24 specimens, $r=0.95944$, $p<0.0001$). For the best fit line, the slope is 1.0661 and the intercept -0.184. The 95% confidence intervals on the slope are 0.8799-1.211 and on the intercept are -0.6065-0.3604. The results of the regression are shown in Figure 4, with the positions of the *Qianzhousaurus sinensis* and *Alioramus altai* type specimens added a posteriori (in other words, they were not included in the analysis, so that the analysis returned a best fit line for all non-long-snouted tyrannosaurids that the positions of the long-snouted specimens could be compared against).

Very clearly the *Qianzhousaurus sinensis* and *Alioramus altai* type specimens fall outside of the 95% confidence intervals as defined by the non-long-snouted taxa (Figure 4). If the two long-snouted specimens are included in the analysis from the beginning, they still fall outside of the 95% confidence intervals. These results indicate that the two long-snouted specimens have

significantly longer skulls relative to their femur length than non-long-snouted tyrannosaurids. Or, put another way, the long-snouted taxa have significantly longer skulls than would be predicted based on their femur lengths if the skull-femur regression of non-long-snouted tyrannosaurids was used as a guide.

This conclusion is reinforced by comparisons with other tyrannosaurids that have nearly identical femur lengths. The type of *Qianzhousaurus sinensis* has a femur that is 700 millimeters long and a skull that is 1000 millimeters long between the premaxilla and paroccipital process. By comparison, a specimen of *Gorgosaurus libratus* in the analysis (American Museum of Natural History AMNH 5664) with a femur length of 700 millimeters has a skull that is only 678 millimeters long, and a specimen of *Tarbosaurus bataar* (Institute of Paleobiology Warsaw ZPAL MgD-I/3) with a femur length of 700 millimeters has a skull that is only 740 millimeters long. The type of *Alioramus altai* has a femur length of 560 millimeters and a skull length of 700 millimeters. By comparison, a specimen of *Tarbosaurus bataar* (Paleontological Institute Moscow PIN 552-2) with a femur length of 560 millimeters has a skull that is only 502 millimeters long.

In summary, the analysis indicates that the long-snouted tyrannosaurids *Qianzhousaurus sinensis* and *Alioramus altai* have a novel bauplan relative to other tyrannosaurids, in which the skull is significantly longer relative to femur length. Furthermore, explicit comparisons with *Tarbosaurus* specimens of the same femur length as both long-snouted holotypes indicates that the long-snouted taxa have substantially longer skulls, which is further evidence that they are not juveniles of *Tarbosaurus* (see also^{1,4}).

Supplementary Note 2

The following discussion outlines the evidence that the *Qianzhousaurus* holotype corresponds to a more mature (skeletally mature and larger) individual compared to the holotypes of *Alioramus altai* and *Alioramus remotus*. A selection of fusion characters and discrete characters supporting these arguments are shown in Figure S1.

Body size

The type specimen of *Qianzhousaurus* is considerably larger than the types of *Alioramus altai* and *Alioramus remotus*. The femur of *Qianzhousaurus* is approximately 70 centimeters long, 25% larger than the 56-cm-long femur of the *Alioramus altai* type. Based on the equations of Christiansen and Farina⁵, which predict body mass based on femur length, this difference in femur length corresponds to approximately a two-fold difference in body mass (~369 kg for the *Alioramus altai* type, ~757 kg for the *Qianzhousaurus* type). Furthermore, the skull of the *Qianzhousaurus* type is 90 cm long anteroposteriorly when measured between the anterior edge of the premaxilla and the posteroventral corner of the quadrate in lateral view, compared to ~63 cm in the *Alioramus altai* holotype and a nearly identical (within 3-5%) reconstructed measure for the *Alioramus remotus* holotype. This is approximately a 43% difference in skull length between the type of *Qianzhousaurus* and the two *Alioramus* specimens.

Body size alone is not a reliable indicator of maturity in living and fossil archosaurs^{6,7}. However, within a single species or closely related taxa, drastic differences in body size between two specimens usually correspond to marked differences in numerical age as determined by histology. This has been empirically demonstrated for many different species of dinosaurs, including the tyrannosaurids *Albertosaurus*, *Daspletosaurus*, *Gorgosaurus*, and *Tyrannosaurus*⁸⁻¹¹. A summary table provided by Myhrvold (2013, Table S6)¹¹ lists femur size and histological age for several tyrannosaurid specimens based on various literature sources⁸⁻¹⁰. In *Gorgosaurus*, a ca. ~56-cm-long femur like that of the *Alioramus altai* type would correspond to a ~7 year old individual as determined by histology, whereas a ~70-cm-long femur like that of the *Qianzhousaurus* type would correspond to a ~14 year old individual. In *Tyrannosaurus*, a ~70-cm-long femur would correspond to ~ 12-year-old individual. Femora that are ca. 56 cm long

are not yet known or measured for *Tyrannosaurus*, but when a body size estimate based on this femur length⁵ is plotted on the body mass vs. age plots of Myhrvold (2013, figure S1)¹¹, the estimated age is approximately 8 years old.

Therefore, if two different closely related tyrannosaurids are a reliable guide, then the differences in femur length between the *Qianzhousaurus* type and the *Alioramus altai* type would correspond to a difference in numerical age of at least a few years, with the *Qianzhousaurus* type being older. As large-scale increases in numerical age correspond to increases in skeletal maturity¹², the *Qianzhousaurus* type would also be predicted to be more mature than the *Alioramus altai* type based on body size alone.

Bone fusion

Introduction: In archosaurs generally, sutures between some adjoining bones (mostly those of the braincase) and different parts of an individual vertebra close as an individual matures^{7,13}. This sequence usually occurs in the following manner: two bony structures that are initially separate begin to fuse, such that they are partially joined together but the suture line between them is still visible, and then completely fuse when the suture is obliterated and no longer visible. We follow Brochu (1996)⁷ and Irmis (2007)¹³ in using the term “open suture” to refer to any suture line that is visible on the surface of the bone, regardless of whether the two fusing elements are firmly attached to each other or not. A “closed suture” is one that is no longer visible. We also use the term “fusion” not in the histological sense, but in the sense of two elements joining together into a single, attached structure (which can have either open or closed sutures).

Ontogenetic trends in suture closing have been little studied in dinosaurs, including tyrannosaurids. In one of the few published studies, Irmis (2007)¹³ described complex patterns of suture closings in tyrannosaurids, and noted that some large, clearly adult specimens (based on histological age of long bones) possess open neurocentral sutures in some vertebrae (e.g., ref 14). Therefore, it is not yet clear, based on large samples of specimens comprising ontogenetic growth series, whether particular patterns of suture closure occur in a characteristic manner during tyrannosaurid growth (e.g., whether the caudal vertebrae close their neurocentral sutures before the cervical vertebrae, which if true would mean that a specimen with closed caudal neurocentral sutures but open cervical sutures would be demonstrably younger and less mature

than one with closed caudal and cervical sutures). Regardless, comparisons of juvenile and adult tyrannosaurid specimens do give some insight into probable ontogenetic patterns of suture change, which are beginning to be fleshed out for *Albertosaurus* and *Tyrannosaurus*^{12,15}. These limited comparisons do not yet provide clear insight into patterns of vertebral suture closing, but do indicate that some cranial sutures become more strongly fused and eventually closed during ontogeny.

Based on these comparisons with other tyrannosaurids, we here compare the state of suture morphology in the holotype of *Qianzhousaurus* and the types of *Alioramus altai* and *Alioramus remotus*, and note clear differences in open vs. closed sutures and the degree of fusion of open sutures. Relying on the principle that a greater degree of fusion and suture closing should generally be indicative of a more skeletally mature individual, we present evidence that the *Qianzhousaurus* holotype is more skeletally mature than the two *Alioramus* holotypes. In the following discussion, all comparisons to the *Alioramus altai* holotype are based on observations of the original specimen (Institute of Geology of Mongolia, IGM 100/1844) and the data and photographs published by Brusatte et al. (2012)¹, and all comparisons to the *Alioramus remotus* holotype are based on the description of Kurzanov (1976)¹⁶ and high resolution photographs of the original specimen (Paleontological Institute Moscow PIN 3141/1).

Nasal: All tyrannosauroids possess fused nasals, in which the left and right elements are joined into a single structure¹⁷. However, portions of the midline suture between the nasals remain open, usually at the anterior and posterior ends of the bone. The degree of openness depends on age and maturity, because the suture progressively closed as an individual matured. This is shown by growth series of *Albertosaurus*/*Gorgosaurus*^{15,17} and *Tarbosaurus*^{18,19}. In *Albertosaurus*/*Gorgosaurus*, the open suture at the posterior end of the nasals of a juvenile specimen (Royal Tyrrell Museum TMP 86.144.1) is approximately 31% of the length of the nasals, whereas in an adult (TMP 86.64.1) the open portion of the suture comprises only 15% of nasal length¹⁷. Carr (1999: figure 2B,C)¹⁵ also showed a similar ontogenetic decrease in the length of the open suture when comparing the juvenile TMP 86.144.1 to a more mature, but not yet fully grown, subadult specimen of *Gorgosaurus* (Royal Ontario Museum ROM 1247). An ontogenetic decrease is also seen in *Tarbosaurus*, as a juvenile described by Tsuihiji et al. (2011)¹⁹ (Mongolian Paleontological Center MPC-D 107/7) has an open suture extending 30% of

nasal length whereas in an adult (Institute of Paleobiology Warsaw ZPAL MgD-I/4) this measure is only 16%. Although the above discussion refers to the trace of the suture on the dorsal surface of the nasal, it is also worth noting that computed tomography data supports the internal ontogenetic closing of the nasal sutures in *Gorgosaurus* (ref 17: fig. 7).

The open suture on the posterior end of the nasals extends for 10% of the length of the bone in the holotype of *Qianzhousaurus*. It is much more extensive in the holotype of *Alioramus altai*, where it extends for 21% of nasal length. The nasal of the *Alioramus remotus* holotype is broken, so exact percentages cannot be calculated, but the open suture extends to nearly the same level anteriorly as the distinctive mound-like midline ornaments. This is also the case in *Alioramus altai*, suggesting that the percentage length of the open suture is similar in both taxa, but different than in *Qianzhousaurus*, in which there is a wide margin between the anterior end of the open portion of the suture and the midline ornaments.

In summary, the midline suture between the left and right nasals closes ontogenetically in tyrannosaurids, such that the portion of open suture is greater in more immature specimens and proportionally decreases with maturity. The smaller length of open suture in the *Qianzhousaurus* type compared to the *Alioramus* holotypes indicates that the *Qianzhousaurus* type is a more skeletally mature individual.

Braincase: Patterns of braincase suture changes during tyrannosaurid ontogeny are less constrained than patterns of nasal suture closing, largely due to the fewer available well preserved braincases (especially of juveniles).

One pattern that does seem clear is that the suture between the exoccipital-opisthotic and prootic closes during ontogeny (in *Tyrannosaurus*, the suture is open in the immature specimens AMNH FARB 5117 and RSM 2523.8 but closed in the more mature MOR 1125 and MOR 980). This suture is open in the type braincases of *Alioramus altai* and *Alioramus remotus*. In *A. altai*, the prootic is a distinctive bone with clear margins, whose posterior end overlaps the exoccipital-opisthotic (the prootic appears to essentially sit on top of the exoccipital-opisthotic like a scab). The suture between the two bones is not only open but is very poorly fused. A band of sediment separates the two bones, and without the cementation provided by this sediment, the bones may have been quite loosely joined in life. Indeed, it appears as if the two bones have moved slightly relative to each other due to their loose connection, so that the overlap of the

prootic may be part artificial. This contrasts greatly with the condition in the type of *Qianzhousaurus*, in which there is a slightly visible suture between the prootic and exoccipital-opisthotic, but it is nearly obliterated and tightly interdigitating, such that the prootic merges smoothly with the exoccipital-opisthotic rather than distinctively overlapping it like in *A. altai*. The much greater degree of prootic-exoccipital-opisthotic fusion in the *Qianzhousaurus* type indicates that it more skeletally mature than either *Alioramus* specimen (and particularly the *A. altai* type).

A second pattern that seems clear is that the suture between the prootic and basisphenoid on the lateral surface of the braincase closes during ontogeny (in *Tyrannosaurus*, the suture is open in the immature specimen RSM 2523.8 but closed in the more mature MOR 1125). The prootic of the *Qianzhousaurus* type is firmly linked to the basisphenoid, with open suture lines barely visible between them. This is not the case in either specimen of *Alioramus*, particularly the type of *A. altai* in which the prootic appears as a discrete element that sits on top of the other lateral braincase bones, with open and loose sutures between them (see further description below). Therefore, the greater degree of suture closure (near obliteration) in *Qianzhousaurus* supports its advanced maturity relative to the two *Alioramus* specimens.

A third pattern that seems clear is that the suture between the exoccipital-opisthotic and basisphenoid on the lateral surface of the braincase closes during ontogeny (in *Tyrannosaurus*, the suture is open in the immature specimen AMNH FARB 5117 but closed in the more mature MOR 1125 and MOR 980). This suture is clearly open in the type of *A. altai* (not clearly observable in *A. remotus*) but only slightly visible because of its near obliteration in the type of *Qianzhousaurus*, once again supporting the greater relative maturity of the *Qianzhousaurus* specimen.

The ontogenetic patterns of other braincase suture morphologies remain less clear. The braincases of large, skeletally mature, adult tyrannosaurids exhibit mostly open sutures between the various braincase bones, although the bones are firmly joined along these visible sutures (e.g., ref 14). Data from other theropod dinosaur growth series demonstrate that the various braincase bones progressively fuse during ontogeny, beginning as single ossifications that join together at open sutures, which increasingly become more firmly joined and sometimes close completely (e.g., ref 20). Therefore, differences in the degree of fusion between the type braincase of *Qianzhousaurus* and the type braincases of *Alioramus altai* and *Alioramus remotus* may give insight into relative maturity.

With this in mind, it may be noteworthy that the braincase sutures of the *Qianzhousaurus* type are much more firmly joined and closer to obliteration than those of either *Alioramus* specimen. The supraoccipital is firmly appressed to the parietals dorsally and anteriorly in *Qianzhousaurus*, but only loosely joined in both *Alioramus* specimens, most notably the type of *A. altai* where the bones are so feebly connected that they have moved apart from each other here during fossilization. The suture between the supraoccipital and exoccipital-opisthotic above the foramen magnum is open but nearly obliterated in the *Qianzhousaurus* type, but is much more visible and less strongly joined in the types of *Alioramus remotus* and *Alioramus altai*, with the latter exhibiting some slight movement between the bones. The prootic of the *Qianzhousaurus* type is firmly linked to the parietal and laterosphenoid on the lateral surface of the braincase, with open suture lines barely visible between them. This is not the case in either specimen of *Alioramus*, particularly the type of *A. altai* in which the prootic appears as a discrete element that sits on top of the other lateral braincase bones, with open and loose sutures between them, as noted above. Finally, in ventral view, the basal tubera of the basioccipital join the basisphenoid at a widely open suture near the posterior end of the basisphenoid recess in the types of *Alioramus altai* and *Alioramus remotus*. This suture is traceable, but only slightly, in the type of *Qianzhousaurus*.

Vertebrae: As outlined above, no clear patterns of vertebral neurocentral suture closure have yet been identified in tyrannosaurids. Our observations of specimens also have yet to show any explicit patterns. However, one feature deserves comment. In the type of *Qianzhousaurus* all dorsal vertebrae exhibit an open neurocentral suture, with a narrow band of sediment between the neural arch and centrum. This is also the case in the holotype of *Alioramus altai*. However, in *A. altai* the degree of fusion appears to be less, because in both well-preserved dorsal vertebrae the arch and centrum are only loosely connected, such that the arch has slipped ventrally to overlap the centrum. No such slippage is seen in the type of *Qianzhousaurus*, despite a similar mode of three-dimensional preservation, indicating that its dorsal neural arches and centra are more strongly fused than those of the *A. altai* type. This may be consistent with a greater skeletal maturity for the *Qianzhousaurus* type.

Discrete characters

Note about discrete characters: Carr (1999)¹⁵ and Carr and Williamson (2004, 2010)^{12,21} outlined a series of consistent ontogenetic changes in the skull morphology of large-bodied derived tyrannosauroids. Many of these changes are seen in large-bodied non-tyrannosauroid tyrannosaurids (*Bistahieversor*), albertosaurine tyrannosaurids (*Gorgosaurus*), and tyrannosaurine tyrannosaurids (*Tyrannosaurus*), meaning that they are highly conserved among derived tyrannosauroids of different body size, ages, and geographic localities. Many of them also relate to the progressively greater development of cranial ornamentation during maturity, a characteristic pattern known in many diverse dinosaur species (Horner and Goodwin 2006). Furthermore, Brusatte et al. (2009)⁴ quantitatively showed that the holotype of *Alioramus altai*, which was histologically aged at nine years of age, had a set of ontogenetically variable features expected for a ca. nine-year-old *Tyrannosaurus*. Taken together, these lines of evidence indicate that the discrete character growth trajectory of derived tyrannosauroid skulls was most likely present in alioraminis, despite their distinct long-snouted bauplan from other derived tyrannosauroids. This conclusion was summarized by Brusatte et al. (2012:187)¹: “(The presence of juvenile features expected of a ca. nine-year-old tyrannosaurid) in *A. altai* reveals that the evolution of the novel long and low skull and mandible does not disrupt the plesiomorphic pattern of (discrete character) development, even when the entire shape of the skull and mandible is transformed.” This means that comparison of ontogenetically variable discrete characters from this growth series can determine whether the holotype of *Qianzhousaurus* was more or less mature than the holotypes of *Alioramus altai* and *Alioramus remotus*.

In the following discussion, “*Qianzhousaurus*” is shorthand for the holotype specimen of *Qianzhousaurus*, and “*A. altai*” and “*A. remotus*”) are shorthand for the holotypes of this taxon. We are only comparing the three individual holotypes here (as only individuals can be compared ontogenetically).

Maxilla: The base of the interfenestral strut is flat in the *A. altai* holotype, a characteristic of immature tyrannosaurids, but is gently concave in *Qianzhousaurus*, characteristic of more mature individuals¹⁵. The external bone surface texture of the anterior maxilla of *Qianzhousaurus* exhibits moderately developed ridges and grooves, which are absent in *A. altai*. This texturing is absent in less mature tyrannosaurids but present, often to an extreme degree, in adults¹⁵. The presence of moderate ridges and grooves in *Qianzhousaurus* is evidence that it is more mature than *A. altai*,

but less mature than adults. The maxillary fenestra of *A. altai* is located approximately midway between the anterior border of the antorbital fossa and antorbital fenestra, characteristic of immature tyrannosaurids, whereas that of *Qianzhousaurus* is positioned closer to the anterior margin of the antorbital fossa as in more mature tyrannosaurids^{12,15}. In *Qianzhousaurus* a less distinct ridge anterior and ventral to the antorbital fossa, separating the fossa from the subcutaneous surface of the maxilla, is present than in *A. altai*. A decrease in the strength of these ridges occurs throughout tyrannosaurid ontogeny^{12,15}. The most posterior neurovascular foramen on the lateral surface of the maxilla above the tooth row breaches the ventral margin of the maxilla in *Qianzhousaurus*, a feature of more mature tyrannosaurids. In *A. altai* it does not breach this margin, as in less mature individuals¹². In *Qianzhousaurus* the promaxillary foramen is round, not slit-like as in *A. altai*. A transition from a slit to a more rounded shape occurs during tyrannosaurid ontogeny¹².

Nasal: In *Qianzhousaurus*, the posterior end of the nasal is slightly constricted in width where it meets the frontals, which is not the case in *A. altai*. This constriction develops from an unconstricted condition during tyrannosaurid ontogeny¹². The lacrimal overlaps the lateral surface of the nasal much more broadly in *Qianzhousaurus* than in *A. altai*, a sign of greater maturity¹².

Lacrimal: The cornual process of *Qianzhousaurus* is proportionally larger than in *A. altai*, is more “inflated” in shape, and has more of an eave-like lateral overhang, all signs of increasing maturity^{12,15,21}.

Jugal: The anterior margin of the postorbital ramus of the jugal is more deeply concave in *Qianzhousaurus* than in *A. altai*, where it is nearly straight. A straight margin becomes more concave throughout tyrannosaurid ontogeny¹². When in articulation with the postorbital, the postorbital ramus of the jugal in *Qianzhousaurus* stops far short of the dorsal border of the lateral temporal fenestra. This is a characteristic of more mature tyrannosaurids relative to the condition in *A. altai*, where the ramus nearly contacts the dorsal border¹². The cornual process along the ventral margin of the jugal is large and projects distinctly ventrally in *A. altai*, an immature character compared to the more mature condition of *Qianzhousaurus* in which the cornual process

is modified into a broad convexity that is much more anteroposteriorly elongate, but ventrally less extensive¹².

Postorbital: The cornual process is a conspicuous bulbous rugosity that extends past the dorsal part of the skull roof in *Qianzhousaurus*. This is a feature of mature tyrannosaurids, relative to the subtle, ridge-like process immediately posterodorsal to the orbit in less mature individuals, including *A. altai*^{12,15,21}. In *A. altai* and *A. remotus* the ventral ramus of the postorbital reaches the ventral margin of the orbit and lacks a subocular process projecting into the orbit. This is a characteristically immature morphology, contrasting with the more mature condition in *Qianzhousaurus* in which the ventral ramus stops far short of the ventral margin of the orbit^{12,15}. Furthermore, *Qianzhousaurus* possesses a subtle subocular process, indicating that it is more mature than *A. altai* and *A. remotus* but less mature than the largest skeletally mature adults. The anterior ramus of the postorbital is short and deep in *Qianzhousaurus*, similar to mature tyrannosaurids but proportionally different from the longer and shallower processes of more immature specimens, including *A. altai* and *A. remotus*^{12,15}. The dorsal margin of the postorbital of *Qianzhousaurus* is convex in lateral view, characteristic of mature tyrannosaurids but unlike the more horizontal margins of *A. altai* and *A. remotus*, which are characteristic of immature individuals^{12,15}. The ventral ramus is wide and plate-like in *Qianzhousaurus*, another feature that develops during maturity from the more gracile and slender processes of more immature individuals like *A. altai* and *A. remotus*^{12,15}.

Frontal: The conjoined frontals of *Qianzhousaurus* are considerably shorter anteroposteriorly and wider transversely relative to the more elongate proportions of *A. altai*, and most likely *A. remotus* (although breakage makes exact measurements uncertain). The frontals become shorter and wider during tyrannosaurid ontogeny^{12,15}.

Parietal: The sagittal crest is lower and wider in *Qianzhousaurus* relative to the taller and thinner condition in *A. altai* and *A. remotus*. A transition between tall/thin and low/wide crests occurs during tyrannosaurid ontogeny^{12,15}. Similarly, the proportionally thicker nuchal crest of *Qianzhousaurus* relative to *A. altai* and *A. remotus* is a sign of greater maturity^{12,15}. Finally, the

nuchal crest has a rugose surface texture in *Qianzhousaurus* but a smooth texture in *A. altai* and *A. remotus*. Rugosities develop during ontogeny in tyrannosaurids^{12,15}.

Braincase: The basiptyergoid processes of *Qianzhousaurus* are located nearly ventral to the level of the basal tubera in lateral view. In *A. altai* and *A. remotus* they are located further anteriorly. A transition from anteriorly positioned processes to those that lie nearly underneath the basal tubera occurs during tyrannosaurid ontogeny¹⁵.

Prearticular: The posterior process of the bone is much deeper proportionally in *Qianzhousaurus* than in *A. altai*. This process deepens during ontogeny^{12,15}.

Dentition: The maxillary and dentary teeth are proportionally wider relative to their length (more incrassate) in *Qianzhousaurus* than in *A. altai*, a sign of greater relative maturity¹². Tooth count is also known to decrease ontogenetically in tyrannosaurids, including albertosaurines¹⁵ and tyrannosaurines¹². *Qianzhousaurus* has fewer teeth in the maxilla (15) than either *A. remotus* (16) or *A. altai* (17), and fewer teeth in the dentary (18) than *A. altai* (20). *Qianzhousaurus* has an identical number of dentary teeth as *A. remotus*, but this is not particularly surprising because there is also individual variation in tooth count in tyrannosaurids^{2,15}. The interplay of ontogenetic and individual variation means that tooth count alone is not necessarily a reliable indicator of ontogenetic stage, but in the case of long-snouted tyrannosaurids it is consistent with other evidence indicating that *Qianzhousaurus* is more mature than *A. altai* and *A. remotus*.

Quantitative Analysis: In order to quantitatively test the relative maturity of the *Qianzhousaurus* type, assuming a *Tyrannosaurus*-like growth trajectory for discrete character change during ontogeny, we followed the protocol of Brusatte et al. (2009)⁴ and coded the specimen for the ontogenetic matrix of Carr and Williamson (2004)¹². We added the *Qianzhousaurus* type to the revised version of the matrix utilized by Brusatte et al. (2009)⁴, which also included the type specimen of *A. altai*. Therefore, this procedure allows for a quantitative comparison of the relative maturity of the *Qianzhousaurus* and *A. altai* types, based on the assumption that both follow the *Tyrannosaurus*-like trajectory. This is a reasonable assumption, given that Brusatte et al. (2009)⁴ found that *A. altai*, which was independently histologically aged at nine years of age, was placed in

the ontogenetic tree of *Tyrannosaurus* in the same position where a ca. nine-year-old *Tyrannosaurus* would be expected.

The version of the ontogeny analysis here includes eight specimens (one hypothetical embryo, five specimens of *Tyrannosaurus rex*, the *A. altai* and *Qianzhousaurus* types) scored for 84 discrete characters that change during ontogeny. The type of *Alioramus remotus* is not included because it cannot be scored for most characters in the dataset and because we have not been able to study the specimen personally. The dataset (Supplementary Data 1) was analysed in TNT using the same protocols as the phylogenetic analysis (see Methods). This resulted in two most parsimonious trees of 97 steps (consistency index=0.948, retention index=0.967). In both trees, and therefore in the strict consensus (Figure S2), the *Qianzhousaurus* type is placed in a more crownward position than the *A. altai* type, which indicates that it is more skeletally mature (see ref 12 for discussion and explanation of the cladistics procedure). The more mature placement of the *Qianzhousaurus* type is supported by extremely high jackknife (100%) and Bremer support (17) values of the *Qianzhousaurus* type + adult *Tyrannosaurus* node. These are the highest support values of any relationships among the ingroup, demonstrating very strong support for the greater relative maturity of the *Qianzhousaurus* type compared to the *A. altai* type.

Bone histology

Counting lines of arrested growth in histological thin section is a widely used method for assessing the numerical age of a specimen and comparing maturity between specimens. The holotype of *Alioramus altai* was histologically aged at nine years old⁴. Unfortunately, histological data is not available for *Qianzhousaurus* because we are not allowed to destructively sample a holotype specimen housed at the Ganzhou Museum at this time. We predict that if histological sampling is possible in the future, the *Qianzhousaurus* type will be greater than nine years old due to its larger size, greater degree of skull fusion, and advanced skeletal maturity relative to the *A. altai* holotype.

Summary

In summary, several lines of evidence indicate that the type of *Qianzhousaurus* is more mature (represents an older and more skeletally advanced individual) than the types of *A. altai* and *A.*

remotus. The femur and skull lengths of the *Qianzhousaurus* type are substantially larger than those of *A. altai* and *A. remotus*, and body size estimates based on femur length indicate that the type individual of *Qianzhousaurus* was approximately double the body mass of the *A. altai* type individual. The skull (nasal) and braincase bones show a greater degree of fusion in the *Qianzhousaurus* type than in either specimen of *Alioramus*, and in many cases sutures that are widely open and only slightly joined in the *Alioramus* specimens are nearly obliterated or completely closed in the *Qianzhousaurus* type. Compared to the types of *Alioramus altai* and *Alioramus remotus*, the *Qianzhousaurus* type possesses a more mature version of numerous discrete characters that are known to ontogenetically vary in a range of other tyrannosauroids (*Bistahieversor*, *Gorgosaurus*, *Tyrannosaurus*). Although the long-snouted body plan of alioramins deviates from the bauplan of other large-bodied tyrannosauroids, these patterns of discrete character change are a hard-wired pattern of growth changes plesiomorphic for Tyrannosauridae and immediate outgroups^{12,15,21} and *Alioramus altai* has been shown to be consistent with this pattern⁴. Therefore, all lines of evidence agree that the *Qianzhousaurus* type is more mature, and likely numerically older, than the *Alioramus altai* and *Alioramus remotus* types. If histological data for the *Qianzhousaurus* type become available in the future we hypothesize that it will be consistent with this hypothesis. Even if we are mistaken, however, the fact remains that the *Qianzhousaurus* type provides clear evidence that long-snouted tyrannosaurids reached twice the body size as the previously known largest long-snouted specimen that can be reliably measured (the type of *Alioramus altai*).

Supplementary Note 3

Primary Phylogenetic Analysis: The primary phylogenetic analysis utilizes the discrete anatomical character dataset of Brusatte and Benson (2013)²³, which is an updated version of a dataset presented by Brusatte et al. (2010)²⁴. We followed the same search protocols are outlined in the original analyses, including utilizing ordered characters where indicated in those studies (see the supplementary material of Brusatte et al. [2010]²⁴ for full details). The full analysis includes 317 characters that are scored for 25 taxa, 21 of which are tyrannosauroids and four of which are outgroups. The dataset was analyzed under parsimony in TNT following the protocols described in the Methods section.

Our analysis includes three new characters:

- 315) Nasal, series of pronounced, discrete rugosities on dorsal surface of middle portion of bone, posterior to the external naris: absent (0); present (1). State 1 is present in *Alioramus remotus*, *Alioramus altai*, and *Qianzhousaurus*.
- 316) Maxillary fenestra, proportions: ratio of maximum anteroposterior length to maximum dorsoventral depth: less than (0) or greater than (1) 1.9. State 1 is present in *Alioramus altai* and *Qianzhousaurus*. It cannot be assessed in *Alioramus remotus*.
- 317) Dentary teeth, number: 17 or less (0); 18 or more (1). State 1 is present in *Alioramus remotus*, *Alioramus altai*, and *Qianzhousaurus*, as well as *Proceratosaurus* and some outgroup taxa (e.g., compsognathids: *Compsognathus*; ornithomimosaur: *Pelecanimimus*).

Our analysis recovers the following unequivocal synapomorphies for Alioramini and subgroups:

- MPT 1:** Alioramini: 23 (state 1); 27 (state 1); 157 (state 1); 162 (state 0); 168 (state 0); 187 (state 1); 191 (state 1); 193 (state 0); 222 (state 1); 295 (state 0); 315 (state 1); 316 (state 1); 317 (state 1). *Alioramus altai* + *Alioramus remotus*: 81 (state 1)
- MPT 2:** Alioramini: 23 (state 1); 157 (state 1); 168 (state 0); 315 (state 1); 317 (state 1). *Qianzhousaurus* + *Alioramus altai*: 25 (state 1)

Common to Both MPTs: Alioramini: 23 (state 1); 157 (state 1); 168 (state 0); 315 (state 1); 317 (state 1)

Supplementary Phylogenetic Analysis: We also included *Qianzhousaurus sinensis* in an alternative tyrannosauroid phylogenetic dataset recently presented by Loewen et al.²⁵ This dataset includes many characters from our primary dataset, along with new character data gathered by Loewen et al. and scorings for new taxa, including the tyrannosaurine *Lythronax argestes*. We did not add any new character data to this dataset and analysed it in TNT using the same protocols used for the primary analysis, which are described in the Methods section.

In some cases Loewen et al. rescored taxa for characters originally presented in the parent dataset of our primary phylogenetic analysis²⁴. In a handful of these cases, where the scoring differences were not due to a redefinition of the character states and disagreed with scores for the long-snouted taxa for identical characters in our primary phylogenetic analysis, we rescored data cells in the Loewen et al. dataset. Our scoring changes, which are limited, include: character 29 (*Alioramus altai* 1 to 0); character 61 (*A. altai* 0 to 1; *Alioramus remotus* 0 to ?); character 89 (*A. altai*, *A. remotus* 0 to 1); character 95 (*A. altai*, *A. remotus*, *Xiongguanlong*, *Raptorex* 0 to 1); character 104 (*A. altai*, *A. remotus*, *Xiongguanlong* 1 to 0); character 114 (*A. altai* 1 to 0); character 122 (*A. altai*, *A. remotus* 1 to 2); character 124 (*A. altai*, *A. remotus* 0 to 1); character 182 (*A. altai*, *A. remotus* 0 to 1); character 194 (*A. altai*, *A. remotus* 0 to 1); character 201 (*A. altai*, *A. remotus* 1 to 0; *Gorgosaurus*, *Albertosaurus* 0 to 1); character 307 (*A. altai* 1 to 0); Character 316 (*A. altai* 1 to 0); character 350 (*A. altai* 0 to 1); character 419 (*A. altai* 0 to 1); character 490 (*A. altai* ? to 1; *A. remotus* 0 to 1).

The analysis returns two most parsimonious trees of 1774 steps (consistency index=0.375; retention index=0.776). The strict consensus is shown in Fig. S3. *Qianzhousaurus* is recovered within a clade of long-snouted taxa that also includes *Alioramus altai* and *Alioramus remotus*. The interrelationships of this clade collapse into a polytomy in the strict consensus, as one MPT finds *Alioramus altai* and *Alioramus remotus* to form a sister-taxon pair relative to *Qianzhousaurus*, while the other finds *Qianzhousaurus* and *Alioramus altai* to form a pair exclusive of *Alioramus remotus*. These are also the two alternative positions for *Qianzhousaurus* in the primary phylogenetic analysis (Fig. 3). The strict consensus topology of all other taxa is identical to that

presented by Loewen et al.²⁵, indicating that the addition of *Qianzhousaurus* and our handful of character rescorings did not greatly influence the relationships of the remaining taxa. The long-snouted clade is placed immediately outside of the Albertosaurinae + Tyrannosaurinae node (Tyrannosauridea), not as basal tyrannosaurines as in the primary analysis. This is a minor discrepancy—essentially the two analyses differ in placing the long-snouted clade by one node apart—and is the only discrepancy between the phylogenetic placements of the long-snouted taxa in the two analyses. Although the Loewen et al. analysis places the long-snouted clade immediately outside of Tyrannosauridae, we classify them as tyrannosaurids in this paper based on the results of our primary analysis.

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