SUPPORTING INFORMATION

TEXT S1: GEOLOGIC SETTING
Elrhaz Formation

The bones of *Nigersaurus taqueti* were found in the El Rhaz Formation of the Tegama Group, which consists of a thick sequence of coarse-to-medium grained, cross-bedded sandstones almost devoid of finer-grained horizons [1,2] (Figure 1S). The beds are considered to be Aptian-to-Albian in age, and the localities in the Ténéré Desert (dubbed "Gadoufaoua") were a considerable distance from deltaic habitats in the region of the Benue Trough (present day Nigeria) (Figure 2S). The aquatic fauna recovered is entirely freshwater.

Nigersaurus was one of the most common large herbivores of its day, judging from the number of specimens collected. Its bones are exceeded in number only by the more robust iguanodontian *Lurdusaurus* [3]. Together, these two herbivores shared their riparian habitat with two relatives, an unnamed titanosaur [2] and the iguanodontian *Ouranosaurus* [4], composing one of the few megaherbivore associations (herbivores more than 10^6 g) with a balance of sauropods and large ornithopods. Predators would have included the giant crocodylomorph S*arcosuchus imperator* [5], the spinosaurid *Suchomimus tenerensis* [6], and similar sized basal abelisaurid and carcharodontosaurid theropods [7].

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Figure S1. Partial skeleton of *Nigersaurus taqueti* (MNN GAD517) discovered during the 2000 Expedition to Niger. Expedition member G. Lyon is seated inside the curve of the proximal caudal vertebrae of a skeleton planed flat by wind-blown sand at a site in Gadoufaoua, Ténéré Desert, Niger (photo by M. Hettwer).
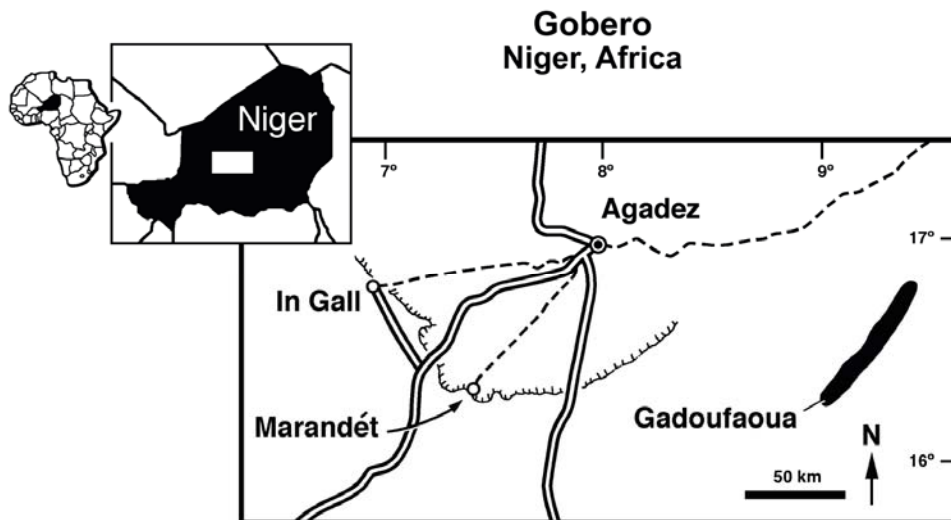

Figure S2. Location of outcrops of the Elrhaz Formation where fossils of *Nigersaurus taqueti* were found.

TEXT S2: THE PROTOTYPE SKULL
µCT Scanning
High-resolution µCT scans of all cranial bones and of the skull cast were completed at the High-Resolution X-ray Computed Tomography Facility at the University of Texas at Austin (UTCT). Scans were made for two principal reasons:
> (1) To see internal and cross-sectional morphologic information
> (2) To replicate and/or reverse the very delicate bones without damage

A portion of the stapes including the footplate is present in place in the braincase. The isolated but closely associated skull and neck bones of MNN GAD512 (MNN = Musée National du Niger) are preserved with little or no distortion. Once freed of the sandstone matrix, the bones are exceptionally fragile, given their lightweight construction. Many of the cranial bones, for example, are thin enough a strong beam of light will through them.

Assembly of the Prototype Skull
Stereolithographic (STL) prototypes at the highest resolution were made from the scans of the bones by Laser Modeling, Inc. (Schaumberg, Illinois). STL employs an ultraviolet laser to selectively cure a liquid plastic resin. This process produces a very detailed part and allows reflecting these parts to create any missing contralateral bones. Many of the bones of the skull were preserved on one or the other side, and the braincase was preserved past the midline. Thus, we recreated the missing portion of the braincase via reflection and any missing opposing elements by reflecting the parts that were preserved.

The following bones of the dorsal skull roof and braincase are not known and were filled in with modeling putty: nasal, lacrimal, quadratojugal, prefrontal, parietal, and supraoccipital. The lateralmost portion of the maxillary also is not known. For the palate, both quadrates are preserved in the holotype. An isolated palatine from a smaller individual is also preserved. The pterygoid and vomer are not known. In the lower jaw, the three main external bones are all that are preserved (dentary, surangular, angular).

To our knowledge, this is the first dinosaur skull rebuilt from STL prototypes of its constituent bones (Figure 3S). These nearly distortion-free bones and their reflected casts (when needed) allowed very little latitude in skull shape during reconstruction. The premaxilla and maxilla articulate and establish the width of the upper jaws and the anterior part of the internasal bar. The well preserved, slender ascending process of the maxilla is complete, and leaves little doubt as to where the joint with the missing lacrimal and nasal would have been. The frontal, postorbital, squamosal, braincase and quadrate articulate and match the muzzle unit when brought together. The only bone of these that articulates with any freedom of movement is the quadrate (because of the missing pterygoid and quadratojugal). Its position, however, is well established by the location of the jaw joint, which can be determined on the surangular (i.e. an everted, thickened edge). The relation of the muzzle and braincase units, thus is well established, as is the position of the occipital condyle, which is positioned ventral to the braincase between and nearly level with the heads of the right and left quadrate.

The bony struts connecting muzzle and braincase units are remarkably weak. The premaxilla, maxilla and jugal never exceed 2 mm in thickness. Their minimum widths between these two skull units are 8, 5, and 10 mm, respectively, for a total cross-

sectional area of 46 mm^2. Missing bones that would have also bridged these units include the quadratojugal, palatine and vomer. The palatine is known from a smaller individual and is a thin, plate-shaped bone as in *Diplodocus*. Assuming the quadratojugal and vomer would be comparably thin (judging from other sauropods), there may be as much as 50 mm^2 of bridging bone missing. The total bone cross-sectional area, thus, is likely to have been as little as 1.0 cm^2. This is all the more remarkable, given that the functioning tooth row is located at the distal end of the muzzle unit.

Figure S3. Assembled semi-translucent skull model of *Nigersaurus taqueti* built from prototyped skull bones (tooth batteries and reconstructed teeth in red) with unknown bones in green modeling clay (photo by T. Keillor).

TEXT S3: ENDOCAST AND LABYRINTH
Methods
The original fossil elements were CT scanned at the High-Resolution X-ray Computed Tomography Facility at the University of Texas at Austin (UTCT). A physical endocast (using traditional latex techniques) was prepared in the Fossil Laboratory at the University of Chicago from an assembled braincase compose of stereolithographic replicas of the preserved elements, mirrored elements (e.g. left frontal), and one restored element (parietal). A resin replica of the physical endocast was subsequently scanned (slice thickness of 92 µm) at the Ohio University MicroCT facility (OUµCT).

A virtual endocast and endosseous labyrinth of the inner ear was created by combining the scan data of the braincase from both UTCT and OUµCT (Figures 4S, 5S). Structures of interest were highlighted (i.e. segmented) from the UTCT scan data of the original fossils using Amira v. 4.1.2. The OUµCT scan data of the physical endocast were registered to the virtual endocast in Amira, allowing addition of the restored parietal-supraoccipital region. Finally, the missing parts of the right side of the endocast, as well as the missing right labyrinth, were added in Amira by mirroring the preserved portions of the left side. Both surfaces and volumes were generated and used to generate Figure 4S and those in the paper (Figure 1F, G). To facilitate discussion, we will refer to the digital casts of structures as if they were the structures themselves (e.g. 'olfactory bulb'). We present additional information on the endocast and labyrinth below; comparative data on the sauropods *Camarasaurus* and *Diplodocus* are published elsewhere [1].

Cranial Endocast
Unlike other sauropods in which an endocast has been prepared, *Nigersaurus* had relatively small dural sinuses over the cerebrum. For the first time among sauropods, many brain divisions and features are discernible including the cerebrum, floccular lobe of the cerebellum, and possibly the optic tectum (optic lobes).

The cerebral hemispheres of *Nigersaurus* are not particularly expanded relative to other sauropods, although this comparison is difficult to make as the cerebrum is not fully exposed in other sauropods. The best comparative measure is the lateral extent of the cerebrum relative to the lateral extent of the endosseous labyrinth in dorsdal view (Figure S4). In *Camarasaurus* and *Diplodocus*, the cerebral portion of the endocast extends laterally about as far as the lateral margin of the lateral semicircular canal [1]; the cerebrum of *Nigersaurus* is comparable or little narrower, probably due smaller venous sinuses.

The small olfactory bulbs lie in front of the cerebrum and are connected by very short olfactory tracts (Figure S4). As in other sauropods, they diverge anteriorly. Compared to other sauropods, the bulbs are small and the tracts almost nonexistent. In other sauropods, the olfactory bulbs also angle strongly dorsally. The marked angulation of the olfactory tracts and bulbs in other sauropods is probably due to the strong retraction of the olfactory region of the nasal cavity (between the orbits in most sauropods). The absence of such angulation in *Nigersaurus* is a byproduct of extreme downward rotation of the muzzle, and a compensatory straightening of the olfactory apparatus.

Rounded swellings behind the cerebral hemispheres on each side may represent the optic tecta or alternatively a foramen for the orbitocranial vein (Figure S4A, B, D). A small floccular lobe of the cerebellum is clearly discernible, the first recorded in a sauropod endocast. The flocculus (cerebellar auricle) in extant birds is involved in the vestibulo-ocular reflex. The cranial nerve foramina, pituitary fossa, cerebral carotid canal are fairly typical of sauropods, although the foramina opening into the orbit are somewhat enlarged.

Endosseous Labyrinth

The left side of MNN GAD512 preserves a complete endosseous labyrinth (Figure S5). It is similar to other sauropods in having an enlarged vestibular region above the fenestra vestibuli and adjacent to the confluence of the semicircular canals. The cochlea (lagena) is somewhat shorter than in other sauropods [1], suggesting that discrimination of air-borne sounds may have been less important in *Nigersaurus*. The semicircular canals are sensitive to acceleration and have important neural links to the eye muscles. Animals with well developed gaze stabilization mechanisms tend to have elongate canals and also tend to be relatively agile, mobile, and jerky in their movements [2]. Sauropods, not surprisingly, have relative short and thick semicircular canals, reflecting diminished gaze stabilization mechanisms [1]. *Nigersaurus*, however, has relatively elongate canals for a sauropod, particularly the lateral canal that may have enhanced control of lateral scanning movements of the head. The differentiation in the endocast of flocculi and optic tecta as well suggests that *Nigersaurus* may have had somewhat enhanced gaze stabilization mechanisms over some other sauropods.

Body and Brain Mass

Body mass of approximately 4 metric tons was estimated by reducing the body mass body calculated for the similarly proportioned, slightly larger (12-meter long) diplodocoid *Dicraeosaurus*. Two mass estimates of 4,421 and 5,400 kg were given recently for this sauropod using the alternative methods of Seebacher [3] and Christiansen [4], respectively. A body mass estimate for *Amargasaurus* of 6853 kg [3] seems high for a sauropod with an estimated length of 10 m, or less than that of *Dicraeosaurus*.

Endocast volumetrics derived from the braincase of the holotypic specimen (MNN GAD512; MNN = Musée National du Niger). Erosion removed about one-third of the left side. The braincase was scanned, prototyped, and reverse-prototyped. The reverse copy was cut to complete the braincase, with the exception of the missing parietal and supraoccipital; the skull roof in this region was finished to fit all sides. *Nigersaurus* has a reduced dorsal dural sinus much smaller than that in *Camarasaurus* and *Diplodocus* (Figure 1G). The only indication of this sinus in *Nigersaurus* is a shallow median depression toward the distal end of the frontal (MS-Figure 1G). As a result, the cerebrum is fully exposed in *Nigersaurus*, and the volume for this portion of the endocast can be measured accurately for the first time in a sauropod.

A standard physical endocast was prepared from the skull roof and ventral portion of the braincase and cut apart (by PCS) to measure volumes by water displacement in a graduated cylinder. The endocast was trimmed fore and aft following Osborn [5], using the constriction between cerebrum and olfactory bulbs (olfactory tracts) anteriorly and immediately posterior to the exits for CN XII posteriorly. This

volume was divided into forebrain (cerebrum) and remainder of the endocast, with nerve stalks trimmed flush. A complete bulb was cut by extending the marked depressions into an ovoid. Water displacement gave volumes of 4, 15, 27 and 42 cm^3, for paired olfactory bulbs, forebrain (cerebrum), mid and hindbrain, and total endocast volume (fore, mid and hind brain), respectively. Independently, these volumes were estimated digitally from a μCT scan of the braincase (by LMW), which also provided the chance to measure the volume of the pituitary fossa (Figure 6S). These very comparable volumetric estimates are the ones we used in the paper (2.9, 16.6, 33.9 and 53.4 cm^3, for paired olfactory bulbs, forebrain, mid/hindbrain, and total endocast volume).

We assessed brain versus body mass in *Nigersaurus* using 95% confidence intervals from a log-log regression based on nonavian reptiles [6]. Although noticeably smaller in volume than comparably sized theropods, we found its brain mass to plot within the 95% confidence limits, using the mass estimate discussed above.

Another popular measure is the Encephalization Quotient (EQ), which presents a comparison of actual brain mass relative to the expected brain mass for an animal of its body size. There are some problems with current methods, because the formulae were not generated with currently acceptable comparative methods. EQ, nonetheless, may constitute a reasonable first approximation. To this end, we used Hurlburt's [7] equation based on extant nonavian reptiles that yields an REQ (Reptile EQ): REQ = MassBrain/0.0155 x MassBody0.553. We calculate MassBrain by multiplying endocast volume by the density of brain tissue (1.036 g cm-3). Typically, a correction factor of 50% is used to account for the mismatch (i.e. MassBrain equals 50% of endocast mass). In *Nigersaurus* the reduced dural venous sinuses may shift the proportion above 50%. Thus we calculated REQ values using the '50% rule' and a '100% rule' (brain and endocast mass are equal). Using an endocast volume of 53.4 cm3, a 100% MassBrain of 55.32 g, a 50% MassBrain of 27.66 g, and a body mass of 4 x 106 g, REQ50% rule equals 0.40 and REQ100% rule equals 0.80.

These values suggest that *Nigersaurus* had a relatively small brain 40–80% the size expected for a reptile of its body size. Witmer et al. [1] calculated the REQ for *Diplodocus* with its larger sinuses using the '50% rule' and arrived at a value of 0.41, almost identical to that for *Nigersaurus*. Pending further study, we conclude that *Nigersaurus* and other sauropods do have relatively smaller brains that other dinosaurs and perhaps rank in the lower range of brain mass among extant nonavian reptiles.

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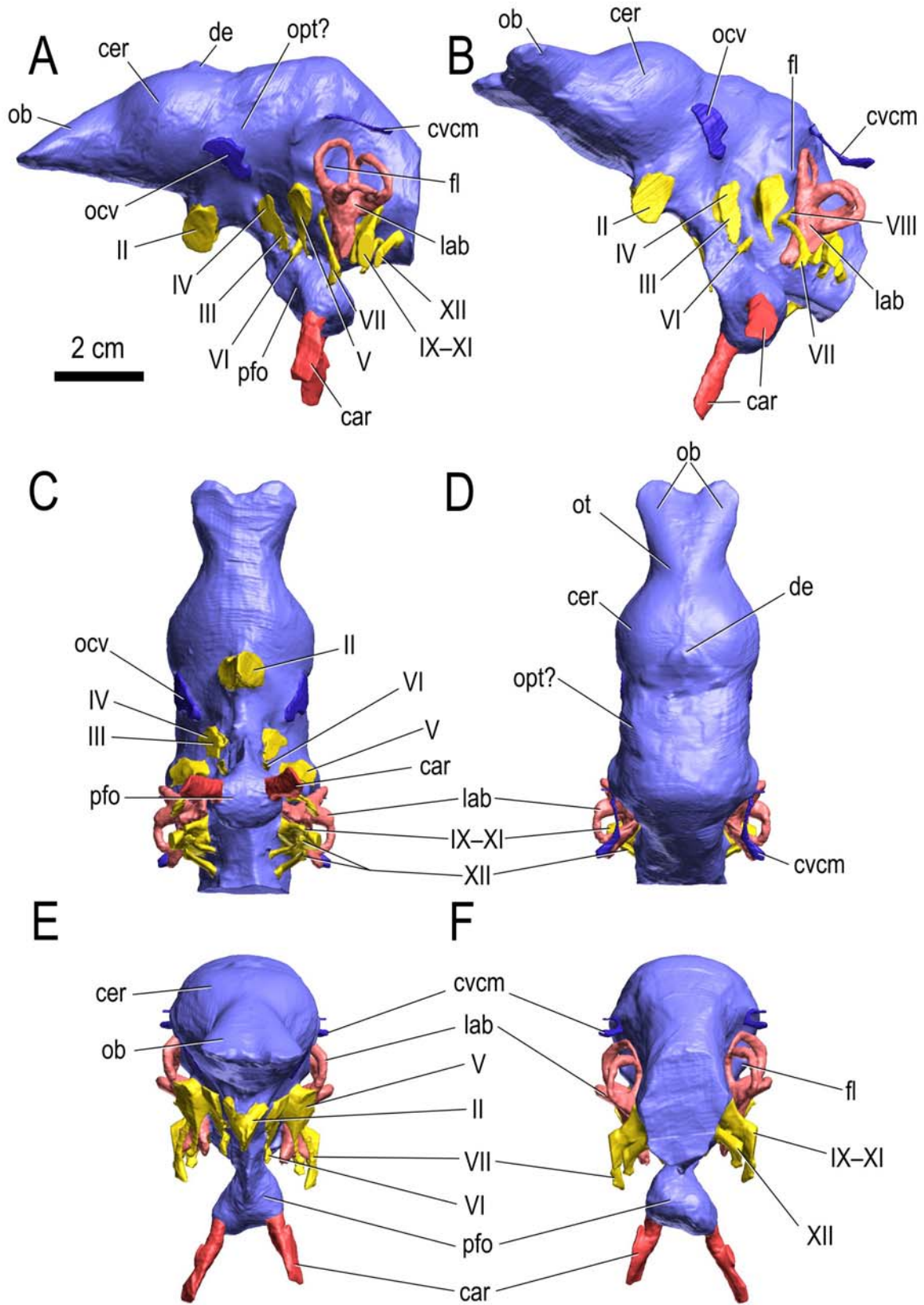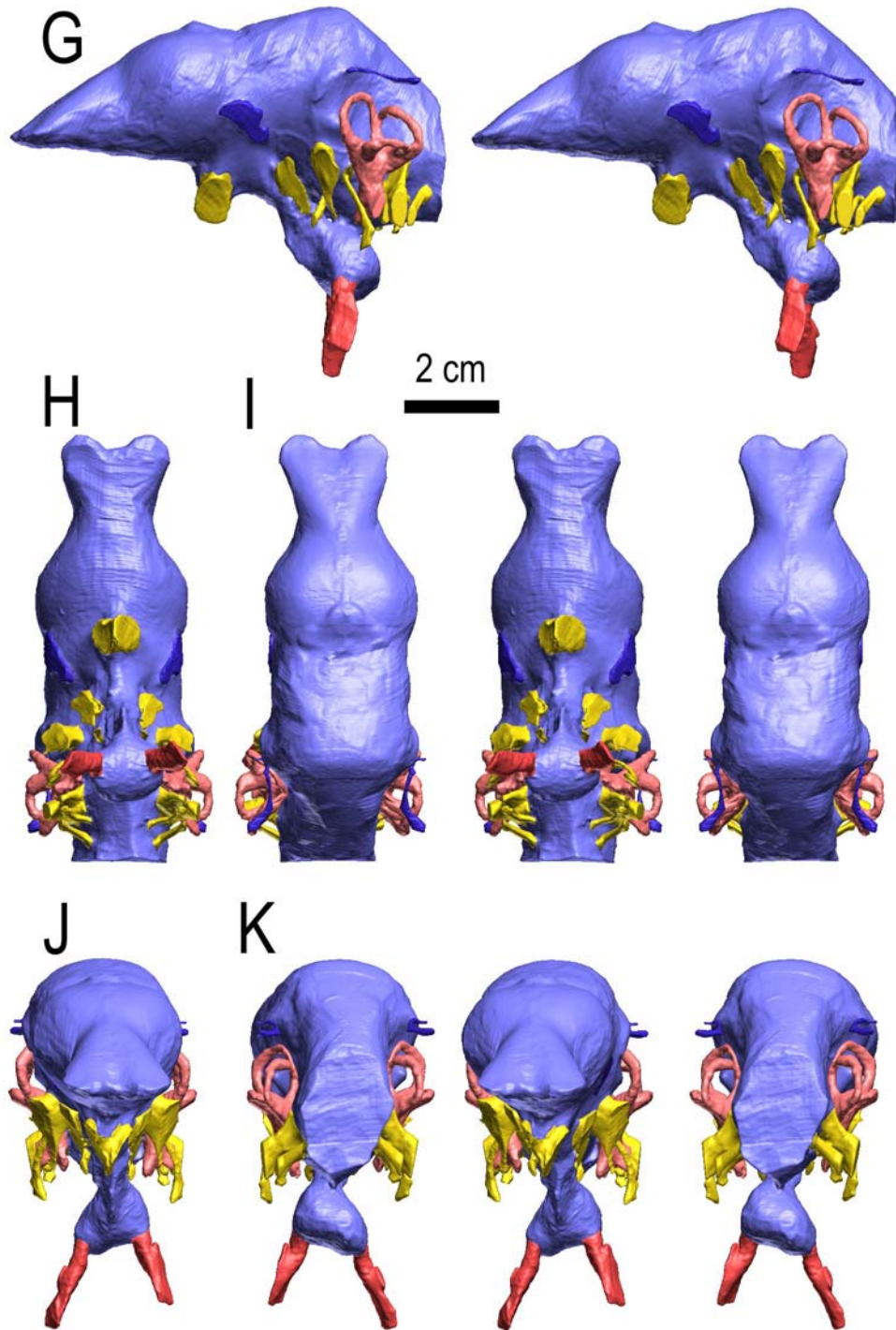
Figure S4. Cranial endocast, endosseous labyrinth, and some endocranial vascular structures in *Nigersaurus taqueti* (MNN GAD512) derived from surface renderings of *μ*CT scan data. (A)-left lateral view. (B)-left anteroventrolateral view. (C, H)-ventral view. (D, I)-dorsal view. (E, J)-anterior view. (F, K)-posterior view. *Color scheme*: *cyan blue*, cranial endocast; *pink*, endosseous labyrinth; *yellow*, nerve canals (some of which also transmit veins); *red*, arterial canals; *dark blue*, smaller venous canals.

Abbreviations: *car*, cerebral carotid artery canal; *cer*, cerebral hemisphere; *cvcm*, caudal middle cerebral vein; *de*, dural expansion; *fl*, flocculus (= cerebellar auricle); *lab*, endosseous labyrinth; *ob*, olfactory bulb; *ocv*, orbitocerebral vein; *opt?*, possible optic tectum (= lobe); *pfo*, pituitary (= hypophyseal) fossa; *II*, optic nerve canal; *III*, oculomotor nerve canal; *IV*, trochlear nerve canal; *V*, trigeminal nerve canal; *VI*, abducens nerve canal; *VII*, facial nerve canal; *VIII*, canal for vestibular branch of vestibulocochlear nerve; *IX–XI*, shared canal for glossopharyngeal, vagus, and accessory nerves and accompanying vessels; *XII*, hypoglossal canal.
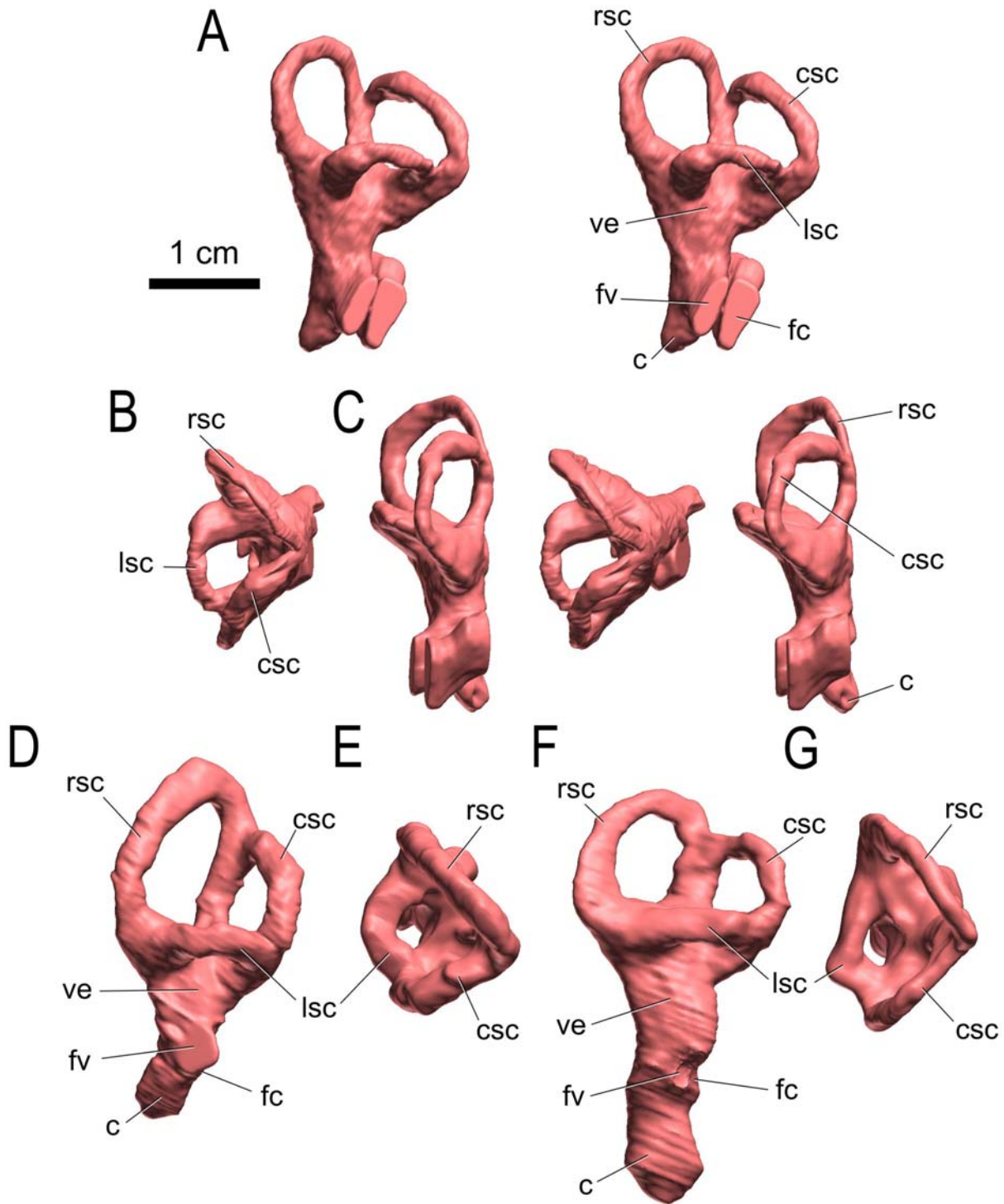
Figure S5. Endosseous labyrinths of the left inner ear of (A-C, stereopairs) the rebbachisaurid *Nigersaurus taqueti* (MNN GAD512), (D-E) the diplodocid *Diplodocus longus* (CM 11161), and (F-G) the basal neosauropod *Camarasaurus lentus* (CM 11338). (A, D, F)-left lateral view. (B, F, G)-dorsal view. (C)-posterior view. *Abbreviations*: *c*, cochlea; *csc*, caudal (posterior vertical) semicircular canal; *fc*, fenestra cochlea (= round window); *fv*, fenestra vestibuli (= oval window); *lsc*, lateral (horizontal)

semicircular canal; *rsc,* rostral (anterior vertical) semicircular canal; *ve,* vestibule of inner ear.
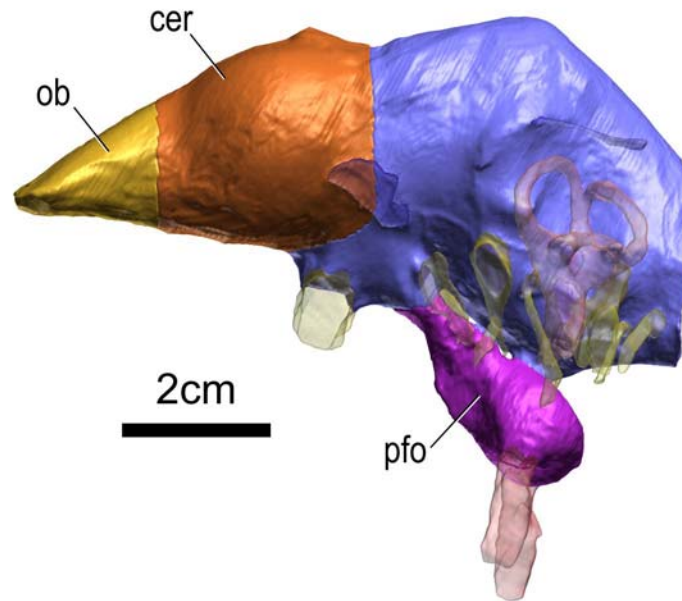

Figure S6. Partitioned endocast with transparent osseous labyrinth from *Nigersaurus taqueti.* Colors highlight the partitions used for digital assessment of endocast volumes.

TEXT S4. MICROWEAR AND INCREMENTAL LINES OF VON EBNER
Methods for Assessing Wear
Eight teeth referred to *Nigersaurus taqueti* were examined for microwear features on enamel and dentine surfaces using a light microscopy-based method [1]. Surfaces were cleaned before molding with 70% isopropyl alcohol to remove surface dust or dirt. Two molds were made for the worn surface of each tooth using a polyvinylsiloxane mold material (President Microsystem 6012, Coltene). The first cast was discarded as any surface artifacts or debris would adhere. High-quality clear epoxy resin was used to make the second cast of each tooth. Wear facets were examined under a light microscope at 70x magnification using reflected light. Wear features were examined in a 0.3mm x 0.3mm area and sorted into four categories: fine scratches (narrow and shallow), coarse scratches (wider and deeper), pits roughly circular depressions), and gouges (irregularly shaped or oblong pits). Preservation permitting, up to four sites were examined on each facet to survey areas of enamel and dentine to eliminate variation. Images were taken using a Spot CCD camera (Spot Insight 11.2 Color Mosaic, Diagnostic Instruments) at the highest resolution available (36 bits/pixel), mounted on a Nikon SMZ 1500 microscope.

Description. *Nigersaurus taqueti* is characterized by teeth with paired wear facets, located opposite each other on the external and internal surfaces of each crown (Figure 2), with angles of about 40° and 5° to the crown axis (as measured from the straighter distal portion of the crown near the facets). The external, or labial, facet is the smaller of the two, and cuts the tooth at a comparative shallow angle. This facet is notable for the presence of a deep trough formed at the enamel-dentine junction, a feature commonly produced by abrasion during tooth-food contact. The concavity is deepest at the base of the facet, indicating tooth abrasion occurred in a predominantly crown-root direction, although in several teeth this facet is slightly asymmetrical, with the apex slightly offset from the midline of the tooth. High-angled facets of this type are also known from the other two main radiations of diplodocoid sauropods, Diplodocidae (*Diplodocus,* CM 1161; CM = Carnegie Museum) and Dicraeosauridae (*Dicraeosaurus,* MB.R. 2197, 2204; MB = Humbolt Museum).

The second facet, located lingually, is proportionally much longer and occurs at a much steeper angle relative to the long axis of the tooth. Unlike the external facet's rounded, U-shaped outline, the internal facet is an elongate trapezoid with a very narrow base. The margins of this facet are smooth and rounded, indicative of attrition caused by tooth-tooth contact, not abrasive contact with plant material or grit. Kellner (1996) figured a tooth (DGM 907-R; DGM = Departamento Nacional de Produçao Mineral) from the Late Cretaceous Bauru Group of southeastern Brazil, which also has a similar pair of labial and lingual wear facets. Although Kellner tentatively considered the tooth to belong to a titanosaur on basis of the abundance of titansaurian bones from the Bauru Basin, thier similarity to *Nigersaurus* is striking [2].

Eight isolated teeth referred to *Nigersaurus* were examined for dental microwear using the light microscopy method of Solounias and Semprebon [1]. All are probably upper teeth, as all have high-angle wear facets on their internal surfaces; lower teeth may have been destroyed in the course of wear [2]. Both lingual and labial facets were examined for the presence of fine and coarse scratches, pits (roughly circular

depressions), and gouges (irregularly shaped or oblong pits). Three teeth were found to be completely unusable due to high levels of taphonomic abrasion. Of the remaining five teeth, most showed evidence of taphonomic alteration, but in each case microwear features were still present and identifiable on at least one aspect of the tooth. Commonly, both on teeth selected for potential features and some remaining that were eliminated before examination, the thin enamel surface of the lingual aspect of the tooth had been worn away, either through use or by taphonomic processes, and no trace of microwear could be found. Those cases are characterized by a coarse, pock-marked surface, and in one case wear so severe that it exposed the pulp cavity.

Labial Facet
Microwear features are most commonly noted on the enamel surfaces of diplodocoid sauropods, but in *Nigersaurus* the labial rim often lacks plain wear features and is instead highly polished, and wear features are more obvious on the dentin. This polishing is not reminiscent of taphonomic alteration by acids, bases, or sand abrasion [3], and is more likely a result of frequent and heavy wear by finely abrasive materials. Microwear features that are present are typically limited to fine scratches oriented roughly labio-lingually, with some inclination medially or laterally, in some cases following the curve of the enamel-dentine contact. Where microwear is quantifiable, feature density is high (7-16 scratches per measurement unit), but within the range noted for *Diplodocus*. Pits are present but rare, gouges and coarse scratches are absent in the enamel surface. Wear features often extend for a short distance onto the labial face of the tooth, basal to the facet. Some gouges are present on the enamel surface basal to the facet of one tooth. On one tooth without an apical facet, long, coarse scratches occur across the entire labial enamel surface, oriented between roughly 33⁰ and 45⁰ to the long axis. Microwear features were also noted on the dentine surface–these were less common (4-11 features per unit study, avg. 7.5) but typically much larger. Wear again consists primarily of fine scratches, often very long (0.1-0.2mm), with both gouges and pits present, possibly due to the softer nature of dentin.

Lingual Facet
Microwear was also noted on the lower-angle facet on the lingual face, although this surface is much more commonly taphonomically abraded beyond use for microwear study; even when features are present, they often occur in oases between heavily abraded regions. These features again consist primarily of long, fine scratches distributed equally across the facet, with pitting and gouging also common. The lateral edges of the facet are characterized by polished edges at coarser magnifications, but at 70x magnification the presence of large, deep scratches oriented along the crown-root axis occasionally appear at the lateral margins of the facet. This is accompanied by irregularly edged pits and gouges. Enamel attrition due to tooth-tooth contact is usually associated with "plucking" of prisms in prismatic mammalian enamel, but its impact on the aprismatic, columnar enamel typical of Diplodocoidea [4] has not been studied; these coarse wear features may represent the results of a similar process. The apex of this facet is typically without features, but occasionally fine scratches oriented along the crown-root direction do appear.

Microwear Summary

The pattern of microwear remaining on the labial facet, with dominance of fine scratches over pits, gouges, and deep scratches, is typical of a diet lacking hard foods (such as seeds) or high amounts of grit [5], although the deep excavation and highly polished enamel surface indicate a highly abrasive foodstuff. In particular, long scratches such as seen in the dentine have been associated with "softer" diets [6]. This agrees with the wear suggested by the presence of a deep erosional "lip" formed at enamel-dentine junction, indicative of heavy wear caused by shearing contact with plant material. Combined with asymmetrical enamel that is thickest on the external face, these data suggest that the small facet represents the "functional" side of the tooth. Dietary inferences in wholly extinct lineages are without much power beyond qualitative assessments, and so no attempt to quantify specific preferred foods of *Nigersaurus* will be made here.

Scratch orientation is variable between teeth but cross scratching is not noted. In each case, predominant scratch orientation is at a slight angle to the long axis. This would seem to indicate a predominantly unidirectional shearing motion with upper and lower teeth meeting essentially parallel to each other. Deviation from the crown-root axis is potentially a function of slightly imperfect occlusion or tooth orientation within the alveolus – the dentition of upper and lower jaws differ in the number of teeth present and the size of those teeth, which may contribute to uneven or off-center wear. The slight asymmetry in the shape of the facet may also be the result of this type of imperfect occlusion. If the upper teeth occlude off-center of the lower teeth, the lateral offset between the points of food contact in the upper and lower teeth will determine the offset in the apex of the labial wear facet. No indication of side-to-side slicing action of the jaws is suggested by the microwear features, and propaliny seems unlikely, given the lack of an attritional facet on the labial surface of any examined teeth.

The internal facet seems to indicate wear primarily by tooth-tooth contact, although microwear features typical of tooth-food contact are also present. The predominance of attritional macrowear features and thin enamel surface suggest that the lingual aspect does not represent a functional food-processing surface, and any tooth-food contact was incidental. As on the labial aspect, the predominantly crown-root orientation of microwear features suggests a vertical slicing action, as does the essentially midline location of the facet apices. The presence of these microwear features, however, reinforces the assertion of Sereno and Wilson [2] that this surface must have been exposed and not covered by a successive tooth in a tooth battery. Although it is possible that each tooth did not meet the tooth labial to it, this seems unlikely in a tooth battery. It is possible that this wear occurred only when the tooth was exposed as the lingual-most rank in the tooth battery "phalanx", and that as the tooth advanced and successive teeth filled in behind it, this surface was no longer unprotected. Given the relative thinness of the enamel on this surface, *Nigersaurus* may have minimized exposure (and therefore wear) on the lingual aspect in this way.

Incremental Lines of von Ebner

Lines of von Ebner were assessed by longitudinal and transverse sections of an intact premaxillary tooth battery that preserved successional teeth in the first and second columns from the midline. In cross-section of two successional crowns in the second

tooth column, approximately 60 and 40 incremental lines of von Ebner are visible for a cross-sectional difference of about 20 lines (days). The age of a tooth and the rate of replacement, however, must ultimately be assessed by counting lines in longitudinal section, because the cone-shaped accumulation of dentine during crown growth [7].

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TEXT S5: PHYLOGENETIC ANALYSIS
The phylogenetic analysis yields 5 shortest trees with one polytomy among ingroups, that between the partially known diplodocoid *Suuwassea*, Dicraeosauridae, and Diplodocidae. Two of the five trees represent alternative arrangements among the outgroups *Omeisaurus*, *Jobaria* and Macronaria. Although there exist only a few shortest trees, tree number increases rapidly when considering trees even one step longer. The reason for this is the high level of missing data in several of the rebbachisaurids included in the analysis. *Rebbachisaurus*, in particular, can be scored postively for only 19 of 102 characters (19% of the data). Limiting ingroups to taxa with less than 50% missing data increases the robustness of the tree but removes most rebbachisaurids with the exception of *Nigersaurus* and *Limaysaurus*.

Character List
The following list includes 102 character statements, 40 and 62 of which code cranial and postcranial variation, respectively. Character format and structure follows recent recommendations [1]. Character statements are attributed to the author that first used them in a qualitative or quantitative cladistic analysis. Characters without attribution are new to this analysis.

Cranial
1. Subnarial foramen and anterior maxillary foramen, position: well distanced from one another (0); separated by narrow bony isthmus (1). [2]
2. Premaxillary anterior margin, shape: without step (0); with marked step, anterior portion of skull sharply demarcated (1). [2]
3. Anteroventrally orientated vascular grooves originating from an opening in the maxillary contact on the premaxilla: absent (0); present (1). [2]
4. Antorbital fenestra, maximum diameter: much shorter than maximum diameter of orbit (0); subequal to orbital maximum diameter (1). [2]
5. Dorsal margin of antorbital fenestra, shape: straight or convex (0), concave (1). [2]
6. Dorsal process of maxilla, posterior extent: anterior to or even with posterior margin of maxilla (0); extending further posterior than body of maxilla (1). [2]
7. External nares, position: terminal (0); retracted to level of orbit (1); retracted to a position between orbits (2). [2]
8. External nares, maximum diameter: shorter than maximum orbital diameter (0); longer than orbital maximum diameter (1). [2]
9. Orbital ventral margin, anteroposterior length: broad, with subcircular orbital margin (0); reduced, with acute orbital margin (1). [2]
10. Quadratojugal, position of anterior terminus: posterior to middle of orbit (0); anterior margin of orbit or beyond (1) [modified from 3]
11. Maxilla, contact with quadratojugal: absent or small (0); broad (1). [modified from 3]
12. Jugal, contribution to antorbital fenestra: very reduced or absent (0); large, bordering approximately one-third its perimeter (1). [2]
13. Prefrontal, posterior process size: small, not projecting far posterior of frontal-nasal suture (0); elongate, approaching parietal (1). [2]
14. Prefrontal, posterior process shape: flat (0); hooked (1). [2]

15. Postorbital, posterior process: present (0); absent (1). [2]
16. Frontals, midline contact (symphysis): sutured (0); fused in adult individuals (1). [2]
17. Frontal, anteroposterior length: approximately twice transverse breadth (0); less than transverse breadth (1). [2]
18. Parietal, contribution to post-temporal fenestra: present (0); absent (1) [2]
19. Postparietal foramen: absent (0); present (1). [2]
20. Parietal, distance separating supratemporal fenestrae: shorter than long axis of supratemporal fenestra (0); twice the length of the long axis of the supratemporal fenestra (1). [2]
21. Supratemporal fenestra: present (0); absent (1). [2]
22. Squamosal, contact with quadratojugal: present (0); absent (1). [2]
23. Quadrate fossa, depth: shallow (0); deeply invaginated (1). [2]
24. Pterygoid, transverse flange (ectopterygoid process), position: posterior of orbit (0); between orbit and antorbital fenestra (1); anterior to antorbital fenestra (2). [2]
25. Supraoccipital, height: twice height of foramen magnum (0); subequal to or less than height of foramen magnum (1). [2]
26. Crista prootica, size: rudimentary (0); expanded laterally into dorsolateral process (1). [2]
27. Basipterygoid processes, length: short, approximately twice basal diameter (0); elongate, at least four times basal diameter (1). [2]
28. Basipterygoid processes, angle of divergence: approximately 45º (0); less than 30º (1). [2]
29. Basal tubera, fusion: unfused (0); fused (1). [4]
30. Basioccipital depression between occipital condyle and basal tubera: absent (0); present (1). [2]
31. Basipterygoid processes, orientation: perpendicular to skull roof (0); angled approximately 45º to skull roof (1). [2]
32. Dentary, anteroventral margin shape: gently rounded (0); sharply projecting triangular process or 'chin' (1). [2]
33. Tooth rows, shape of anterior portions: narrowly arched, anterior portion of tooth rows V-shaped (0); broadly arched, anterior portion of tooth rows U-shaped (1); rectangular, tooth-bearing portion of jaw perpendicular to jaw rami (2). [2]
34. Tooth rows, length: extending to orbit (0); restricted anterior to orbit (1); restricted anterior to subnarial foramen (2). [2]
35. Crown-to-crown occlusion: absent (0); present (1). [2]
36. Occlusal pattern: V-shaped wear facets (0); single planar facet (1); paired planar facets (2). [modified from 2]
37. Tooth crowns, orientation: aligned along jaw axis, crowns do not overlap (0); aligned slightly anterolingually, tooth crowns overlap (1). [2]
38. Tooth crowns, cross-sectional shape at midcrown: elliptical (0); D-shaped (1); cylindrical (2) [2]
39. Dentary teeth, number: greater than 20 (0); 17 or fewer (1). [2]
40. Replacement teeth per alveolus, number: two or fewer (0); three or more (1). [modified from 2]

Postcranial

41. Dorsal pneumatopores (pleurocoels): absent (0); present (1). [2]
42. Dorsal vertebrae, height of neural arch: less than height of centrum (0); subequal or greater than height of centrum (1).
43. Dorsal vertebrae, spinodiapophyseal webbing: laminae follow curvature of neural spine in anterior view (0); laminae "festooned" from spine, dorsal margin does not closely follow shape of neural spine and diapophysis (1).
44. Atlantal intercentrum, occipital facet shape: rectangular in lateral view, length of dorsal aspect subequal to that of ventral aspect (0); expanded anteroventrally in lateral view, anteroposterior length of dorsal aspect shorter than that of ventral aspect (1). [2]
45. Cervical vertebrae, number: fewer than 10 (0); 10 (1); 12 (2); 13 (3); 14 or more (4). [2]
46. Anterior cervical neural spines, shape: single (0); bifid (1). [2]
47. Anterior cervical vertebrae, height:length ratio: height less than or roughly equal to length of centrum(0); height 1.5 times length of centrum (1). [modified from Casanovas et al. 2001]
48. Mid-cervical centra, anteroposterior length:height ratio of posterior face: 2.5-3 (0); 4+ (1). [2]
49. Middle and posterior cervical neural arches, centroprezygapophyseal lamina (cprl), shape: single (0); divided (1). [2]
50. Posterior cervical vertebrae, accessory lateral lamina connecting postzygodiapophyseal and spinoprezygapophyseal laminae: absent (0) present (1) [5]
51. Cervical vertebrae, epipophyseal-prezygapophyseal lamina (eprl): absent (0); present (1).
52. Cervical vertebrae, longitudinal ridge on ventral surface: absent (0), present (1).
53. Posterior cervical neural spines, shape: single (0); bifid (1). [modified from 2]
54. Anterior cervical vertebrae, parapophyses: without pneumatization (0); with pneumatic cavity (1).
55. Middle and posterior cervical vertebrae, parapophyses: without pneumatization (0); with pneumatic cavity (1).
56. Middle cervical vertebrae, angle between postzygodiapophyseal and spinopostzygapophyseal laminae: acute (0); approximately 90º (1). [3]
57. Mid-cervical neural spines, orientation: vertical (0); anteriorly inclined (1). [3]
58. Mid-cervical neural spines, height: approximately as high as neural arch (0); considerably higher than neural arch (1). [modified from 3]
59. Posterior cervical neural arches, accessory spinal lamina: absent (0); present, running vertically just posterior to spinoprezygapophyseal lamina (1). [2]
60. Posterior cervical neural and/or anteriormost dorsal neural spines, orientation: vertical (0); inclined anteriorly (1). [3]
61. Posterior cervical and anterior dorsal bifid neural spines, median tubercle: absent (0); present (1). [2]
62. Posterior cervical and anterior dorsal bifid neural spines, shape: widely diverging (0); narrow, parallel to converging (1). [3]
63. Dorsal vertebrae, number: 13 (0); 12 (1); 11 (2); 10 or less (3). [3, modified from 2]
64. Middle and posterior dorsal vertebrae, pleurocoels: absent (0); present (1).

[modified from 3]
65. Dorsal neural spines, length: twice centrum length (0); approximately four times centrum length (1). [2]
66. Dorsal transverse processes, orientation: horizontal or only slightly inclined dorsally (0); more than 30⁰ inclined dorsally from the horizontal (1). [3]
67. Middle and posterior dorsal neural arches, centropostzygapophyseal lamina (cpol), shape: single (0); divided (1). [2]
68. Middle and posterior dorsal neural arches, prezygoparapophyseal lamina (prpl): absent (0); present (1). [2]
69. Middle and posterior dorsal neural arches, posterior centroparapophyseal lamina (pcpl): absent (0); present (1). [2]
70. Anterior caudal neural spines, shape: tapering or not flaring distally (0); flared distally, with pendant triangular lateral processes (1). [2]
71. Posterior dorsal neural arches, hyposphene-hypantrum articulations: present (0); absent (1). [2]
72. Posterior dorsal neural spines, shape: rectangular through most of length (0); 'petal' shaped, expanding transversely through 75% of its length and then tapering (1). [2]
73. Sacral neural spines, length: twice centrum length (0); nearly four times centrum length (1). [modified from 2]
74. First caudal centrum, articular face shape: flat (0); procoelous (1); opisthocoelous (2); biconvex (3). [2]
75. Caudal neural spines, elliptical depression between spinodiapophyseal lamina and postspinal lamina on lateral neural spine: absent (0); present (1).
76. Caudal neural spines, triangular lateral processes: absent (0); present (1).
77. Anterior caudal centra (excluding the first), articular face shape: amphiplatyan (0) procoelous (1) [modified from 2]
78. Anterior caudal neural spines, spinoprezygapophyseal lamina-spinopostzygapophyseal lamina contact: absent (0); present (1). [2]
79. Anterior caudal vertebrae, lateral spinopostzygapophyseal lamina: absent (0); present (1). [6]
80. Anterior caudal transverse processes, shape: triangular, tapering distally (0); winglike (1). [2]
81. Anterior caudal transverse processes, diapophyseal laminae (acdl, pcdl, prdl, podl): absent (0); present (1). [2]
82. Anterior caudal transverse processes, anterior centrodiapophyseal lamina (acdl), shape: single (0); divided (1). [2]
83. Distalmost caudal centra, articular face shape: platycoelous (0); biconvex (1). [2]
84. Distalmost caudal centra, length-to-height ratio: less than 4 (0); greater than 5 (1). [2]
85. Distalmost biconvex caudal centra, number: 10 or fewer (0); more than 30 (1). [2]
86. Cervical ribs, length: long, overlapping several centra posterior (0); shorter than or roughly equivalent to centrum length (1). [2]
87. Chevrons, "crus" bridging haemal canal: present (0); absent (1). [2]
88. Scapula, acromion process dorsal margin: convex or straight (0); with U-shaped concavity (1). [7]

89. Scapulocoracoid, angle of articulation relative to scapular blade: 90 degrees (0); less than 90 degrees (1). [modified from 8]
90. Scapular blade, shape: acromial edge not expanded (0); rounded expansion on acromial side (1); racquet-shaped (2). [2]
91. Scapular glenoid, orientation: relatively flat or laterally facing (0); strongly beveled medially (1). [2]
92. Coracoid, anterodorsal corner shape: subrectangular (0); rounded or curved (1).
93. Humerus, midshaft cross-section, shape: circular, major and minor axes subequal (0); elliptical, major axis twice minor axis (1). [2]
94. Humerus, pronounced proximolateral corner: absent (0); present (1) [2]
95. Pubis, ambiens process development: small (0); prominent, projecting anteriorly from anterior margin of pubis (1). [2]
96. Ischial distal shaft, shape: bladelike, medial and lateral depths subequal (0); triangular, depth of ischial shaft increases medially (1). [reversed from 2]
97. Ischial distal shafts, cross-sectional shape: V- shaped, forming an angle of nearly 50° with each other (0); flat, nearly coplanar (1). [2]
98. Ischium, iliac peduncle shape: straight or widening in smooth curve distally (0); narrow, with distinct "neck" (1).
99. Ischium, elongate muscle scar on proximal end: absent (0); present (1).
100. Distal end of ischial shaft expanded: absent (0); present (1).
101. Femur, pronounced ridge on posterior surface between greater trochanter and head: absent (0); present (1).
102. Metatarsal I distal condyle, posterolateral projection: absent (0); present (1). [2]

Character–Taxon Matrix
The following are scores for 102 characters in 13 terminal taxa and 3 outgroups. Characters include state "0" (= primitive), states "1-4" (derived), "?" for missing information, and "9" for inapplicable data. All characters are binary except 11 (characters 8, 26, 27, 42, 43, 45, 47, 58, 78, 92, 118). All multistate characters were treated as unordered except the three that code positional change and are presumed to transform in an ordered fashion in development (8, 27, 43).

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Jobaria
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    09009000010010001000?0
MACRONARIA
    0100001110000000010010011000000001110011010003000000001100000991100010000000000?0
    09009010010010001000000
Apatosaurus
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    101111 0000101011000101
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Suuwassea
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Diplodocus
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11111100100110110000101
Brachytrachelopan
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Dicraeosaurus
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1011?100?0011111000101
Amargasaurus
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?????1???0??10????????
Limaysaurus
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0911?11112000000110000
Nigersaurus
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??11?1?10201010?11101?
Rebbachisaurus
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Cathartesaura
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09?????112????????????
Zapalasaurus
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??????????????001?00??
Histriasaurus
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Spain_Rebbach.
????????????????????????????????????1????0011?11??????0????1??0??1????11000?
09????????????0111?1?
;
END;

Temporal Range
The sources for temporal range data in Figure 4 is given below:

<u>Outgroups</u>

Macronaria	Kimmeridgian-Maastrictian	
Jobaria	Neocomian	[7]
Omeisaurus	Oxfordian	[8]

<u>Ingroups</u>

Cathartesaura	Turonian-Coniacian	[9]
Rebbachisaurus	Cenomanian	[7]
Limaysaurus	Aptian-early Turonian	[10]
Nigersaurus	Aptian-Albian	[7]
Histriasaurus	late Hauterivian- early Barremian	[11]

Zapalasaurus	Barremian-early Aptian	[11]
Burgos taxon	late Barremian- early Aptian	[12]
Amargasaurus	Barr-early Aptian	[10]
Dicraeosaurus	Kimmeridgian-Tithonian	[13]
Brachytrachylopan	Tithonian	[3]
Suuwassea	Tithonian	[14]
Diplodocus	Kimmeridgian, Tithonian	
Apatosaurus	Kimmeridgian, Tithonian	[15]

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