ELECTRONIC SUPPLEMENTARY MATERIAL

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Article: No gastric mill in sauropod dinosaurs: new evidence from analysis of gastrolith mass and function in ostriches

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Supplementary Methods

Relative gastrolith mass data

Ostriches

To compare gastrolith mass to body mass, 347 stomachs of slaughtered ostriches of known weight were sampled from healthy free-ranging farm animals in Germany and South Africa. Samples from 135 German ostriches were collected between November 2000 and May 2003. Most were raised in large enclosures (total size: approximately 20 hectares) on the “Gemarkenhof” farm. Age (in months) and gender was recorded from all German birds. Body mass was measured for a few of the birds and later estimated to the nearest 5 kg by the farmer (R. Schumacher). In contrast, all South African birds were weighed shortly after death. The German and South African birds had *ad libitum* access to pebbles for swallowing throughout their lifetime, including the last days prior to their slaughter (pers. obs. OW, 2000-2003, and A. Olivier, pers. comm. 2003).

South African birds were sampled because of their more natural habitat compared to that of the German specimens. Material was collected during slaughtering of ostriches in an abattoir of the Klein Karoo Co-operative in Oudtshoorn, Klein Karoo, between 31st January 2003 and 14th February 2003. The birds originated from several farms in the Klein Karoo basin. A total number of 212 animals were sampled.

Approximately 10% of the birds regurgitated stones (usually only small pebbles) during death throes (pers. obs. OW 2003). This was assisted by the inverted position of the birds on the abattoir conveyor line. Because the slaughtering process was rapid (usually more than one animal was processed each minute), it was not possible to collect the stomach contents with the same accuracy as in Germany. It is likely that some stones might have been lost during opening of the stomach as well as during transfer into the bucket. However, the maximum mass of the lost stones was visually estimated at <10 g, less then 1% of the total gastrolith mass.

The advantage of the South African birds lies in the exactly determined body mass and their more “natural” habitat. The stomach contents of all animals were weighed and then washed with water until all plant matter was separated from the gastroliths. The stones were air-dried and weighed.

Other birds

To supplement the ostrich data, we added reliable data for 26 species of birds compiled from the ornithological literature (see Supplementary Table 1). The comparative data for birds also suggest that relative gastrolith mass scales with an exponent of 1 and not with the exponent for basal metabolic rate which is 0.75. This exponent could have been expected from gastroliths being an integral part of the digestive system.

Dinosaurs

About 250 pebbles were found associated with the skeletal remains of *Seismosaurus*. Since several pebbles are still enclosed in matrix, the total gastrolith mass could only be estimated. The weight estimate is based on an interpolation of the volume of the *Seismosaurus* gastroliths as given in Gillette (1994). All available material in the collection of the New

Mexico Museum of Natural History (NMMNH 3690) was examined in 2002. However at this time some of the gastrolith specimens were on loan in Japan.

For *Caudipteryx*, a mean gastrolith mass of 88 g was calculated based on a volume estimate of the gastrolith clusters for all published specimens (for methods see Cheng *et al.* 2006). In combination with our estimate of *Caudipteryx* body mass as 7 kg, this results in a ratio of 1.25% of gastrolith mass to body mass.

Taphonomic field work in Upper Jurassic sauropod quarries

Methods

We visited a number of documented gastrolith sites, including classic North American outcrops of Upper Jurassic and Lower Cretaceous strata, as well as other Jurassic sauropod localities world-wide. Additionally, we studied the taphonomy of numerous sauropod finds to assess potential associations of gastroliths and the possible reasons for their absence. Field work and first hand observations were conducted at many sites in the Morrison Formation, including the Carnegie Quarry in Dinosaur National Monument (Utah), Como Bluff and Bone Cabin Quarry (Wyoming), Dry Mesa Dinosaur Quarry (Utah), Howe Quarry (Wyoming), and Howe Stephens Quarry (Wyoming). These sites were complemented with Jurassic localities near Lourinhã in Portugal and in the Chubut region in Argentina.

Fieldwork included the comparative study of sediments, the sauropod finds at these localities, their taphonomy, and the search for exotic stones in and around the quarries. Special focus was given to localities preserving articulated and well-associated sauropod skeletons. Furthermore, field localities and material of *Cedarosaurus*, *Seismosaurus*, and *Dinheirosaurus* holotypes (see above) were examined. The taphonomy of *in situ* sauropod skeletons at Dinosaur National Monument was studied regarding possible gastrolith loss. Data were recovered from the literature regarding the Tendaguru sauropod finds in Tanzania/Africa (Janensch 1929; Heinrich 1999). Detailed descriptions of the localities and their taphonomy are published elsewhere (Wings 2004).

Visits to museum collections (American Museum of Natural History, New York City; College of Eastern Utah Prehistoric Museum, Price, Utah; Denver Museum of Natural History, Denver, Colorado; New Mexico Museum of Natural History, Albuquerque, New Mexico; Carnegie Museum of Natural History, Pittsburgh, Pennsylvania; Yale Peabody Museum, New Haven, Connecticut; Museum für Naturkunde, Humboldt University, Berlin, Germany; Staatliches Museum für Naturkunde Stuttgart, Germany; Sauriermuseum Aathal, Switzerland) complemented the field work to study gastrolith material and the general bone preservation from these and other sites such as Tendaguru. Historic field notes and publications about the quarries were also studied regarding the occurrence of gastroliths, sedimentology, taphonomy and faunal lists (Wings 2004).

Results

Our field work and collections visits indicate that overall occurrence of gastroliths in sauropods is extremely rare (Supplementary Table 2)**.** Among the examined North American localities and specimens, there is conclusive evidence (gastroliths contained in fine-grained matrix without similar pebbles, direct association with bones, pebbles deposited as clusters) for genuine gastroliths only in two isolated skeletons: the holotypes of *Seismosaurus* and *Cedarosaurus*. Gastroliths were also found in one out of 15 *Barosaurus* skeletons from the Howe Quarry (Wyoming) (Michelis 2004). Most of the other sauropod quarries and isolated skeletons lacked any possible gastroliths. The greatest number of isolated putative gastroliths (about 600) was found in the Dry Mesa Quarry (Utah) which preserves the remains of at least 20 sauropod individuals. On a world-wide scale, only about 2-4% of the sauropod finds have associated stones for which gastroliths are a plausible explanation (Wings 2004).

Supplementary Tables

Supplementary Table 1. Mean gastrolith mass vs. mean body mass in 27 species of living birds was compiled from own research (ostriches) and the ornithological literature. In several cases, mean values for body mass and gastrolith mass were calculated from different sources. Seasonal change in diet (e.g. summer: insects; winter: plant material) commonly occurs for several of the listed birds and complicates a correlation between diet and quantity of gastroliths. However, note the correlation between high relative gastrolith mass and an herbivorous diet (predominately herbivorous species are marked in grey).

Species	Mean total gastrolith mass [g]	Sample size (number of individuals)	Reference for gastroliths	Mean body mass [g]	Reference for body mass	Gastroliths in % of body mass
Corvus cornix (Dun Crow)	2.5	1738	(Rörig 1900)	493	(Rörig 1900)	0.5
Corvus frugilegus (Rook)	3.2	918	(Rörig 1900)	480	(Rörig 1900)	0.7
Corvus corone	3.3	62	(Rörig 1900)	510	(Rörig 1900)	0.7
Garrulus glandarius (Jay)	1.2	-	(Mangold 1927)	164	(Blotzheim 1993)	0.7
Columba palumbus (Wood Pigeon)	4.9	-	(Mangold 1927)	487	(Hoyo et al. 1997)	1
Tetrao urogallus (Capercaillie)	25	-	(Mangold 1927)	2975	(Hoyo et al. 1992)	0.8
Tetrao tetrix (Black Grouse)	7.9	-	(Mangold 1927)	1050	(Hoyo et al. 1992)	0.8
Anthus pratensis (Meadow Pipit)	0.0089	79	(Walton 1984)	19.4	(Blotzheim 1985)	0.1
Phasianus colchicus (Pheasant)	4.8	-	(Mangold 1927)	1190	(Hoyo et al. 1992)	0.4
Perdix perdix (Grey Partridge)	2.87	15	(Bialas et al. 1996)	383	(Hoyo et al. 1994)	0.8
Coturnix coturnix (Quail)	0.2	-	(Mangold 1927)	113	(Hoyo et al. 1994)	0.2
Grus grus (Crane)	38	-	(Mangold 1927)	5400	(Hoyo et al. 1996)	0.7
Cygnus olor (Mute Swan)	69.8	7	(Owen & Cadbury 1975; Thomas et al. 1977)	10800	(Hoyo et al. 1992)	0.7
Cygnus columbianus (Bewicks Swan)	28.5	13	(Owen & Cadbury 1975)	5600	(Hoyo et al. 1992)	0.5
Anas acuta (Pintail)	2.5	34	(Thomas et al. 1977)	850	(Hoyo et al. 1992)	0.3
Anas crecca (Teal)	0.9	112	(Thomas et al. 1977)	350	(Hoyo et al. 1992)	0.3
Anas platyrhynchos (Mallard)	3.8	113	(Thomas et al. 1977)	1163	(Hoyo et al. 1992)	0.3
Anas strepera (Gadwall)	3.9	15	(Thomas et al. 1977)	920	(Hoyo et al. 1992)	0.4
Anas penelope (Wigeon)	4.5	224	(Thomas et al. 1977)	693	(Hoyo et al. 1992)	0.7
Anas clypeata (Shoveler)	1.6	44	(Thomas et al. 1977)	755	(Hoyo et al. 1992)	0.2
Aythya ferina (Porchard)	2.9	9	(Thomas et al. 1977)	1000	(Hoyo et al. 1992)	0.3
Aythya fuligula (Tufted Duck)	1.7	13	(Thomas et al. 1977)	1200	(Hoyo et al. 1992)	0.1

Gallinula chloropus (Moorhen)	3.3	25	(Thomas et al. 1977)	314	(Blotzheim 1973)	1.1
Fulica atra (Coot)	10.5	7	(Thomas et al. 1977)	835	(Blotzheim 1973)	1.3
Numida meleagris (Helmeted Guinea-Fowl)	3.3	-	(Ayeni et al. 1983)	1375	(Hoyo et al. 1994)	0.2
Erithacus rubecula (European Robin)	0.067	88	(Herrera 1977)	17.2	(Herrera 1977)	0.4
Struthio camelus (Ostrich)	930	347	(Wings 2004)	88900	(Wings 2004)	1.1

Supplementary Table 2. Summary of information for selected quarries. For references and discussion see Wings (2004).

Locality	**Stratigraphy**	**Depositional environment**	**Sedimentology**	**Taphonomy**	**Origin of carcasses**	**Amount of material**	**General diversity**	**Sauropod diversity**	**No. of sauropod individuals**	**No. of gastroliths/ exoliths**
Carnegie Quarry, Dinosaur National Monument	Morrison Fm., Brushy Basin Member	River channels	Coarse sandstone, in parts conglomeratic	Carcasses washed together, articulated skeletons are abundant	Allochthonous – parauthochtonous	Some 5000 bones, 60 - 300 Dinosaurs	High	4 genera	>20	0
Cleveland-Lloyd Dinosaur Quarry	Morrison Fm., Brushy Basin Member	Water hole, oxbow lake	Mudstone	Miring in mud	Autochthonous	10000 disarticulated bones of at least 70 individuals	Medium	3 valid genera, maximum 6 genera	10	2?
Como Bluff/Bone Cabin Quarry	Upper part of the Morrison Fm.	River channels	Fine-grained sandstones and claystones	Isolated skeletons and articulated skeletons washed together	Allochthonous– parauthochtonous	Thousands of bones (only in BCQ approx. 69 partial skeletons)	High	5 genera	Como Bluff: unknown BCQ: 44	Como: 0 BCQ: 0
Dry Mesa Quarry	Morrison Fm., Brushy Basin Member	River channels	Conglomeratic sandstones	Bones washed together, mainly disarticulated skeletal elements	Allochthonous	More than 4000 mainly isolated skeletal elements	Very high (highest in the Morrison Fm.)	5 genera	>20	500-600
Howe Quarry	Morrison Fm. (145.7 Ma)	Water hole, oxbow lake	Siltstone, in parts sandy	Miring in mud	Autochthonous	More than 4000 bones of at least 25 animals	Low	3 genera	25	64
Cedarosaurus site	Cedar Mountain Fm., Yellow Cat Member	Floodplain with low water energy	Mudstone	Isolated skeleton resting on its belly	Parautochthonous - autochthonous	Isolated skeleton	Isolated find	1 genus	1	115
Seismosaurus site	Morrison Fm., Brushy Basin Member	River channels	Sandstone	Partly preserved isolated skeleton	Parautochthonous	Isolated skeleton	Isolated find	1 genus	1	>240

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