The first megalosaurid tooth from South Korea

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We describe a theropod tooth from the Early Cretaceous of South Korea. It is similar to the teeth of *Prodeinodon* from the Early Cretaceous of Mongolia and Guangxi, China and the teeth of *Szechuanosaurus campi* from the Late Jurassic of Kuangyuan, N. Sichuan, China. The tooth is slender antero-posteriorly and its posterior margin is straight. This discovery confirms that megalosaurids survived beyond the Jurassic–Cretaceous boundary and occurred in Europe, North America and East Asia.

DINOSAURS from the Cretaceous of South Korea are known only from trace fossils and fragmentary bones[1–4]. An isolated theropod dinosaur tooth was collected from the Early Cretaceous (Hauterivan–Barremian) Hasandong Formation in the non-marine Kyongsang Supergroup of South Korea. The Kyongsang Supergroup has produced plants, freshwater molluscs, insects, tortoises, dinosaur tracks and bird tracks including web-footed species[2,5,6]. Fossil collection in the Hasandong Formation has produced three sauropod teeth that can be attributed to *Chiayüaurus*, Titanosaurid?, and Camarasaurid?[1].

The crown of KS 7001 (Kyeongnam Science High School Museum) is 62 mm tall and its basal length is 19.3 mm. The basal width is 12.6 mm. The specimen has serrations on both anterior and posterior margins. The anterior serrations are fine. Frequency of serrations on the posterior margin increases from the base to the tip of the crown (24/10 mm to 34/10 mm). The serrations on the anterior margin are coarser than on the posterior margin (24/10 mm to 29/10 mm). The crown is compressed antero-posteriorly. The posterior margin of KS 7001 is straight, while the anterior margin curves posteriorly. Irregular longitudinal striations occur on both lingual and labial surfaces. The tip of the crown and the posterior portion of the crown base are damaged.

KS 7001 is unique in having transverse lines on the lateral surface near the posterior margin, that run up to midline of the tooth (Figure 1). These lines are not growth lines and are continuous with serrations on the posterior margin. The crowns of megalosaurids are flattened laterally and curved backward[7–11]. It is usual for the front serrations to become less distinct or even obliterated by wear[11]. KS 7001 is strongly compressed laterally as in megalosaurids (Figure 2).

Based on the dentary teeth of *Megalosaurus hesperis* (British Museum of Natural History R. 332), posteriorly located teeth tend to have straighter posterior margins than do anteriorly located teeth. The anterior teeth are curved more backwards. The shape of KS 7001 indicates that it is a shed tooth from the posterior portion of the maxilla or dentary.

KS 7001 and *Prodeinodon kwangshiensis* (IVPP V4794) from the Early Cretaceous of China have similar crown shapes while the crown of KS 7001 is wider than teeth of *Prodeinodon* from Mongolia (American Museum of Natural History 6531 and 6265) and China (Institute of Vertebrate Paleontology and Paleoanthropology V4794).

The cross-section of KS 7001 resembles teeth of

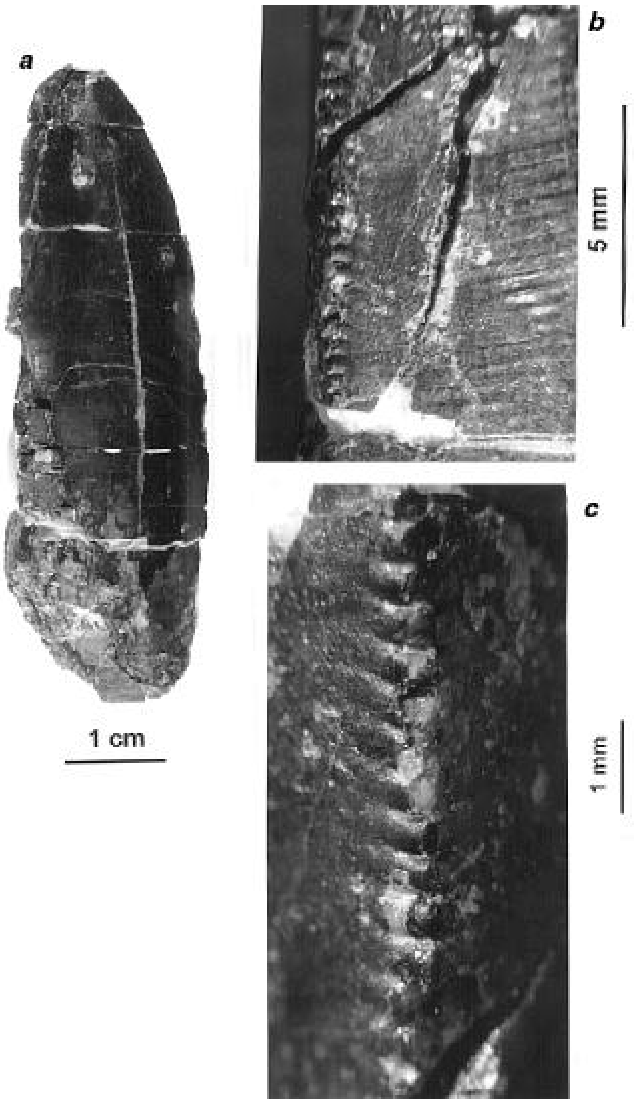

Figure 1. KS 7001 (***a***) lateral view; (***b***) close-up of transverse lines which are continuous with serrations, (***c***) serrations of posterior margin.

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Prodeinodon mongoliense (AMNH 6265) from the Oshih Formation of Mongolia in shape and thickness (Figure 3). The ratios of base diameters (antero-posterior length/ labial–lingual width) are 1.45 ~ 1.66 (KS 7001) and 1.63 (AMNH 6265). The ratio for teeth of *Szechuanosaurus campi* is 1.50 ~ 1.69, indicating that they are as wide as KS 7001. KS 7001 and teeth of *S. campi* are relatively wider than teeth of *P. kwangshiensis* and *Wakinosaurus satoi* (Table 1 and Figure 2). Cross-sections of teeth of *P. kwangshiensis* and *W. satoi* indicate that their teeth are labio-lingually compressed and the anterior and posterior ends are tapered (Figure 3).

Differentiation in tooth shapes among theropods may suggest different diets. The labio-lingually compressed teeth such as those of *P. kwangshiensis* and *W. satio* are adapted for slicing, while antero-posteriorly compressed teeth such as in KS 7001, *S. campi* and *P. mongoliense* are adapted for biting and piercing.

A tooth crown (Mifune Dinosaur Museum 341) from Japan is similar to KS 7001 in having a laterally compressed shape. However, MDM 341 has arcuate enamel wrinkles that sweep down and away from the serrations on the distal margins of the labial and lingual surfaces[12]. Similar enamel wrinkles are known in only a few theropods such as *Carcharodontosaurus* from Egypt, Morocco, Brazil, Tunisia, and Algeria[12–15]. The teeth of *Carcharodontosaurus* are flattened, recurved and broad antero-posteriorly, with serrated anterior and posterior carinae[13]. On both sides of the crown, arcuate enamel wrinkles curve toward the marginal serrations and often extend across the crown[15].

Table 1. Measurement and ratios (length and width of cross-sections) of KS 7001 and other theropod teeth (in mm)

	Antero-posterior length	Labial-lingual width	Ratio: antero-posterior/ labial-lingual
KS 7001	Top: 17.1	10.3	1.66
	Middle: 17.4	10.5	1.66
	Bottom: 17.9	12.3	1.45
			Average: 1.59
Szechuanosaurus campi			
(IVPP V235)	22	13	1.69
(IVPP V236)	21	14	1.50
Prodeinodon mongoliense			
(AMNH 6265)	13.4	8.2	1.63
(AMNH 6531)	16.7	8.8	1.90
Prodeinodon kwangshiensis (IVPP V4795)	25.4	8.6	2.95
Carcharodontosaurus saharicus (SGM-Din 3)	43.5	15.7	2.77
Wakinosaurus satoi	Top: 27	8.5	3.17
	Bottom: 32.8	10.4	3.15
			Average: 3.16

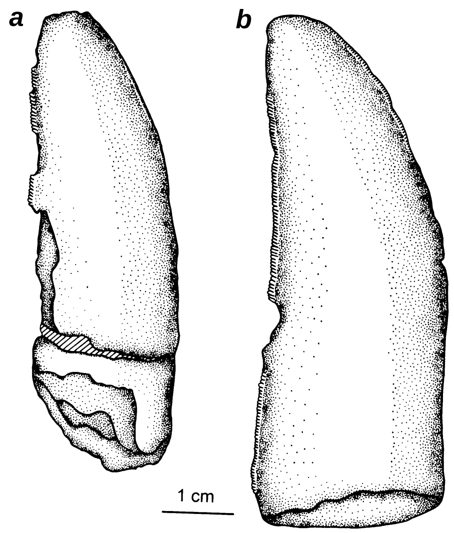

Figure 2. Lateral view of (***a***) KS 7001 and (***b***) *Prodeinodon kwangshiensis* (IVPP V 4794).

Table 2. Megalosaurid

	Locality	Age	Material	Reference
Torvosaurus tanneri	USA (Dry Mesa Quarry, Colorado)	Late Jurassic (Morrison formation)	Skull, mandible, teeth, skeletons	17, 19
Edmarka rex	USA (Como Bluff, Wyoming)	Late Jurassic (Middle to Late Tithonian)	Left jugal, left scapulocoracoid, dorsal ribs, caudal	8
Megalosaurus bucklandi	England (North Yorkshire), France	Middle–Late Jurassic	Jaw with teeth, rib, dorsal, caudal, sacral, pelvis, femur	7, 30
Megalosaurus wetherilli	USA (Arizona)	Early Jurassic	Complete skeletons	31
Megalosaurus hesperis	England (Dorset)	Middle Jurassic	Skull elements including maxillary teeth and dentary teeth	25
Megalosaurus nethercombensis	England (Dorset)	Middle Jurassic	Dentary with teeth, tibia, femora, pubis, astragalus, caudal, dorsal	25, 32
Prodeinodon kwangshiensis	China (Guaangxi)	Early Cretaceous	Teeth	20
Prodeinodon mongoliense	Mongolia (Oshih Basin)	Early Cretaceous	Teeth	23
Szechuanosaurus campi	China (Kuangyuan, N. Sichuan)	Late Jurassic	Teeth	24
Wakinosaurus satoi	Japan (Kurate Gun)	Early Cretaceous	Teeth	22
Xuanhanosaurus qilixiaensis	China (Xuanhan County, Sichuan Basin)	Middle Jurassic	Forearm, cervical, dorsal, pectoral girdle	18

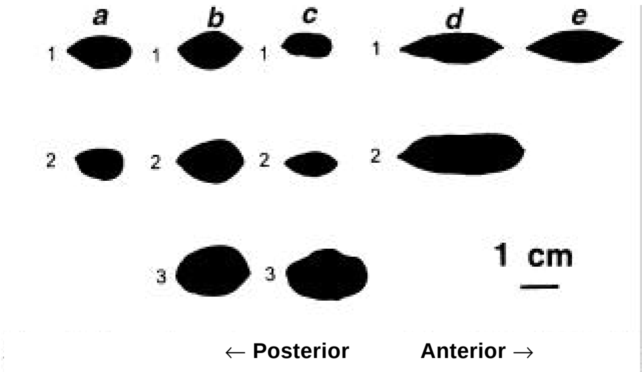

Figure 3. Cross-section of teeth of megalosaurids from East Asia. ***a***, *Prodeinodon mongoliense* (1, AMNH 6531; 2, AMNH 6265); ***b***, KS 7001 (1, top; 2, middle; 3, bottom); ***c***, *Szechuanosaurus campi* (1, IVPP V 239; 2, V 238; 3, V 236); ***d***, *Wakinosaurus satoi* (1, middle; 2, bottom), and ***e***, *Prodeinodon kwangshiensis* (IVPP V 4795).

Megalosaurids occupied Europe, North America, and East Asia from the Middle Jurassic to the Late Early Cretaceous[7,16–25] (Table 2). The records in Europe and North America are all from the Jurassic, while some megalosaurids such as *Prodeinodon* and *Wakinosaurus* discovered in East Asia, are from the Early Cretaceous[20,22,23,26]. Bakker[26] argued that the terminal Jurassic extinction eliminated megalosaurids and the most specialized allosaurids. However, discoveries from East Asia indicate megalosaurids survived the Jurassic–Cretaceous boundary. The Hasandong Formation of Kyongsang Supergroup produces more than 40 theropod footprints, including one track-way consisting of six consecutive footprints[27]. This megalosaurid tooth from the Hasandong Formation may be one of the theropod makers and prove useful in the reconstruction for Early Cretaceous of Korea.

This discovery of KS 7001 is the first report of a megalosaurid from Korea. This new discovery and recent reports, including tyrannosaurs from Thailand and Japan provide significance for our understanding of Early Cretaceous radiations of theropod dinosaurs in Asia[28,29].

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