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Original Article

Second discovery of a spinosaurid tooth from the Sebayashi Formation (Lower Cretaceous), Kanna Town, Gunma Prefecture, Japan

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Abstract: A fragment of an isolated tooth is described from the Lower Cretaceous Sebayashi Formation of the Sanchu Group. Its crown is almost round in cross section and shows distinctive flutes. Between the flutes, there are longitudinal finely granular structures. The distinctive carinae have poorly defined serrations. It is probably assigned as a spinosaurid theropod dinosaur and is the second report from Japan. This spinosaurid tooth is found from the higher stratigraphic horizon of the same formation than the first. The occurrences of spinosaurids from two horizons suggest that spinosaurids might have habituated this area during the deposit of the Sebayashi Formation. The dental comparison between Asian and other spinosaurids suggests that Asian spinosaurids may have unique dental characteristics and be different from any known spinosaurids, although the phylogenetic relationships between Asian and other spinosaurids (baryonychines and spinosaurines) are unclear.

Key words: Dinosaur, Spinosauridae, Sebayashi Formation, Gunma Prefecture, Kanna Town

Introduction

A fragmentary dinosaur tooth was collected in a fossil-digging site near Mamonosawagawa River of Kanna Town, Tano Gun, Gunma Prefecture by two children, Taisei Kanai and Hirohito Kanai from Nagano Prefecture, on 29 April in 2015 (36°04’ 18,7”N; 138°49’ 46.3”E; Fig. 1). The fossil-digging site, managed by Kanna Dinosaur Center, opened in 1999 and yielded a number of invertebrate (bivalves and gastropods) and plant fossils. Some vertebrate fossils, including two small fishes, a ganoid scale, and an unidentified bone fragment, have been found. No dinosaur fossils have come from this site until now, although four kinds of dinosaur fossils have been reported from Kanna Town (Hasegawa et al., 1999, 2003; Takakuwa et al., 2008; Molnar et al., 2009).

Heretofore, some dental nomenclatures, especially crown enamel ornamentations, for spinosaurids are used as in Table 1. Macro-sized and longitudinal ornamentation on the crown is characteristic in spinosaurids and had been called as crest, flute, ridge, and striation (Fig. 2A). Gradually, “crest” is used as a comb of feathers or skin on the head of a bird or other animal or the top of a mountain or hill. A “ridge” seems to be good as this

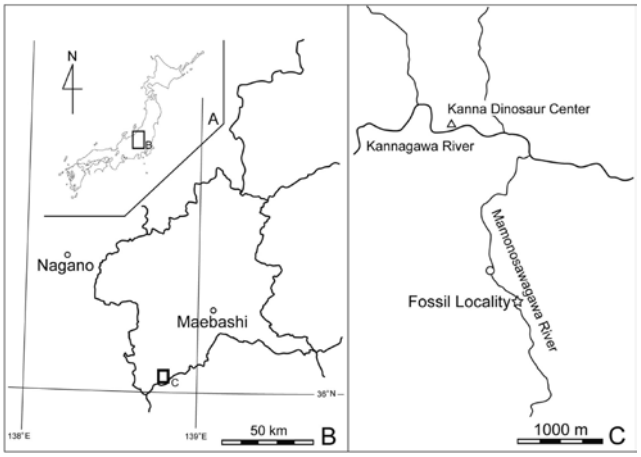

Fig. 1. Map showing the locality of KDC-PV-0003. A. the Japanese Islands, B. Magnified map of area (B) surrounded by bold line shown in fig. A, C. Magnified map of area (C) surrounded by bold line shown in fig. B. Circle and star symbols in fig. C show the localities of GMNH-PV-999 (first spinosaurid tooth in this area) and KDC-PV-0003, respectively.

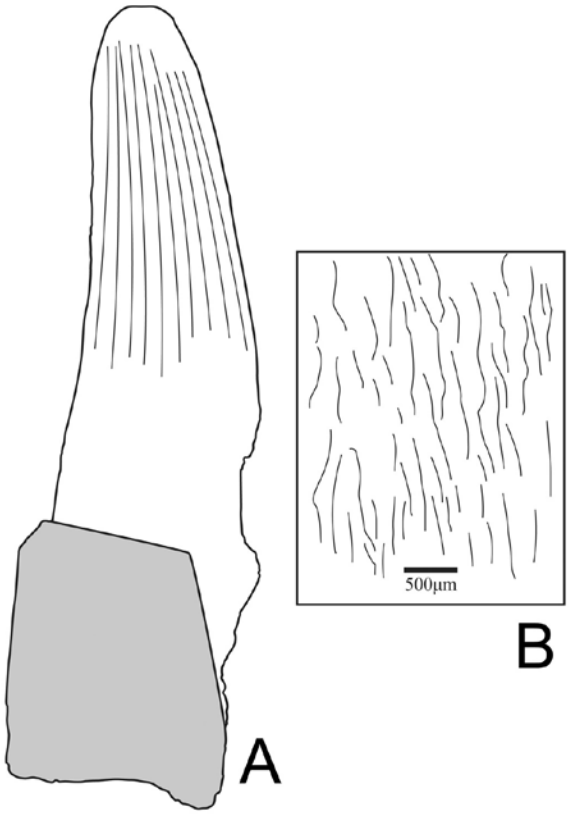

Fig. 2. Sketches of spinosaurid crown (A) and high magnification in basal labio-anterior view based on GMNH-PV-999.

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TABLE 1. Comparison list of dental nomenclatures in Spinosauridae.

Nomenclature	Description	Literature
Macro-structure as shown in fig. 2A		
crest	longitudinal crests separated by broad grooves	Salgado et al. (2009)
sub-facet; flute	longitudinal sub-facets (or flutes)	Medeiros (2006)
facet; ridge	longitudinal ridges and facets	Martill & Hutt (1996)
flute	flutes; fluting	Mateus et al. (2011)
flute; ridge	fluted; ridges	Charig & Milner (1997)
flute; ridge	fluted, vertical ridges	Sues et al. (2002)
flute; ridge	fine vertical ridges; fluting	Dal Sasso et al. (2005)
ornamentation	strong dorso-ventral ornamentation	Hone et al. (2010)
ridge	ridges	Buffetaut & Ingavat (1986)
ridge	an ornamentation of well-marked apicobasal ridges	Buffetaut et al. (2008)
ridge	ridge	Buffetaut (2011)
ridge	a distinct enamel ornamentation of apicobasal ridges	Richter et al. (2013)
ridge	apico-basal ridges	Serrano-Martinez et al. (2016)
striation	striations	Hasegawa et al. (2003)
striation	striations	Hasegawa et al. (2010)
Micro-structure as shown in fig. 2B		
flute	small, irregular, weak flutes of enamel	Richter et al. (2013)
granule	finely granular appearance	Charig & Milner (1997)
granule	finely granular appearance; granular enamel texture	Hasegawa et al. (2003)
granule	numerous irregular, elongated granular structure	Hasegawa et al. (2010)
granule; wrinkle	granular texture; fine, short enamel wrinkles	Sues et al. (2002)
rugose	finely rugose	Martill & Hutt (1996)
striation; wrinkle	striation, wrinkled, wrinkles, micro-wrinkled enamel	Mateus et al. (2011)
textured	textured enamel surfaces	Sereno et al. (1998)
veined	deeply veined enamel texture	Serrano-Martinez et al. (2016)
wrinkle	a finer ornamentation of sinuous wrinkles	Buffetaut et al. (2008)
wrinkle	small wrinkles, anastomosed and spread longitudinally	Salgado et al. (2009)
wrinkle	very fine wrinkling	Buffetaut (2011)

nomenclature but always needs its orientation such as vertical, dorso-ventral, and apicobasal. So we follow "flute" for macro-sized and longitudinal ornamentation on the crown because it has priority to "striation" and can simply show the shape. On the other hand, micro-sized ornamentation between macro-sized and longitudinal ones on the crown had been named as granule, wrinkle, textured, and veined (Fig. 2B). "Rugose", "textured", and "veined" are not nouns but adjectives. "Wrinkle" may be confusing because it is also used as transverse corrugations on the labial and lingual sides of the tooth (Brusatte et al., 2007). Here we use "granule" because it has priority to other words and includes its outline and features.

Geology and Age

The site exposes the lower part of the Sebayashi Formation of the Sanchu Group. It is assigned as the Barremian in age based on ammonites from the underlying Ishido Formation and bivalves from the upper part of the Sebayashi Formation (Matsukawa, 1988; Terabe and Matsuoka, 2009).

Abbreviations

IVPP: Institute of Vertebrate Paleontology and Paleoanthropology, Beijing, China
KDC-PV: Paleo-Vertebrate Collection of Kanna Dinosaur Center, Kanna, Tano, Gunma, Japan
GMNH-PV: Paleo-Vertebrate Collection of the Gunma Museum of Natural History, Tomioka, Gunma, Japan
MUPE HB: Azanak site collection, the Museo Paleontológico de Elche, Alicante, Spain
XMDFEC: Xixia Museum of Dinosaur Fossil Eggs of China

Systematic paleontology

Family Spinosauridae Stromer, 1915
Spinosauridae gen. et sp. indet.

Material. A fragmentary theropod tooth (KDC-PV-0003; Fig. 3)
Locality. Fossil-digging site near "Sazanami-iwa" that is a natural monument of Gunma Prefecture, Kagahara, Kanna Town, Tano Gun, Gunma Prefecture, Japan (36°04'18,7"N; 138°49'46.3"E)
Formation. The lower part of the Sebayashi Formation of the Sanchu Group
Age. Barremian
Description. A fragmentary tooth crown is conical and slender with slight recurvature. The preserved crown height is 10 mm. Based on the preserved crown base, basal length is 7.4 mm, basal width is 6.8 mm, and the ratio of basal width and length is 0.92. The basal cross section is almost circular and is distinguished from typical theropods such as *Allosaurus*, *Tyrannosaurus*, and *Bambiraptor* (Smith et al., 2005). There is distinctive mesial carina with 2-3 poorly defined serrations per 1 mm, but the distal carina is covered by matrix. The serration size is irregular along the mesial carina as in baryonychines. In basal view, the crown exposes dentine with 5.5 mm in mesiodistal length. The dentine is covered by an enamel layer with 1.6 mm in thickness. The enamel surface has at least twelve flutes. Eleven of twelve flutes run through the preserved crown, whereas the first flute in both sides of the mesial carina ends at the basal half of the preserved crown. The number of the flutes matches with that of the first spinosaurid tooth from this formation (GMNH-PV-999). In between flutes, there is finely granular structure. The structure is sharper than those of GMNH-PV-999, suggesting that the flowed distance of the crown may be shorter than that of GMNH-PV-999. The granular enamel sculpture near interdenticle sulci has 45 degree

orientation to the carina and is identical to those of GMNH-PV-999 (Hasegawa et al., 2003).

Discussion

KDC-PV-0003 is the second spinosaurid record from Japan. The first record is also from the same formation. The horizontal distance between the beds of GMNH-PV-999 and KDC-PV-0003 is about 300 m. The dips between two beds vary from 50 to 70 degree, although the strike is almost invariable. Taking the dips into consideration, the thickness of strata between two beds is from 230 to 282 m. Although the sedimentary speed for the lower part of the Sebayashi Formation is unknown, it may suggest that a time interval during the deposition of 230-282 m sediments was suitable environment for spinosaurids.

In 2003, there were at least two reports on spinosaurid theropods from Asia, *Siamosaurus* from Thailand and an isolated tooth from Japan (Buffetaut and Ingavat, 1986; Hasegawa et al., 2003). Kobayashi et al. (1964) described two isolated teeth with circular section and flutes from the Khorat Series of Thailand and tentatively identified with those of ichthyosaur and plesiosaur. However, it may be necessary to check the possibility that they belong to the Spinosauridae. Recently, some spinosaurids were discovered from east and southeastern Asia (Milner et al., 2007; Buffetaut et al., 2008; Hone et al., 2010; Allain et al., 2012). A partial postcranial skeleton of a spinosaurid theropod was discovered from the Aptian Khok Kruat Formation in northeastern Thailand. An isolated tooth may belong to *Siamosaurus*, but whether it is from the same individual or is evidence of scavenging remains uncertain (Milner et al., 2007). Hou et al. (1975) initially described five isolated teeth from the Lower Cretaceous Napai Formation of southern China as the pliosaur *Sinopliosaurus*. However, the re-examination of the materials by Buffetaut et al. (2008) assigned them as a spinosaurid theropod. One of them is more complete than others. The dental morphology is similar to the present described tooth in having distinct carinae with poorly defined serrations, twelve flutes on each face, not all flutes extend for the whole length of the crown, and a finely granular structure on the enamel (Buffetaut et al., 2008). Hone et al. (2010) reported an isolated baryonychine tooth from Henan Province in China. The crown has the smooth enamel surface on labiolingual sides and a CBR (crown base ratio; Smith et al., 2005) of 0.6. On the mesial and distal carinae, there are 4.8 and 4.5 denticles per mm, respectively. However, the baryonychine crowns are fluted on the lingual surfaces of *Baryonyx* and have CBRs between 0.71 and 0.96 in *Baryonyx* and *Suchomimus* (Charig and Milner, 1997; Smith et al., 2005). Additionally, the denticles count per mm of the Henan crown is much lower than other baryonychines (Table 2). *Ichthyovenator* is composed of partially articulated skeleton without any teeth (Allain et al., 2012).

To compare five isolated spinosaurid teeth from Asia with other diagnostic spinosaurids (basal spinosaurid *Ostafrikasaurus*; baryonychine *Baryonyx* and *Suchomimus*; spinosaurine *Irritator*), five ingroup taxa, six isolated teeth specimens, and eleven characters (modified from table 1 of Mateus et al., 2011) are used in this analysis with *Torvosaurus* as an outgroup (Table 2). *Ichthyovenator* from Laos, *Angaturama* and *Oxalaia* from Brazil, and *Cristatusaurus* from Niger are not included in this analysis because the dentition is not preserved. Most dental characters of *Spinosaurus* have been described based on only isolated teeth from the Kem Kem Beds (Hasegawa et al., 2010; Mateus et al., 2011). However, it may be difficult to identify as *Spinosaurus* teeth based on only isolated teeth because at least three spinosaurine dental morphotypes occur from the beds (Richter et al., 2013). Here we deal with the

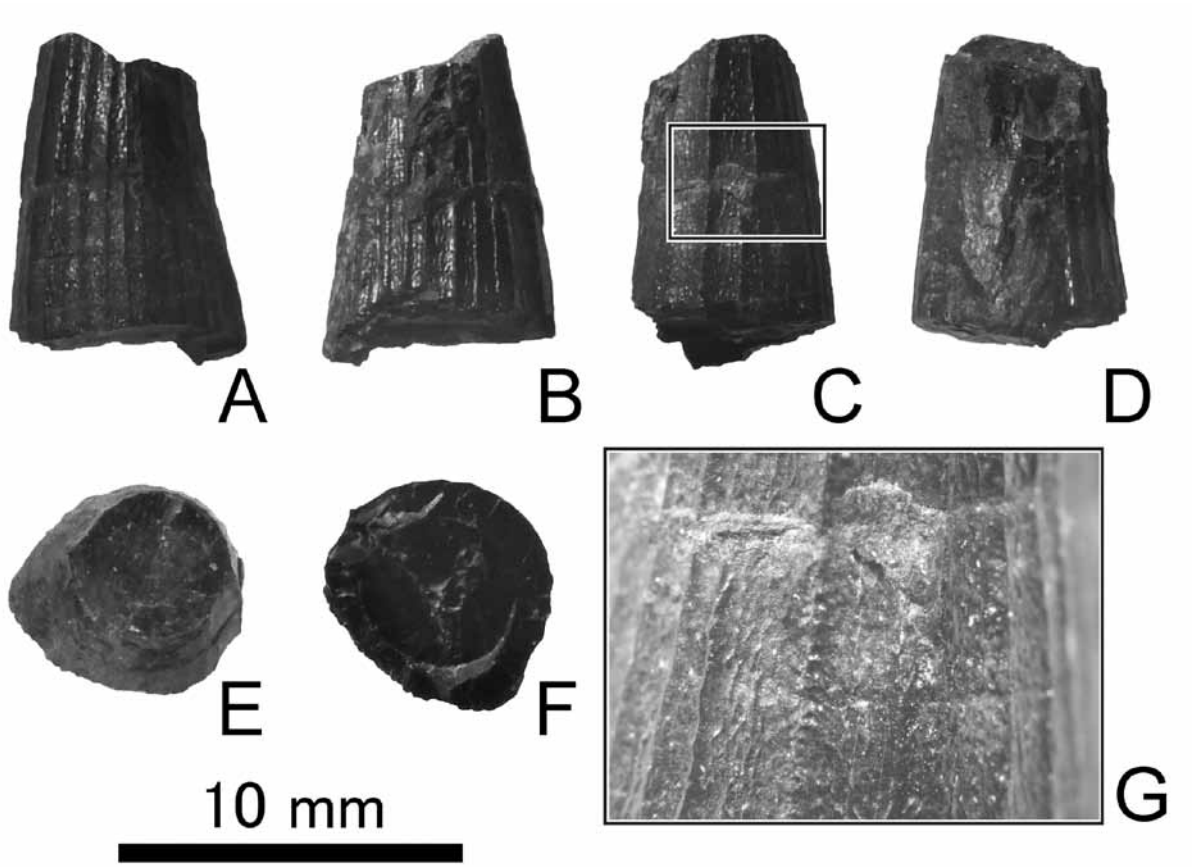

Fig. 3. KDC-PV-0003 in labial (A), lingual (B), mesial (C), distal (D), top (E) and basal (F) views. Scale bar = 10 mm. G.Magnification of area which is surrounded by bold line in fig. C. Fine serrations on mesial carina and granular enamel texture in between flutes are observed.

TABLE 2. Dental characters in *Torvosaurus tanneri* (as outgroup) and spinosaurid dinosaurs. This table is that table 1 of Mateus et al. (2011) is modified.

	Outgroup	Spinosauridae		Asian Spinosauridae			Baryonychinae		Spinosaurinae		
Taxon	*Torvo-saurus*	MUPE HB-87	*Ostafrika-saurus*	*Siamo-saurus*	IVPP V 4793	GMNH-PV-999	KDC-PV-0003	*Baryonyx*	*Suchomimus*	*Irritator*	Spinosaurines from Kem Kem Beds	XMDFEC V0010
Age	Late Jurassic	?Bathonian	late Kimmeridgian	Valanginian to Barremian	Early Cretaceous	Barremian	Barremian	Barremian	late Aptian	Albian	Early Cenomanian	middle Santonian
Literature		Serrano-Martinez et al. (2016)	Buffetaut (2011)	Buffetaut & Ingavat (1986)	Buffetaut et al. (2008)	Hasegawa et al. (2003)	This study	*1	Sereno et al. (1998)	Sues et al. (2002)	*2	Hone et al. (2010)
enamel surface of the crown	smooth	sculptured	sculptured	sculptured	sculptured	sculptured	sculptured	sculptured	sculptured	sculptured	sculptured	smooth
Presence of flutes	no	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	no
Tooth crown suboval to subcircular in cross-section	no	no	no	yes	yes	yes	yes	yes	yes	yes	yes	no
exceptionally long and slender tooth roots	no	N/A	N/A	N/A	N/A	N/A	N/A	yes	yes	yes	yes	N/A
curvature of the crown	yes	no	no	no	no	no	N/A	yes	yes	no	no	yes
base of the crown enamel surface	smooth	N/A	N/A	N/A	N/A	N/A	N/A	sculptured	smooth or poorly sculptured	?smooth	N/A	smooth
45 degree orientation of emamel sculpture near interdenticle sulci	no	no	no	N/A	N/A	yes	yes	yes	yes	yes	yes	no
Carinae bearing 5 or more denticles per mm	no	no	no	N/A	N/A	N/A	no	yes	yes	N/A	N/A	no
irregular denticle size along carinae	no	no	yes	N/A	N/A	N/A	yes	yes	yes	N/A	N/A	no
well-pronounced carinae	no	no	no	N/A	no	N/A	no	no	no	yes	yes	no
number of flutes on both crown sides	N/A	N/A	14	30	24	24	20-?24	6-8	0-10	7	10-40	N/A

*1 Charig & Milner (1997); Mateus et al. (2011); *2 Dal Sasso et al. (2005); Hasegawa et al. (2010); Richter et al. (2013)

teeth as "spinosaurines from the Kem Kem Beds". Mateus et al. (2011) showed that a spinosaurid tooth has the following features: suboval to subcircular cross-section, presence of flutes on the crown, and exceptionally long and slender tooth root. Additionally, the following features are regarded as characteristic of Baryonychinae: curvature of the crown, sculptured base of the crown enamel surface (smooth or poorly sculptured base of the crown enamel surface in *Suchomimus*), 45 degree orientation of enamel sculpture near interdenticle sulci, carinae bearing six or more denticles per mm, and irregular denticle size along carinae. Fig. 5 of Sues et al. (2002) and plate IV of Hasegawa et al. (2010) showed *Irritator* and Kem Kem spinosaurines also have 45 degree orientation of enamel sculpture near interdenticle sulci, indicating that this character may be a synapomorphy for Baryonychinae, or Baryonychinae and Spinosaurinae, and at least some Asian spinosaurids. Smith et al. (2005) measured four isolated *Suchomimus* teeth and showed three of them bear under six denticles per mm on carinae. Then, one of the baryonychine characters is modified as carinae bearing five or more denticles per mm. On the other hand, spinosaurine teeth are additionally characterized by smooth base of the crown enamel surface (reversal) and unserrated and well-pronounced carinae. Number of flutes on both crown sides is much more like spinosaurines than baryonychines.

Four Asian spinosaurid teeth (*Siamosaurus*, IVPP V 4793, GMNH-PV-999, and KDC-PV-0003) indicate that these teeth bear the following combination of characters: nearly straight crown (unknown in KDC-PV-0003), under five denticles per mm on carinae (unknown in *Siamosaurus*, IVPP V 4793, and GMNH-PV-999), and over twenty flutes on both crown sides (Table 2). The combination does not match with those of Baryonychinae or Spinosaurinae and may be unique to Asian spinosaurids. An isolated tooth from Henan Province of China bears no spinosaurid characters as mentioned above (Table 2). Hone et al. (2010) described that the tooth (XMDFEC V0010) is a sub-circular in cross section but that fig. 1 of Hone et al. (2010) shows it is a typical theropod-like cross section.

The shape of GMNH-PV-999 is better preserved than that of the present described specimen, but in details, the latter shows more features than the former based on the preservation qualities of serrations and granular structure between flutes. Two spinosaurid teeth from Japan are similar to *Siamosaurus* from Thailand and IVPP V 4793 from China as mentioned above, although there are some differences (size, thickness, and flute counts). Probably the differences may be caused by dental arrangement due to different tooth position. Unfortunately, the four Asian spinosaurid teeth are not associated with skulls. Precise identification remains limited till the discovery of an Early Cretaceous spinosaurid skull associated with teeth from Asia.

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群馬県神流町に分布する下部白亜系瀬林層から産出したスピノサウルス科の歯化石の第2標本

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要旨：下部白亜系山中層群瀬林層から遊離した歯化石が発見された．その歯冠部の断面はほとんど円形で，明瞭な条線をもつ．その条線の間には微細な顆粒状構造が存在する．明瞭に区別できる切縁には貧弱な境界をもつ鋸歯がある．この歯はスピノサウルス科のものであり，日本からは2番目の報告となる．今回発見されたスピノサウルス科の歯は最初のものよりも同じ層の上位から発見されている．異なる層準からのスピノサウルス科の産出は瀬林層の堆積時において，この地域にはスピノサウルス科にとって適した環境が維持されていたことが言える．アジア産と他のスピノサウルス科の系統関係は未解決であるが，それらの歯の比較はアジア産のスピノサウルス科が独特な歯の特徴を持っており，これまで知られているスピノサウルス科とは異なる可能性を示唆している．

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