

## A new carnosaur (Dinosauria, Theropoda) from the Jurassic of Xinjiang, People's Republic of China

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In 1987, a Sino-Canadian expedition known as the Dinosaur Project (China – Canada – Alberta – Ex Terra) discovered a large theropod skeleton in the Upper Jurassic Shishugou Formation of the Junggar Basin in northwestern China. The well-preserved skeleton lacks much of the tail and most of the arms, but is otherwise nearly complete. The new genus and species, *Sinraptor dongi*, represents a poorly understood stage of theropod evolution, even though a related form, *Megalosaurus*, was the first dinosaur described and named (by W. Buckland in 1824). *Sinraptor* has a large pneumatopore in the jugal, a pronounced postorbital rugosity, a relatively long intertemporal bar in which the postorbital appears very short in lateral aspect, and a pneumatic palatine. It is more advanced than *Piatnitzkysaurus* from Argentina, less derived than *Allosaurus*, and shows its strongest similarities to *Yangchuanosaurus*. The preorbital skull length of *Sinraptor* is relatively longer than in *Yangchuanosaurus*, but the skull is relatively lower. A specimen from Sichuan recently described as "*Yangchuanosaurus*" *hepingensis* represents a second species of *Sinraptor*. *Sinraptor* and *Yangchuanosaurus* are united in a new family of theropods, the Sinraptoridae.

En 1987, une expédition sino-canadienne, appelée le Projet Dinosaures, a permis la découverte d'un grand squelette de théropode dans la Formation de Shishugou du Jurassique supérieur, dans le bassin de Junggar localisé dans le nord-ouest de la Chine. Il manque à ce squelette bien conservé une portion importante de la queue et la majeure partie des membres, néanmoins le squelette est presque complet. Le nouveau genre et espèce, *Sinraptor dongi*, représente un stade mal connu de l'évolution des théropodes, en dépit du fait que le premier dinosaure qui a été décrit et nommé (par W. Buckland en 1824), *Megalosaurus*, était une forme apparentée. Le *Sinraptor* est caractérisé par un gros pneumatopore dans le jugal, une rugosité prononcée du postorbital, une barre intertemporale relativement longue montrant en vue latérale un postorbital très court, et une palatine pneumatique. Il est plus évolué que *Piatnitzkysaurus* d'Argentine, et moins apparenté à *Allosaurus*, mais ses traits caractéristiques le rapprochent beaucoup plus de *Yangchuanosaurus*. La longueur du préorbital sur le crâne de *Sinraptor* est relativement plus longue que celle de *Yangchuanosaurus*, cependant le crâne est relativement plus bas. Un spécimen cueilli à Sichuan, décrit récemment comme « *Yangchuanosaurus* » *hepingensis*, représente une seconde espèce de *Sinraptor*. Les espèces *Sinraptor* et *Yangchuanosaurus* sont réunies dans une nouvelle famille de théropodes, les Sinraptoridés.

[Traduit par la rédaction]

一九八七年，中加恐龙项目考察队在中国西北准格尔盆地上侏罗世的石树沟组发现了一具大型兽脚类骨架。除了大部分尾部和前肢缺失外，其它骨骼部分均保存完好。该骨架属于一新属新种，*Sinraptor dongi*。尽管与其相关的 *Megalosaurus* 是由 W. Buckland 在一八二四年所描述命名的最早的恐龙，本新属种代表了兽脚类演化中一个所知甚少的环节。*Sinraptor* 的特征是颧骨发育一大的气腔，眶后部有一明显褶皱，颧颧间骨较长并包含侧视显得很短的眶后骨，以及腭骨气腔化。它比阿根廷出产的 *Piatnitzkysaurus* 更为进步，比 *Allosaurus* 更为原始，但与 *Yangchuanosaurus* 最为相近。与 *Yangchuanosaurus* 相比，*Sinraptor* 的头骨显得更长更低。最近在四川所发现并且被描述命名为 "*Yangchuanosaurus*" *hepingensis* 的标本应归于 *Sinraptor* 属的第二个已知种。*Sinraptor* 和 *Yangchuanosaurus* 现被归入兽脚类的一新科，称之为 Sinraptoridae。

[译文由杂志社提供]

В 1987 г. Сино-канадская экспедиция, известная как Проект по динозаврам обнаружила крупный скелет теропода в верхнеюрской формации Шишугоу бассейна Джунгар

(северо-западная часть Китая). У хорошо сохранившегося скелета отсутствует большая часть хвоста и большая часть передних конечностей, но в остальном он почти цел. Новый род и вид *Sinraptor dongi* представляет собой плохо изученную стадию эволюции теропода, хотя родственная форма *Megalosaurus* была первым описанным и получившим название динозавром (W. Buckland, 1824). *Sinraptor* имеет крупный пневматофор в скуловой кости, хорошо выраженную заглазничную складку, относительно длинную межвисочную дугу, в которой заглазничная складка выглядит очень короткой по простиранию и пневматическую небную. Он более прогрессивен, чем *Piatnitzkysaurus* из Аргентины и менее изучен по происхождению, чем *Allosaurus*, но имеет большое сходство с *Yangchuanosaurus*. Предглазничная черепная линия *Sinraptor* относительно длиннее, чем у *Yangchuanosaurus*, но череп сравнительно низкий. Экземпляр из Сичуан, недавно описанный как "*Yangchuanosaurus*" *hepingensis* представляет собой второй вид *Sinraptor*. *Sinraptor* и *Yangchuanosaurus* объединены в новое семейство теропод Sinraptoridae.

[Перевод выполнен для редакции Научно-Исследовательские Журналы]

### Introduction

The fossil resources of northwestern China have long been a source of speculation for scientists, but because of its inaccessibility, the region remained virtually unexplored palaeontologically until recently. In 1931, part of the Sino-Swedish expedition visited a site north of the Tian Shan, where they excavated the first dinosaur from Xinjiang, a sauropod later described as *Tianshanosaurus chitaiensis* (Young 1937). The general location of the excavation site is known to be in the foothills of the Tian Shan southeast of Qitai (Chitai), but the quarry could not be relocated in 1987.

Between 1963 and 1966, the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP) (Beijing) sent a number of expeditions to the Xinjiang (Sinkiang) Autonomous Region to look at sites ranging in age from Permian to Cretaceous (Zhao et al. 1987). In 1982 and 1983, the IVPP returned to the Junggar (Dsungar, Dzungar) Basin and worked north of Jimsar near a desert community known as Jiangjunmiao ("General Jiang's temple"). Shortly after camp was set up, two dinosaur skeletons (a sauropod and a theropod) were discovered in the Middle Jurassic (Fig. 1) Wucaiwan Formation. The theropod has only recently been described (Zhao and Currie 1993).

A survey team of the Sino-Canadian expedition, known as the Dinosaur Project (China - Canada - Alberta - Ex Terra), visited the exposures near Jiangjunmiao in 1986 and found enough material in the Wucaiwan ("five-colored streambed") and overlying Shishugou ("stone tree ravine") formations (Fig. 1) to plan for a full expedition the following year. In September 1987, a large theropod was discovered by Zhi-Ming Dong about 5 km from the 1983 discovery, but in the higher formation. Both authors of this paper were involved in the excavation, which was not completed until the 1988 expedition.

The Shishugou Formation (Shishu Formation of McKnight et al. 1990) is made up of sandstones, siltstones, mudstones, and minor lenses of limestone, all of which were laid down in alluvial, fluvial, or lacustrine environments. The beds of the locality studied by McKnight et al. (1990) were deposited by wide, shallow, meandering, mixed-load streams of low gradient. The formation has produced turtles, a lizard, the abundant remains of a sauropod related to *Mamenchisaurus*, hypsilophodonts (Dong 1989), and a mammal (Chow and Rich 1984). Fossil "forests" are common, and give the formation its name

("stone tree ravine"). Study of the fossil wood, which has been identified as the conifer *Araucarioxylon*, suggests that the climate was mild, with seasonal variation of precipitation (McKnight et al. 1990).

Good skeletons of large theropods have been collected in the Jurassic beds of China (Dong 1992). These include *Gasosaurus constructus* (Dong and Tang 1985), *Szechuanosaurus campi* (Young 1942), "*Yangchuanosaurus*" *hepingensis* (Gao 1992), *Yangchuanosaurus magnus* (Dong et al. 1983), and *Yangchuanosaurus shangyuensis* (Dong et al. 1978). All of these carnosaurs were collected from the Sichuan basin of southern China. *Gasosaurus* is the earliest form, and was recovered from the Middle Jurassic Lower Shaximiao (Xishaximiao) Formation. A skeleton of *Szechuanosaurus* came from the lower part of the Upper Shaximiao (Shangshaximiao) Formation, and the remaining forms came from higher in the same formation. As will be demonstrated in this paper, "*Y.*" *hepingensis* shows stronger affinities to the new genus and species from northwestern China than it does to either of the described species of *Yangchuanosaurus*. It is referred to here as a distinct species of the new genus from Xinjiang, although detailed study of the original specimen may eventually show it is a distinct genus.

### Systematic palaeontology

Dinosauria Owen, 1842  
Theropoda Marsh, 1881  
Carnosauria von Huene, 1920  
Sinraptoridae new family  
*Sinraptor* new genus

### Abbreviations

BMNH, British Museum (Natural History), London; BYU, Brigham Young University, Provo; CMN, Canadian Museum of Nature, Ottawa; CV, Municipal Museum of Chungqing; IVPP, Institute of Vertebrate Paleontology and Paleoanthropology, Beijing; USNM, United States National Museum of Natural History, Smithsonian Institution, Washington; UUV, University of Utah, Vertebrate Paleontology Collection, Salt Lake City; ZDM, Zigong Dinosaur Museum, Zigong, Sichuan, China.

### Etymology

"Sinae" is a Latin name for an oriental people and refers to China; "raptor" is Latin for robber.

### Genoholotype

IVPP 10600, nearly complete skull and most of postcranium, lacking most of front limbs and part of the tail.

### Family diagnosis

Sinraptorids are large theropods from the Jurassic of Asia. More derived than megalosaurids but similar to allosaurids in that last maxillary tooth anterior to orbit; antorbital sinus extends into interior of lacrimal, nasal, and jugal; ventral end of postorbital above ventral margin of orbit; upper quadrato-jugal prong of jugal shorter than lower prong; quadrate—quadratojugal fenestra present with associated sinus; pneumatic basisphenoidal recess; braincase box has opened up posteriorly between tubera, which are no longer pedunculate; oval muscular attachment on basioccipital; downturned paroccipital processes; posteroventral limit of the exoccipital—opisthotic contacts the basisphenoid but is separated from the basal tubera by a notch; at least incipient separation of ophthalmic from other branches of trigeminal nerve. Tenth presacral vertebra in process of incorporation into dorsal rather than cervical region; triangular neurapophysis; axial neural spine reduced; no ventral keel on the axial centrum; parapophyses reduced in lateral extension from the primitive condition; anteroposteriorly thin rib heads; elongate scapular blade sharply set off from acromial process and glenoid lip; obturator fenestra of ischium opens into notch, thereby producing distinct obturator process; fifth metatarsal is relatively shorter than in more primitive genera.

Sinraptorids are more primitive than allosaurids in that quadrate is more elongate; paroccipital processes not as strongly downturned; distal end of scapula not expanded.

Sinraptorid autapomorphies include the presence of two or more sets of accessory openings in antorbital fossa connected to the maxillary sinus; low lacrimal horn; ventral margin of axial intercentrum rotated above ventral margin of axial centrum. Family includes specimens referred to informally as “*yangchuanosaurs*” by Bakker et al. (1992).

### Generic diagnosis

Total skull length and preorbital skull length relatively longer than in *Yangchuanosaurus*, but skull relatively lower. Large pneumatopore in jugal; pronounced postorbital rugosity; lateral temporal fenestra large with relatively long, straight intertemporal bar; very short lateral exposure of intertemporal process of postorbital; palatine pneumatic between internal naris and postpalatine fenestra.

### *Sinraptor hepingensis* new combination

#### Material

Skull, axial skeleton, pectoral and pelvic girdles, left femur (ZDM 0024) from the Upper Shaximiao Formation (Upper Jurassic) of Zigong, Sichuan, People's Republic of China. Originally described as *Yangchuanosaurus hepingensis* by Gao (1992).

### *Sinraptor dongi* new species (Fig. 2)

#### Etymology

The species is named after the discoverer of the type specimen, Zhi-Ming Dong, who also worked on the description of a closely related form, *Yangchuanosaurus*.

#### Holotype

IVPP 10600, nearly complete skull and most of postcranium, lacking most of front limbs and part of the tail.

PERIOD	GROUP	FORMATION
Lower Cretaceous	Tugulu Group	Hutubihe Formation (Barremian)
		Qingshuihe Formation (Berriasian)
Upper Jurassic	Shuixigou Group	Shishugou Formation
J <sub>2,3</sub>		Wucaiwai Formation
Middle Jurassic		Xishanyao Formation (Bajocian)
J <sub>1,2</sub>		Sangongke Formation (Toarcian)
Lower Jurassic		Badaowan Formation (Hettangian-Pliensbachian)

FIG. 1. Stratigraphy of Jurassic and Cretaceous rocks of the Jiangjunmiao section of the Junggar Basin.

### Referred specimens

There are nine isolated, shed teeth in the collections of the IVPP that were recovered from a sauropod (IVPP 87001) found in a quarry less than a kilometre from the holotype. All specimens were collected by the Dinosaur Project in 1987 and 1988.

### Locality and age

The holotype was recovered from the Upper Jurassic Shishugou Formation (Fig. 1), about 65 m above the contact with the Wucaiwai Formation. The locality is 25 km northeast of Jiangjunmiao, Xinjiang.

### Diagnosis

Large theropod more than 7.2 m long at maturity. Quadrato-jugal process of jugal divided into three prongs; pronounced postorbital rugosity forms lateral margin of relatively large, triangular space on dorsal surface of skull; jugal ramus of palatine extends ventrally below level of maxillary suture in a distinct process; hollow interior of ectopterygoid confluent with anteroventral pneumatic opening medial to jugal contact; exoccipitals extend ventrally below basal tubera; occipital condyle oriented posteroventrally. Inflection in atlas—axis complex brings vertebral column under back of skull more markedly than in *Yangchuanosaurus*. Differs from *S. hepingensis* in having relatively lower, longer premaxilla; more numerous and elaborate accessory pneumatic openings in antorbital fossa; more limited lateral exposure of intertemporal process of postorbital; longer subtemporal bar.

### Description

The holotype of *S. dongi* (IVPP 10600) was found lying on its right side. Whereas the right side of the skull, the vertebrae, the right hand, and the right hind limb remained in articulation, much of the left side of the body had become disarticulated and had drifted from the balance of the skeleton before burial. Teeth of the left mandible had fallen out, but most were recovered with the rest of the skeleton. The specimen was partially disarticulated, but was not widely scattered. A sauropod cervical and a sauropod scapula had been washed into the site before burial.

The specimen was found in a reddish, cross-bedded, arenaceous siltstone interpreted as a sheet-wash, ephemeral stream deposit.

The skull is almost 90 cm long, with a preorbital length of 52 cm. The height of the skull in front of the orbit is 33 cm. In comparison, the skull of *Y. shangyuensis* (CV 00215) is

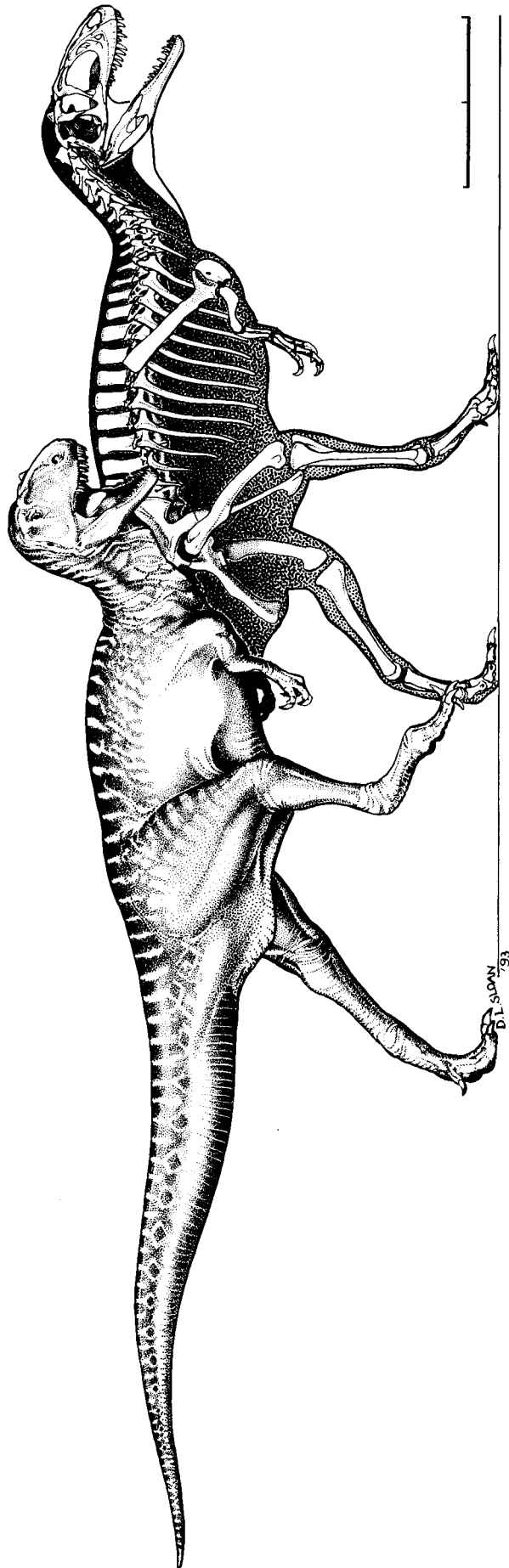


FIG. 2. Reconstruction of *Sinraptor dongi*, a megalosaurid grade theropod from the Shishugou Formation (Upper Jurassic) of the Xinjiang Autonomous Region of northwestern China. Scale bar = 1 m.

78 cm long (Dong et al. 1978), about 10% shorter, and 50 cm high. The type specimen of *Y. magnus* (CV 00216, Dong et al. 1983) has a larger skull, with an estimated length of 111 cm and a height of 65 cm. Finally, the skull of "*Y.*" *hepingensis* (ZDM 0024) is 104 cm long and 59.5 cm high (Gao 1992). Femur length is a relatively stable standard of measurement in theropods, and can be used to assess proportional differences of the skull. The skull/femur ratio is similar in *Y. shangyuensis* (0.92), *Y. magnus* (1.17), *Ceratosaurus* (1.00, Gilmore 1920), and in tyrannosaurids (0.97–1.17). The skull of USNM 4734 (0.72) is significantly shorter than the femur (Gilmore 1920). Although this allosaurid is generally referred to as *Allosaurus*, other specimens show that the skull of *Allosaurus* is as long or longer than associated femora (R.T. Bakker, personal communication, 1993). The skull height of *Y. shangyuensis* is 61% the length of the femur, compared with only 38% in *Sinraptor*. The elongate appearance of the *Sinraptor* skull, when compared with *Y. shangyuensis*, can be attributed mostly to its relatively lower cranial height at the orbit, but it is also relatively longer.

There are five major openings on each side of the skull (external naris, antorbital fenestra, orbit, upper and lateral temporal fenestrae), and three accessory openings in the maxilla (Fig. 3). The external naris is a relatively small, triangular aperture with an anteroposterior length of 6.5 cm, whereas the anterodorsal narial margin is 9 cm long. The naris is bound entirely by the premaxilla and nasal, and the maxilla is excluded from the opening. This is the plesiomorphic state found in primitive theropods like *Herrerasaurus* (Sereno and Novas 1992), in contrast with *Allosaurus* (Madsen 1976), *Monolophosaurus* (Zhao and Currie 1993), and some Cretaceous theropods (Currie 1985). The triangular antorbital fenestra is enormous, covering almost half (23 cm) the preorbital skull length and two thirds (20 cm) of the height. The jugal forms part of the boundary in *Sinraptor*. In some reconstructions of *Allosaurus* (Madsen 1976), the jugal is excluded from the margin of the fenestra, although it does reach the antorbital fenestra in at least some specimens (R.T. Bakker, personal communication, 1993). The keyhole-shaped orbit is high (21.5 cm), but relatively short anteroposteriorly (13.5 cm). The outline of the lateral temporal opening has been altered by the crushing at the back of the skull, but is clearly rectangular, with a long intertemporal bar. The elongate intertemporal bar seems to be autapomorphic for *Sinraptor*. The long subtemporal bar is a primitive characteristic for theropods (Bakker et al. 1992).

Anterior to the orbit, the side of the skull is a relatively flat, vertical face, clearly set off from the narrow skull roof. A sharply defined ridge separates the dorsal and lateral surfaces of the nasal and lacrimal bones. The ridge, which overhangs the face by as much as 1.5 cm at the anteriormost nasal-lacrimal contact, is relatively straight in profile and is only slightly rugose, as in *Allosaurus* (Madsen 1976). In contrast, the ridge is arched and more rugose in *Y. shangyuensis* (Dong et al. 1978; IVPP 4615). There are no nasal, lacrimal, frontal, or postorbital horns, as there are in *Ceratosaurus*, *Carnotaurus*, allosaurids, and tyrannosaurs, and in this character sinraptorids are like megalosaurids.

The paired premaxillae form the sharp, narrow tip of the skull. Each is pierced by more than a dozen foramina (Fig. 4A) for branches of the medial ethmoidal nerve and subnarial artery. The premaxillae contact each other in an extensive, flat suture. The maxillary body is higher than long in *Ceratosaurus*, *Yangchuanosaurus* (IVPP 4615), and *Torvosaurus*, whereas it is longer than high in *Allosaurus* (Britt 1991) and marginally

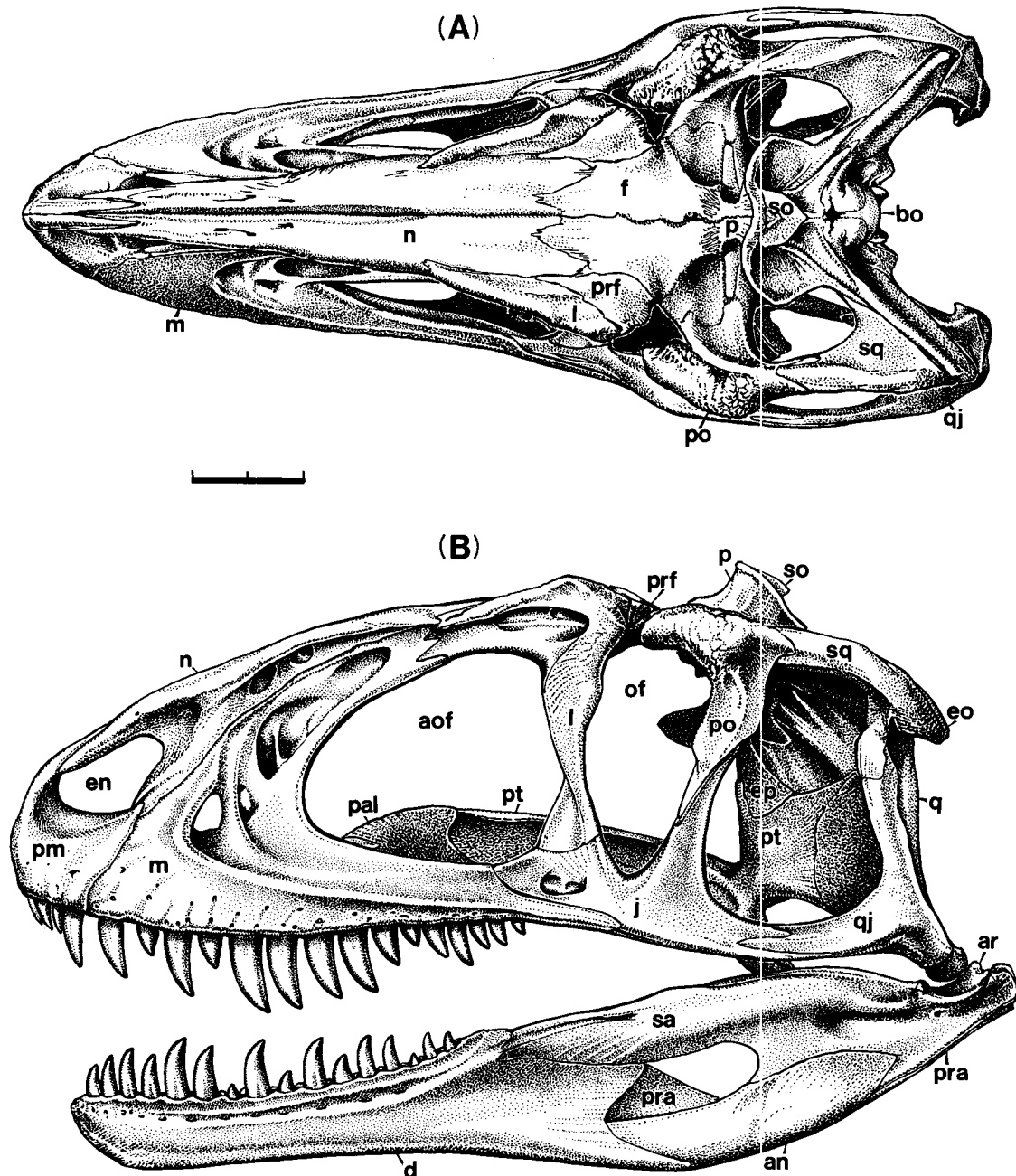


FIG. 3. Reconstruction of skull and mandible of *Sinraptor dongi* (IVPP 10600) in dorsal (A) and lateral (B) views. an, angular; aof, antorbital fenestra; ar, articular; bo, basioccipital; bs, basisphenoid–parasphenoid complex; d, dentary; ecpt, ectopterygoid; en, external naris; eo, exoccipital; ep, epipterygoid; f, frontal; j, jugal; l, lacrimal; m, maxilla; n, nasal; of, orbital fenestra; p, parietal; pal, palatine; pm, premaxilla; po, postorbital; prf, prefrontal; pra, prearticular; pt, pterygoid; qj, quadratejugal; q, quadrate; sa, surangular; so, supraoccipital; sq, squamosal; vo, vomer. Scale bar = 10 cm.

longer than high in IVPP 10600. As in *Allosaurus*, the anterior margin is almost vertical, and there is a sharp inflection anterior to the base of external naris. In contrast, the maxillary body of *Torvosaurus* (Britt 1991) slopes posteriorly, and the inflection between the maxillary and supranarial process is in a more posterodorsal position. There is a 10 cm high, slightly convex contact with the maxilla. Above this contact, a short (2 cm) posterodorsal (subnarial) process extends beyond the maxilla to contact the subnarial process of the nasal. The premaxilla forms the anterolateral boundary of the subnarial foramen, which is most evident in the lateral surface of the subnarial

process of the nasal. This is a distinct difference from the situation in *Allosaurus*, where the subnarial foramen passes between the premaxilla and the maxilla. Internally, a maxillary process (Fig. 4D) extends posteromedially beyond the posterior margin of the premaxilla, presumably to strengthen the contact with the maxilla. The maxillary process is lower in position than that of *Allosaurus* (Madsen 1976), whereas that of *Megalosaurus* *hesperis* (BMNH R332) is intermediate between *Sinraptor* and *Allosaurus*. The supranarial process inclines posterodorsally at an angle of about 40° from the ventral margin and extends above the narial opening for more than 8.5 cm. Distally this

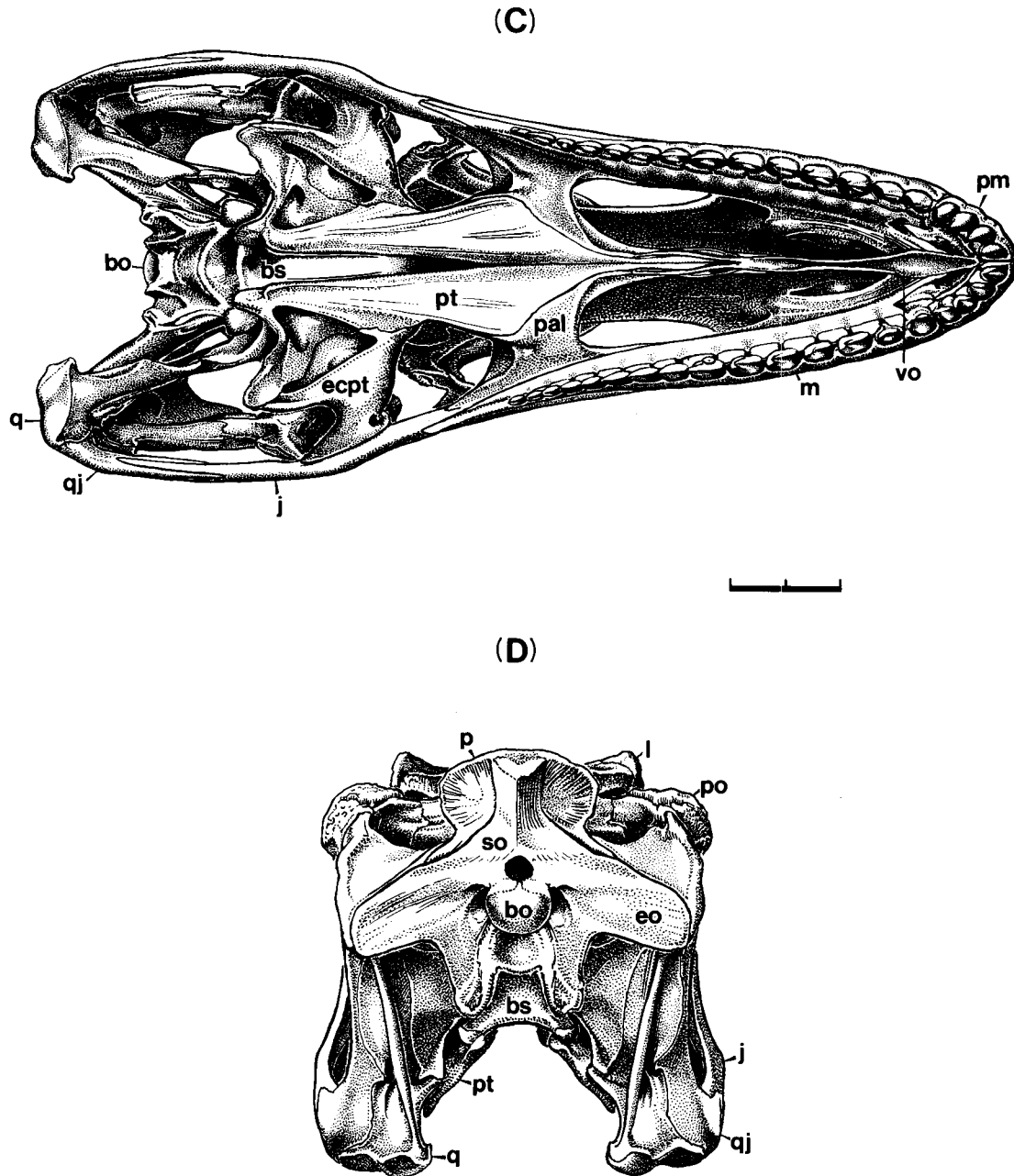


FIG. 3 (concluded). Palatal (C) and occipital (D) views.

process sits in a groove on the dorsal surface of the nasal. There are four interdental plates, which increase posteriorly in height (Fig. 4D). In contrast with *Allosaurus* (Madsen 1976), *Torvosaurus* (Britt 1991), and most theropods, the plates of *Sinraptor* and "*M. hesperis* (BMNH R332) are not fused to each other. The first plate is small, the second is longer than tall, and the last two are taller than long. The last interdental plate is almost 3 cm high. In *Allosaurus* (UUVP 1622), all premaxillary dental plates are about the same height. Of the four premaxillary teeth, the last tooth is the highest in the left premaxilla. The second tooth is broken distally, but has the same basal diameter as the fourth. *Allosaurus* has five premaxillary teeth, ceratosaurids and *Torvosaurus* (BYU 4882) have three, and most other theropods, including *S. hepingsensis*, *Y. shangyuensis*, *Y. magnus*, abelisaurids, *Eustreptospondylus*,

*Herrerasaurus*, *Marshosaurus*, *Monolophosaurus*, *Proceratosaurus bradleyi* (Woodward 1910), and tyrannosaurs, have four. The number of premaxillary teeth in theropods is not good for determining relationships, although it is clear that the primitive premaxillary tooth count is four. Because the premaxillae meet at an acute angle, the premaxillary teeth are not D-shaped in section as they are in tyrannosaurids (Currie et al. 1990). However, the anterior carina is on the lingual side of the tooth, as in allosaurids and dromaeosaurids, but in contrast with *Torvosaurus* (Britt 1991). *Ceratosaurus* has no anterior carina on premaxillary teeth (R.T. Bakker, personal communication, 1993).

The maxilla (Figs. 4B, 4C) is more than 42 cm long, is excluded from the border of the external naris by the premaxilla and nasal, but forms most of the anterior margin of the ant-

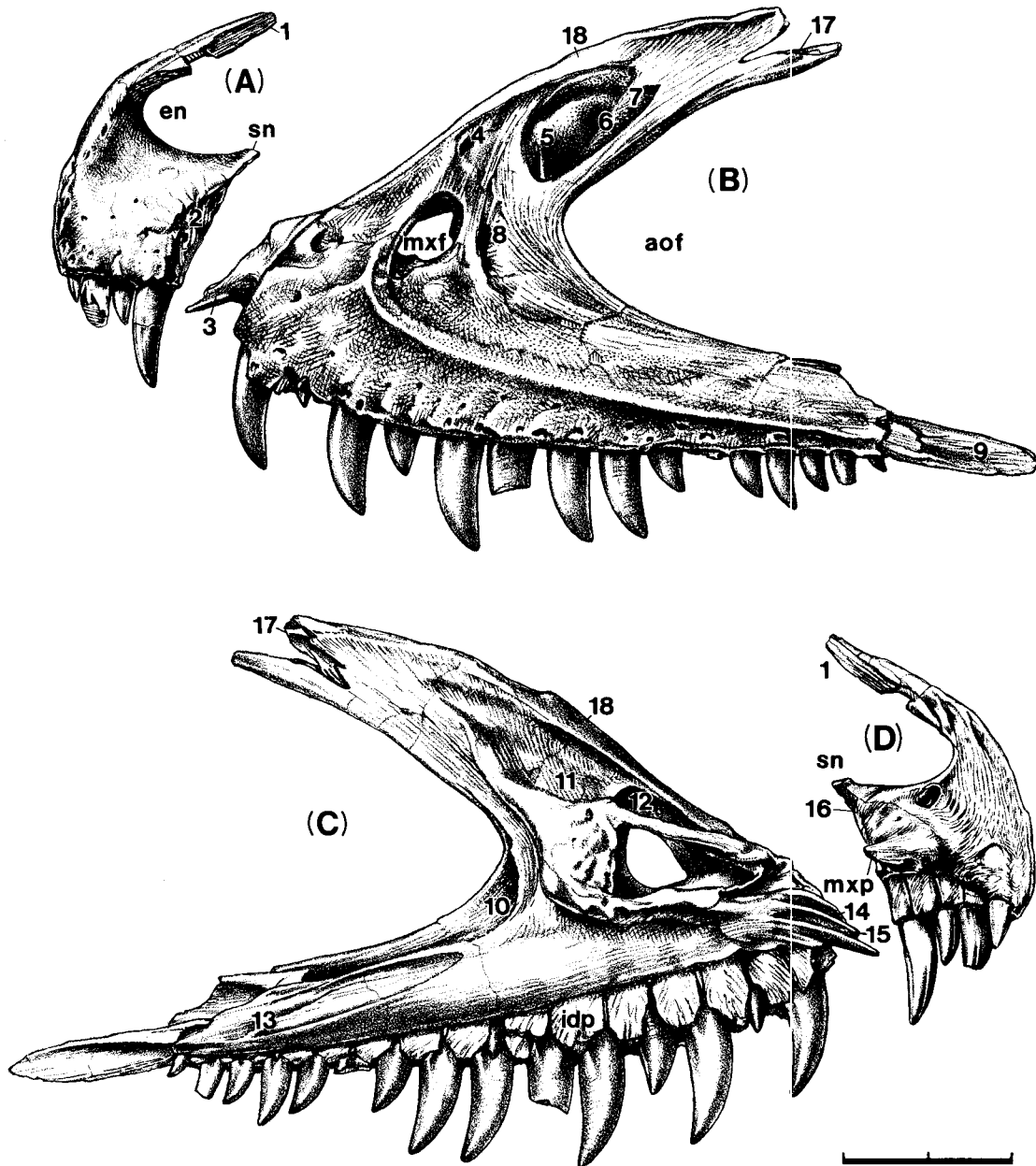


FIG. 4. *Sinraptor dongi* (IVPP 10600). Left premaxilla in lateral (A) and medial (D) views; left maxilla in lateral (B) and medial (C) views. aof, antorbital fenestra; en, external naris; idp, interdentary plates; mxf, maxillary fenestra; mxp, maxillary process; sn, subnarial process. 1, nasal suture of the premaxilla; 2, maxillary suture of premaxilla; 3, premaxillary suture of anteromedial process of the maxilla; 4, foramen; 5, 6, 7, 8, pneumatic openings; 9, jugal suture of the maxilla; 10, 11, 12, pneumatic openings; 13, palatine suture; 14, pterygoid suture on anteromedial process of the maxilla; 15, slot for vomer; 16, premaxillary contact on anteromedial process of the maxilla; 17, lacrimal contact; 18, nasal suture. Scale bar = 10 cm.

orbital opening. A smaller maxillary fenestra pierces the maxilla between the external naris and the antorbital opening. There are 15 maxillary alveoli, which is similar to the case in *Yangchuanosaurus*, with 14 or 15 tooth positions in *Y. shangyuensis* and 14 in *Y. magnus* (Dong et al. 1983). As in *Yangchuanosaurus* and *Allosaurus*, the lateral surface of the maxilla is rugose only along its anterior edge and immediately above the tooth row, where it is pierced by the superior labial foramina for branches of the superior alveolar nerve and maxillary artery. The rest of the lateral surface of the maxilla is smooth and somewhat indented, forming a border around the antorbital fenestra for the antorbital fossa (Witmer 1987).

The maxillary fenestra is found near the anteroventral apex of the antorbital fossa, its ventral margin at about the same level as a line drawn from the floor of the naris to the floor of the antorbital fenestra. Other foramina are also found within the boundaries of the fossa, but are variable between the left and right sides. One is behind the maxillary fenestra, and although it does not pass directly through the bone, it is connected anteriorly to the maxillary sinus. The most conspicuous depression is posterodorsal to the maxillary fenestra. Within the depression is a relatively large foramen that passes ventromedially to open into the roof of the maxillary sinus, and two smaller, more posterior foramina that pass posteriorly into the

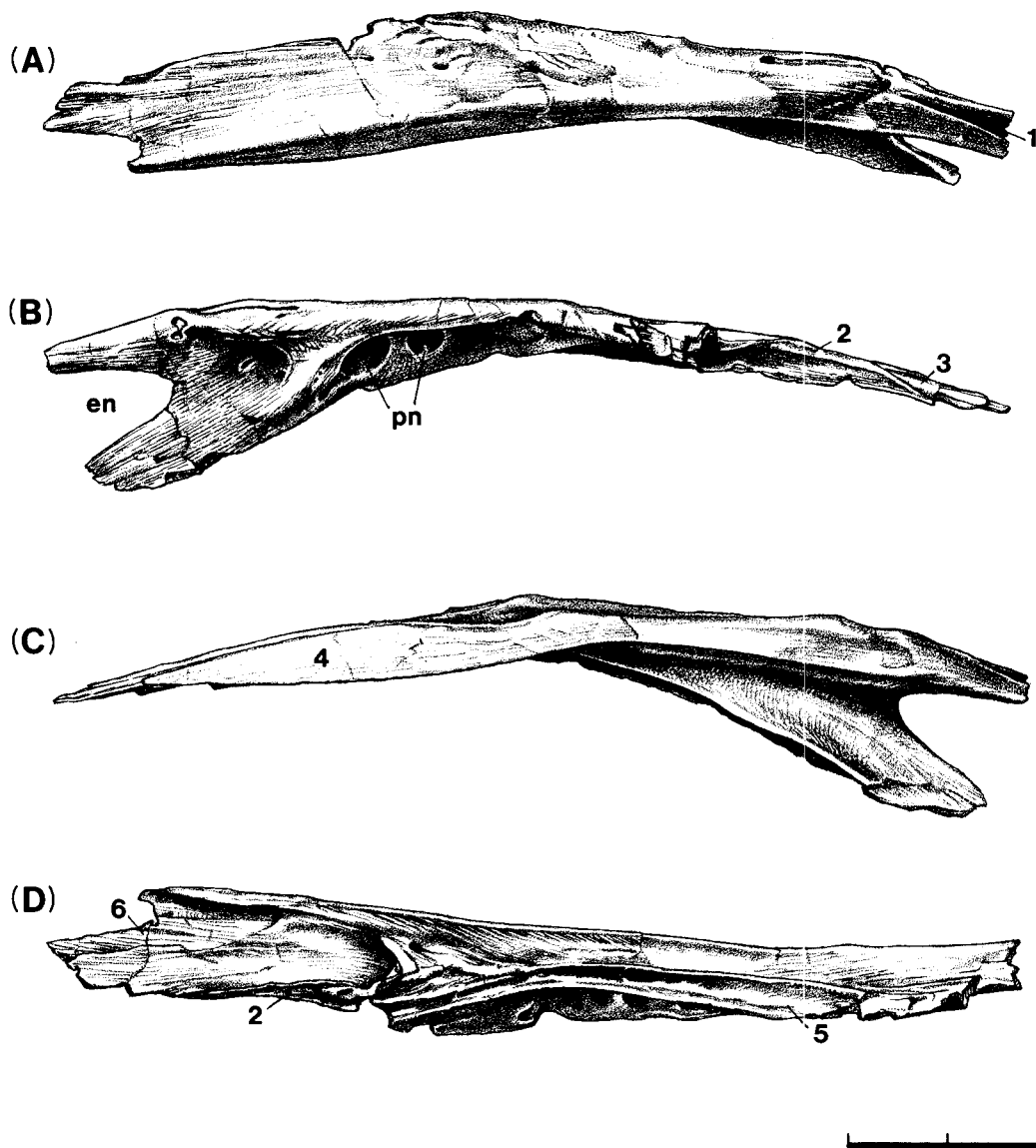


FIG. 5. *Sinraptor dongi* (IVPP 10600). Left nasal in dorsal (A), lateral (B), medial (C), and ventral (D) views. en, external naris; pn, pneumatopore. 1, premaxillary suture; 2, lacrimal contact; 3, prefrontal suture; 4, medial suture; 5, contact with maxilla; 6, contact with frontal. Scale bar = 10 cm.

antorbital fenestra. A small opening passes through the anterior margin of the antorbital fossa anterodorsal to the maxillary fenestra. A second pneumatopore is ventral to the nasal-maxillary suture on the right side only. This complex of accessory openings, although variable in details, is characteristic of the Sinraptoridae. The posterodorsal process of the maxilla passes between the nasal bone and the antorbital fenestra, and bifurcates distally to embrace a pronged anteroventral process of the lacrimal. The maxilla overlaps the lateral edge of the lacrimal prong, but is overlapped by the prong ventromedially. Overall, the morphology of the maxilla is not significantly different than that of *Y. shangyuensis*. In *Allosaurus*, there is only a single maxillary fenestra, but otherwise the maxilla is similar. The maxillae of *Carnotaurus* (Bonaparte et al. 1990), *Ceratosaurus* (Gilmore 1920), *Indosuchus* (Chatterjee 1978), and *Torvosaurus* (Britt 1991) are quite different in that most of the lateral surfaces are rugose, showing that the antorbital fossae are not as well developed, and there are no distinct maxillary fenestrae.

The medial surface of the maxilla (Fig. 4C) has a prominent anterodorsal process that contacts the maxillary process of the premaxilla ventrolaterally, the vomer ventromedially, and the anterodorsal process of the other maxilla dorsomedially. The maxillary sinus is housed medially by a bulbous expansion of the medial wall of the maxilla. There is a single large opening medially, and at least four small ones. The sinus is closed internally in "*M.*" *hesperis* (BMNH R332) and *Piatnitzkysaurus* (Bonaparte 1986), and has two medial openings in *Allosaurus* (Madsen 1976). *Torvosaurus* (BYU 9122) and *Ceratosaurus* (J.H. Madsen and S.P. Welles, personal communication, 1992) lack maxillary fenestrae and sinuses, and consequently lack the bulbous medial processes and associated medial openings.

As in the premaxilla, the interdental plates are separate from each other as in "*M.*" *hesperis* (BMNH R332), *Monolophosaurus*, *Piatnitzkysaurus*, and tyrannosaurids. Interdental plates are fused in *Allosaurus*, *Torvosaurus* (Britt 1991), and dromaeosaurids (Currie 1987).

The nasal (Fig. 5) is 51.5 cm in length, almost three times



the length of the frontal. The dorsal surface is flat and relatively wide for most of its length, and is clearly delimited from the nasal contribution to the antorbital fossa. In these characteristics, it is similar to *Yangchuanosaurus* and *Allosaurus*. The dorsal surface is dorsally convex and rugose in abelisaurids (Bonaparte and Novas 1985; Bonaparte et al. 1990), *Monolophosaurus*, and tyrannosaurids. The medial internasal suture is smooth and rounded for most of its length (Fig. 5C), but is flatter and more pronounced posteriorly. This suggests that some vertical and rotational movement, for shock absorption, may have been possible between the nasals above the maxillae. The nasal is split anteriorly (Fig. 5A), and the ends are separated by the premaxillae for a length of 2.3 cm on the ventral surface and more than 8 cm dorsally (the nasal process of the premaxilla sits in a groove on the dorsal surface of the nasal). As in *Monolophosaurus*, *Yangchuanosaurus*, and *Allosaurus*, the nasal forms the anterodorsal portion of the lateral wall of the antorbital fossa. In *Ceratosaurus*, the nasal forms part of the anterodorsal margin of the antorbital fossa, but does not contribute significantly to the lateral wall (J.H. Madsen and S.P. Welles, personal communication, 1992). Two pneumatic openings invade the nasal along the margin of the antorbital fossa, compared with one (Madsen 1976; BYU 4777), two (Gilmore 1920), or three (BYU 2028) in *Allosaurus*. Although the pneumatic openings of IVPP 10600 are only separated by 1.8 cm, they do not connect internally. The anterior pneumatopore expands medially and anteriorly into a hollow space that invades the internarial and subnarial processes of the nasal, whereas the posterior pneumatopore connects posteriorly with the hollow interior of the dorsal plate. An elongate groove on the ventral surface of the nasal (Fig. 5D) overlaps the elongate but thin dorsal margin of the nasal process of the maxilla. The edge in groove arrangement would have provided a strong contact between the maxilla and nasal, but would have permitted some lateral–medial rotation of the maxilla. Posteromedial to the posterior end of the suture with the maxilla, the nasal overlaps the anterior tip of the lacrimal. The lacrimal suture (Fig. 5D) rotates posteriorly until it is lateral in orientation. This suture is strengthened by longitudinal ridges and grooves that would have permitted no movement between these bones. There is a relatively short and shallow suture for the prefrontal posterolaterally (Fig. 5B). Each nasal bifurcates posteriorly where it overlaps (Fig. 5D) an anteroposteriorly elongate shelf of the frontal, as in most other theropods.

The lacrimal (Figs. 6B, 6D, 6E) is 18.5 cm long and 27 cm high. The dorsolateral horn at the front of the orbit is very low compared with that of *Allosaurus* and *Ceratosaurus* (Gilmore 1920), and is even less prominent than that of *Y. shangyuensis* (Dong et al. 1978). The lacrimal has a limited dorsal exposure (Fig. 3A). Anteriorly, there are interdigitating sutures with the maxilla and nasal. The lateral surface of the lacrimal is sculptured posterodorsally, as in other theropods, and obviously had a close association with the skin. In lateral aspect, the posterior margin of the ventral process of the lacrimal has a double concavity separated by a short process (for attachment of the Ligamentum suborbitale) that marks the anteroventral extent of the eyeball itself. With the exception of *Abelisaurus* (Bonaparte and Novas 1985), *Monolophosaurus*, and *Y. shangyuensis*, the posterior margin of the preorbital bar of large theropods is uniformly concave in lateral view. The position and size of the eyeball can be deduced from tyrannosaurids because of a similar process on the postorbital bone. Below this low process of the lacrimal in IVPP 10600,

the preorbital bar narrows to 2 cm in lateral aspect. The posteroventral end of the lacrimal expands somewhat for its contact with the jugal, but not to the same extent as in *Y. shangyuensis*. Ventrally, the lacrimal is overlapped by the jugal but does not contact the maxilla. In contrast, the lacrimal may contact the maxilla externally in *Allosaurus* and *Ceratosaurus* (Gilmore 1920).

As in other large theropods, there is a large lateral, pneumatic opening into a vacuity in the main posterodorsal body of the lacrimal (Fig. 6E). Two smaller, more anterior openings penetrate the dorsal margin of the antorbital fossa on the right lacrimal, but there is only one on the left side. It is not unusual for cranial pneumatic features to be asymmetrical (Currie 1985). A canal passing anteromedially from the more anterior vacuity to the medial surface of the bone posterior to its contact with the maxilla (Fig. 6D) probably housed the superior nasal artery and the ramus nasalis of the ophthalmic nerve. Madsen (1976) and others have speculated on the presence of a gland in the main dorsolateral vacuity, possibly a specialized lacrimal gland to keep the eye moist. As in other large theropods, the relatively large lateral opening is a posterodorsal extension of the smooth-surfaced antorbital fossa, and is not associated with the lacrimal ducts. The function of this opening is best interpreted as a pneumatic diverticulum of the nasal cavity (Witmer 1987). Several small foramina pierce the orbital wall of the preorbital bar to enter a medial vacuity (Fig. 6D) from behind. These are probably the lacrimal ducts, and it is possible that the medial vacuity housed a moisturizing gland. It is not known if there are connections within the bone between the lateral and medial vacuities.

Posteromedial to the lacrimal, there is a triangular prefrontal (Fig. 3A) almost identical to that of *Allosaurus*, but relatively shorter (8.5 cm) and broader (48 mm). The orbital margin is rugose and thick, and continues laterally onto the lacrimal and medially onto the frontal. The lateral suture (Fig. 6A) is concave centrally to fit over a prominent process on the lacrimal (Fig. 6D) and tapers anteriorly and anteroventrally as in *Allosaurus*. The surface is rugose, and no movement would have been possible. Medially, there is a deep, firm sutural contact with the frontal, and a more limited suture for the nasal (Fig. 6B).

In contrast with *Monolophosaurus*, the dorsal surface of the frontal of IVPP 10600 is flat (Fig. 7D). This bone is narrower than it is in *Allosaurus*, and therefore appears to taper more sharply anteriorly. The skull of the type specimen of *Y. shangyuensis* (CV 00215) is laterally crushed, making it difficult to determine the width of the skull. However, there does not appear to have been any telescoping of the bones in the interorbital region, and it is likely that the skull was also relatively narrow. The interfrontal suture is more or less straight anteriorly, and more sinuous posteriorly. The orbital rim is emarginated between the prefrontal and postorbital, giving the frontal limited access to the orbital rim, as in allosaurids and tyrannosaurids. The surface of the bone is smooth in contrast with the ornamented surface in *Abelisaurus* (Bonaparte and Novas 1985).

There is a deeply interdigitating but more or less transverse frontoparietal suture. At the dorsal limit of the upper temporal fenestra, the suture is strengthened by additional bone deposition on the frontal and parietal, and this protrudes laterally into the fenestra (Fig. 7D). There is no sharp sagittal crest along the midline of the parietal, and in this sense *Sinraptor* is as primitive as all theropods except the Tyrannosauridae and Troodontidae. As in *Yangchuanosaurus* and *Allosaurus*, there

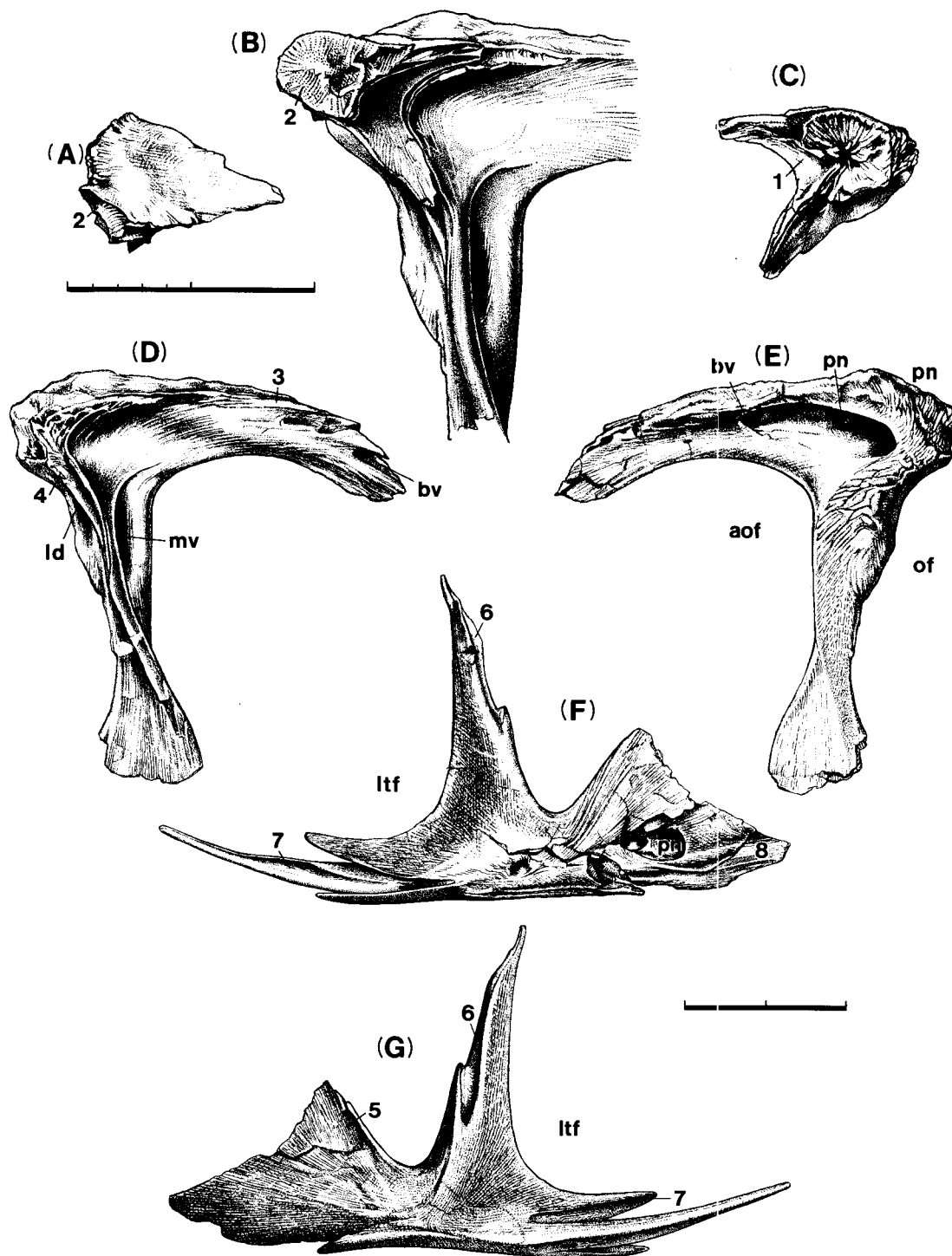


FIG. 6. *Sinraptor dongi* (IVPP 10600). Left prefrontal in dorsal (A) and lateral (C) views; left prefrontal and lachrymal in medial view (B); left lacrimal in medial (D) and lateral (E) aspects; right jugal in lateral (F) and medial (G) views. aof, antorbital fenestra; bv, blood vessel; ld, lacrimal duct; ltf, lateral temporal fenestra; mv, medial vacuity; of, orbital fenestra; pn, pneumatic opening. 1, contact with frontal; 2, lacrimal contact; 3, nasal suture; 4, prefrontal suture; 5, lacrimal contact; 6, contact with postorbital; 7, contact with quadratojugal; 8, contact with maxilla. Scale bar = 10 cm.

is a strong nuchal crest however. The prominent top of the crest is broken off at the midline of the skull to expose its contact with the supraoccipital (Fig. 7). The parietal does not extend much above the supraoccipital, which is a primitive characteristic not seen in tyrannosaurids and troodontids.

As in *Yangchuanosaurus* (Dong et al. 1978) and to a lesser

extent in *Allosaurus*, the postorbital (Figs. 8A, 8B) has thickened into a prominent orbital rugosity. This is not as well developed as the postorbital "horn" of some tyrannosaurids, however (Bakker et al. 1988). In IVPP 10600, this is 3 cm thick dorsoventrally, and projects forward to close the slotlike gap between the postorbital and lacrimal (Fig. 3A). The inter-

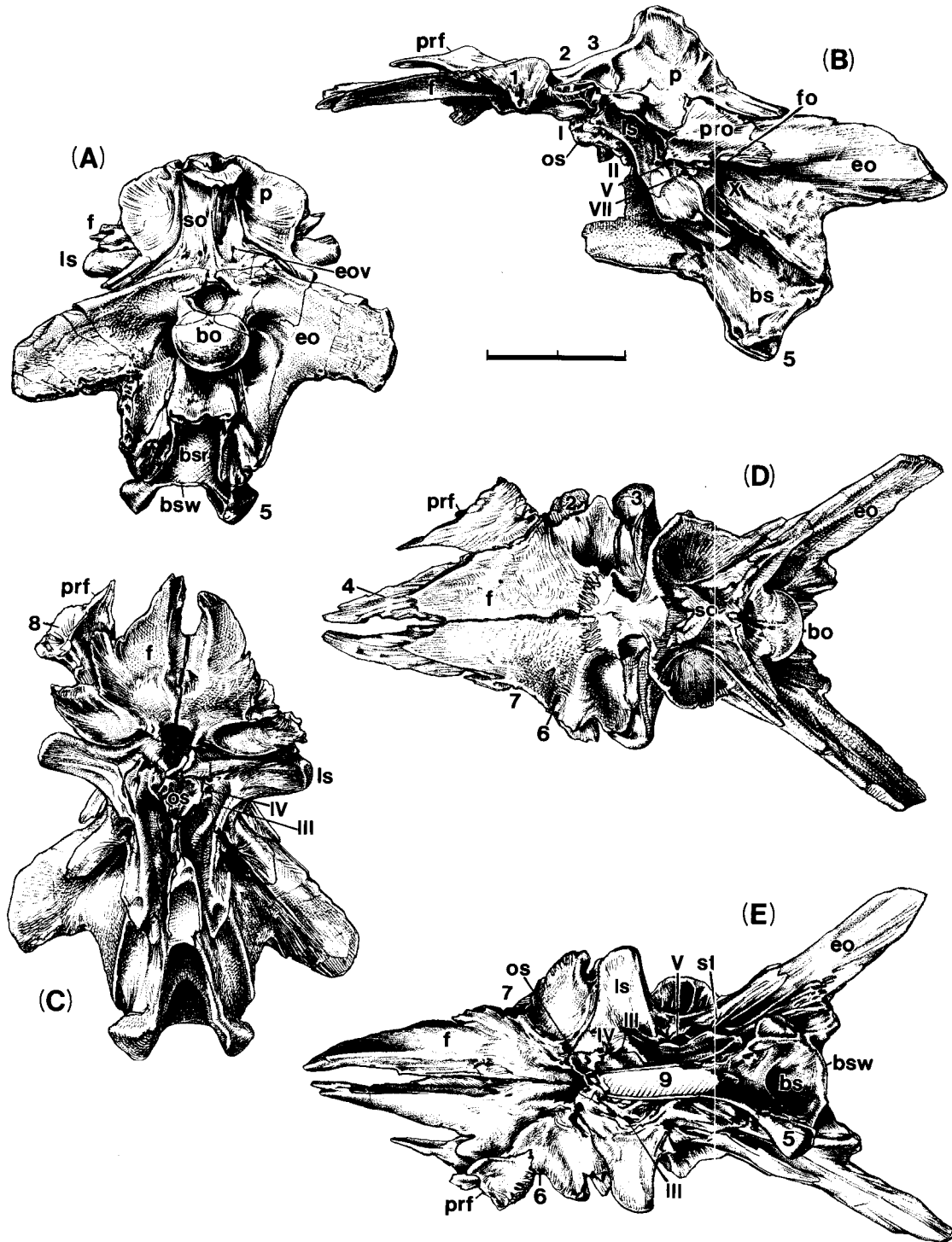


FIG. 7. Braincase of *Sinraptor dongi* (IVPP 10600) in occipital (A), left lateral (B), anteroventral (C), dorsal (D), and ventral (E) views. bo, basioccipital; bs, basisphenoid-parasphenoid complex; bsr, basisphenoid recess; bsw, basisphenoid web; eo, exoccipital-basioccipital complex; eov, external occipital vein; f, frontal; fo, fenestra ovalis; ls, laterosphenoid; os, orbitosphenoid; p, parietal; prf, prefrontal; pro, prootic; so, supraoccipital-epiotic complex; st, stapes; 1, prefrontal suture of frontal; 2, postorbital suture of frontal; 3, postorbital suture of laterosphenoid; 4, nasal suture of frontal; 5, pterygoid articulation of basiptyergoid process; 6, orbital rim of frontal; 7, prefrontal suture of frontal; 8, lacrimal suture of prefrontal; 9, longitudinal trough beneath cultriform process; I, II, III, IV, V, VII, X, cranial nerves. Scale bar = 10 cm.

temporal ramus of the postorbital is distinctive in comparison with *Yangchuanosaurus*, *Allosaurus*, and most other theropods. In lateral view, the intertemporal ramus appears very short, and does not extend much posterior to the postorbital ramus. However, viewed medially, the intertemporal ramus of

the postorbital extends posteriorly most of the length of the elongate intertemporal bar, and sits in a deep slot on the medial face of the intertemporal process of the squamosal. This configuration is identical on right and left postorbitals. In other theropods, the intertemporal ramus of the postorbital has

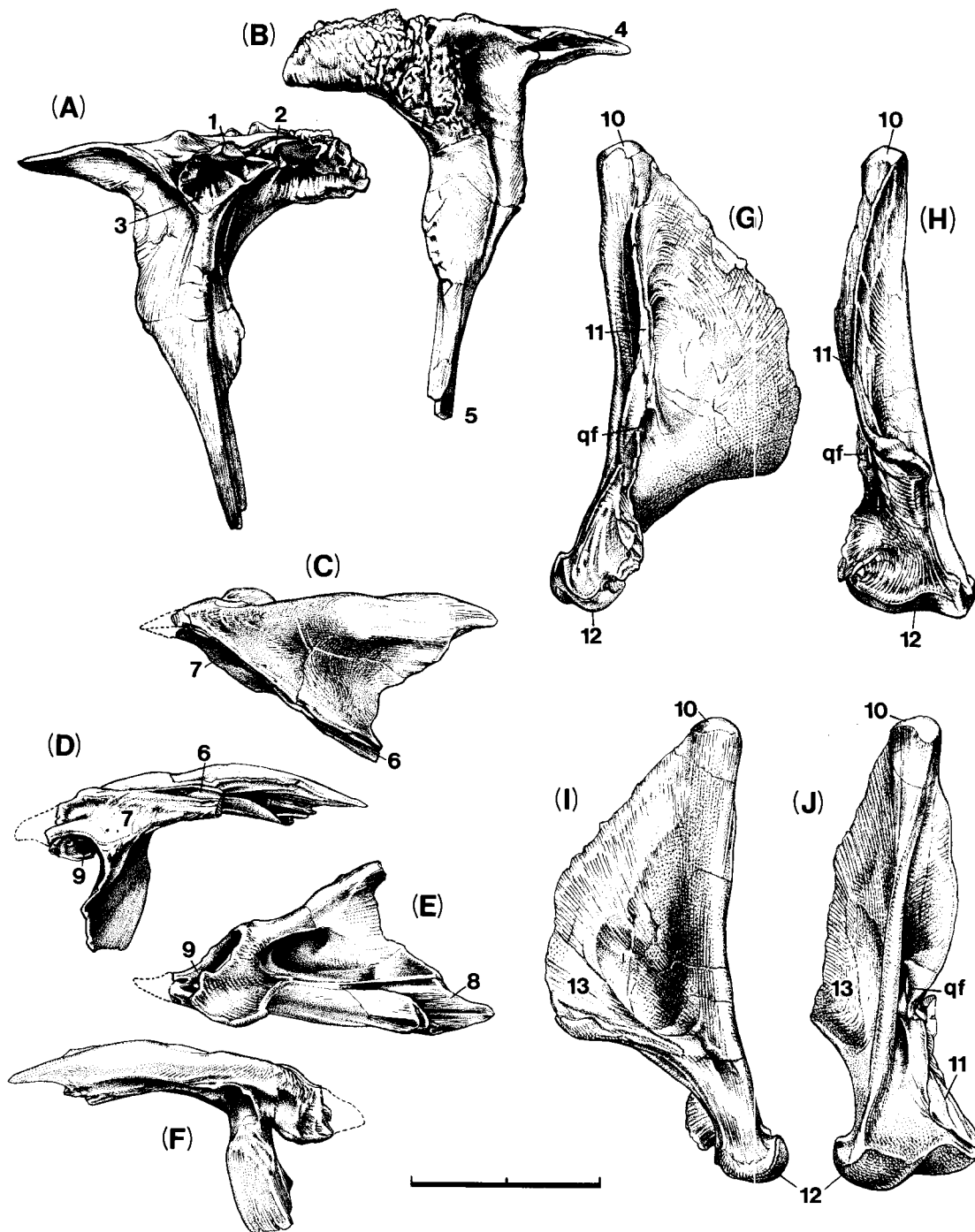


FIG. 8. *Sinraptor dongi* (IVPP 10600). Left postorbital in medial (A) and lateral (B) views; left squamosal in dorsal (C), medial (D), ventral (E), and lateral (F) aspects; right quadrate in lateral (G), anterior (H), medial (I), and posterior (J) views. qf, quadrate foramen. 1, contact on postorbital for parietal; 2, contact on postorbital for frontal; 3, postorbital articulation; 4, suture for squamosal; 5, contact with jugal; 6, parietal suture; 7, contact surface for paroccipital process; 8, postorbital suture; 9, quadrate articulation; 10, quadrate cotyle; 11, quadratojugal suture; 12, mandibular condyles; 13, pterygoid contact. Scale bar = 10 cm.

a long lateral exposure that tends to laterally overlap the intertemporal process of the squamosal (Gilmore 1920; Madsen 1976; Currie 1985).

The jugal (Figs. 6F, 6G) is similar to those of most other large theropods in that it separates the maxilla and lacrimal to take part in the rim of the antorbital fenestra (Fig. 3B). The long, sloping maxillary suture is overlapped laterally by the maxilla, which also wraps around underneath the jugal for

limited coverage of the medial side. As in *Edmarka* (Bakker et al. 1992), the posterolateral prong of the maxilla that overlaps the outer surface of the jugal is overlapped dorsolaterally itself by a thin, blade-like everted sheet of the jugal. The anterolateral surface is depressed where it contributes to the antorbital fossa. There is a prominent depression in the wall of the antorbital fossa in this region (Figs. 3B, 6F). Two pneumatic openings invade the jugal from this depression in a manner

reminiscent of tyrannosaurids. There appears to have been a single, small pneumatopore in *S. hepingensis* (Gao 1992). The jugal is pneumatic in *Monolophosaurus* and some specimens of *Allosaurus* (USNM 4734, UUVV 1403, UUVV 3894, UUVV 3981), although the pneumatopores are small in comparison with *Sinraptor* and tyrannosaurids. Breaks in the jugal of IVPP 10600 show that the suborbital and postorbital processes of the jugal were air filled. The postorbital process of the jugal is tall and slender (a primitive characteristic) with a long, sloping contact with the postorbital bone. The postorbital overlaps the jugal slightly laterally along this contact (Fig. 6F), which appears to be the remnant of a primitive contact well developed in *Dilophosaurus*, *Ceratosaurus*, and *Edmarka* (Bakker et al. 1992). The ventral portion of the postorbital wraps around onto the medial surface, and the tip inserts into a notch on the anteromedial surface of the jugal (Fig. 6G) as in *Allosaurus* (Madsen 1976, Pl. 4). In *Sinraptor* and *Allosaurus*, this notch is high above the ventral margin of the orbit, whereas in *Edmarka* (Bakker et al. 1992) these are at the same level. Posteriorly, there is an unusual, autapomorphic contact with the quadratojugal. In most theropods, the quadratojugal process of the jugal splits posteriorly into two. In *S. dongi*, however, the lower of these two prongs has divided into two, one branch contacting the ventral surface of the quadratojugal, and a long slender process that sat in a groove on the medial surface of the quadratojugal. The condition in *S. hepingensis* is not clear, although published figures (Gao 1992) suggest there are only two prongs. Unlike ceratosaurs and torvosaurids (Bakker et al. 1992), the uppermost prong of the quadratojugal processes of *Sinraptor* and *Allosaurus* is much shorter than the ventromedial prong.

In posterior view, the squamosal has a relatively weak parietal process (Fig. 3D), even if the extension overlain by the parietal is included, in comparison with *Allosaurus* (Gilmore 1920). This is another feature in which this genus is more primitive than *Allosaurus* and most Cretaceous theropods. The region of overlap by the paroccipital process is relatively narrow in comparison with *Allosaurus* (Gilmore 1920).

The occiput (Figs. 3D, 7A) is well preserved, although crushing has rotated it somewhat upward in relation to the skull roof. The foramen magnum, as preserved, is 3 cm wide and 2.5 cm high. The occipital condyle is 5 cm across and 4 cm in height. The sutures of the occiput are not closed, suggesting immaturity.

A conspicuous midline ridge on the supraoccipital is comparable with that of *Yangchuanosaurus* (personal observation) and *Allosaurus* (Madsen 1976). The anterior surface of the supraoccipital is invaded by a midline process of the parietal (Fig. 7D). The supraoccipital makes a small contribution to the margin of the foramen magnum on the midline. There is a long, relatively smooth suture with the parietal, which makes no sharp incursion into the supraoccipital as in *Allosaurus* (Madsen 1976). The supraoccipital and epiotic are coossified as in most dinosaurs, although a rugose region lateral and ventral to the exit of the external occipital vein may be the remnant of a separate epiotic.

The basioccipital composes the largest part of the occipital condyle (Fig. 7A), and as in *Allosaurus* makes a narrow contribution to the floor of the foramen magnum. The basioccipital also forms the posterior portions of the basal tubera. These processes are relatively small in *Sinraptor*, and as in *Allosaurus*, the width across the basal tuber is less than the transverse diameter of the occipital condyle. This is not the case in

dromaeosaurids (Colbert and Russell 1969), troodontids (Currie 1985), and tyrannosaurids (Bakker et al. 1988).

There is no division evident between the exoccipital and opisthotic in any known theropod. The exoccipitals are separated from each other by the supraoccipital above the foramen magnum and by the basioccipital below (Fig. 7A). The paroccipital process is relatively wide and shallow, in contrast with the deeper tyrannosaurid condition (R.T. Bakker, personal communication, 1989). When the braincase is corrected for distortion, the paroccipital process turns downwards distally, but not as sharply as in *Allosaurus*. At least two branches of the XIIth cranial nerve emerge in a depressed area between the occipital condyle and the paroccipital process. *Sinraptor* is unusual in that the exoccipitals extend significantly more ventrally than the basal tubera. In most theropods, including dromaeosaurids (Colbert and Russell 1969), allosaurids (Gilmore 1920), and tyrannosaurids (Bakker et al. 1988), the ventral limit of the exoccipital–opisthotic along the basioccipital and basisphenoid suture is either at the same level or is dorsal to the level of the basal tubera. A notch separates the basal tuber from the more anteroventral extension of the exoccipital–basisphenoid suture as in allosaurids.

The basisphenoid–parasphenoid is a complex structure of thin webs of bone. Anteriorly, the cultriform process is incomplete. However, the base of the process is formed by two longitudinal, thin (1.2 mm) webs of bone that converge and join dorsally, arching over a ventrally oriented longitudinal trough (Fig. 7E) that is more pronounced than that of *Allosaurus*. The longitudinal webs are continuous posteriorly with the prominent basiptyergoid processes. A transverse ridge extends medially, anteriorly, and dorsally from the basiptyergoid process to meet its counterpart on the midline, delimiting the posterior extent of the cultriform trough. There is a deep, medial concavity behind this ridge. Another transverse plate of bone is formed by ridges originating from the posteromedial borders of the basiptyergoid processes. This is equivalent to the basiptyergoid web of Bakker et al. (1988). As in most theropods, including allosaurids (Madsen 1976), dromaeosaurids (Colbert and Russell 1969), and tyrannosaurids (Bakker et al. 1988), there is a large basisphenoid recess between the basiptyergoid web and a similar transverse plate joining the basitubera. The basisphenoid recess of *Sinraptor* is relatively short anteroposteriorly, and is more posteriorly oriented than that of *Allosaurus*. There do not appear to be any pneumatic openings associated with the internal carotid, such as are found in *Allosaurus* and tyrannosaurids.

A large crista prootica extends anteroventrally from the main body of the prootic, obscuring the foramen for the internal carotid. The fifth cranial nerve emerges from a large foramen between the prootic and laterosphenoid, and was clearly channelled posteriorly and ventrally across the surface of the former bone. The opening is dorsoventrally constricted at one point. The constriction is an incipient division of the foramen into a separate anterior exit for the ophthalmic branch of the trigeminal. In later theropods, including *Allosaurus*, troodontids, and tyrannosaurids, the separation is complete. The seventh cranial nerve was completely surrounded by the prootic, whereas the fenestra ovalis was bound only anterolaterally by that bone.

The delicate orbitosphenoids were crushed and distorted, but appear to be similar to those of *Allosaurus* (Madsen 1976) in most essential features. They contact each other both above and below the single, medial exit for the optic nerves (Fig. 7C).

Portions of the bases of both stapes are preserved, emerging

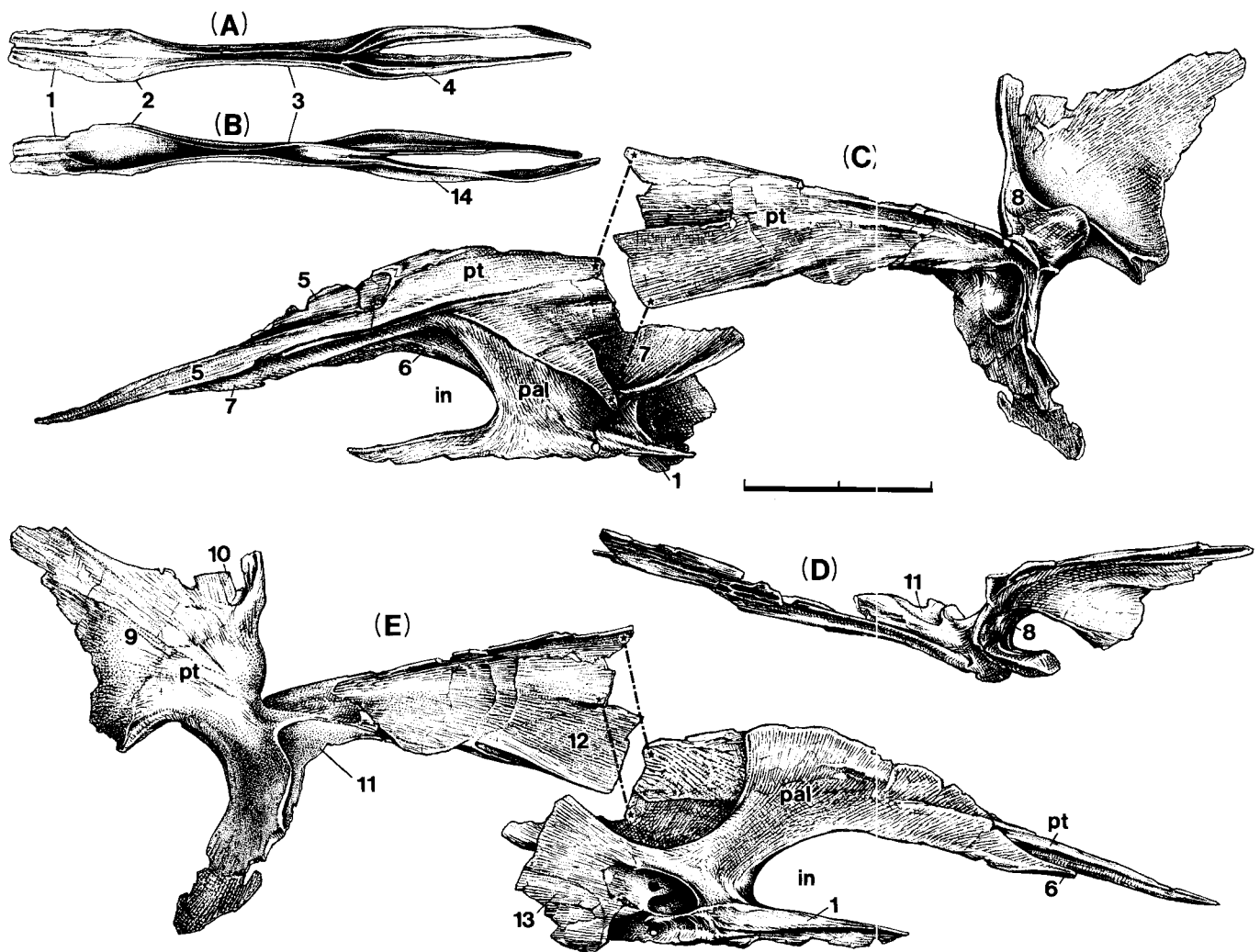


FIG. 9. Palatal elements of *Sinraptor dongi* (IVPP 10600). Vomers in dorsal (A) and ventral (E) aspects; right palatine and pterygoid in medial (B) and lateral (D) views; posterior region of pterygoid in dorsal aspect (C). in, internal naris; pal, palatine; pt, pterygoid; 1, contact with maxilla; 2, anterior limit of preserved pterygoid on vomer; 3, anterior limit of preserved palatine on vomer; 4, groove for pterygoid; 5, medial suture; 6, vomer sutural surface on palatine; 7, pterygoid suture on palatine; 8, basipterygoid articular surface; 9, quadrate contact on pterygoid; 10, epipterygoid suture; 11, ectopterygoid suture; 12, palatine contact; 13, sutural surface on palatine for jugal; 14, suture for palatine. Scale bar = 10 cm.

from the fenestra ovalis on either side. The delicate shaft is 1.7 mm in diameter.

IVPP 10600 includes an almost complete pair of vomers (Figs. 9A, 9B), coossified at mid-length, in contact but still distinct from each other anteriorly, and widely separated posteriorly. The vomers extend posteriorly to about the level of the 11th maxillary alveolus. The wedge-shaped, dorsally vaulted anterior end of the vomers would have contacted the premaxilla. Ventrolaterally, there are longitudinally ridged, sutural surfaces (Fig. 9A) where the vomers fit into slots in the anteromedial processes of the maxillae. The vomers are deepest in the fused section at mid-length, in contrast with *Allosaurus*, where the greatest depth is in the palatine process. Thin ridges delimit deep, longitudinal, midline troughs on the dorsal (Fig. 9A) and ventral (Fig. 9B) surfaces. The dorsal trough may have housed the paired anterior tips of the pterygoids. This trough is not present in *Allosaurus*, where the pterygoids do not appear to have reached the vomers (Madsen 1976). Posteriorly, the palatine processes separate on the midline, tapering caudally as they diverge. On the right side, the vomer

was found in articulation with the palatine, its lateral surface contacting the medial edge of the palatine along the margin of the internal naris. Near the anterior end of the palatine process a trough appears on the dorsal edge, passing from the lateral edge of the process anteromedially to the midline trough of the paired vomers (Fig. 9A). The anteriorly converging troughs may mark the point of convergence and contact of the pterygoids.

The right palatine (Figs. 9C, 9D) is complete, but the left lacks the pterygoid process and the distal end of the vomerine ramus. As in other theropods, the maxillary suture is elongate, extending from the back of alveolus 7 to a position between the last tooth and the back of the maxilla. Posteriorly, the suture enters a notch between the main body of the palatine and a distinct ventral process, not seen in *Allosaurus* (Madsen 1976), of the jugal process of the palatine. The medial surface of this process (Fig. 9C) contacts the maxilla, and the outer (Fig. 9E) is part of the extensive, squamose jugal suture. The jugal process does not appear to have contacted the lacrimal, in contrast with *Ceratosaurus* (Gilmore 1920) and *Monolophosaurus*. The jugal ramus does not extend as far posteriorly as the postero-

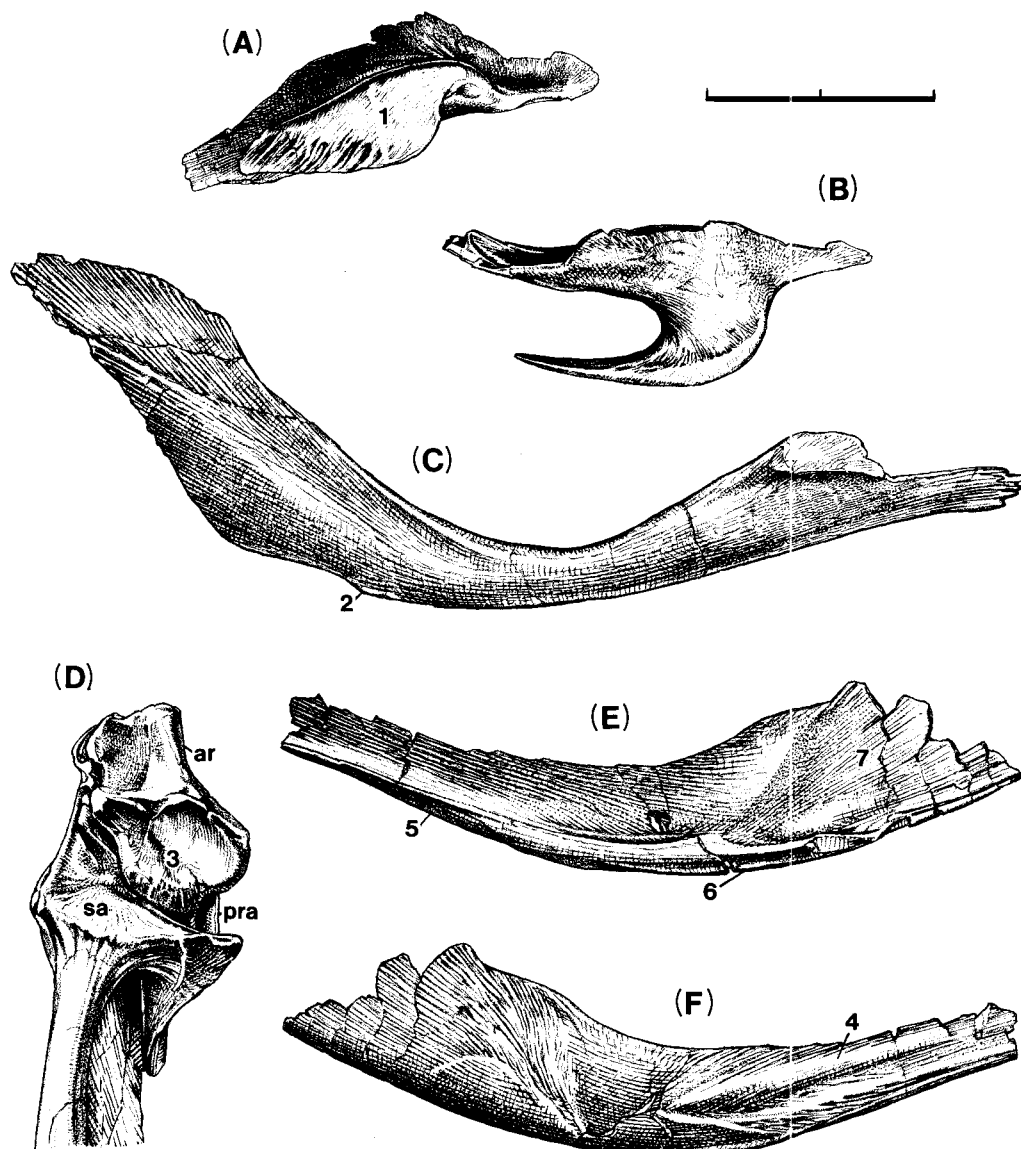


FIG. 10. *Sinraptor dongi* (IVPP 10600). Right ectopteryoid in lateral (A) and dorsal (B) views; right prearticular in medial aspect (C); right jaw articulation showing articular and parts of surangular and prearticular in dorsal view (D); right angular in medial (E) and lateral (F) aspects. ar, articular; pra, prearticular; sa, surangular; 1, jugal contact; 2, most posterior point of contact between angular and prearticular; 3, glenoid; 4, contact with dentary and splenial; 5, prearticular suture; 6, contact with dentary; 7, surangular suture. Scale bar = 10 cm.

medial pterygoid branch of the palatine, which is not the case in *Allosaurus*. A foramen pierces the jugal ramus as in *Allosaurus*, although it is associated with a distinct, pneumatic pit on the lateral surface in *Sinraptor* (Fig. 9E). The pneumatic diverticulum of the antorbital sinus extended anteriorly, medially, and dorsally into the base of the vomerine ramus of the palatine (between the internal naris and postpalatine fenestra). Pneumatic palatines are also known in tyrannosaurids (Molnar 1991). The vomerine branch of the palatine tapers to a sharp point that extends anteriorly well beyond the limits of the palatamaxillary suture, again in contrast with *Allosaurus*. It extends dorsomedially above the pterygoid to meet the other palatine in a medial suture (Fig. 9C). The vomer extended along the ventral margin of the vomerine ramus, and had a more extensive contact on the medial surface of the palatine (Fig. 9C) than has been reported in other theropods.

A complete right (Figs. 10A, 10B) and an almost complete left ectopteryoid were recovered. This hook-shaped bone is

not significantly different from that of *Allosaurus* in lateral and dorsal aspects. Like most theropods (Molnar 1991) except *Ceratosaurus* (J.H. Madsen and S.P. Welles, personal communication, 1992), the ectopteryoid is invaded medially by a deep pit. In contrast with other known forms, however, the hollow interior of the main body extends laterally into the neck of the hooked jugal process, and opens ventrolaterally through a large foramen medial to the anterior end of the jugal contact. In *Sinraptor*, the hollow interior may be linked to the antorbital pneumatic system.

The well-preserved, right pterygoid (Figs. 9C, 9D, 9E) is the longest cranial bone, its 64 cm extending most of the length of the skull. The elongate, tapering anterior palatal ramus meets the opposite pterygoid on the midline, as in most theropods except tyrannosaurids (Russell, 1970). The paired pterygoids sit in slot on the dorsal surface of the vomer, and almost reach far enough forward to contact the maxillae (Fig. 9A). Although Madsen (1976) did not show the pterygoid of *Allosaurus* reach-

ing the vomer, it does in AMNH 600 (R. T. Bakker, personal communication, 1993), *Ceratosaurus* (Gilmore 1920), and most other theropods. Ventral to the medial suture, the pterygoids diverge ventrolaterally, producing a highly arched roof to the mouth, in strong contrast with the horizontal palatal process of the tyrannosaur pterygoid (Molnar 1991). There is a long, deep squamose suture with the palatine (Figs. 9C, 9E). Medial to the postpalatine fenestra, the palatine wraps around the bottom of the pterygoid (Fig. 9C), virtually excluding it from the margin of the fenestra. Close to the posterior limit of the contact between these two bones, the palatine diverges from the margin of the fenestra, and is underlain by a narrow tongue of the pterygoid (Fig. 9E). This narrow tongue appears to be all that separates the palatine and ectopterygoid, and is the only contribution that the pterygoid makes to the margin of the postpalatine fenestra. Although this is similar to the situation in *Dromaeosaurus*, the pterygoid seems to have contributed more to the fenestral margin in *Allosaurus* (Madsen 1976) and tyrannosaurs (Russell 1970).

The ectopterygoid contacts both the palatal and ventral rami of the pterygoid, with an invasive, laterally overlapping squamose suture between the two (Fig. 9E). Ventrally, the ectopterygoid contact is restricted to the anterior margin of the ventral ramus, but appears to twist somewhat onto the medial surface as well. There is a depression on the medial side of the ventral ramus that is continuous with the hollow in the base of the ectopterygoid, and that ends in a distinct pit posterodorsally. This probably marks the position of an air sac. The quadrate ramus is a thin curved sheet of bone, strengthened anteriorly and ventrally by ridges of bone on the medial surface (Fig. 9C). On the medial surface at the base of the quadrate ramus is a fingerlike projection (Figs. 9C, 9D) that folded around the basiptyergoid process of the basisphenoid-parasphenoid complex. The curved dorsal margin is notched on the lateral surface for a strong contact with the epiptyergoid (Fig. 9E). The posterior extent of the epiptyergoid is unknown, although the degree of apparent overlap in *Allosaurus* (Madsen 1976) appears to have been much greater. The quadrate ramus has a free dorsal margin between the epiptyergoid and quadrate sutures. Posteriorly, the ramus increases more in relative height than that of *Allosaurus*. The pterygoid has an extensive, squamose suture (Fig. 9E) for the pterygoid ramus of the quadrate, which wraps around its thin posteroventral margin.

There are four premaxillary, 14 maxillary, and 16 dentary tooth positions. The longest crown in the right maxilla is 6.8 cm high. Nine laterally compressed teeth with roots were found with IVPP 10600, and had dropped out of the left dentary. None of these teeth, the longest of which has a crown 4 cm long, are as large as the anterior maxillary teeth. The roots are not quite double the length of the crowns. One tooth has a large resorption pit in the wall of the root. Three of the teeth show breakage and subsequent wear at the tips.

#### Lower jaw

The external mandibular fenestra is much larger (Fig. 3B) than it is in *Allosaurus* (Madsen 1976), and is comparable in relative size to the fenestrae in *Coelophysis* (Colbert 1989), *Ceratosaurus* (Gilmore 1920), and abelisaurids (Bonaparte et al. 1990). In theropods the external mandibular fenestra is almost always present at the junction of the dentary, angular, and surangular, but takes a number of different forms. The larger size of this opening in sinraptorids is possible because of modifica-

tions in the shape of the surangular and the posterior margin of the dentary.

As in almost all theropods (Bakker et al. 1988), including *Herrerasaurus* (Serenó and Novas 1992), there is an intramandibular joint. A posteriorly projecting lateral process of the dentary near the dorsal margin, referred to subsequently as the intramandibular process of the dentary, fits into a slot in the labial side of the surangular (Fig. 3B). An anteriorly projecting tongue, the intramandibular process of the surangular, extends ventrolateral to the intramandibular process of the dentary. The two processes seem to have been separated when the jaw was in a natural position. As the jaws opened, the dentary and splenial would have been pulled posteriorly until the intramandibular processes interlocked. Further movement would have pivoted around this point. Below this, the surangular is overlapped by the dentary in a way that would have permitted fore-aft sliding. Ventrally, the anterior end of the angular had a sliding joint between the dentary and the splenial, separating them posteriorly. On the lingual side of the jaw, some vertical rotation was possible between the prearticular and splenial.

The left dentary (Figs. 11A, 11B) is virtually complete, whereas the right lacks its anterior end. This bone is relatively long and low, with generally concave upper and lower margins in lateral view. The lateral surface of the bone is pierced by a dorsal row of mental foramina for innervation of the skin and lips by the inferior alveolar nerve (Fig. 11A). These foramina are relatively large and undoubtedly communicated with the internal vascular system as well. Smaller, less prominent foramina open close to the anteroventral margin of the lateral surface. The interdental symphysis is poorly defined, and allowed movement between the lower jaws. The dental shelf is thick, and splits posterior to the last alveolus to accept the anterior end of the surangular, which extends for at least 3.5 cm underneath the dental shelf. The articulation would have permitted flexion at the intramandibular joint, but would have locked to prevent hyperextension. Although the suprudentary was not recovered with IVPP 10600, there is contact surface for it on the posteromedial surface of the dental shelf. A ventromedial shelf, which wrapped under the anterior tip of the angular, tapered posteriorly to ventrally expose the angular at the back of the dentary. Contact between the angular and dentary was loose, and would have allowed a relatively great range of anteroposterior sliding. Posteriorly, the dentary is deep, and is concave lingually where it forms the lateral wall of the Meckelian canal. As in *Allosaurus*, two foramina enter the bone close to where the Meckelian canal passes between the dentary and splenial to become the medially open Meckelian groove. The upper foramen (presumably entering the inferior alveolar canal) is smaller, but would have been used by the inferior alveolar nerve and the internal mandibular artery. The Meckelian groove is shallow as in all other theropods except troodontids (Currie 1987). Two foramina exit the lingual surface of the bone at the anterior end of the Meckelian groove, one of which was probably for the symphyseal ramus of the inferior alveolar nerve. There are 16 alveoli, which falls within the range of variation for allosaurids (Madsen 1976). *Yangchuanosaurus* has fewer dentary teeth, with 14 in the right and 15 in the left dentary of CV 00215 (Dong et al. 1983). The interdental plates are separate. There is a longitudinal groove between the bases of the interdental plates and the dorsal surface of the dental shelf for the dental artery, branches of which pass between the interdental plates into each alveolus. Rehealed



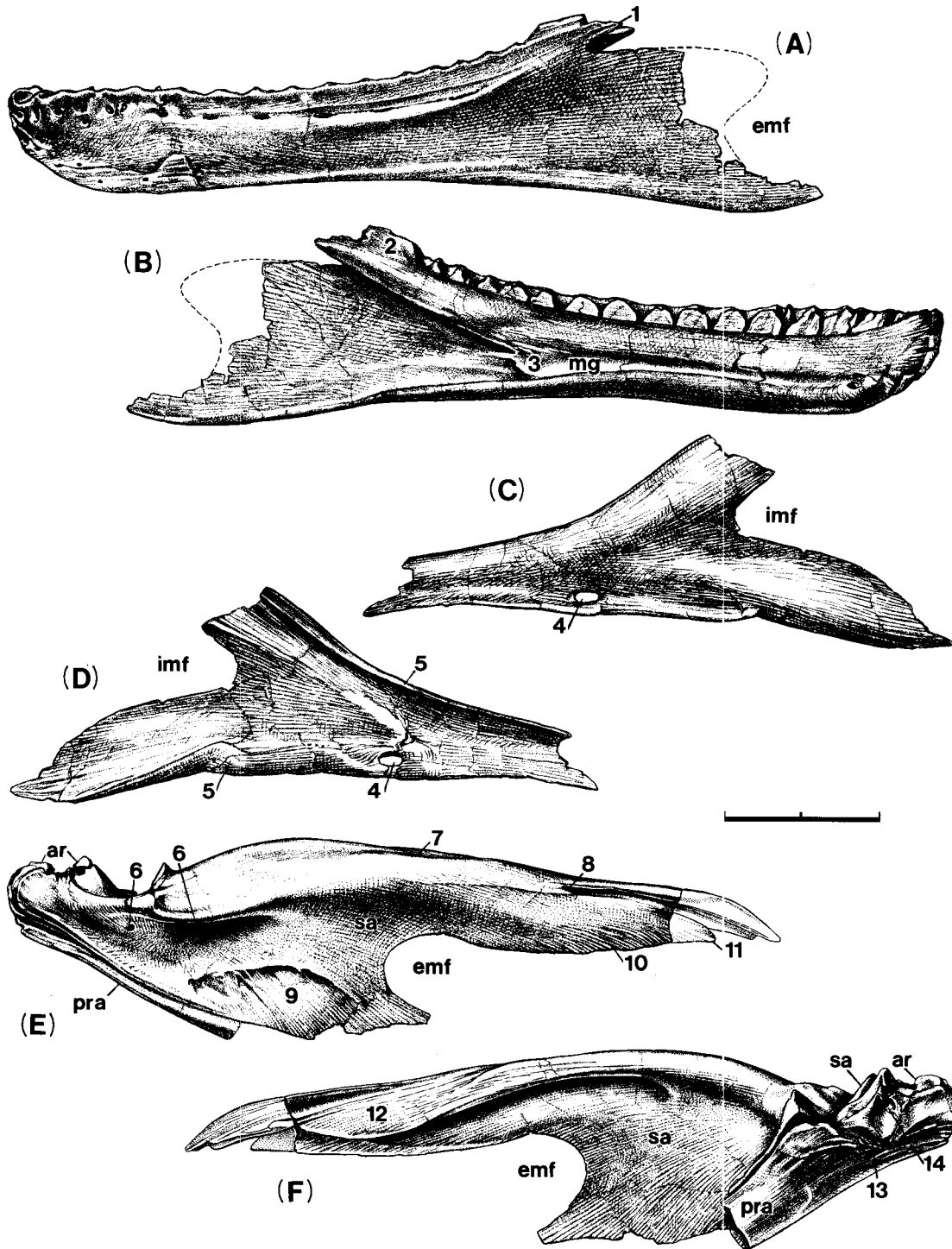


FIG. 11. *Sinraptor dongi* (IVPP 10600). Left dentary in lateral (A) and medial (B) views; left splenial in lateral (C) and medial (D) views; left surangular in lateral (E) and medial (F) views. ar, articular; emf, external mandibular foramen; imf, internal mandibular fenestra; mg, Meckelian groove; pra, prearticular; sa, surangular; 1, intramandibular process of dentary; 2, contact for supradentary bone; 3, foramina for branches of inferior alveolar nerve; 4, anterior mylohyoid foramen; 5, sutural contact for dentary; 6, posterior surangular foramen; 7, insertion of the *M. adductor mandibulae externus*; 8, anterior surangular foramen; 9, contact with angular; 10, contact with maxilla; 11, intramandibular process of surangular; 12, contact with coronoid; 13, contact on articular for prearticular; 14, foramen posterior chorda tympani. Scale bar = 10 cm.

bite marks on the dentaries of IVPP 10600 could not have been self-inflicted, and suggest the possibility of intraspecific combat (D.H. Tanke, personal communication, 1993).

The triangular splenial (Figs. 11C, 11D) is a relatively thin,

curved plate of bone, concave laterally and convex medially. The posterior margin is deeply emarginated to form the anterior border of the internal mandibular fenestra. Although the ventral margin thickens posteriorly to form a shelf that cradles

the anterior end of the angular, it does not wrap around the ventral margin of the dentary as in *Herrerasaurus* (Sereno and Novas 1992), *Ceratosaurus* (USNM 4735), dromaeosaurids, and other primitive theropods. The anterior mylohyoid foramen (Meckelian canal of Madsen 1976) is completely surrounded by the splenial, in contrast with *Allosaurus* and *Monolophosaurus*, where the foramen is more appropriately described as a slot in the lower margin of the splenial.

The right surangular is virtually complete. The anterior surangular foramen (for cutaneous branches of the inferior alveolar nerve, Oelrich 1956) is continuous anteriorly with a groove, as in *Allosaurus*, *Monolophosaurus*, and other theropods. The lower margin of the groove is formed anteriorly by a fingerlike process that extends laterally over the labial surface of the dentary. A similar fingerlike process of the dentary contacts the lateral and dorsal margins as the groove reenters the jaw between the surangular and dentary. The surangular tapers to a thin plate wedged beneath the dental shelf of the dentary. The 3.5 cm covered section of the surangular could have slid forward another 2–3 cm, at which point the fingerlike processes of the dentary and surangular would have interlocked, preventing any further motion in that direction. There is an extensive squamose suture for the angular (Fig. 11E), and posterolaterally the surangular is underlain by the prearticular. The posterolaterally oriented posterior surangular foramen is found anterolateral to the glenoid, beneath a powerful lateral ridge (Fig. 11E). A second, smaller foramen is found in a more anterior position beneath the same ridge. Medially the surangular is thickened dorsally, as in all theropods, along the dorsal margin of the adductor fossa. The dorsal surface of this ridge has a longitudinal depression for insertion of the muscle (M.) adductor mandibulae externus. The immovable squamose suture with the coronoid is along the anterolateral surface of the ridge. Posteriorly, the ridge extends medially into a hooked process delimiting the posterior margin of the adductor fossa and contacting the prearticular medially (Fig. 10D). The surangular makes a small contribution to the ridge separating the two depressions of the glenoid, and would have contacted most of the lateral condyle of the quadrate. The surangular extends posteriorly to the end of the retroarticular process.

The angular of *Sinraptor* is a shallowly curved plate of bone strengthened by a thick ventral margin (Figs. 10E, 10F). An extensive area of the bone is overlapped laterally by the dentary, but the surface is smooth, and sliding movement was possible. A more limited sliding articulation with the splenial covers the medial surface of the ventral ridge. Posteriorly, the angular laterally overlaps the surangular. Radiating ridges and grooves on the sutural surfaces, which have well-defined borders, show that this contact was immovable. Unlike *Allosaurus*, there is no other contact between the angular and surangular. The ventral edge of the angular is thickest where it forms the ventral margin of the jaw between the posterior tips of the dentary and splenial. The posterior end of the angular of *Sinraptor* is anterior to the level of the articular bone, as in most theropods other than *Allosaurus*.

The prearticular is a thin plate of bone, expanded vertically at either end (Fig. 10C). Anteriorly, there is no evidence of the sutural surfaces with the coronoid, or the articular surface with the splenial. Posteriorly, the bone is thickened by a ventromedial ridge. The anterior half of the ridge contacts the angular, and posteriorly it forms the ventral margin of the jaw. Whereas the sutural contact with the angular is smooth and rounded, that with the surangular is strengthened by ridges and troughs. The

lateral surface has extensive contacts with the articular and the postadductor process of the surangular (Fig. 10D). The posterior end does not taper to a point as it is in *Allosaurus*, but has a number of fingerlike processes for attachment of ligaments.

*Sinraptor* lacks the neomorph antarticular of *Allosaurus* (Madsen 1976).

The medial glenoid and most of the interglenoid ridge for the jaw articulation are found on the articular (Fig. 10D). Overall, the bone is much more elongate than that of *Allosaurus* (Gilmore 1920; Madsen 1976) or tyrannosaurids (Lambe 1904; Osborn 1912; Molnar 1991), mostly because of its long retroarticular process. The retroarticular process is directed posterolaterally as in most theropods, whereas that of *Allosaurus* extends posteromedially from the glenoid. Ventrally, the articular narrows to a thin plate of bone that is squeezed between the surangular and prearticular posteriorly and that is sutured to the lateral surface of the prearticular anteriorly. This ventral ridge is thick in *Allosaurus*, and does not extend as far forward. Posteromedial to the ridge behind the medial glenoid is a distinct depression (Fig. 11F). A medially open groove enters the depression posterodorsally, and a foramen enters the bone anteroventrally. The canal and foramen would have been used by the chorda tympani and posterior condylar artery (Heaton 1979). The articular and prearticular have separated slightly in IVPP 10600 (Fig. 11F), exposing the opening for the chorda tympani. There is no evidence to suggest the articular of *Sinraptor* was pneumatic, although in tyrannosaurids diverticula of the middle ear air sacs invade the articulars alongside the chorda tympani, enlarging the foramina. Heavy scarring ventromedial to the posterior foramen of the chorda tympani marks some of the insertion of the pterygoideus musculature. The depressor mandibulae inserted onto the posterior surface of the retroarticular process, and down onto the prearticular.

A pair of hyoid bones was recovered with IVPP 10600, the most complete of which (Fig. 12A), lacking only its anterior tip, is 50 cm long. Throughout most of its length, ceratobranchial I is about 5 mm × 12 mm, tapering gradually to a point posteriorly. It becomes more platelike (16 mm × 4 mm) 150 mm from the front, anterior to which it gradually constricts to a maximum dimension of 9.5 mm. The anterior end is a thin (less than 1 mm), wide (25 mm) plate of bone that tapers rapidly anteriorly. Hyoids are fragile, often ossified late or not at all, and, when fragmentary, tend to be misidentified as pieces of cervical ribs or gastralia, and consequently are not known for most theropods. The ceratobranchials of *Syntarsus* (Rowe 1989) and *Carnotaurus* (Bonaparte et al. 1990) are not as elongate as that of *Sinraptor*, and are truncated, rather than tapering, anteriorly where they meet the corpus. Hyoid elements of *Ceratosaurus* (Gilmore 1920) and *Dromaeosaurus* (Colbert and Russell 1969) are too poorly known for meaningful comparison.

#### *Axial skeleton*

All of the cervical, dorsal, and sacral vertebrae were collected, although the sacral neural arches were not found. Several complete caudals were also recovered, along with a few caudal centra. There are 23 presacral vertebrae, as in most theropods. The division between cervical and dorsal regions cannot be defined with certainty because none of the ribs are complete enough to determine their relationship to the pectoral girdle. Although vertebral anatomy suggests that there were nine cervicals and 14 dorsals, as in *Allosaurus* (Madsen 1976) and *Acrocanthosaurus* (Stovall and Langston 1950), rib head anatomy shows there were 10 cervicals. The closest relative of

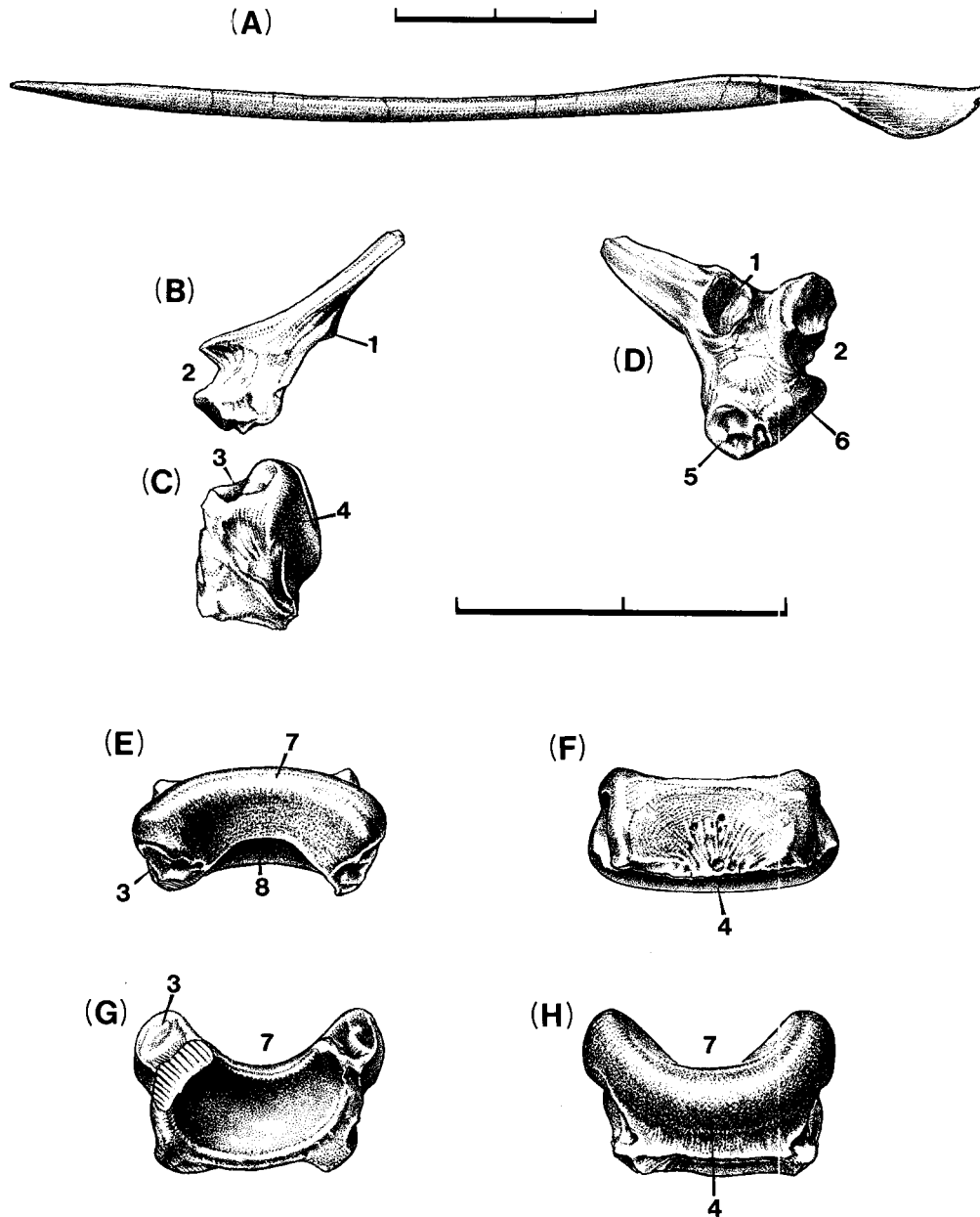


FIG. 12. *Sinraptor dongi* (IVPP 10600). (A) ceratobranchial I, probably dorsal view of left ceratobranchial; (B) left neurapophysis in lateral aspect; (C) atlantal intercentrum in lateral aspect; (D) left neurapophysis in medioposteroventral view; atlantal intercentrum in dorsal (E), ventral (F), anterior (G), and posterior (H) views. 1, postzygapophysial facet; 2, neural canal margin; 3, suture for neurapophysis; 4, axial articulation on atlas; 5, suture on neurapophysis for atlantal intercentrum; 6, articular surface for occipital condyle; 7, odontoid concavity; 8, articular surface on atlantal intercentrum for occipital condyle. Scale bars = 10 cm (shorter bar for Fig. 12A, longer bar for Figs. 12B–12H).

*Sinraptor*, *Yangchuanosaurus*, has 10 cervicals and 13 dorsals (Dong et al. 1983).

The sutures between the neural arches and the centra are still evident, although fusion had started. The neurapophysis had not fused to the atlantal intercentrum, and the odontoid had not fused to the axis. None of the sacral centra had fused to each other, although the posterior sections of the first sacral neural arch and spine are broken in a manner that suggests there was fusion to the neural arch of the second sacral. The degree of fusion confirms that IVPP 10600 was immature.

Most of the atlas–axis complex is preserved (Figs. 12, 13), and only the right neurapophysis is completely lacking. The left neurapophysis, unlike that of *Ceratosauros* (Gilmore 1920),

is not an elongate L-shaped bone, but is more triangular (Fig. 12D), as in *Allosaurus* (Madsen 1976) and more advanced forms. There is no prezygapophysis on the neurapophysis, a good indication that there was no proatlas. The atlantal intercentrum is closer to that of *Ceratosauros* or *Torvosaurus* (Britt 1991) than it is to *Allosaurus* in that the odontoid concavity in the dorsal surface is smoother and deeper. There is a distinct ventrolateral process (Fig. 12G) on the atlantal intercentrum, as in *Torvosaurus* (Britt 1991) and *Carnotaurus* (Bonaparte et al. 1990). The surface of the process is finished bone, and it would not have articulated with a cervical rib.

The second and subsequent cervicals were articulated when found, but had pulled 15 cm away from the skull and atlantal

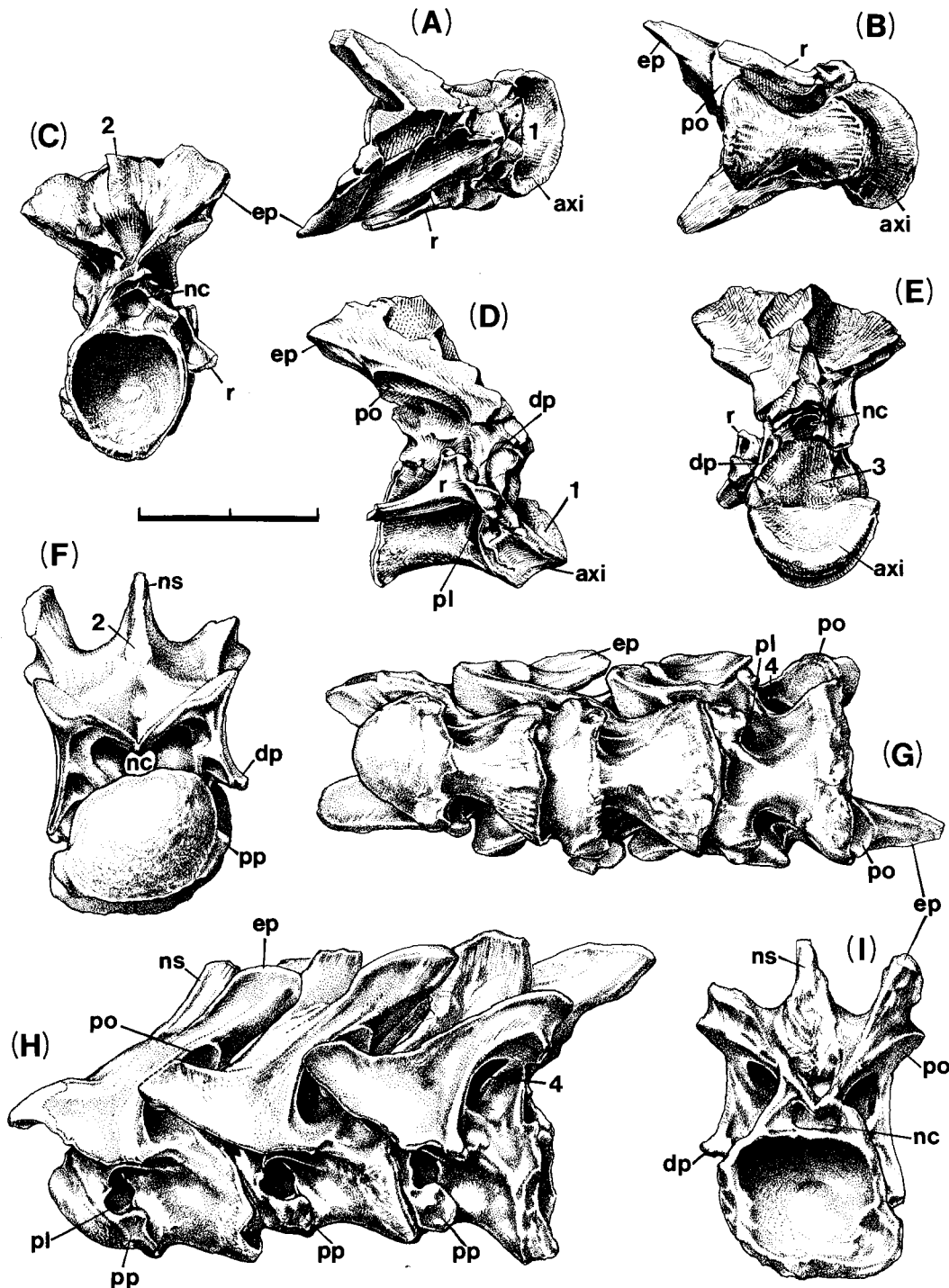


FIG. 13. Cervical vertebrae of *Sinraptor dongi* (IVPP 10600). Axis in dorsal (A), ventral (B), posterior (C), right lateral (D), and anterior (E) views; cervical 3 in anterior aspect (F); cervicals 3, 4, 5 in ventral (G) and left lateral (H) views; fifth cervical in posterior view (I). axi, axial intercentrum; dp, diapophysis; ep, epipophysis; nc, neural canal; ns, neural spine; po, postzygapophysis; pl, pleurocoel; pp, parapophysis; r, rib; 1, facet for atlantal intercentrum; 2, scar of interspinous ligament; 3, sutural surface for odontoid; 4, most posterior pneumatic fossae of neural arch. Scale bar = 10 cm.

intercentrum before burial. The odontoid, a smoothly rounded hemisphere of bone, was found by itself near the back of the skull.

The axial intercentrum, which is 7.2 cm across, is firmly attached to the axial centrum, although the line of fusion is still visible. Whereas the ventral margin of the intercentrum forms a continuous line with the ventral margin of the axial centrum in

*Dilophosaurus*, *Ceratosaurus*, *Carnotaurus*, *Piatnitzkysaurus*, and *Allosaurus*, in *Sinraptor* the ventral margin of the intercentrum rises sharply anteriorly (Fig. 13D). The anterior surface of the axial centrum faces anterodorsally, as does the articular surface of the axial intercentrum for the atlantal intercentrum. In *Allosaurus* (Madsen 1976), the axial centrum is almost as long dorsally as it is ventrally, and the suture between

the axial centrum and intercentrum is vertical. The shapes and alignment of the axial intercentrum and centrum served to bring the neck underneath the occipital condyle to support the skull in a manner that is unique amongst Jurassic theropods, with only *Monolophosaurus*, *Y. magnus* (Dong et al. 1983), and an undescribed theropod (BYU 21704) showing a tendency towards doing the same thing.

The centrum of the axis is 7.2 cm long ventrally (6.4 cm dorsally), and has a pleurocoel near its anterodorsal contact with the intercentrum. As in *Szechuanosaurus*, *Yangchuanosaurus* (Dong et al. 1983), and *Allosaurus*, the ventral surface of the centrum is broad and relatively flat (Fig. 13B), and there is no ventral keel. The atlantal centra of *Syntarsus* (Rowe 1989), *Dilophosaurus* (Welles 1984), *Ceratosaurus* (Gilmore 1920), and *Carnotaurus* (Bonaparte et al. 1990) are all keeled. As in *Yangchuanosaurus*, *Carnotaurus*, and *Ceratosaurus*, the posterior surface of the centrum, when viewed laterally, forms an acute angle with the ventral margin to a greater degree than in *Allosaurus* or *Dilophosaurus*.

The pleurocoel is larger and in a more anterior position than it is in *Allosaurus* or *Monolophosaurus*. There are no pleurocoels in the axial centra of *Syntarsus* (Rowe 1989) and *Dilophosaurus* (Welles 1984), but there are a pair of small pleurocoels in *Carnotaurus* (Bonaparte et al. 1990). On the left side of the axis of IVPP 10600, the pleurocoel has a double entrance and deeply invades the body of the centrum, and appears to extend into the neural arch. That of the right side (Fig. 13D) is a simple, single pit that does not penetrate as far. As in most primitive theropods, the bilateral pneumatic chambers are separated by a thin, medial wall within the body of the centrum.

Much of the neural spine of the axis was lost, but it is evident from the base that it is inclined posterodorsally as in *Yangchuanosaurus* and *Allosaurus*, and does not extend anteriorly beyond the anterior zygapophysis, as it does in more primitive forms like *Coelophysis*, *Dilophosaurus*, *Carnotaurus*, and *Ceratosaurus*. There is a long, well-defined epiphysis extending behind the postzygapophysis of the axis of *Sinraptor*. Elongate epiphyses are generally present in more primitive large theropods like *Dilophosaurus* (Welles 1984), *Carnotaurus* (Bonaparte et al. 1990), and *Piatnitzkysaurus* (Bonaparte 1986), and are greatly reduced in *Allosaurus* and tyrannosaurids. A thin bony lamina extends from the dorsal surface of the epiphysis to the posterodorsally inclined neural spine. There is a deep posterior fossa between the laminae and the posterior zygapophyses, beneath the neural spine. In more advanced theropods, like *Allosaurus*, this lamina is not present, and an emargination separates the epiphysis from the neural spine. *Yangchuanosaurus* apparently has a shallow emargination in the lamina separating the posterior zygapophysis from the neural spine (Dong et al. 1983). The relative length of the diapophysis is intermediate between *Ceratosaurus* and *Allosaurus*. The posterior zygapophysis is large and triangular, and is only inclined about 20° from horizontal (Fig. 13C).

The 10th presacral vertebra of IVPP 10600 is identified as a cervical, although it is morphologically nearly identical to the 10th presacral of *Allosaurus*, which is a dorsal. The identification is based on the anatomy of the associated rib. The parapophysis is restricted to the centrum, and the diapophysis extends more posteroventrally than laterally. These two characters clearly distinguish it from the 11th presacral (first dorsal).

Each of the postaxial cervical vertebrae (Figs. 13, 14) is opisthocoelous, and is invaded anterolaterally by a pleurocoel, found dorsomedial to the parapophysis. The pleurocoels open

into a pair of internal chambers separated by a midline wall of bone (Fig. 14B). This arrangement is widespread in theropods, although the pneumatic interiors of *Acrocanthosaurus* or tyrannosaurid centra are cancellous. The anterior ball-like articular surface of the *Sinraptor* centrum is more typical for large Jurassic theropods than the flattened convexity of a *Ceratosaurus* cervical (Gilmore 1920). The anterior articulation of the centrum lacks the distinct rim seen in *Torvosaurus* cervicals (Britt 1991).

Cervical neural arches are invaded ventrolaterally by pneumatic fossae as in *Ceratosaurus*, *Torvosaurus* (Britt 1993), *Piatnitzkysaurus* (Bonaparte 1986), *Allosaurus* (Gilmore 1920), and *Carnotaurus* (Bonaparte et al. 1990). There are three chambers on each side, separated by thin laminae. The most anterior fossa invades the base of the prezygapophysis. A second is found beneath the transverse process, and the most posterior one extends dorsoposteriorly into the posterior zygapophysis (Figs. 13G, 13H, 13I). Neural arch pneumaticity is characteristic of all theropods (Britt 1993), although it can take different forms in different lineages (Colbert 1989). In *Allosaurus* and *Monolophosaurus*, the lateral fossae of the cervical neural arch are shallow compared to those of *Sinraptor*, while in *Carnotaurus* only the pneumatic fossa posteroventral to the transverse process remains.

As in *Torvosaurus* (Britt 1991), *Carnotaurus*, and *Piatnitzkysaurus*, the epiphyses are powerfully developed in the anterior cervicals (Figs. 13G, 13H, 13I), but are lost by the last cervical (Fig. 14C). The epiphyses, which are stronger in *Sinraptor* than any other theropod except *Carnotaurus*, provide good leverage for the intersegmental muscles. Although this gave the animal more strength for holding up the head, the short muscle fibres would have reduced the neck's ventral flexibility.

Neural spines of *Sinraptor* anterior cervicals are relatively shorter than those of *Ceratosaurus* and *Allosaurus*, and the epiphyses are significantly longer. The neural spines of the third and fourth cervicals are anteroposteriorly short and are inclined more strongly posterodorsally than in *Allosaurus*, suggesting there was more curvature in the neck of *Sinraptor*. The neural spines of the posterior cervicals are relatively higher than those of *Allosaurus*, but are still shorter than those of *Ceratosaurus*.

The dorsal vertebrae of *Sinraptor* (Figs. 14–17) are closest to those of *Yangchuanosaurus* and *Torvosaurus*. The first four could be defined as pectorals (Welles 1984) because the parapophysis is on both the centrum and the neural arch. Using this definition, the last pectoral in *Allosaurus* is also the 14th presacral, although the incorporation of a cervical into the thoracic series gives it a total of five pectorals. The centrum of the first dorsal is clearly opisthocoelous, the second is transitional, and the third (13th presacral) is amphiplatyan. The amphiplatyan condition develops in the cervicals of *Carnotaurus* (Bonaparte et al. 1990), whereas it only develops in the fifth dorsal (14th presacral) of *Allosaurus* (Madsen 1976) and the sixth (15th presacral) of *Monolophosaurus*. The first four or five dorsals of *Acrocanthosaurus* are probably opisthocoelous (Stovall and Langston 1950). Large pleurocoels invade the centra posterior to the parapophyses of the first four dorsals. Central pleurocoels are smaller in *Allosaurus*. The last central pleurocoel is in the 14th presacral of *Sinraptor* and the 13th presacral of *Allosaurus* (Madsen 1976). Pleurocoels are found in all dorsals of *Torvosaurus* (Britt 1991).

Sharply defined midline keels extend anteriorly into prominent hypapophyses in the first and, to a lesser extent, second dorsals. These are developed for attachment of the *M. longus*

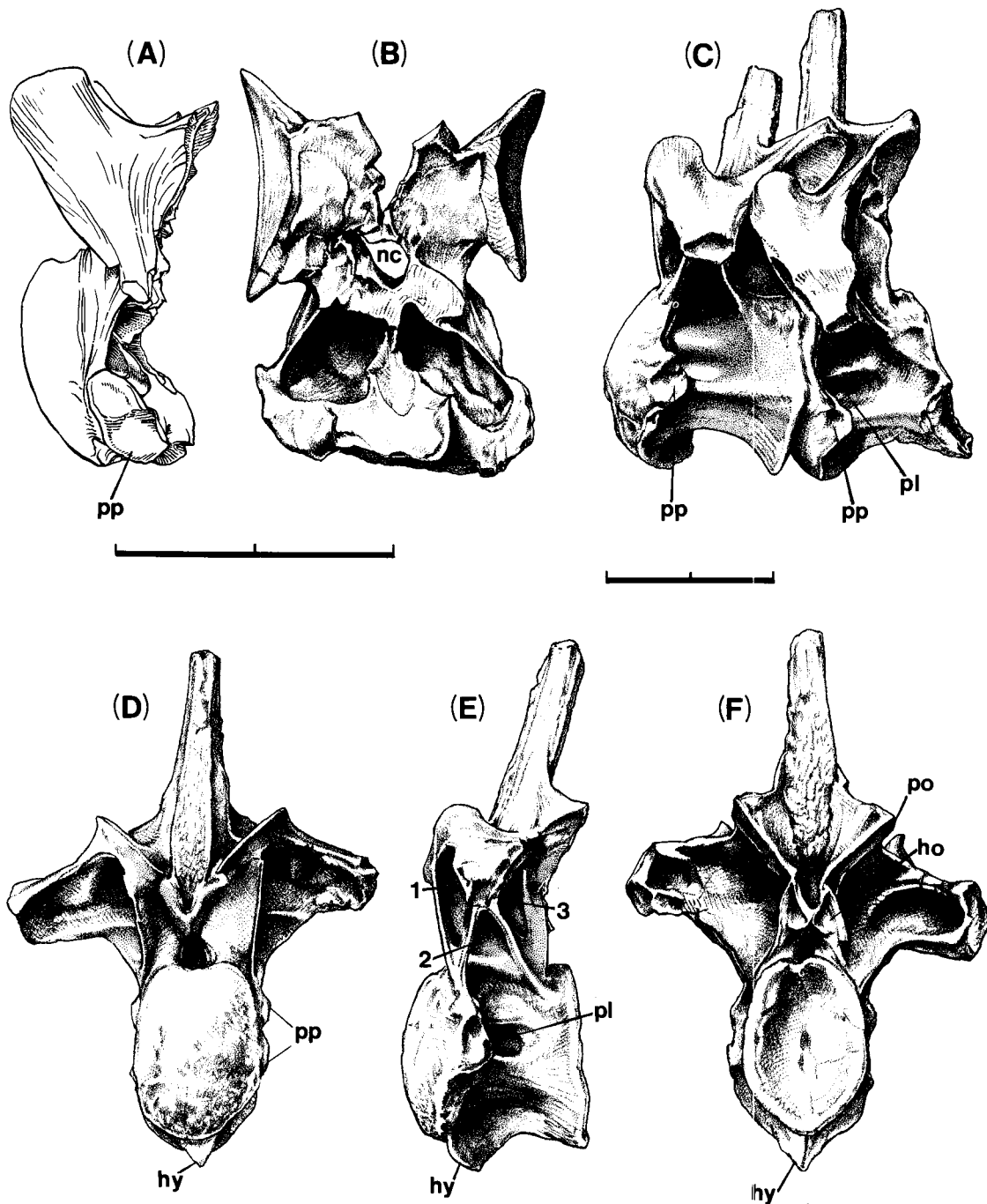


FIG. 14. *Sinraptor dongi* (IVPP 10600). Fragment of sixth cervical in left lateral (A) and posterior (B) views; last two cervicals in left lateral aspect (C); first dorsal vertebra in anterior (D), left lateral (E), and posterior (F) views. ho, hyosphene; hy, hypapophysis; nc, neural canal; po, postzygapophysis; pl, pleurocoel; pp, parapophysis; 1, infraprezygapophysial fossa; 2, infradiapophysial fossa; 3, infrapostzygapophysial fossa; Scale bars = 10 cm (longer bar for Figs. 14A and 14B, shorter bar for Figs. 14C–14F).

colli ventralis for ventral flexion of the head and neck. The most prominent hypapophysis of *Allosaurus* is in the second dorsal (Madsen 1976), which is the 11th presacral vertebra, as in *Sinraptor*. This shows that although *Allosaurus* has incorporated one of the cervicals into the thorax, the hypaxial musculature had not changed.

The neural spines of the first two dorsals are anteroposteriorly short and spinelike, similar to those of the posterior cervicals. The third dorsal spine (Fig. 15D) is anteroposteriorly broader, and the fourth and subsequent neural spines are plate-

like in lateral view. Spine height increases posteriorly progressively throughout the first 10 dorsals. The height of the 11th is unknown, but the 12th and 13th neural spines are considerably shorter than that of the 10th, and the 11th was presumably intermediate between the 10th and 12th. Anterior dorsal spines (1–6) slope posteriorly in relation to the axis of the centrum, middorsal spines are perpendicular, and posterior spines (11–13) slope somewhat anteriorly, showing that the backbone was arched in the thoracic region. The tall, platelike spines are similar to those of *Metriacanthosaurus* (Huene 1926; Walker 1964),

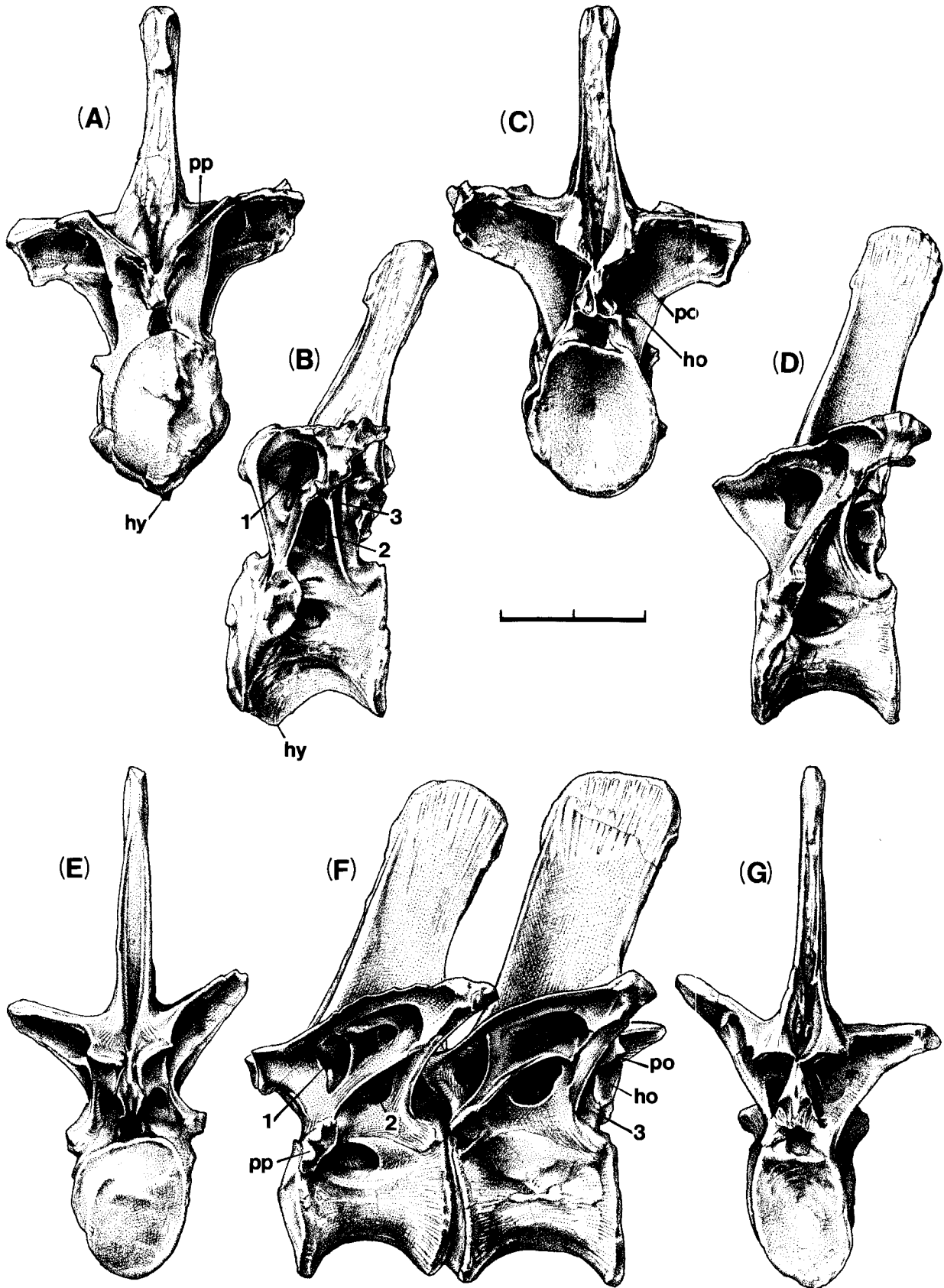


FIG. 15. Dorsal vertebrae of *Sinraptor dongi* (IVPP 10600). Second dorsal in anterior (A), left lateral (B), and posterior (C) views; left lateral view of dorsal 3 (D); anterior aspect of fourth dorsal (E); fourth and fifth dorsals in left lateral view (F); posterior view of dorsal 5 (G). ho, hyposphene; hy, hypapophysis; po, postzygapophysis; pp, parapophysis; 1, infraprezygapophysial fossa; 2, infradiapophysial fossa; 3, infrapostzygapophysial fossa. Scale bar = 10 cm.

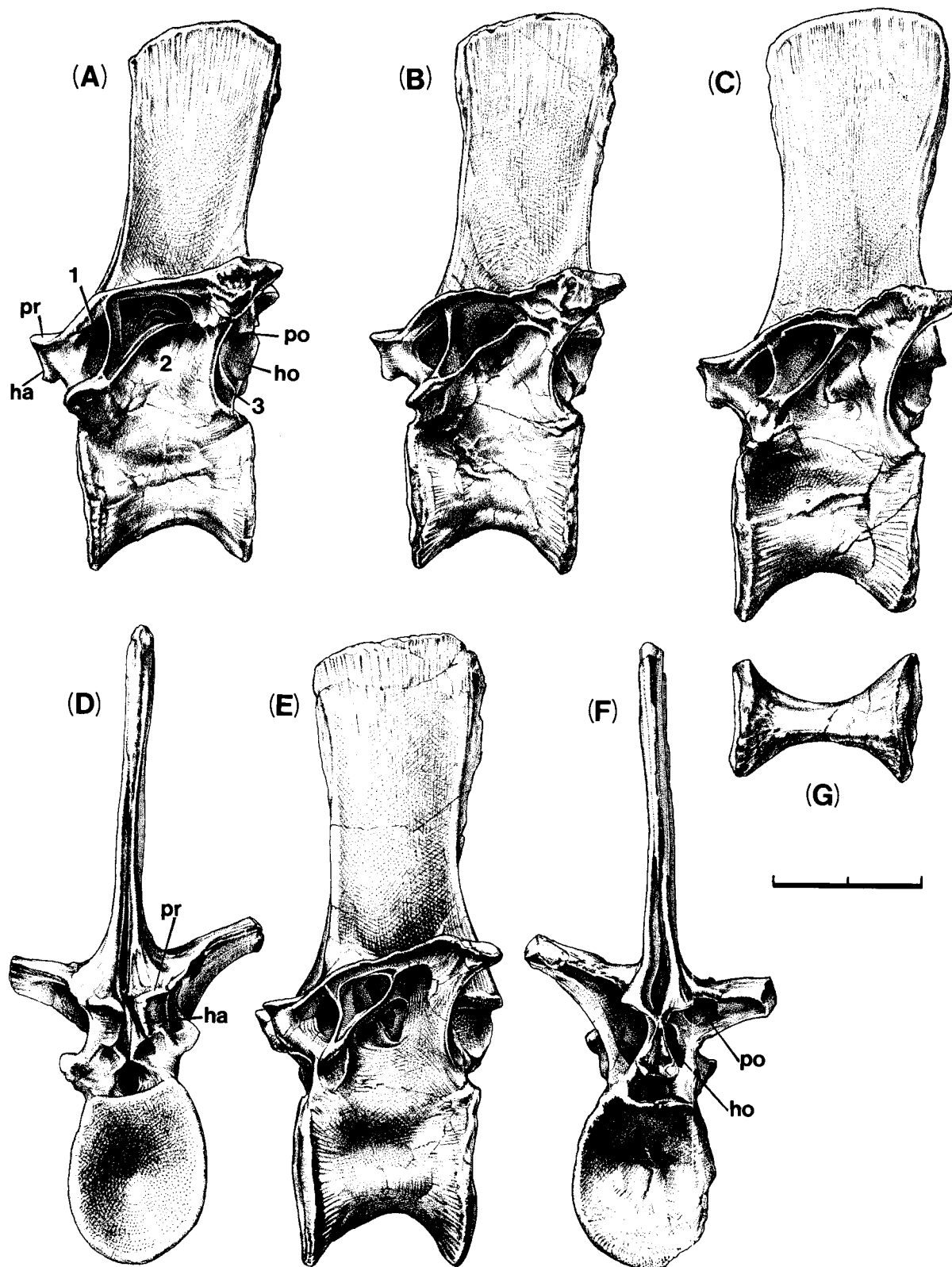


FIG. 16. Dorsal vertebrae of *Sinraptor dongi* (IVPP 10600). Left lateral views of the sixth (A), seventh (B) and eighth (C) dorsals; ninth dorsal vertebra in anterior (D), lateral (E), posterior (F), and ventral (G) views. ha, hypantrum; ho, hyposphene; po, postzygapophysis; pr, prezygapophysis; 1, infraprezygapophysial fossa; 2, infradiapophysial fossa; 3, infrapostzygapophysial fossa. Scale bar = 10 cm.

*Torvosaurus* (Britt 1991), and *Yangchuanosaurus*. Those of *Allosaurus* and *Monolophosaurus* are not as quadrangular in outline, and are relatively shorter than those of *Sinraptor*.

A hypantrum-hyposphene articulation is present in all dorsal

centra, in contrast with *Allosaurus*, which lacks this articulation on the first five dorsals (Madsen 1976). The hypantrum is supported by a distinct process (Fig. 16A) beneath the anterior zygapophysis.



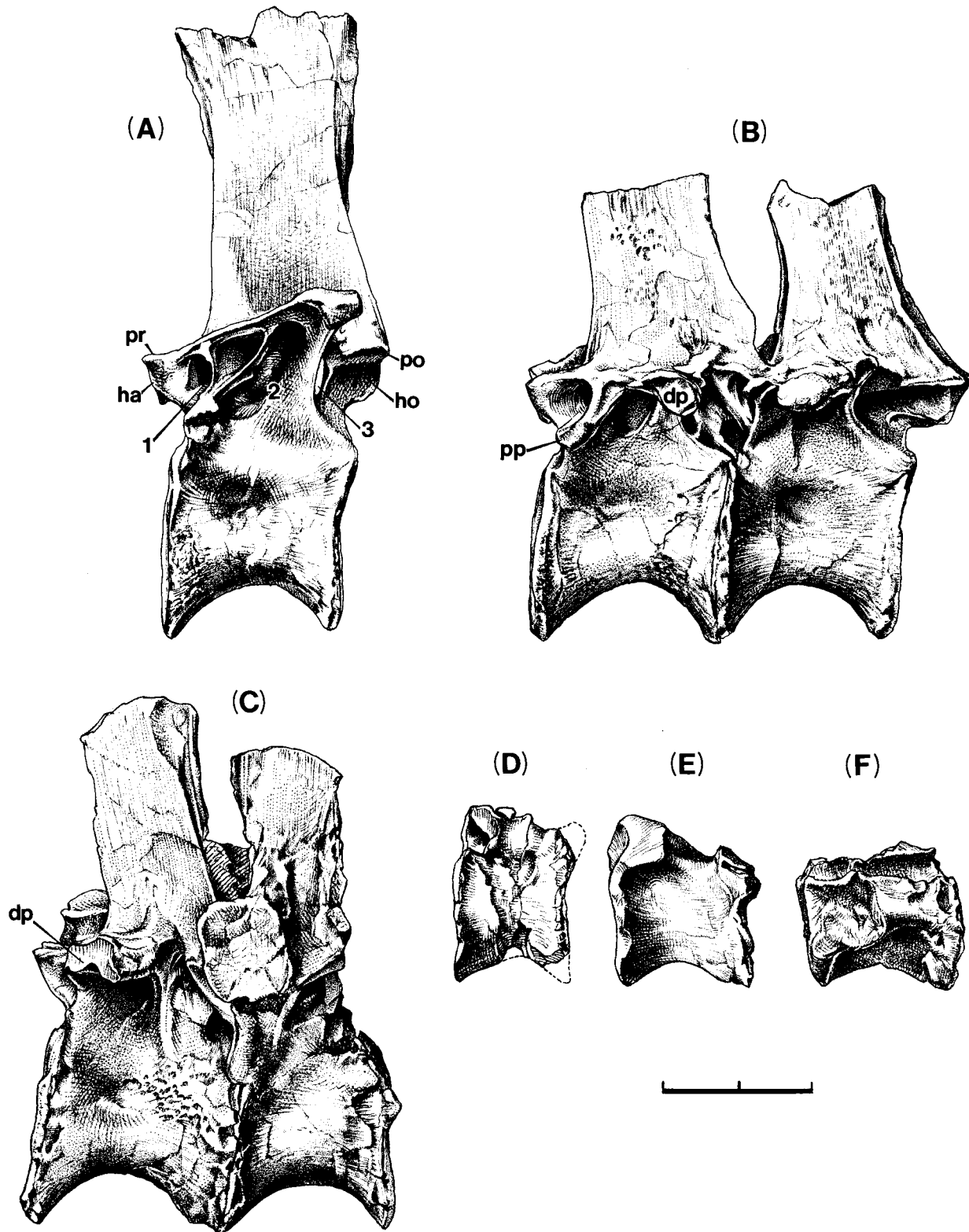


FIG. 17. *Sinraptor dongi* (IVPP 10600). Left lateral views of the tenth (A), eleventh and twelfth (B) dorsals; lateral view of the last dorsal and first sacral vertebrae (C); lateral views of the second (D), third (E), and fourth (F) sacral centra. dp, diapophysis; ha, hypantrum; ho, hyposphene; po, postzygapophysis; pp, parapophysis; pr, prezygapophysis; 1, infraprezygapophysial fossa; 2, infradiapophysial fossa; 3, infrapostzygapophysial fossa. Scale bar = 10 cm.

The neural arches of the dorsal vertebrae are elaborately excavated. As in most other large Jurassic theropods, a shelf-like lamina joins the prezygapophysis, diapophysis, and postzygapophysis. A powerful ridge extends posteroventrally from

the prezygapophysis and hypantrum to the parapophysis, forming the anterior margin of a pneumatic fossa (infra-prezygapophysial fossa of Britt 1993). The posteroventral wall of this fossa is formed by a lamina of bone joining the parapophysis

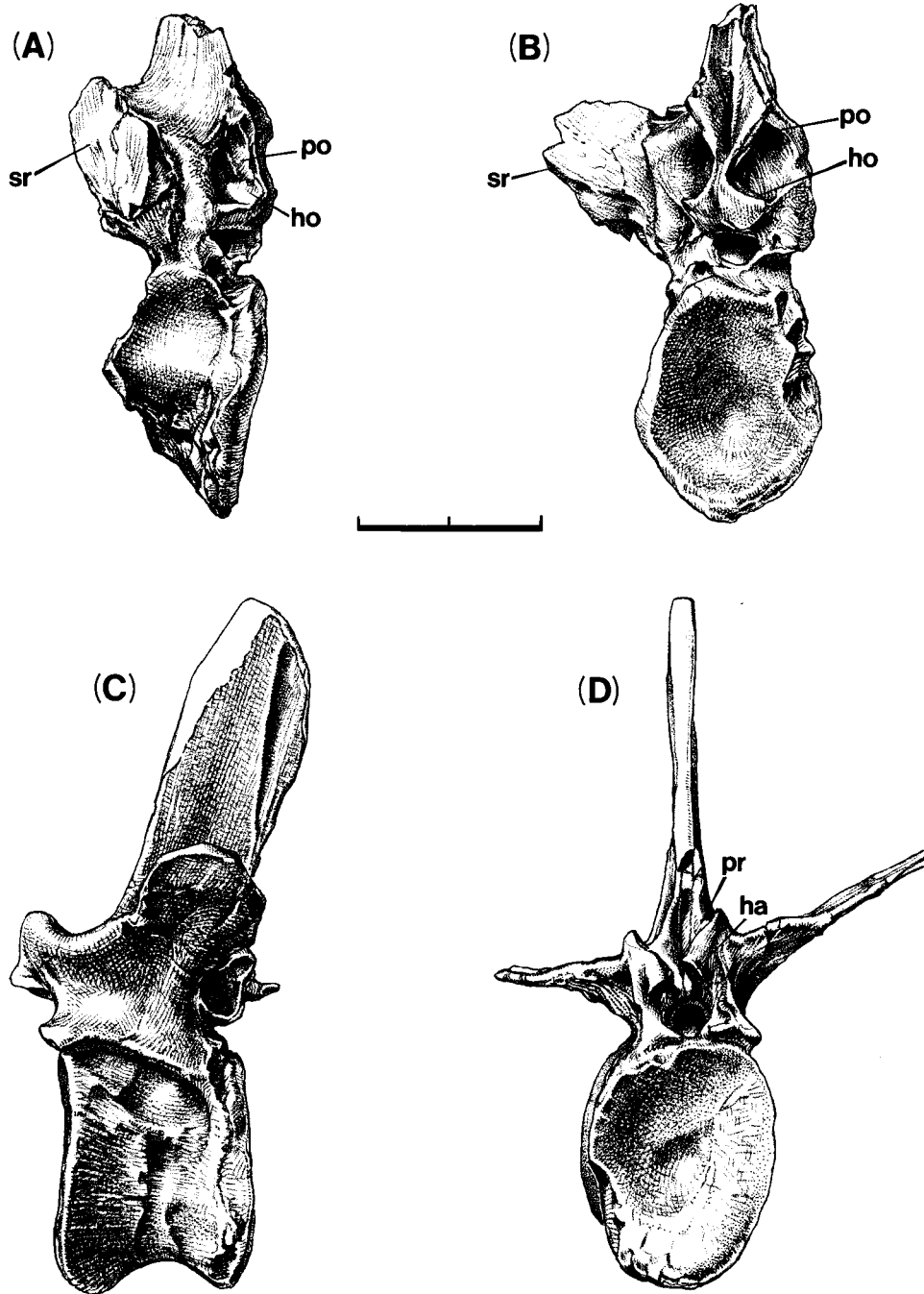


FIG. 18. Last sacral and an anterior caudal vertebra of *Sinraptor dongi* (IVPP 10600) in lateral (A, C), posterior (B), and anterior (D) views. ha, hypantrum; ho, hyposphene; po, postzygapophysis; pr, prezygapophysis; sr, sacral rib. Scale bar = 10 cm.

and diapophysis (Figs. 15B, 15D). In the middorsal region, two or more laminae join the parapophysis to the horizontal lamina between the prezygapophysis and the diapophysis (Figs. 15F, 16A, 16B, 16C, 16E, 17A, 17B). These laminae merge in progressively more posterior dorsals, until they become a single sheet of bone in each of the last two dorsals (Figs. 17B, 17C). The infradiapophysial pneumatic fossa (Britt 1993) is found posterior to this lamina, and ventral to the transverse process (Figs. 14E, 15B, 15F, 16A, 17A). A strong ridge supports the posterior margin of the transverse process, and forms the anterolateral margin of a pneumatic fossa (infra-postzygapophysial fossa) associated with the postzygapophysis and hyposphene. This fossa is deep, and in more posterior

dorsals invades the neural canal (Fig. 17A). Pleural diverticula would have communicated above the neural canal through these openings in the infra-postzygapophysial fossa (Britt 1993). Such connections have been only rarely reported (Britt 1991).

There were five sacral vertebrae in *Sinraptor* (Figs. 17, 18). The first sacral was still in contact with the last dorsal when found, but the rest of the sacrum was disarticulated. The neural arches are detached in four of the sacrals, and there was no fusion between the sacral centra. The second, third, and fourth neural arches were not recovered. The neural arch of the fifth sacral remained in association with its centrum, even though the two parts are separate.

The first sacral (dorsosacral) is characterized by an exten-

TABLE 1. Vertebral measurements (in millimetres) of type specimen of *Sinraptor dongi*

Vertebra No.	Cen leng	Post wid	Mid wid	Total heig	Heig n.s.	Leng n.s.	wid n.s.	Zyg. wid
2	78	65	28	175+	82+	—	—	—
3	74	—	—	174+	—	21	—	—
4	85	—	—	175	—	25.5	—	—
5	80	—	—	180	—	55	—	—
6	—	—	—	—	—	—	—	—
7	—	—	—	—	—	—	—	—
8	—	—	—	—	—	—	—	—
9	100	—	—	210	—	26.5	—	—
10	87	—	—	255	145	22	—	—
d1	83.5	—	—	295	177	23.5	—	110
d2	94	—	—	320	197	29	—	99
d3	95.5	—	—	330	228	46	—	57
d4	101.5	—	—	330	—	62	—	55
d5	110	—	—	355	240	81	—	—
d6	115	—	—	355	240	84.5	—	70
d7	113	88	—	365	250	91.5	—	61
d8	118	90	—	385	265	93	—	62
d9	113	100	—	400	285	88.5	—	55
d10	119	110	—	380+	—	90	—	56
d11	120	124	48	—	—	82.5	15	58
d12	122	120	49	—	—	72	16.5	54
d13	122	—	—	400	265	68	—	—
s1	108	—	—	—	—	—	—	—
s2	78.5	77.5	—	—	—	—	—	—
s3	99	96+	—	—	—	—	—	—
s4	104.5	—	—	—	—	—	—	—
s5	—	96	—	285+	110+	—	—	—
c1	77	116	64	255+	115+	56	16	48
c-a	103	—	—	—	—	—	—	—
c-b	102.5	96+	47+	360+	220+	60	13.5	53
c-c	87.5	—	—	365+	215+	—	—	—
c-d	85	—	—	270	135	52.5	—	—
c-e	95.5	—	—	268+	145+	69	—	—
c-f	110	—	—	220+	120+	59	—	—

NOTES: Cen leng, length of centrum; post wid, maximum width of posterior end of centrum; mid wid, width of the waist of the centrum; total heig, total height of vertebra including centrum and neural spine (measured at posterior end); heig n.s., height of the neural spine measured from top of neural canal; leng n.s., anteroposterior length (minimum) of the neural spine measured above the neural arch; wid n.s., width of the neural spine measured above the neural arch; zyg. wid, distance between the lateral margins of the articulating facets of the anterior zygapophyses; c, caudal; d, dorsal; s, sacral; +, incomplete bone.

sive articular facet for the first sacral rib (Fig. 17C). The diapophysis is anterior in position, and high above the centrum as in other theropods. As in *Dilophosaurus* (Welles 1984), *Gasosaurus* (Dong and Tang 1985), *Megalosaurus* (Buckland 1824; Owen 1856), and *Y. magnus* (Dong et al. 1983); the sacral rib did not contact the centrum. *Allosaurus* is different in that the first sacral rib does have a limited contact with the centrum.

The anterior face of the second sacral centrum is smoothly concave, showing that fusion of the first sacral into the sacrum probably occurred at a later time than coossification of the second, third, and fourth sacrals.

The fifth sacral (second caudosacral) was eroded anteriorly and on the right side, but the sacral rib is still attached to the left side (Fig. 18). The posterior zygapophyseal articulation and the hyposphene are sunk into a hollow (Figs. 18A, 18B) in the posterior surface of the neural arch.

The sutural surface for the second sacral rib is shared by the first and second sacrals, that for the third rib contacts the

second and third sacrals, and that of the fourth has at least a small contact with the third sacral.

Seven reasonably complete caudal vertebrae were recovered with fragments of several more. Only the first caudal vertebra can be identified with certainty. It is anteroposteriorly shorter than the others (Table 1). The ventral surface of the centrum is convex, and lacks the paired keels characteristic of more distal caudals. In lateral aspect, the ventral margin of the centrum curves upwards from the anterior intervertebral articulation, so the level of the posterior intervertebral facet is almost 2 cm higher. This would have raised the tail slightly, and is a specialization not known in *Allosaurus* (where the posterior intervertebral facet is actually lower than the anterior one), *Dilophosaurus*, *Monolophosaurus*, *Yangchuanosaurus*, or tyrannosaurids. The posterior intervertebral surface is bevelled ventrally. The posterior zygapophysis and hyposphene are sunk into a pit in the base of the neural spine as in the last sacral and other proximal caudals. Hyposphenes do not persist into the tail of *Allosaurus* as they do in more primitive forms like

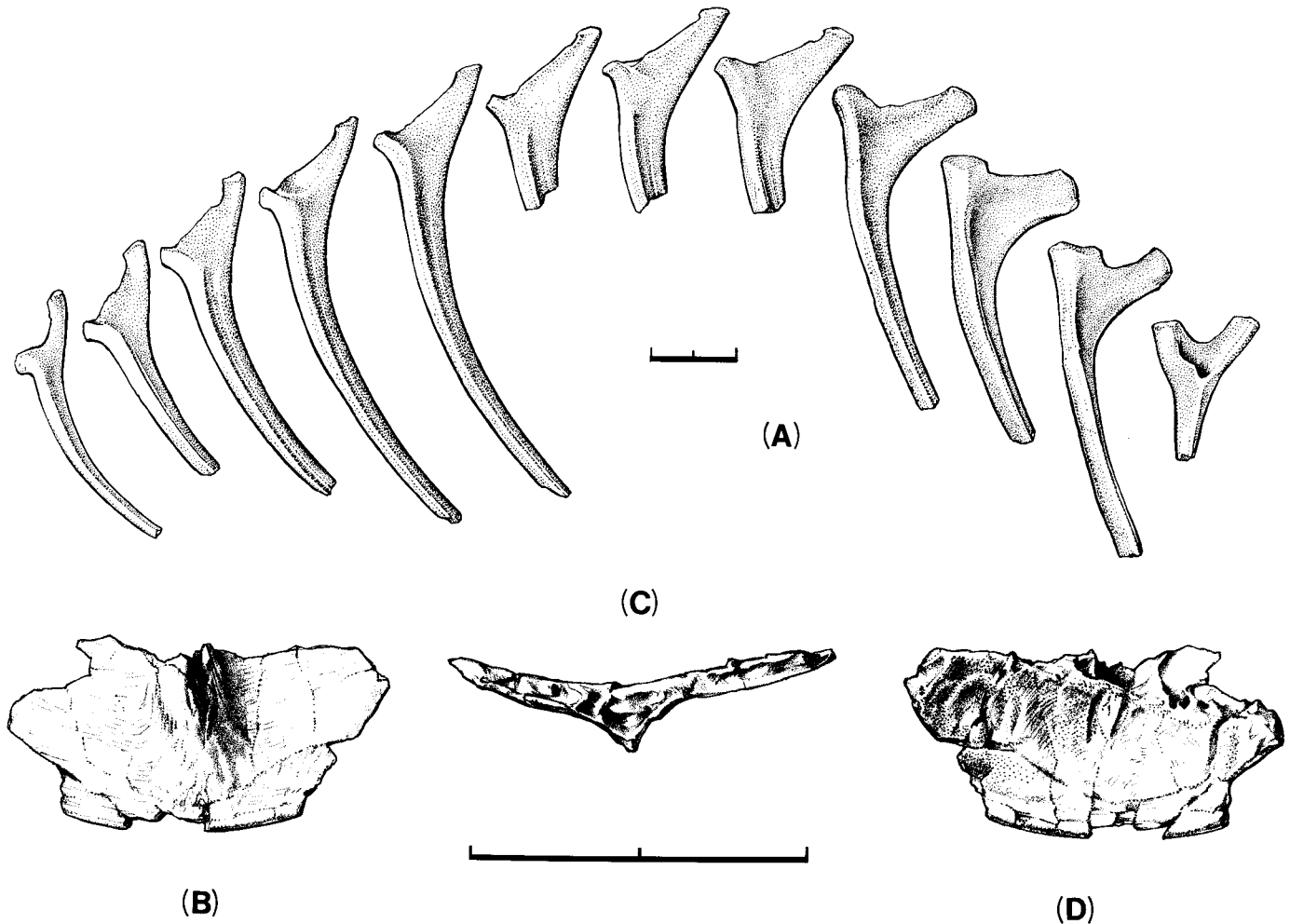


FIG. 19. *Sinraptor dongi* (IVPP 10600). Last cervical and first to eleventh right dorsal ribs in anterolateral view (A); sternum in ventral (B), anterior (C), and dorsal (D) views. Scale bars = 10 cm (shorter bar for Fig. 19A, longer bar for Figs. 19B–19D).

*Monolophosaurus* and *Sinraptor*. The spine is high but relatively short anteroposteriorly. The platelike transverse processes curve posterolaterally, but maintain an anteroposterior length of about 4.5 cm. Transverse processes of the first caudal of *Allosaurus* expand distally.

Two other proximal caudals were recovered. The ventral margin of the more anterior centrum has a double keel, and the posterior intervertebral face is bevelled ventrally for the haemal arch (Figs. 18C, 18D). The neural arch had not fused to the centrum, both hypantrum and hyposphene are present, and the transverse process expands distally.

Another proximal caudal (*c-c* in Table 1) has lost the hypantrum–hyposphene articulations, which are not found in mid or distal caudals either.

*Sinraptor* did not have an atlantal rib, which was still retained by more primitive theropods like *Herrerasaurus* (Sereni and Novas 1992) and *Syntarsus* (Rowe 1989).

The cervical ribs are not fused to the vertebrae, which is another indication of immaturity. None of the cervical ribs are complete distally. There is a double-headed, slender axial rib (Fig. 13D), the flattened shaft of which is as thin as 1.5 mm. Of the dozen cervical ribs recovered with IVPP 10600, none is significantly different from those of *Allosaurus*. The capitulum and tuberculum tend to be closer together in *Sinraptor*. The anterolateral process associated with the tubercular head is

relatively longer than that of *Allosaurus*, and the inflection ventrally is not as pronounced. In the third cervical rib, a lamina of bone bridges the capitulum and tuberculum, and only a shallow notch separates the two articular facets. The bridge and the capitulum are excavated posteromedially by a large pneumatic sinus that actually pierces the articular facet of the capitulum. Anteromedially another excavation enters the base of the shaft of the rib between the tuberculum and the bridging lamina. The lamina between the two hollows is thin but continuous, and there was no direct connection between the anterior and posterior sinuses. The proximal rib shaft is a curved plate of bone, convex in section medially. At a distance of 6.5 cm from the posterior margin of the tuberculum, the shaft narrows suddenly on the dorsal edge from a dorsoventral height of 1.8 cm to a narrow shaft of 1.1 cm. This presumably marks the point where it contacts the next cervical rib. Distally the rib is a flattened oval in section. The next few cervicals appear to have had the same kind of rib head, although the anterolateral process, the tuberculum, the capitulum, and the shaft become progressively larger in succeeding sections. The sudden reduction in shaft width persists for at least the next two cervicals.

The last cervical rib is the 10th (Fig. 19A). The capitulum and tuberculum have become widely separated, and the articular facets lie in the same plain. However, the anterolateral process

persists, even though it is clearly reduced in comparison with more anterior cervicals. A deep pocket is found between the bases of the capitulum, tuberculum, and anterolateral process. There is a depression but no pneumatic pocket on the postero-medial surface of the rib. The first dorsal rib (10th presacral section) of USNM 4734 of *Allosaurus* (Gilmore 1920) resembles the last cervical (10th presacral section) of *Sinraptor* in having a vestigial anterolateral process. This is not the case for the first dorsal rib of *Allosaurus* figured by Madsen (1976).

The dorsal ribs (Fig. 19A) have all the characteristics noted in other large theropods (Bakker et al. 1992). Most have depressions on the posteromedial surface of the web between the bases of the capitula and tubercula. This depression houses a pneumatopore in the fifth dorsal of the right side, and this is the only rib of IVPP 10600 with a hollow shaft. The second dorsal rib (presacral 12) has capitular (5.2 cm × 2.0 cm) and tubercular (5.5 cm × 3.1 cm) articulations that are conspicuously larger than the capitular (4.4 cm × 1.8 cm) and tubercular (3.8 cm × 2.0 cm) articulations of the third and succeeding ribs. The shaft of the second is also conspicuous thicker and stronger, its maximum cross-sectional diameters being 2.6 cm × 2.7 cm at the end of the preserved section, compared with 2.5 cm × 2.0 cm at the same level in the third dorsal rib. In general, the tuberculum is more sharply separated from the capitular-tubercular web than those of *Allosaurus* (Gilmore 1920; Madsen 1976) and *Edmarka* (Bakker et al. 1992), but is similar to the tubercula of *Megalosaurus* (Owen 1856) and *Yangchuanosaurus* (Dong et al. 1983). The anterior intercostal ridge of each rib continues proximally to reinforce the tuberculum, like most theropods except for *Edmarka* (Bakker et al. 1992). The ribs of *Sinraptor* are anteroposteriorly thinner than those of *Edmarka*, *Megalosaurus*, and other, more primitive carnosaurs. Part of an anterior rib from the left side preserves a rehealed break. The break had occurred near the base of the capitulum, telescoping the two parts, which rehealed completely but imperfectly.

Only one sacral rib, the fifth of the left side, was recovered (Figs. 18A, 18B).

Gastralia were scattered throughout the quarry, although few are complete. The longest preserved section is 29 cm, and represents most of a gastral rib from immediately lateral to the midline of the posterior region. Medially, it is dorsoventrally flattened, and the cross-sectional dimensions are 4.2 mm × 9.2 mm. As the ventral rib sweeps up and back, it becomes almost round in cross section. Distally, as it tapers to a point, it has a trough on the dorsal surface for articulation with the more lateral gastral rib. Several fragments preserve the medial end of the gastralia where they articulate with gastralia from the opposite side of the body. The spoon-shaped posterior surface of the proximal hook articulated with the head of a more posterior abdominal rib from the other side of the body, while the outer surface of the curve articulated with the posterior facet of the next more anterior one. The margins around the facet are thickened and scarred for the attachment of ligaments. The arrangement along the midline is not unlike that seen in tyrannosaurids (Lambe 1917; Maleev 1974). In contrast with tyrannosaurids, however, there were more than two segments between the midline and the distal ends of the dorsal ribs. One complete segment has a knoblike medial end, with a diameter of 1 cm, which resembles some of the abdominal ribs of USNM 8367 (Gilmore 1920). This abdominal rib, which is 18.5 cm long, flattens out and flares to maximum anteroposterior length of 15 mm at a point where it is only

6.6 mm high. As it curves dorsolaterally it tapers to a point, the upper surface of which apparently had an elongate articulation with another abdominal rib. This means that at least some of the mediolateral series were composed of at least three segments per side.

#### *Appendicular skeleton*

The pectoral girdles and front limbs were largely destroyed by erosion. All of the left and most of the right scapulae are preserved. The acromial process is pronounced and is sharply offset from the anterodorsal margin of the scapular blade, as in *Allosaurus*, not *Ceratosaurus* (Gilmore 1920). The left scapula is 75.5 cm long (72 cm of the right is preserved). In lateral view, the maximum dimension of the proximal expansion is 22.5 cm, and the bone is 5.5 cm thick (mediolaterally) at the coracoid suture in the glenoid. The acromial process is concave externally (subacromial depression), and is quite thin at the coracoid suture. The proximodistal height of the acromial process (Fig. 20A) is relatively lower than that of *Allosaurus*, but compares well in this character with *S. hepingensis* (Gao 1992) and *Piatnitzkysaurus* (Bonaparte 1986). The relatively straight blade is constricted above the acromial process to a minimum of 8.9 cm. At this point, the scapula is 7 mm thick at the anterodorsal edge, and 42 mm at its thickest point near the posteroventral margin. Distal to this point, the blade expands somewhat (on the anterodorsal side), then reaches its minimum width of 8.5 cm. Beyond that it expands gradually towards the distal end, where it is an 8 mm thick plate of bone more than 13 cm across perpendicular to the longitudinal axis. The proximal third of the scapular blade is thin along the anterior margin, where it forms a shallow trough on the medial surface. Scarring oriented anterodorsally presumably marks the insertion of the levator scapulae inferioris. The thin expansion along the anterodorsal margin of the scapular blade of *Megalosaurus bucklandi* (Walker 1964) is probably a more pronounced version of this muscle insertion, although it might also mark the origin of the scapular deltoid. The thick posteroventral margin of the proximal half of the scapular blade bears a sharp central ridge that divides two elongate troughs, and probably marks the origin of the subscapularis musculature. In general proportions, the scapular blade is as elongate as that of *Allosaurus* (Gilmore 1920), but has a somewhat wider shaft. Overall, the scapula is intermediate between megalosaurid and allosaurid types. Like a megalosaur (Bakker et al. 1992), the anterodorsal and posteroventral margins are nearly parallel sided, and there is no conspicuous distal expansion. However, the scapular blade of *Sinraptor* is closer to that of an allosaurid, as it is more elongate and is offset more sharply from both the acromial process and the glenoid lip.

The sternum is a poorly known bone seldom reported in theropods. The lack of recognition of sternals in most theropods is probably related to the small size of these elements and delayed ossification. Although the margins are incomplete, the sternum of IVPP 10600 (Figs. 19B, 19C, 19D) was wider (120 mm) than long (57 mm). It is relatively smaller than the equivalent bone in *Albertosaurus* (Lambe 1917), *Carnotaurus* (Bonaparte et al. 1990), *Oviraptor* (Barsbold 1983), *Velociraptor* (Barsbold 1983), and *Xuanhanosaurus* (Dong 1984). The sternals of *Carnotaurus*, *Albertosaurus*, and some specimens of *Oviraptor* are paired, although this is related to immaturity. The complete fusion of the paired sternals into a single median element suggests IVPP 10600 was mature, even though many of the sutures in the skull and vertebrae had not coossified.

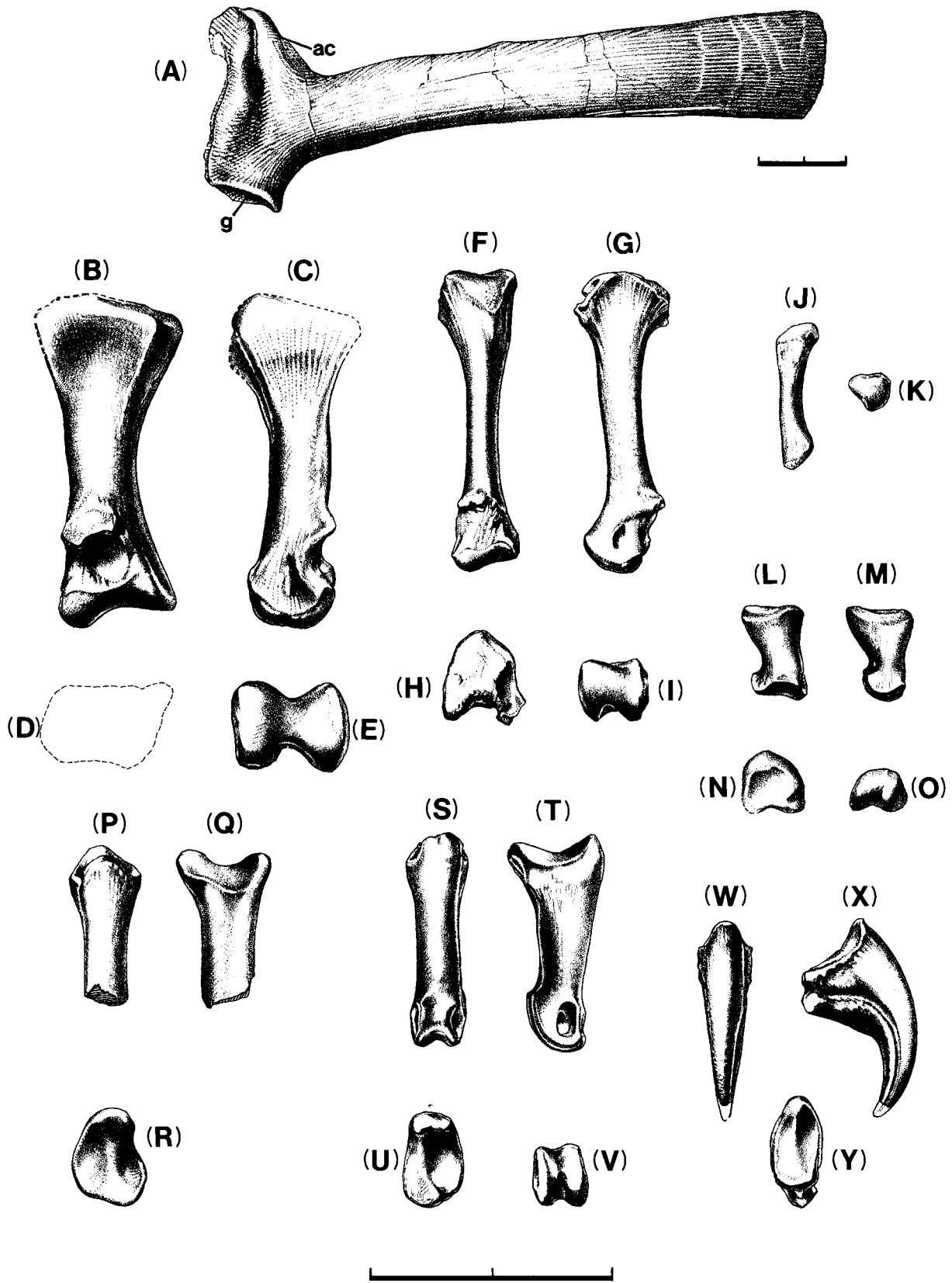


FIG. 20. Anterior limb elements of *Sinraptor dongi* (IVPP 10600). left scapula in lateral aspect (A); left metacarpal II in extensor (B), medial (C), proximal (D), and distal (E) views; metacarpal III in dorsal (F), medial (G), proximal (H), and distal (I) aspects; metacarpal IV in dorsal (J) and proximal (K) views; manual phalanx III-1 in dorsal (L), medial (M), proximal (N), and distal (O) aspects; manual phalanx I-1 in dorsal (P), medial (Q), and proximal (R) views; manual phalanx II-2 in dorsal (S), medial (T), proximal (U), and distal (V) views; manual ungual (II-3 or III-4) in dorsal (W), medial (X), and proximal (Y) views. ac, acromial process; g, glenoid. Scale bars = 10 cm (shorter bar for Fig. 20A, longer bar for Figs. 20B–20Y).

The sternum is somewhat asymmetrical, and appears to have overlapped the right coracoid to a greater degree than the left. As in *Albertosaurus* (Lambe 1917), the surface of the bone is smooth ventrally and rough dorsally. There is a ventral midline keel, which is most pronounced anteriorly. The dorsal surface of the keel is concave, and a pit extends posteriorly into the body of the sternum (Fig. 19C). Two pairs of ribs attached to the sternum directly, as in *Carnotaurus* and *Albertosaurus*, and the anterior costal articulations extended farther laterally than the posterior ones. In *Velociraptor* and *Oviraptor*, the sternals are longer anteroposteriorly, although it is not known how many ribs would have contacted the sternals directly.

Manual elements (Fig. 20) include the second to fourth metacarpals, and phalanges I-1, II-2, II-3, and III-1. The second and third metacarpals and phalanx I-1 of the left hand were found in articulation, but the remaining elements were disassociated. Because the first phalanx had apparently maintained its position in relation to the second metacarpal, it is evident that the first metacarpal was relatively short (less than 75 mm). The proximal articulation of phalanx I-1 is only 28 mm across, however, showing that this was not as strong an element as its equivalent in *Allosaurus*. It was nevertheless a more powerful element than that of *Ceratosaurus* (Gilmore 1920). The distal articulation also clearly had a more distally placed lateral condyle as in allosaurids, tyrannosaurids, and many of the small theropods. The second metacarpal is the largest, stoutest element of the metacarpus, and is similar in shape and relative size to that of *Allosaurus*. Metacarpal III is only marginally shorter than the second, but is much slenderer, with less than half the transverse diameter at mid-shaft (compared with 50% in *Allosaurus* and 69% in *Ceratosaurus*, Gilmore 1920). The relationship of these two elements is typical of allosaurids. The third metacarpal of *Dilophosaurus* is more slender than the second, but is a longer element (Welles 1984). The distal ends of metacarpals II and III of *Sinraptor* look as if they were broken, shifted, and rehealed (Figs. 20B, 20C, 20F, 20G). However, this discontinuity of the extensor surface is natural, and can also be seen in the same elements of *Allosaurus* (Gilmore 1920, Fig. 45; Madsen 1976, Pl. 43). This feature seems to be present in *Ceratosaurus*, but is not as obvious because of the short, stout nature of the metacarpals. The ridge and depression may represent the origins of relatively powerful dorsometacarpal muscles.

Another element appears to be a vestigial fourth metacarpal (Figs. 20J, 20K), although it was not found in association with the other metacarpals. It is a short (57 mm), slender element with a relatively broad proximal articulation and a flattened distal end. In shape it is similar to the fourth metacarpals of *Dilophosaurus* (Welles 1984) and *Ceratosaurus* (Gilmore 1920), but it is relatively shorter (43% the length of the second metacarpal, compared with 65% in *Dilophosaurus* and 70% in *Ceratosaurus*). The fourth metacarpal of *Carnotaurus* is highly specialized and cannot be compared with that of *Sinraptor*. The flattened nature of the distal end suggests that the phalanges were no longer present in this genus. The fourth metacarpal and its digit have been lost in more advanced theropods, including *Allosaurus*.

The proportions of the manual elements (Fig. 20) are closer to those of *Allosaurus* than they are to *Ceratosaurus* (Gilmore 1920). Only the proximal end of the first phalanx of the first digit (Figs. 20P, 20Q, 20R) was collected, but it was obviously an elongate element as in *Allosaurus*, and would have been more than 100 mm long if complete. Phalanx II-1 is absent,

but the elongate nature (87 mm, or 66% the length of its metacarpal) of II-2 is suggestive of, but not as derived as, *Allosaurus* (102 mm in USNM 4734, or 82%; Gilmore 1920). The second ungual is nearly identical in shape and curvature to that of *Allosaurus*, but is again relatively shorter in relation to its metacarpal.

Only one phalanx of digit III has been preserved (Figs. 20L, 20M, 20N, 20O). The first phalanx is 38 mm, which is more elongate than the equivalent element in *Ceratosaurus*, but shorter than that of *Allosaurus*. The proximal articulation is a simple, shallow concavity as in *Allosaurus*, but the distal articulation is turned laterally on its shaft so that the finger would have been oriented outwards. There are no collateral ligament fossae on the distal end of this phalanx.

The large, blade-like ilia closely resemble those of other large theropods (Fig. 21). In overall shape, the anterior blade is deeper and the posterior blade is not as tapering as those of *M. bucklandi* (Owen 1856) and *Torvosaurus tanneri* (Britt 1991). The ilium of *Y. shangyuensis* (Dong et al. 1983), judging from photographs, is poorly reconstructed and should have a deeper anterior blade and less tapering posterior blade. The height to length index (Britt 1991) of *Sinraptor* is 0.36, which is comparable to that of *Allosaurus*. Most of the lateral surface of the iliac blade formed a smoothly concave surface for attachment of the iliofemoralis musculature (Romer 1923). The pubic peduncle is long and well developed with a rugose distal sutural contact that is anteroposteriorly longer (13 cm) than it is wide (8 cm). The acetabulum is 21 cm long (anteroposteriorly) at its lateral margin. There is a wide supraacetabular shelf (Fig. 21C) that is continuous anteriorly with the lateral margin of the pubic peduncle, and morphologically is closer to *Metriacanthosaurus* (Huene 1926; Walker 1964), *Monolophosaurus*, *Piatnitzkysaurus*, and *Torvosaurus* than to *Allosaurus*. The preacetabular notch is closer to the latter, however, in being relatively wider and more open. The ventral margin of the anterior blade is narrow and simple like that of *Torvosaurus* (Britt 1991). As in *Allosaurus*, the posterior margin of the ilium was squared off. The medial blade of the ilium arises from the base of the ischial peduncle and is oriented posterodorsally to form a trough (more than 90 mm across) for the caudofemoralis brevis musculature (Fig. 21C). Compared with *Ceratosaurus* (Molnar et al. 1990), the brevis shelf is relatively narrow, as in *Allosaurus* and more advanced large theropods. The medial surface of the iliac blade has ventral rugosities for attachment of the sacral ribs (Fig. 21B), but is still relatively smooth because of immaturity. Although CV 00215 (*Yangchuanosaurus*) is a smaller individual than IVPP 10600, the ilium is strongly attached to the sacral ribs and pubis (Dong et al. 1983), showing that it was a more mature animal. The fact that IVPP 10600 is both larger and less mature shows that *S. dongi* was a larger animal than *Y. shangyuensis*.

The paired pubes (Fig. 21) are almost 70 cm long. In outline, they are similar to those of *Gasosaurus* (Dong and Tang 1985), *Monolophosaurus*, *Piatnitzkysaurus*, *Torvosaurus* (Galton and Jensen 1979), and *Yangchuanosaurus*, except that the enlarged obturator foramen (with a proximodistal diameter of 13.5 cm) opens ventrally to form an incipient notch. The shaft of the pubis is dorsoventrally flattened, so that it is 6 cm wide by 2.5 cm. The medial margin is a thin longitudinal plate of bone. Although separated by postmortem crushing (Fig. 21G), the pubes met in a midline symphysis along most of their length. As in *Torvosaurus* (Galton and Jensen 1979) and *Allosaurus* (Gilmore 1920), the pubes separate along the midline between

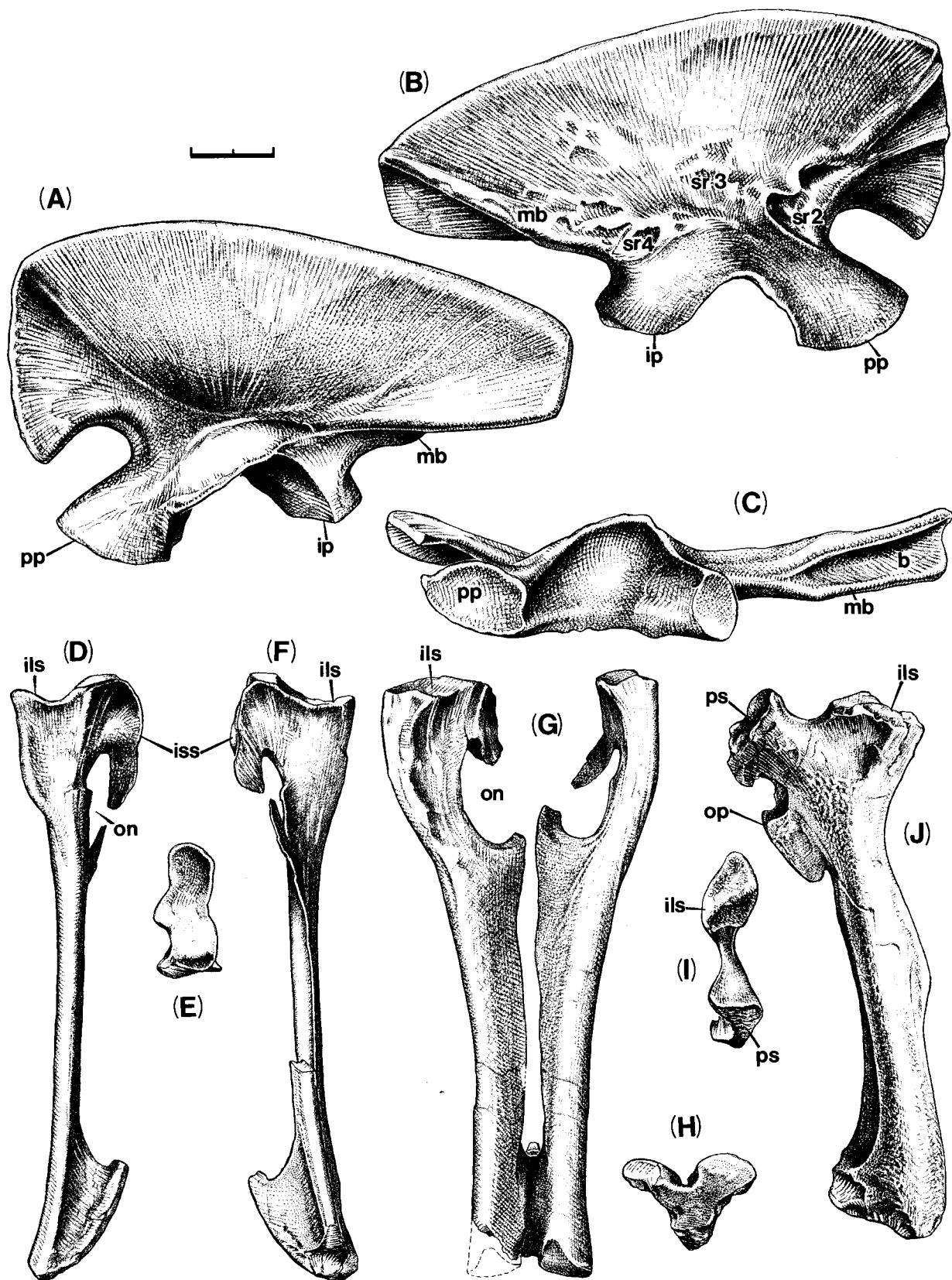


FIG. 21. Pelvic elements of *Sinraptor dongi* (IVPP 10600). Left ilium in lateral (A), medial (B), and ventral (C) views; left pubis in lateral (D), proximal (E), medial (F, with distal end of right pubis) aspects; paired pubes in dorsal (G) and distal (H) views; proximal view of right ischium (I); left lateral aspect of paired ischia (J); b, origin of caudofemoralis brevis musculature; ils, iliac suture; ip, ischial peduncle; iss, ischial suture; mb, medial blade; on, obturator notch; op, obturator process; pp, pubic peduncle; ps, pubic suture; sr2, sr3, sr4, attachment scars of the sacral ribs. Scale bar = 10 cm.



the midline symphysis and the distal, coossified expansions. Distally the shaft forms a shelf of bone dorsolateral to the posteroventral "bootlike" expansion characteristic of most theropods. The expansion is moderate in comparison with *Ceratosaurus* (B. Britt, personal communication, 1991), *Allosaurus*, and tyrannosaurids (Lambe 1917). The cross-section of the distal end of the pubis resembles an inverted L (Fig. 21H) similar to that of *Metriacanthosaurus* (Huene 1926; Walker 1964) and *Torvosaurus* (Galton and Jensen 1979) but unlike those of *Dilophosaurus* and *Allosaurus* (Gilmore 1920), which are triangular in section.

The paired ischia (Figs. 21I, 21J) are 65 cm long, measured from the ventral end of the iliac suture to the distal end. Although shorter than the pubis, the relatively straight shaft of the ischium is more robust, with a minimum diameter of 4 cm. The iliac and pubic sutures have rugose surfaces (Fig. 21I), but IVPP 10600 was too young for these contacts to have fused up. The expanded distal ends of the ischia had coossified, however. The pelvic canal is narrow, and even if the specimen had not been crushed would have been less than 10 cm across. There is a well-developed obturator process for attachment of the ischial head of the puboischiofemoralis externus. A distinct obturator process, separated from the pubic peduncle by a notch, is not found in *Carnotaurus*, *Ceratosaurus* (Gilmore 1920), *Dilophosaurus*, *Piatnitzkysaurus*, or *Torvosaurus*, so a continuous ventral lamina represents the plesiomorphic state for large theropods. The ventral lamina is pierced by a fenestra in *Monolophosaurus* and possibly *Yangchuanosaurus* (Dong et al. 1983). A flange of bone posteroventral to the pubic peduncle is a remnant of the plate of bone that closes the fenestra in the ventral lamina of these other genera. The derived condition of the obturator process seen in *Sinraptor* is also found in *Acrocanthosaurus* (Stovall and Langston 1950), *Allosaurus*, and *Gasosaurus*, and developed independently in other lines of theropods. The shaft of the ischium is straight, although a distinct crest on the posterodorsal surface of the ischium gives the impression that the shaft is curved in lateral view (Fig. 21J). The surface of the shaft lateral to this crest is shallowly concave, and with the ridge probably formed the origin for powerful adductor musculature (Romer 1923). Equivalent development of this crest has only been reported in *Yangchuanosaurus*, although it is present in *Acrocanthosaurus*, *Allosaurus*, and *Megalosaurus* (Stovall and Langston 1950). The shaft expands distally, mostly anteroventrally, to a depth of 13 cm.

The femora (Fig. 22) are 876 mm long (measured along the outer condyle), which is only slightly shorter than the length of the skull. In IVPP 10600, the maximum width of the proximal head of the femur is 207 mm and the distal width is 195 mm. The gently curved shaft has a width of 80 mm (anteroposteriorly) by 97 mm (mediolaterally), which suggests that the individual weighed less than a metric tonne (Anderson et al. 1985). The proximal surface of the head of the femur and the greater trochanter is unfinished bone, and the two regions are continuous. In proximal view, this surface is transversely elongate (Fig. 22C), and fits comfortably within the acetabulum beneath the supraacetabular shelf. The anterior margin of the proximal joint faces 45° laterally from the transverse axis of the distal condyles. Therefore, the longitudinal axis of the hip joint is oriented posterolaterally so that as the leg swung forward, it also swung outward from the hips. During locomotion, this would have caused the hips to swing to the left as the right leg was brought forward, and to the right again as the body

shifted over the right foot. There is a ridge along the posterior margin of the flattened medial surface of the head (Figs. 22C, 22E), with an associated groove as in *Dilophosaurus*. The lesser trochanter is large and platelike like those of *Allosaurus*, *Gasosaurus*, *Yangchuanosaurus*, and *Megalosaurus*, and is separated from the main body of the femur by a deep slot. The presumably plesiomorphic state of a more distal, relatively shorter and more divergent lesser trochanter has been retained by *Carnotaurus*, *Ceratosaurus*, *Dilophosaurus*, and *Xenotarsosaurus* (Martínez et al. 1986). As in *Allosaurus*, the main nutrient foramen enters the shaft of the femur on the anterodorsal surface just distal to the base of the lesser trochanter. The fourth trochanter is a pronounced crest proximal to mid-shaft. The medial side is concave (Fig. 22A) for insertion of the caudofemoralis longis muscle. Distally, there is a sharp ridge on the anterodorsal surface (the mediolateral crest of Bonaparte et al. 1990) that probably was the origin for the M. femorotibialis externus (Fig. 22D). As in other theropods, the distal head is divided into two condyles, the lateral one with a narrow tibial articular protuberance (the ectocondylar tuber of Welles 1984), the lateral edge of which contacted the fibula. There is a deep intercondylar groove on the posteroventral surface, the floor of which has a low but pronounced longitudinal ridge (Fig. 22E), possibly for attachment of the anterior cruciatum ligament.

The left tibia is 769 mm long and the right is 776 mm long, or approximately 88% the length of the femur. This proportion is comparable with other large theropods, including *Allosaurus* (87%, Madsen 1976), *Ceratosaurus* (90%, Gilmore 1920), *Daspletosaurus* (87%, Russell 1970), *Albertosaurus*, and *Tyrannosaurus*. The proximal width of the tibia is 200 mm, the distal width is 195 mm, and the minimum shaft diameter is 65 mm anteroposteriorly (at that level, the shaft is 94 mm mediolaterally). The mid-length circumference of the shaft is 25 cm, and the circumference to length ratio is 32, showing that the tibia is more gracile than those of *Torvosaurus* and *Ceratosaurus* (Britt 1991), and falling within the range expected of *Allosaurus*. The paired articulations on the proximal end of the tibia are not as deeply separated by the posterior intercondylar groove as those of *Allosaurus* or *Torvosaurus*, but they do have the same disparity in height, the medial being higher than the lateral (Fig. 22K). The more lateral articular surface continues onto the lateral surface as an articulation for the fibula. Between the fibular articulation and the cnemial crest is a deep, smooth-surfaced incisura tibialis (Fig. 22I). The cnemial crest is powerfully developed, but as in *Allosaurus* it is noticeably less pronounced than that of *Ceratosaurus* (Gilmore 1920). A groove on the anteromedial margin of the crest is presumably for attachment of the femorotibialis muscle, and the M. iliotibialis would have inserted onto the top of the crest. Distal to the head, there is a pronounced ridge (crista fibularis) on the lateral margin of the extensor surface for attachment of the proximal interosseum tibiofibulare ligaments and articulation (Fig. 22L) with the fibula. This ridge is strong in *Allosaurus*, *Carnotaurus*, and *Piatnitzkysaurus*, but is not as pronounced in *Ceratosaurus* and *Dilophosaurus*. The extensor surface of the shaft is flattened, whereas the other surfaces are evenly rounded in cross section. The ascending process of the astragalus rises up only 12% of the length of the bone, compared with 20% in allosaurids and up to 33% in tyrannosaurids (Molnar et al. 1990). The distal end of the extensor surface of the tibia is flattened for the astragalus, calcaneum, and distal

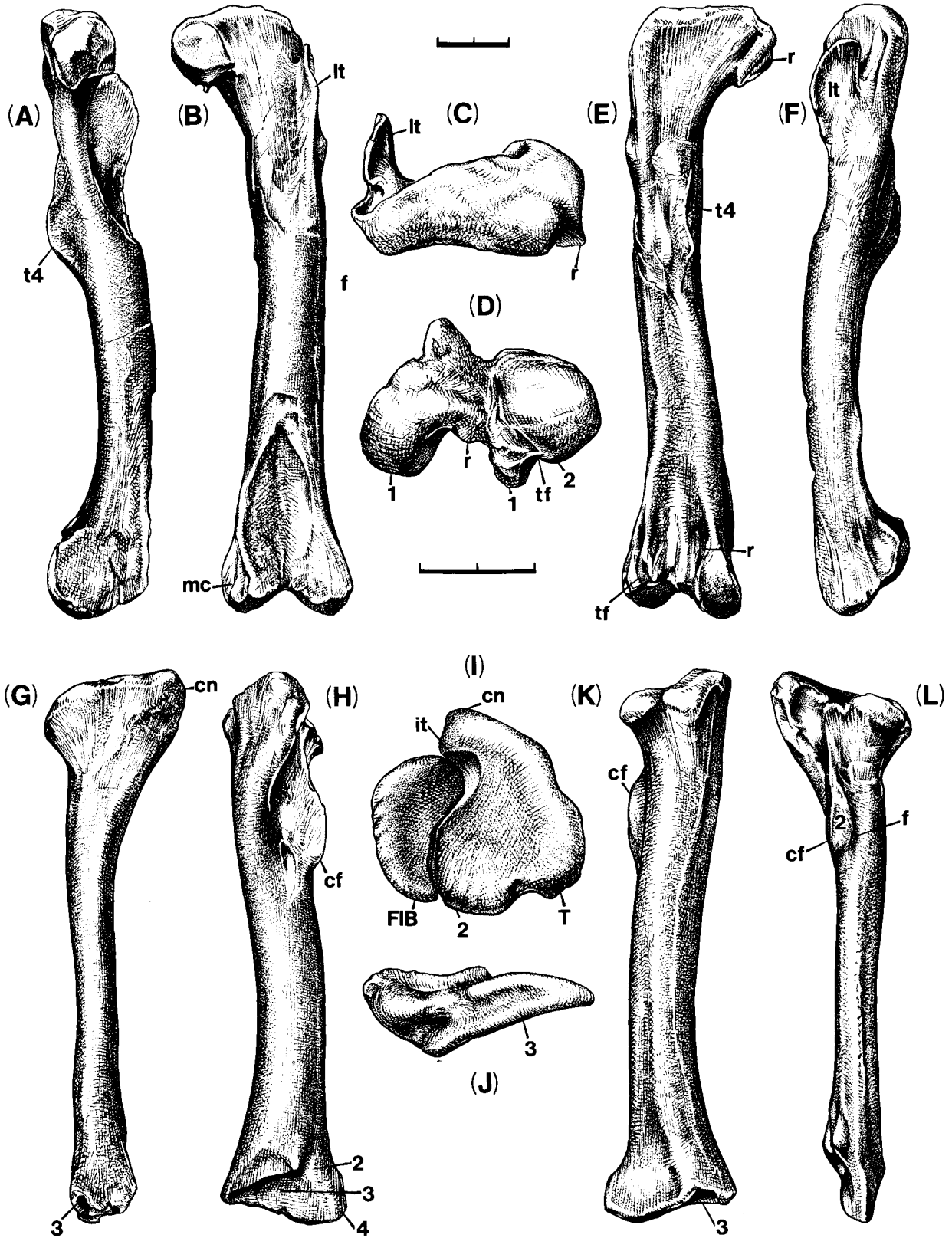


FIG. 22. Hind limb elements of *Sinraptor dongi* (IVPP 10600). Left femur in medial (A), anterior (B), proximal (C), distal (D), posterior (E), and lateral (F) views; left tibia in medial (G), anterior (H), distal (J), posterior (K), and lateral (L) aspects; tibia and fibula in proximal view as found with latter bone shifted anteriorly (I). cf, crista fibularis; cn, cnemial crest; f, foramen; FIB, fibula; it, incisura tibialis; lt, lesser trochanter; mc, mediolateral crest; r, ridge; T, tibia; tf, trochlea fibularis; t4, fourth trochanter; 1, articular surface for tibia; 2, articular surface for fibula; 3, contact with astragalus; 4, contact for the calcaneum. Scale bars = 10 cm (shorter bar for Figs. 22A, 22B, 22E–22H, 22K, 22L; longer bar for Figs. 22C, 22D, 22I, 22J).

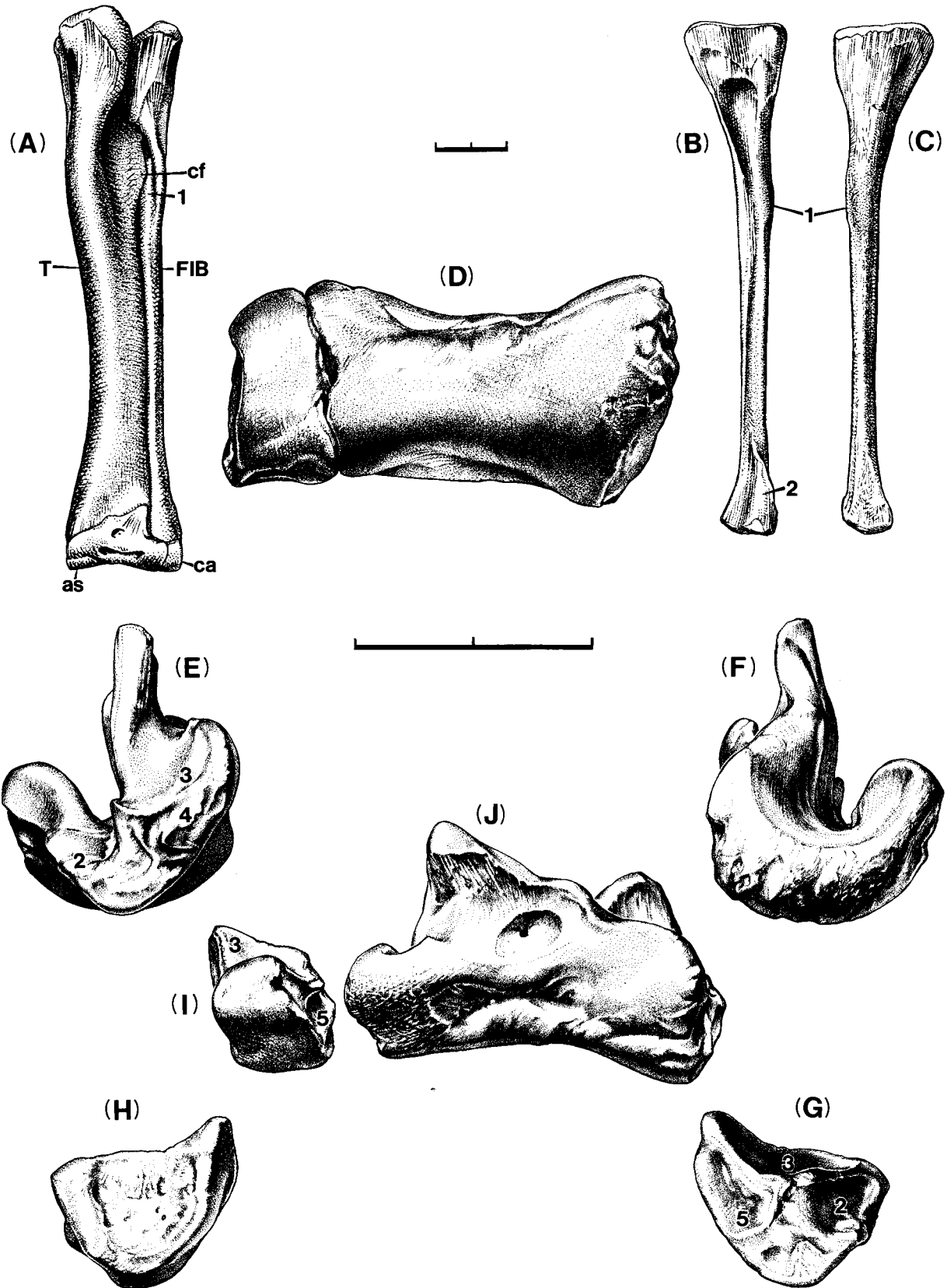


FIG. 23. Hind limb elements of *Sinraptor dongi* (IVPP 10600). anterior view of left tibia, fibula, astragalus, and calcaneum (A); left fibula in medial (B) and lateral (C) views; right calcaneum and astragalus, distal aspect (D); right astragalus in lateral (E), medial (F), and anterior (J) views; right calcaneum in medial (G), lateral (H), and anterior (I) aspects. as, astragalus; ca, calcaneum; cf, crista fibularis; FIB, fibula; T, tibia; 1, rugose thickening on fibula for interosseum tibiofibulare ligaments; 2, articulation for tibia; 3, articulation for fibula; 4, contact with calcaneum; 5, sutural surface for astragalus. Scale bars = 10 cm (shorter bar for Figs. 23A–23C, longer bar for Figs. 23D–23J).

end of the fibula. A sharply defined ridge (Figs. 22H, 22J) overlaps the sloping dorsomedial edge of the ascending process and contacts the fibula laterally. The distal end of the tibia is relatively thin anteroposteriorly (Fig. 22J), and for articulation with the astragalus has a transverse groove that wraps around onto the flexor surface of the tibia medially (Fig. 22K) where it ends in a deep pit.

The fibula is 697 mm long on the left side, and 729 mm on the right. The proximal head (Fig. 22I) is 129 mm anteroposteriorly, the shaft narrows (Fig. 23A) to 32 mm (mediolaterally), and the distal head expands to 77.5 mm. The ratio of length of fibula to distal width produces an index of 9.2, suggesting the fibula of *Sinraptor* is more gracile than those of *Allosaurus*, *Ceratosaurus*, and *Torvosaurus* (Britt 1991). Below the crista fibularis of the tibia, the anteromedial edge of the fibula is thickened and rugose as in *Allosaurus*, *Dilophosaurus*, *Szechuanosaurus* (Dong et al. 1983), tyrannosaurids (Lambe 1917), *Xenotarsosaurus*, and *Yangchuanosaurus*, for the interosseum tibiofibulare ligaments. The narrow foramen interosseum distale passes obliquely between the bones medial to this thickening. The distal half of the fibula is closely appressed to the tibia. There is a flat articular surface on the posterior side of the lower end for the tibia (Fig. 23B), and the distal end sits in a cuplike socket formed by the astragalus and calcaneum (Fig. 23A). The medial edge of the distal articulation for the tibia is a well-defined ridge that contacts the astragalus and tibia.

The astragali and calcanea are uncrushed and well preserved, and clearly fit the allosauroid pattern of Welles and Long (1974). The astragalus has a complex articulation with the calcaneum. The lateral margin of the astragalus (Fig. 23E) has a distinct notch on the anterior surface that receives a process of the calcaneum. This is similar to the situation reported in *Allosaurus* (Welles and Long 1974), although the notch is not as pronounced in the Chinese specimen and compares more favourably with *Torvosaurus* (Britt 1991). In *Ceratosaurus* (USNM 4735), the calcaneum is fused to the astragalus. Fusion seems to have occurred in at least one more specimen (J.H. Madsen, personal communication, 1991), suggesting that this tendency is widespread in the genus. The two proximal tarsals are fused in *Xenotarsosaurus*. Although these bones were not fused in *Sinraptor*, there would have been little potential of independent movement.

The astragalus covers the distal end of the tibia, the latter inserting into a transverse trough that is deep, and anteroposteriorly narrow (Figs. 23E, 23F). There is a relatively high (more than 3.5 cm) process on the posterior margin of the articulating surface close to the medial edge (Figs. 23E, 23F, 23J). This process fits into a deep depression in the distal articulating surface of the tibia, and would have prevented movement between the bones in the living animal. The same peg and pit arrangements can be seen in *Allosaurus* and *Torvosaurus*, but are not nearly as well developed. Dong et al. (1983) described the articulating surface for the distal end of the tibia as a V-shaped notch in *Yangchuanosaurus*, suggesting the presence of the posterior process as in *Sinraptor*.

The proximal articular surface of the astragalus has a distinct division separating its contacts for the tibia and fibula (Fig. 23E). The fibular articulation is a shallow depression anterolateral to the ascending process, but is wider than in other large theropods, where contact between the fibula and astragalus tends to be limited.

The ascending process is approximately 4 cm high, but rises 9 cm above the distal end of the tibia. It makes up only about one third the height of the astragalus when viewed anteriorly (Fig. 23J), which is significantly less than the proportions seen in *Allosaurus* (Gilmore 1920), *Poekilopleuron* (Eudes-Deslongchamps 1838), tyrannosaurids, and probably *Acrocanthosaurus* (Stovall and Langston 1950). In theropods, the ascending process shows a tendency towards negative allometry (Currie and Peng 1993; Madsen 1976; Welles and Long 1974), so the low ascending process of IVPP 10600 cannot be attributed to immaturity, but is clearly more primitive than *Allosaurus* in this character. *Ceratosaurus* (J.H. Madsen, personal communication, 1991), *Dilophosaurus*, *Eustreptospondylus* (Huene 1926; Walker 1964), *Gasosaurus*, *Szechuanosaurus* (Dong et al. 1983), *Torvosaurus* (Britt 1991), and *Yangchuanosaurus* all have low ascending processes, like *Sinraptor*.

The ascending process is different from the almost symmetrical process in *Allosaurus* (Madsen 1976), and arises on the lateral side of the astragalus and tapers distally from the medial side. This lateral cant is characteristic of theropods with low ascending processes. There is a vertical groove on the posterior surface of the ascending process, similar to *Torvosaurus* (Britt 1991) but different than the depressions found in *Dilophosaurus* and *Allosaurus*.

The base of the ascending process is excavated on the extensor surface for the joint capsule, and there is a horizontal groove (Figs. 23D, 23J) running across the face of the condyles as in *Allosaurus*.

The calcaneum (Fig. 23) is a relatively small element, its maximum width (4.5 cm) being 29% of the greatest width of the astragalus (15.5 cm). Its maximum anteroposterior length is 8.3 cm, and its height is 7.0. The calcaneum figured by Madsen (1976) is relatively smaller, having a maximum width of only 24% of the astragalus. Whereas the calcaneum of *Allosaurus* tapers posteriorly, those of IVPP 10600 (Fig. 23D) and *Torvosaurus* (Britt 1991) taper anteriorly. It does not completely cover the end of the fibula, but shares this articulation with the astragalus. In contrast with *Yangchuanosaurus* (Dong et al. 1983), the anterior aspect of the calcaneum of *Sinraptor* is wider ventrally than dorsally (Fig. 23A). About two thirds of the dorsal surface articulates with the fibula, and one third articulates with the tibia (Fig. 23G), the two surfaces being separated by a prominent ridge directed posterolaterally from the astragular contact. Like *Allosaurus* but unlike *Torvosaurus*, the articular surface for the fibula is a distinct concavity with a higher lateral margin. The calcaneum meets the astragalus with a tight-fitting, undulating contact (with a tongue and two pits on the medial articulating surface—Figs. 23G, 23I) that matches the calcaneal contours of *Allosaurus* and *Dilophosaurus*, but with more subtle curves than the former.

Distal tarsals are not often recovered with specimens because of delayed ossification and small size. There are three distal tarsals in *Syntarsus* (Rowe 1989) and tyrannosaurids (Lambe 1917; Maleev 1974), but this number has been reduced to two in *Allosaurus*, *Deinonychus* (Ostrom 1969), and ornithomimids (Osmólska et al. 1972). *Sinraptor* had only two distal tarsals. The third and fourth distal tarsals of the right pes, and the left fourth distal tarsal were recovered (Fig. 24). All of these elements were disarticulated, but because of the lack of crushing in the foot elements of IVPP 10600, they can be easily repositioned. In relative size and shape, these elements are not significantly different from those of *Allosaurus*, although the

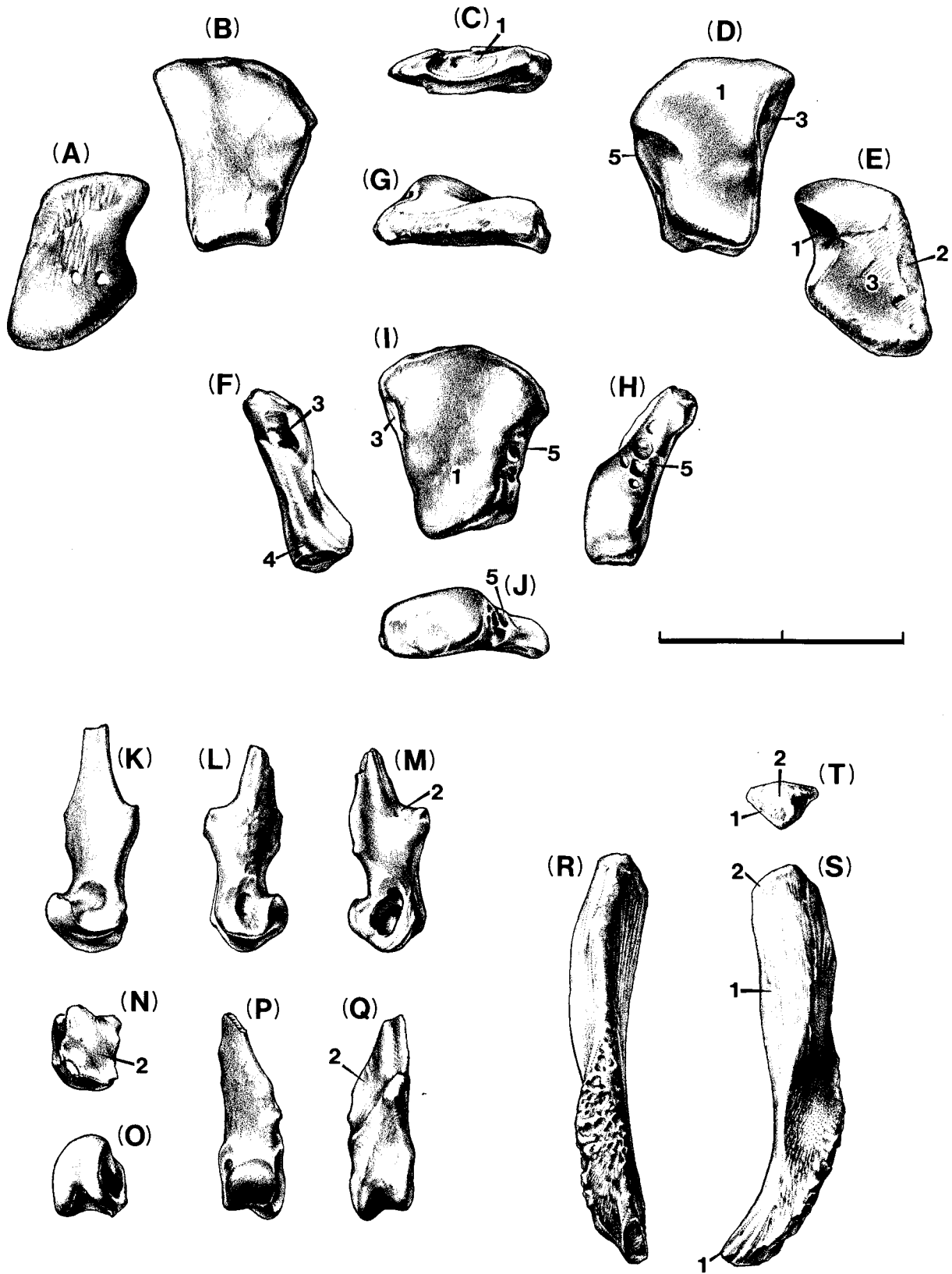


FIG. 24. Pedal elements of *Sinraptor dongi* (IVPP 10600). Right distal tarsal III in dorsal view (A); right distal tarsal IV in dorsal view (B); right distal tarsal III in lateral (C) and ventral (E) views; right distal tarsal IV in ventral aspect (D); left distal tarsal IV in medial (F), anterior (G), lateral (H), ventral (I), and posterior (J) views; anterior aspect of left metatarsal I (K); right metatarsal I in anterior (L), posterior (M), proximal (N), distal (O), extensor (P), and flexor (Q) aspects; right metatarsal V in lateral (R), medial (S), and proximal (T) views. 1, articulation for metatarsal IV; 2, contact surface for metatarsal II; 3, articular surface for metatarsal III; 4, contact with distal tarsal III; 5, articulation for metatarsal V. Scale bar = 10 cm.

third is more elongate anteroposteriorly. The greatest dimension (posteromedial to anterolateral axis) of the third distal tarsal is 7.6 cm. It covers approximately the posterior half of the proximal articulation of the third metatarsal. Madsen (1976) reported that distal tarsal III of *Allosaurus* has well-defined cavities on the medial and lateral margins of the ventral surface. The lateral margin in IVPP 10600, as in *Allosaurus*, is concave in dorsal view. The ventrolateral surface of this margin is a depression with finished bone that fits over the medial end of the fourth distal tarsal (Fig. 24E). A small section of finished bone is evident near the medial margin of the ventral surface. It was evidently not a well-developed pit, but Madsen (1976) reported that it is not well defined in young specimens of *Allosaurus* either. This hollow (Fig. 24E) overlaps the posterolateral edge of the proximal articulation of the second metatarsal.

The maximum width of the fourth distal tarsal is 6.9 cm, with an anteroposterior length of 7.8 cm. The thickness is variable, reaching its maximum (2.5 cm) posterolaterally (Fig. 24J). The fourth is thick (2.1 cm) near its anteromedial limit (where it fills in the gap between the astragalus and metatarsal IV), but thins to 1.6 cm anterolaterally. The fourth tarsal prevented the calcaneum from contacting the fourth metatarsal. A short region of finished bone close to the anterior margin of the medial surface articulates with the anterolateral margin of the proximal articulation of metatarsal III, and shows that the fourth also separated the astragalus from the fourth metatarsal. As in *Allosaurus*, the fourth distal tarsal extended posteriorly beyond the proximal articulation of the fourth metatarsal. A pitted region on the posterolateral surface marks the contact with the proximal head of the fifth metatarsal.

Metatarsal I was recovered for both feet (Fig. 24). As pointed out by Welles (1984), the proximal end of the first metatarsal has been lost by most theropods (metatarsal V is misidentified sometimes as the proximal section of the first metatarsal (Madsen 1976; Molnar et al. 1990; Ostrom 1969)). In both specimens, the proximal tip of the metatarsal has been broken, but the bone would have been no shorter than 9 cm. The exact position of the first metatarsal in relation to the second is difficult to determine. It is assumed from the contours of metatarsal I and a flattened area on the second metatarsal that the first metatarsal was applied to the posteromedial surface of the second, approximately 10 cm from the distal end of the latter bone. The elongate proximal articulation is convex in section (Figs. 24M, 24N, 24Q), and would have allowed the first digit some freedom of movement. The main shaft of this metatarsal diverged vertically from the shaft of the second metatarsal at an angle of about 30°. The distal articulation is expanded on the extensor surface, which would have allowed the animal to raise the first digit until it was almost horizontal. In contrast with the other metatarsals and phalanges, however, maximum flexion of the first phalanx on the metatarsal would have brought the long axes of the two bones into line (that is, it would have straightened out the toe). The first phalanx of the first digit has a roughly triangular, concave proximal articulation (Figs. 25N, 25O) that would have allowed more abduction, adduction, and rotation on the metatarsal than was present in the ginglymoid joints of the other toes. The proximal articulation, which tends to be at right angles to the axis of the bone in most phalanges, is rotated 15° outwards. Combined with the divergence of the first metatarsal, the first digit then would normally stick out about 30° from the main axis of the metatarsus. As the first phalanx was raised, it would tend to rotate around its long axis

until its medial surface was facing dorsally (and its lateral surface would be oriented ventrally).

The second, third, and fourth metatarsals (Figs. 26, 27) were the major weight-bearing elements, and are similar to those of most large Jurassic theropods. The metatarsals are more gracile than those of *Acrocanthosaurus* (Stovall and Langston 1950), *Torvosaurus* (Britt 1991), and most other Jurassic theropods. The third metatarsal (410 mm long) is 47% the length of the femur, compared with 38–44% in *Allosaurus* (Gilmore 1920), 41% in *Ceratosaurus*, 45% in *Eustreptospondylus* (Huene 1926), 52% in *Piatnitzkysaurus*, and 57–72% in tyrannosaurids (Russell 1970). Elongation of the metatarsus is generally considered to be a progressive characteristic associated with the development of greater speed. However, it is also true that immature theropods can have relatively longer metatarsals than adults (Russell 1970; Currie and Peng 1993), so it is possible that a larger specimen of *Sinraptor* would have a relatively shorter metatarsus that is more comparable with *Allosaurus*.

The second metatarsal of IVPP 10600 is 360 mm long, compared with 410 mm for the third and 375 mm for the fourth. In *Ceratosaurus* (Gilmore 1920) the second metatarsal is longer than the fourth, and the two are subequal in length in *Szechuanosaurus* (Dong et al. 1983), but all other large Jurassic theropods are like *Sinraptor* in the relative lengths of these two bones.

Both IVPP 10600 and *Allosaurus* have third metatarsals with more slender proximal articulations (Fig. 26) than those of *Torvosaurus* and *Ceratosaurus*. Like *Allosaurus* (Gilmore 1920) and *Torvosaurus*, the third metatarsal differs from *Ceratosaurus* in being wider along the anterior edge than the posterior margin of the proximal articulation. This is a significant, derived character that is used by Gauthier (1986) to help define the Tetanurae and by Paul (1988b) to help define his Intertheropoda. *Sinraptor* also differs from *Ceratosaurus* by having sinuous, rather than flat (in proximal view) contacts between the metatarsals. Collateral ligament pits (Fig. 26E) are well developed on the distal end of metatarsal III, in contrast with the broad concavities of *Torvosaurus*. *Sinraptor* is closer to this genus than to *Allosaurus* in the outline of the distal articulation (Fig. 27E) in that the separation between the two condyles is less distinct.

The proximal articulation of the fourth metatarsal is elongate and triangular in outline (Fig. 26A), contrasting strongly with the broader, almost quadrangular shapes of *Dilophosaurus* and *Ceratosaurus* metatarsal IV's. In outline, the posterolateral margin is concave, as in *Allosaurus* (Madsen 1976) and *Megalosaurus* (Huene 1926), not convex as in *Torvosaurus* (Britt 1991). The shaft has a gentle outward curve, intermediate between the apparently straight shaft of *Torvosaurus* and the stronger curvature of most other large Jurassic theropods. The fifth metatarsal (Figs. 24R, 24S, 24T) articulates with the outside margin of the flattened posterior surface of the shaft. The proximal articulation extends for 6 cm, below which the two bones separate for a distance of 8.5 cm. The distal end of metatarsal V contacts the fourth (Fig. 26D) for a short distance along the sharp ridge (*crista plantares lateralis*) dividing the flexor and lateral surfaces of the larger bone. Below this contact is an elongate (2.5 cm × 10 cm) depression (Fig. 26D) with a rugose surface. This marks the origin of flexor muscular (probably *M. lumbricalis*) for the third and fourth toes.

Both of the fifth metatarsals were recovered with IVPP 10600, and are comparable with those of *Allosaurus* (tentatively identified by Madsen (1976) as the proximal portion of metatarsal I)

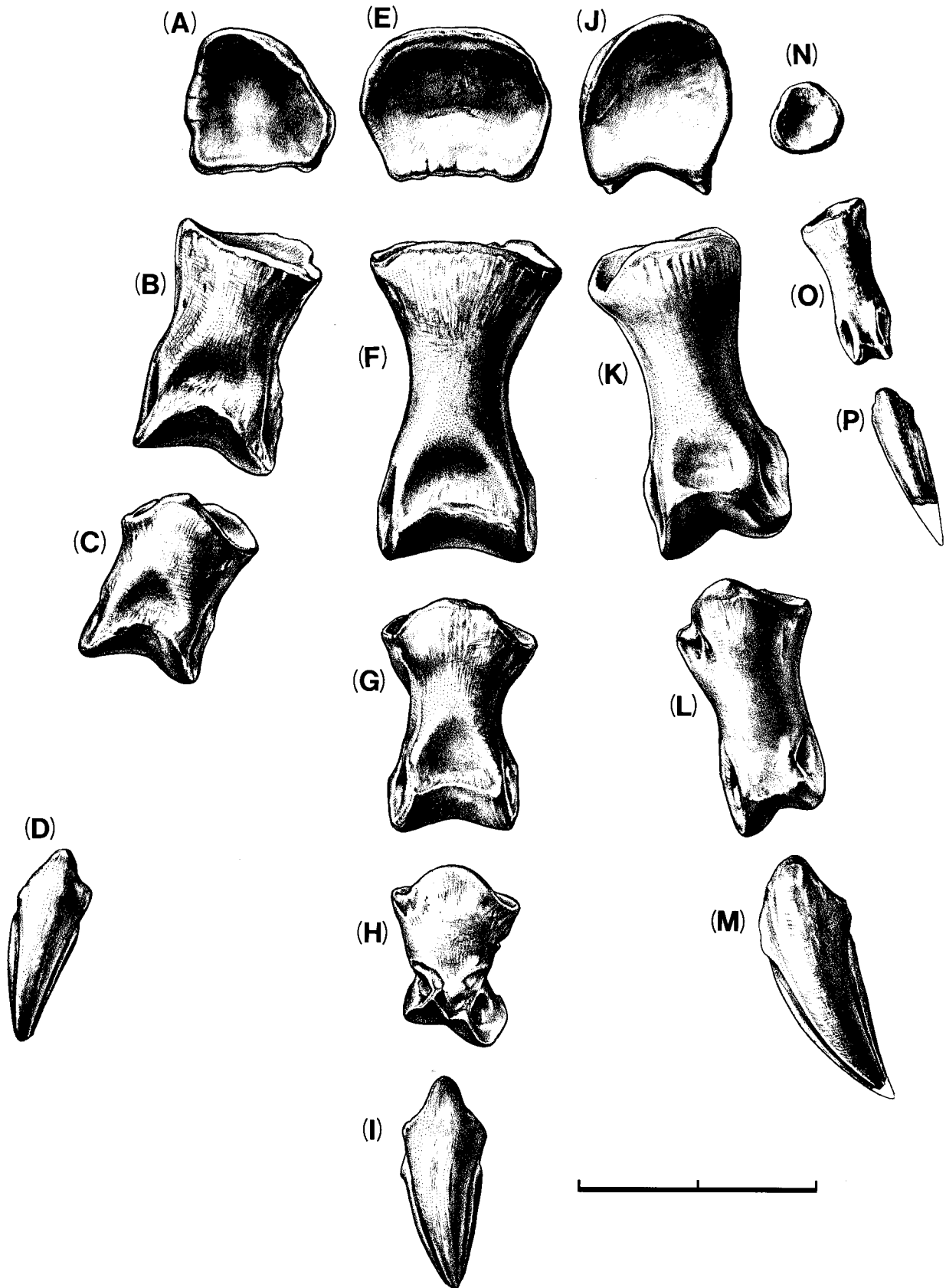


FIG. 25. Right pedal elements of *Sinraptor dongi* (IVPP 10600). Proximal aspect of phalanx IV-1 (A); dorsal views of phalanges IV-1 (B), IV-2 (C), IV-5 (D); proximal aspect of III-1 (E); dorsal views of phalanges III-1 (F), III-2 (G), III-3 (H), and III-4 (I); proximal aspect of phalanx II-1 (J); dorsal views of II-1 (K), II-2 (L), and II-3 (M); proximal aspect of phalanx I-1 (N); dorsal views of phalanges I-1 (O) and I-2 (P). Scale bar = 10 cm.

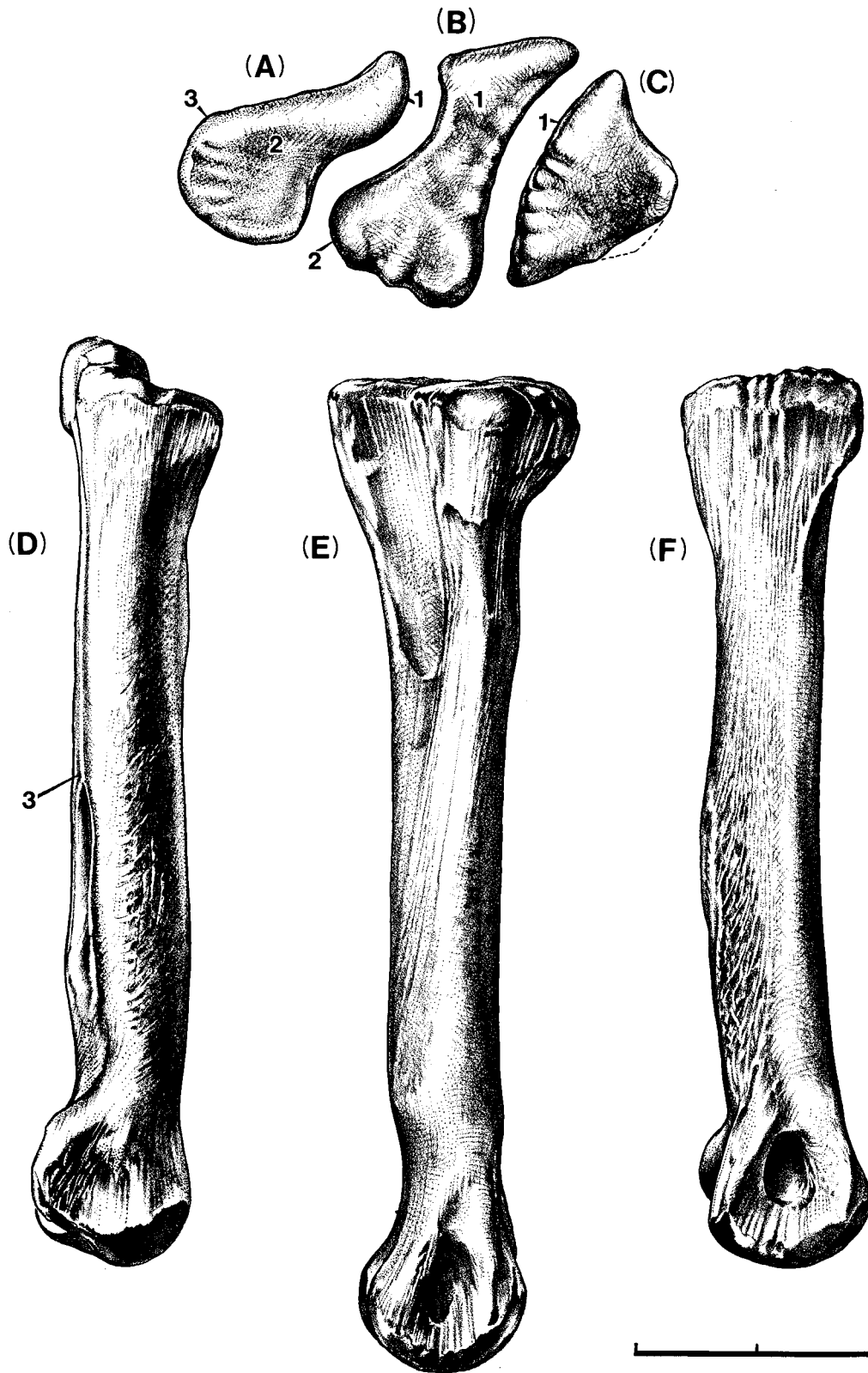


FIG. 26. Right metatarsus of *Sinraptor dongi* (IVPP 10600). Proximal views of metatarsals IV (A), III (B), and II (C); lateral views of metatarsals IV (D), III (E), and II (F). 1, contact surfaces for distal tarsal III; 2, articular surface for distal tarsal IV; 3, distal contact point between metatarsals IV and V. Scale bar = 10 cm.

and tyrannosaurids (Lambe 1917). Metatarsal V is 65 mm long, 16% the length of the third metatarsal, and tapers distally through a gentle curve. The proximal end is triangular in section (Fig. 24T), and contacts the posterodistal margin of the

fourth distal tarsal. The elongate, flattened anteromedial surface articulates with the fourth metatarsal (Fig. 24T), as does the distal tip. The posterolateral surface of the shaft is flat proximally and convex in section distally. A sharp inflection



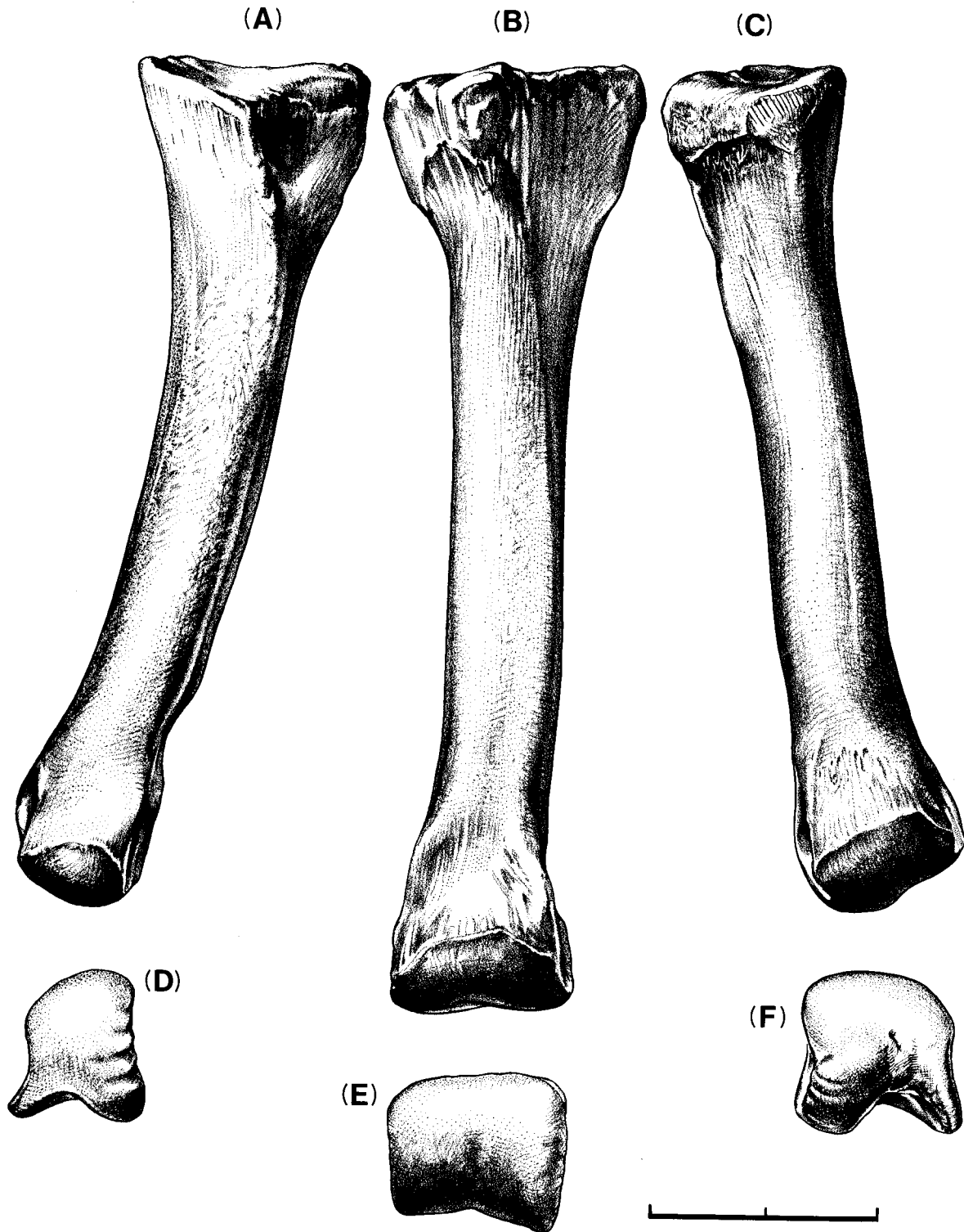


FIG. 27. Right metatarsus of *Sinraptor dongi* (IVPP 10600). Anterior views of metatarsals IV (A), III (B), and II (C); distal views of metatarsals IV (D), III (E), and II (F). Scale bar = 10 cm.

separates it from the posteromedial surface of the proximal end. This ridge is smooth proximally but becomes wide and rugose distally (Fig. 24R). The rugosities were presumably for ligamentous attachments to the other metatarsals. The expansion of the ridge creates a deep trough (Fig. 24T) on the medial side of the fifth metatarsal. This smooth-walled trough is continuous with the flexor surface of metatarsal IV, and together they formed most of the flexor sulcus for transmission of the

tendons of the gastrocnemius, M. flexor digitorum longus, and other flexor musculature. In most features, the fifth metatarsal of *Sinraptor* is like that of tyrannosaurids (Lambe 1917; Maleev 1974), but is about half of the length relative to the third metatarsal. The tyrannosaurid fifth metatarsal is relatively longer distal to the rugose surface on the posterior ridge, whereas the proportions are about the same in *Allosaurus* as in *Sinraptor*. The fact that the fifth metatarsal is 42% the length of the third

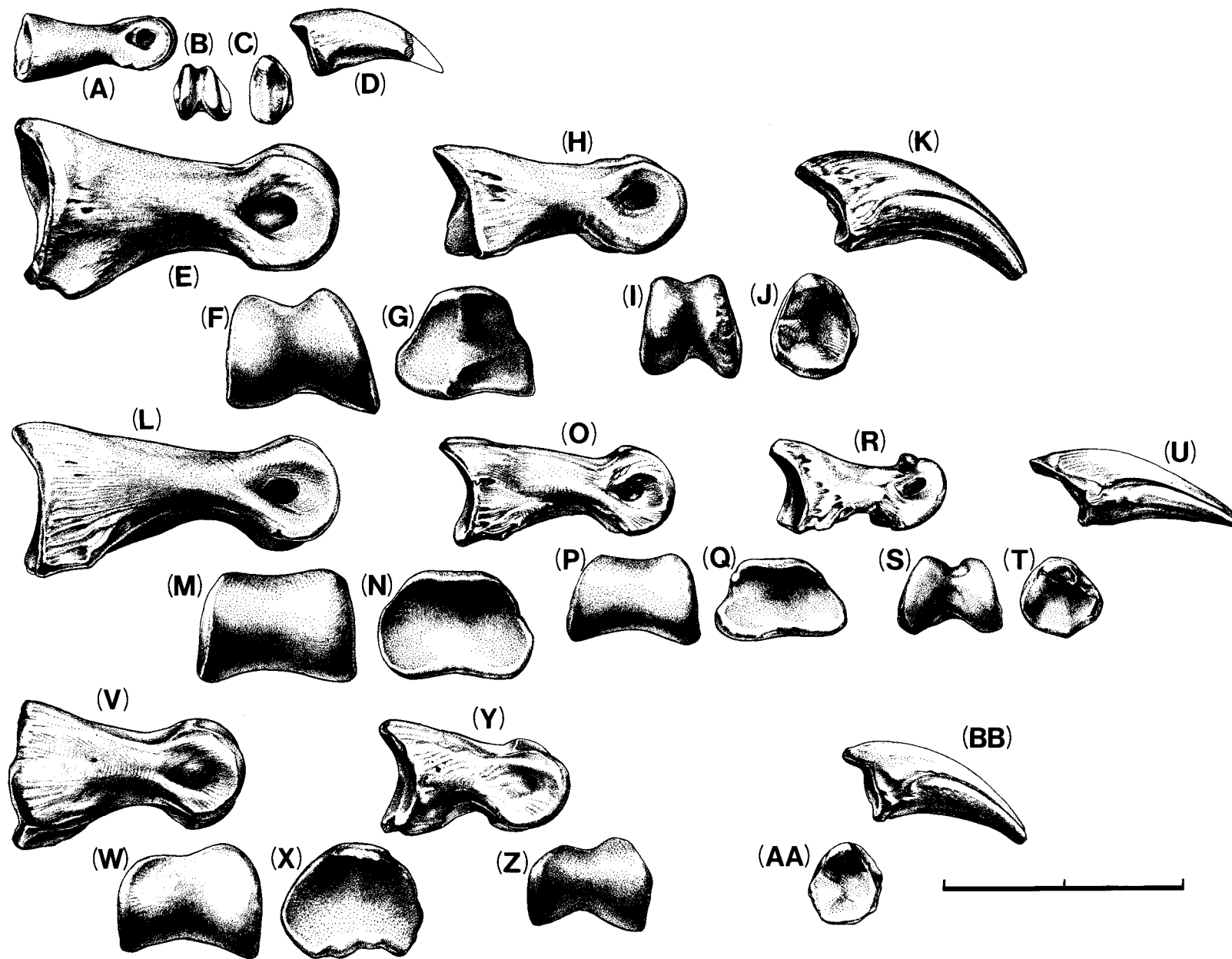


FIG. 28. Right pedal phalanges of *Sinraptor dongi* (IVPP 10600). Phalanx I-1 in lateral (A) and distal (B) views; I-2 in proximal (C) and lateral (D) aspects; II-1 in lateral (E) and distal (F) views; II-2 in proximal (G), lateral (H), and distal (I) views; II-3 in proximal (J) and lateral (K) aspects; III-1 in lateral (L) and distal (M) aspects; III-2 in proximal (N), lateral (O), and distal (P) views; III-3 (pathological) in proximal (Q), lateral (R), and distal (S) views; proximal (T) and lateral (U) aspects of III-4; lateral (V) and distal (W) views of IV-1; IV-2 in proximal (X), lateral (Y), and distal (Z) views; proximal (AA) and lateral (BB) aspects of ungual phalanx IV-5. Scale bar = 10 cm.

in *Dilophosaurus* suggests that the longer tyrannosaurid fifth is more primitive than those of *Sinraptor* and *Allosaurus*.

Neither the right nor left foot is complete, although between the two all phalanges are known except for IV-4 (Figs. 25, 28). The third toe is 90% the length of the third metatarsal, and 43% the length of the femur. The proximal phalanges of each digit are the most elongate. As in other theropods, the dorsal surface of each phalanx (with the exception of I-1, II-2, and the unguals) is excavated on the extensor surface proximal to the distal articulation. The collateral ligament fossae tend to be equally developed on phalanges of the third digit. However, the fossae are more strongly developed on the lateral side of phalanges II-1 and II-2 (Figs. 28E, 28H), whereas the lateral fossae are shallow on phalanges of the fourth digit (Figs. 28V, 28Y). The penultimate phalanges of the first three digits (and presumably that of the fourth as well) are easily identified because the collateral fossae are relatively closer to the extensor surfaces (Figs. 28H, 28R). Insertions for the collateral ligaments and the flexor digitalis brevis are well marked by rugosities on the sides near the proximal end of each phalanx. The distal articular surface of phalanx III-3 of the left foot is pathological (Figs. 25H, 28R). The medial condyle is distorted, and is visibly shorter than the lateral condyle. The end of the toe would have twisted medially. The pedal unguals are broad and well rounded in section, and are not significantly different from those of *Allosaurus*. Scarring marks the insertion point of the *M. extensor digitorum longus* posterodorsally, and the *M. flexor digitorum longus* on the posteroventral surface of each unguis.

### Discussion

Although IVPP 10600 was an estimated 7.2 m in length, it was not fully mature when it died. The cranial sutures, including the contacts between the exoccipitals and basioccipital, are tight but not fused. The supraoccipital contacts with the parietal and exoccipitals are still visible. Fusion was not complete between the odontoid and axis, between the neural arches and centra, between any of the sacral centra, nor between the sacral vertebrae and ribs. The scapula and coracoid were unfused, as were the pelvic elements. However, the sternum is ossified into a single medial element, and the distal ends of the pubes and ischia had coossified, which indicates the animal was close to maturity.

*Sinraptor*, assigned to the Sinraptoridae, allows us to evaluate the systematic positions of large theropods. The Middle to Late Jurassic sinraptorids are more advanced than abelisaurids (*Abelisaurus* and *Piatnitzkysaurus*), but generally more primitive than allosaurids (*Allosaurus* and *Acrocanthosaurus*). There are many plesiomorphies (as determined by comparison with *Ceratosaurus*) in *Sinraptor* that distinguish it from allosaurids. The lateral temporal fenestra is relatively large, and there is a long subtemporal bar. The premaxilla contacts the nasal ventral to the external naris, and carries four teeth. The squamosal retains a tympanic process. Interdental plates are not fused to each other. The prefrontal is a relatively large bone. The palatal rami of the pterygoids meet on the midline in *Sinraptor*, whereas they are apparently separated in *Allosaurus* (Madsen 1976). The ophthalmic nerve exited the braincase with the maxillo-mandibular trunk of the trigeminal nerve, although separation has started. The quadrate is intermediate between the tall (relative to skull height) type found in *Ceratosaurus* and the low quadrate of *Allosaurus*. In the mandible, the surangular is a

relatively low bone even though the jaw is deep, and does not contact the angular anteriorly. The mylohyoid foramen is closed ventrally. The angular does not extend posteriorly to the level of the articular. In outline the articular of *Sinraptor* is relatively wider. There is no antarticular. A diapophysis is retained by the axis. The odontoid cavity in the atlantal intercentrum is deep. The pneumatic chambers within the centra of the cervicals and anterior dorsals are simple, and are not subdivided by numerous trabeculae. The epiphyses of cervical vertebrae are elongate, and are connected to the neural spine by laminae. The hyposphene-hypantrum articulations are not restricted to the cervicals and anterior dorsals. The 10th presacral vertebra is a cervical, and has not been fully incorporated into the thorax. Neural spines are tall, thin, and bladefike. The first sacral rib does not contact the first sacral centrum. Metacarpal III has not been displaced to the palmar surface of the second metacarpal. There is a vestigial fourth digit in the hand. The distal end of the scapula is not expanded. The supraacetabular shelf of the ilium is broad. An opening penetrates the base of the pubis. The pubic boot is small, and the distal end of the pubis is L-shaped in cross section, not triangular. The paired pubes contact each other along most of their length, as do the paired ischia. The distal end of the fibula is relatively broad. The ascending process of the astragalus is relatively low, and the notch for the calcaneum is not as deep. Although these characters do not define sinraptorids, the differences help distinguish them from allosaurids.

Even though *Sinraptor* is more primitive than *Allosaurus*, numerous synapomorphies separate both animals from *Ceratosaurus*, abelisaurids, megalosaurids, and other primitive theropods. These are listed along with the family diagnosis, and need not be repeated here. Some of these characters may ultimately be found in megalosaurids, but for now can be used to define the clade Allosauroidae, which includes Allosauridae and Sinraptoridae.

Abelisaurids (*Abelisaurus*, *Carnotaurus*, *Piatnitzkysaurus*, and possibly some poorly known forms from Africa and Europe) split off the evolutionary line of carnosaurs leading to allosaurids before *Sinraptor*. Braincase and ischial and femoral structure in particular are more primitive.

*Megalosaurus* and its kin seem to be closely related to allosauroids, although precise relationships are difficult to determine in the absence of sufficient understanding of their anatomy. As defined by Bakker et al. (1992), megalosaurids have lost the quadrate-quadratojugal fenestra, do not have a lacrimal horn, have not pneumatized the lacrimal, and have expanded the middle part of the scapular blade. Where known, they lack the synapomorphies listed above for the Allosauroidae but are more advanced than abelisaurids. The Megalosauridae has long been a convenient taxon in which to dump large theropods that could not be defined as ceratosaurids or allosaurids. *Eustreptospondylus* (Huene 1926), *Torvosaurus* (Britt 1991), and *Edmarka* (Bakker et al. 1992) are large theropods that appear to be more closely related to *Megalosaurus* than to either *Sinraptor* or *Yangchuanosaurus*. Whether the Megalosauridae is a natural group cannot be determined without additional material of *Megalosaurus* and *Torvosaurus*, and a better description of *Eustreptospondylus*. Other specimens referred to the Megalosauridae are generally either too incomplete or too poorly known to do so with confidence.

*Sinraptor* shows the strongest similarity to *Yangchuanosaurus*, which is not completely known. Both genera were found on

the same continent in beds of equivalent age with similar faunal associations (Dong 1992). The skull of *Sinraptor* is relatively longer than those of *Yangchuanosaurus*. To better support the skull and as a means of shifting the centre of gravity closer to the hips, the occipital condyle has rotated ventroposteriorly, and the atlas-axis complex has been modified into a position that is as much below the condyle as it is behind it. Similar changes occurred independently in some tyrannosaurids (*Tyrannosaurus*, *Tarbosaurus*, *Alioramus*). The arrangement of the accessory fenestra in the antorbital fossa seems to be a synapomorphy of these genera. Three species of *Yangchuanosaurus* have been described from the Upper Shaximiao (Shangshaximiao) Formation of the Sichuan basin of southern China, but one of the species is reassigned in this paper to *Sinraptor*. *Sinraptor* has a relatively longer, lower skull than *Yangchuanosaurus*. It can also be easily distinguished by the large size of the lateral temporal fenestra, by the intertemporal prong of the postorbital that is covered laterally by the squamosal, by a postorbital rugosity that almost closes the gap between the lacrimal and postorbital, and by the presence of an extra process of the jugal contacting the quadrate-jugal. A stronger inflection in the atlas-axis complex brings the vertebral column under the back of the skull.

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