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1. Stein, R. S. & Lisowski, M. The 1979 Homestead Valley earthquake sequence, California: Control of aftershock and postseismic deformation. *J. Geophys. Res.* **88,** 6477–6490 (1983).
2. Reasenberg, P. A. & Simpson, R. W. Response of regional seismicity to the static stress change produced by the Loma Prieta earthquake. *Science* **255,** 1687–1690 (1992).
3. Hudnut, K. W., Seeber, L. & Pacheco, J. Cross-fault triggering in the November 1987 Superstition Hills earthquake sequence, southern California. *Geophys. Res. Lett.* **16,** 199–202 (1989).
4. Jaumé, S. C. & Sykes, L. R. Changes in the state of stress on the southern San Andreas Fault resulting from the California earthquake sequence of April to June 1992. *Science* **258,** 1325–1328 (1992).
5. Harris, R. A. & Simpson, R. W. Changes in static stress on southern California faults after the 1992 Landers earthquake. *Nature* **360,** 251–254 (1992).
6. Stein, R. S. The role of stress transfer in earthquake occurrence. *Nature* **402,** 605–609 (1999).
7. Wald, D. J. & Heaton, T. H. Spatial and temporal distribution of slip for the 1992 Landers, California, earthquake. *Bull. Seismol. Soc. Am.* **84,** 668–691 (1994).
8. Hudnut, K. W. *et al.* Seismic displacement of the 1992 Landers Earthquake sequence. *Bull. Seismol. Soc. Am.* **84,** 625–645 (1994).
9. King, G. C. P., Stein, R. S. & Lin, J. Static stress change and the triggering of earthquakes. *Bull. Seismol. Soc. Am.* **84,** 935–953 (1994).
10. Erickson, L. L. *A Three-dimensional Dislocation Program with Applications to Faulting in the Earth.* Thesis, Stanford Univ. (1986).
11. Hardebeck, J. L., Nazareth, J. J. & Hauksson, E. The static stress change triggering model: Constraints from two southern California aftershock sequences. *J. Geophys. Res.* **103,** 24427–24437 (1998).
12. Deng, J. & Sykes, R. L. Evolution of the stress field in southern California and triggering of moderate-size earthquakes: A 200-year perspective. *J. Geophys. Res.* **102,** 9859–9886 (1997).
13. Seeber, L. & Armbruster, J. G. The San Andreas fault system through the Transverse Ranges as illuminated by earthquakes. *J. Geophys. Res.* **100,** 8285–8310 (1995).
14. Toda, S., Stein, R. S., Reasenberg, P. A., Dieterich, J. H. & Yoshida, A. Stress transferred by the 1995 M_W = 6.9 Kobe, Japan shock: Effect on aftershocks and future earthquake probabilities. *J. Geophys. Res.* **103,** 24543–24565 (1998).
15. Gross, S. & Burgmann, R. Rate and state of background stress estimated from the aftershocks of the Loma Prieta, California earthquake. *J. Geophys. Res.* **103,** 4915–4927 (1998).
16. Scholz, C. *The Mechanics of Earthquakes and Faulting* 53–66, 328–330 (Cambridge Univ. Press, New York, 1990).
17. Dieterich, J. H. & Kilgore, B. Implications of fault constitutive properties for earthquake prediction. *Proc. Natl Acad. Sci.* **93,** 3787–3794 (1996).
18. Menke, W. *Geophysical Data Analysis: Discrete Inverse Theory* 53 (Academic Press, 1989).
19. Harris, R. A. & Simpson, R. W. Suppression of large earthquakes by stress shadows: A comparison of Coulomb and state-and-rate failure. *J. Geophys. Res.* **103,** 24439–24451 (1998).
20. Deng, J., Hudnut, K., Gurnis, M. & Hauksson, E. Stress loading from viscous flow in the lower crust and triggering of aftershocks following the 1994 Northridge, California, earthquake. *Geophys. Res. Lett.* **26,** 3209–3212 (1999).

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The earliest known sauropod dinosaur

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Sauropods were a very successful group of dinosaurs during the Jurassic and Cretaceous periods, but their earlier history is poorly known. Until now, the earliest reported sauropod bones were from the Early Jurassic[1–3], and the only tentative evidence of earlier sauropods was in the form of controversial footprints[4,5]. Here we report the discovery of an incomplete sauropod skeleton from the Late Triassic period of Thailand, which provides the first osteological evidence of pre-Jurassic sauropods. This dinosaur is markedly different from prosauropods and substantiates theoretical predictions that there was a fairly long period of sauropod evolution during the Triassic.

Dinosauria Owen, 1842
Saurischia Seeley, 1888
Sauropodomorpha Huene, 1932
Sauropoda Marsh, 1878
Isanosaurus attavipachi gen. et sp. nov.

Etymology. Generic name from *Isan*, the local name for northeastern Thailand, and *sauros*, Greek for lizard. Specific name in honour of P. Attavipach, former Director General of the Thai Department of Mineral Ressources, a long-time supporter of palaeontological research.

Holotype. Associated skeletal elements (Fig. 1) consisting of one cervical, one dorsal and six caudal vertebral centra, the neural arch of a posterior dorsal vertebra, two chevron bones, fragmentary ribs, a right sternal plate, a right scapula and a left femur (Palaeontological collection, Department of Mineral Ressources, Thailand: CH4).

Horizon and locality. The bones were found in 1998 in a natural outcrop of dark red sandstones of the Nam Phong Formation at Phu Nok Khian hill near Ban Non Thaworn village, in Chaiyaphum Province, on the Khorat Plateau of northeastern Thailand. They are clearly remnants of a single skeleton that had largely been eroded away before the first elements were discovered. Unfused neurocentral sutures indicate that the individual (possibly about 6.5 m long) may not have been fully grown.

Age. The fluviatile Nam Phong Formation contains palynomorphs showing that it cannot be younger than Rhaetian[6], and overlies the Huai Hin Lat Formation, which is well dated as Norian on the basis of its vertebrate fauna and palynoflora. It is therefore well dated as late Norian or Rhaetian[6].The only vertebrate fossil hitherto reported from the Nam Phong Formation was fused ischia referred to a large prosauropod[7]. Whether they might in fact belong to *I. attavipachi* cannot be ascertained because no ischia were found at Phu Nok Khian.

Diagnosis. A primitive sauropod dinosaur with a robust femur bearing a very prominent, acuminate, S-shaped fourth trochanter located in the proximal half of the bone.

Some characters of *I. attavipachi* clearly place it among the Sauropoda, whereas others indicate a basal position within that group. It has been compared with prosauropods[8], especially the somewhat sauropod-like Melanorosauridae[9,10], and with primitive sauropods. Although other primitive sauropods are known[11], comparisons were made mainly with the following sufficiently well described forms, with significant skeletal elements also present in the Thai specimen: *Vulcanodon karibaensis*[1] (basal Jurassic, Zimbabwe), *Barapasaurus tagorei*[2] and *Kotasaurus yamanpalliensis*[3] (from the supposedly Early Jurassic Kota Formation of India, which may in fact be as recent as Early Cretaceous on the basis of palynology; G. V. R. Prasad, personal communication), *Zizhongosaurus chuanchengensis*[12] and *Gongxianosaurus shibeiensis*[13] (Early Jurassic, China), and *Shunosaurus lii*[14] (Middle Jurassic, China). The vertebrae differ from those of prosauropods, but in many respects are less advanced than those of later sauropods. A short cervical centrum, with parapophyses at mid-height (suggesting a posterior position), is markedly opisthocoelous, unlike the amphicoelous centra of prosauropods or the anteriorly flat ones of *Gonxianosaurus*[13]. It shows a strong ventral median ridge, a primitive feature in sauropods[15]. Its sides are deeply concave rather than excavated by real pleurocoels as in more advanced sauropods. Such lateral depressions also occur on a posterior dorsal centrum. In this regard, the presacral vertebrae of *I. attavipachi* resemble those of *B. tagorei* and *S. lii*. An isolated neural arch, probably from a posterior dorsal vertebra, is remarkably tall, as in some later sauropods, but unlike the relatively low neural spines of prosauropods. However, the spine is longer (rostrocaudally) than it is broad (transversely), which is primitive for sauropods[16]. In this respect, *Isanosaurus* is less advanced than *B. tagorei* and *Z. chuanchengensis*, in which the spine is broadened transversely; it resembles Middle Jurassic sauropods, such as *S. lii*, *Lapparentosaurus madagascariensis* from Madagascar and *Volkheimeria chubutensis* from Patagonia, which show laterally flattened dorsal neural spines[15,17]. Incipient posterolateral laminae and a ridge extending from the transverse process to the base of the spine are sauropod features[15] not seen in prosauropods (including sauropod-like forms such as *Lessemsaurus*[17], from the Late Triassic of Argentina), and more developed in later forms[15], including *Volkheimeria* and *Lapparentosaurus*[17]. The caudal centra are amphicoelous. The incomplete scapula is reminiscent of *Shunosaurus*, with a moderate, dorsally rounded proximal expansion (primitive for sauropods[15]), and a slight distal expansion. The semicircular sternal plate bears a low ridge on the outer surface.

The 76-cm-long femur of *I. attavipachi* (Fig. 2) is robust, with a sauropod-like straight, craniocaudally flattened shaft, with no indication of the sigmoid curvature usually seen in prosauropods (including large forms such as *Riojasaurus*[18], although some melanorosaurids, such as *Camelotia*[9], have fairly straight femora). There is a well defined, dorsomedially oriented articular head, unlike the condition in prosauropods, which have a more hook-shaped articular head, even in large plateosaurids[19] and melanorosaurids[9,10]. The greater trochanter is massive and bulging. There is no evidence of a lesser trochanter, unlike the condition in prosauropods[8] and *Vulcanodon*[1]. The fourth trochanter is in a very proximal position, as in some primitive dinosaurs[20]. It forms a prominent S-shaped ridge on the caudal face of the shaft, close to the medial edge, ending distally in a slightly hook-shaped acute tip reminiscent of *Barapasaurus* and *Vulcanodon*. Although not wing-shaped as in prosauropods, the fourth trochanter of *Isanosaurus* is more prominent than in *Vulcanodon*, *Shunosaurus* and *Barapasaurus*. Its very peculiar shape, unlike the condition in other sauropods, is considered as an autapomorphic character of this taxon, which otherwise mainly shows features that are plesiomorphic for sauropods. The strongly expanded distal end of the femur shows massive condyles, a well developed ectepicondyle (not usually seen in

Figure 2 Left femur of *Isanosaurus attavipachi* (CH4-1). **a**, Anterior and **b**, posterior views. The arrow shows the peculiar S-shaped fourth trochanter. The white area between the fourth trochanter and the proximal articular head corresponds to a section of the specimen where the outer part of the bone is damaged but an inner continuity is present. Scale bar: 10 cm.

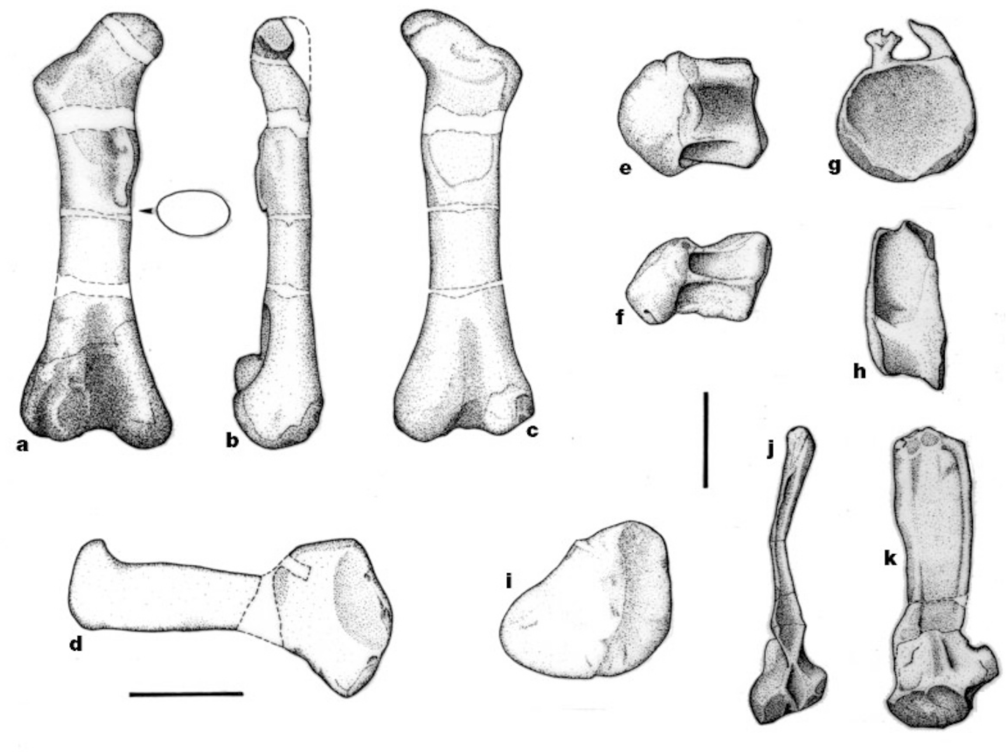

Figure 1 *Isanosaurus attavipachi*, elements of the holotype, palaeontological collection of the Department of Mineral Ressources, Thailand, no. CH4. **a**–**c**, Left femur (CH4-1) in posterior (**a**, with cross-section at level of distal end of fourth trochanter), medial (**b**) and anterior (**c**) views. **d**, Right scapula in lateral view. **e**, **f**, Centrum of cervical vertebra (CH4-3) in left lateral (**e**) and ventral (**f**) views. **g**, **h**, Centrum of posterior dorsal vertebra (CH4-6) in posterior (**g**) and left lateral (**h**) views. **i**, Right sternal plate in external view. **j**, **k**, Neural arch of posterior dorsal vertebra (CH4-7) in posterior (**j**), and right lateral (**k**) views. Horizontal scale bar (for **a**–**d**): 20 cm. Vertical scale bar (for **e**–**k**): 10 cm. Drawings by H.T.

prosauropods), and no longitudinal crest proximal to the lateral condyle (unlike prosauropods[10]).

I. attavipachi can clearly be placed among the Sauropoda because of the above-mentioned derived sauropod characters of its vertebrae and femur, which separate it from the Prosauropoda. Its primitive features are not particularly reminiscent of the Prosauropoda; rather, they seem to illustrate an early stage in the evolution of characters more fully developed in later, more advanced sauropods. Comparisons with other primitive sauropods reveal differences (notably in the femur), but their phylogenetic significance is uncertain. Although there is no consensus about the relationships of the oldest sauropods, recent phylogenies[15,16,21,22] consistently place *Vulcanodon* in a very basal position; *Gongxianosaurus* also exhibits a number of primitive features reminiscent of prosauropods[13]. Comparisons between *Isanosaurus* and *Vulcanodon* are difficult, because few significant elements are known in both, although their femora are different. The opisthocoelous cervical vertebrae of *Isanosaurus* show that it is more advanced than *Gongxianosaurus*, in which there are no opisthocoelous vertebrae[13]; their femora also appear to be different. Uncertainties about the interrelationships of early sauropods, as expressed by the common use of the paraphyletic family Vulcanodontidae[15], make it difficult to assess the exact phylogenetic and systematic position of *Isanosaurus*. A detailed analysis of early sauropod phylogeny being outside the scope of this paper, we refer *Isanosaurus* to Sauropoda incertae sedis.

The discovery of *I. attavipachi* not only shows that by late Triassic times the Sauropoda had already appeared, but also suggests that they must have had a relatively long and almost completely unknown evolutionary history in the Late Triassic, during which they coexisted with another group of large-bodied, heavily built sauropodomorphs, the melanorosaurid prosauropods. This is not unexpected, as calibrated phylogenies of the Sauropoda[16,22] all show the history of the group extending well down into the Late Triassic. However, this assumption was theoretical and based mainly on the idea that the Sauropoda are the sister-group of the Prosauropoda. The remains of *I. attavipachi* are the first osteological evidence demonstrating the existence of Triassic sauropods. Previously, the only tentative fossil evidence for Triassic sauropods consisted of footprints[4,5] (especially *Deuterosauropodopus*[23], from Lesotho), the attribution of which to sauropods is controversial[4,5,24,25].

Northeastern Thailand was already linked to China in the Late Triassic[26], and the earliest well attested sauropod is thus an Asian form. Even if ichnological evidence from the Late Triassic of southern Africa is inconclusive, *Vulcanodon* definitely indicates that sauropods occurred there at the very beginning of the Jurassic. Convincing sauropod footprints have been reported from the basal Jurassic (Hettangian) of Poland[27] and Italy[28]. All this suggests that by the time of the Triassic–Jurassic boundary, sauropods already had a vast geographical distribution, doubtless made possible by Pangaean palaeogeographical conditions. □

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1. Cooper, M. R. A reassessment of *Vulcanodon karibaensis* Raath (Dinosauria: Saurischia) and the origin of the Sauropoda. *Palaeontol. Afr.* **25,** 203–231 (1984).
2. Jain, S. L., Kutty, T. S., Roychowdhury, T. & Chatterjee, S. in *IV International Gondwana Symposium* 204–216 (Hindustan Publishing Corporation, Delhi, 1979).
3. Yadagiri, P. A new sauropod *Kotasaurus yamanpalliensis* from Lower Jurassic Kota Formation of India. *Rec. Geol. Surv. India* **11,** 102–127 (1988).
4. Ellenberger, F. & Ellenberger, P. Principaux types de pistes de vertébrés dans les couches du Stormberg au Basutoland (Afrique du Sud). *C. R. Somm. Séanc. Soc. Géol. Fr.* **4,** 65–67 (1958).
5. Charig, A. J., Attridge, J. & Crompton, A. W. On the origin of the sauropods and the classification of the Saurischia. *Proc. Linn. Soc. Lond.* **176,** 197–221 (1965).
6. Racey, A. *et al.* Stratigraphy and reservoir potential of the Mesozoic Khorat Group, NE Thailand. *J. Petrol. Geol.* **19,** 5–40 (1996).
7. Buffetaut, E., Martin, V., Sattayarak, N. & Suteethorn, V. The oldest known dinosaur from southeast Asia: a prosauropod from the Nam Phong Formation (late Triassic) of northeastern Thailand. *Geol. Mag.* **132,** 739–742 (1995).
8. Galton, P. M. in *The Dinosauria* (eds Weishampel, D. B., Dodson, P. & Osmolska, H.) 320–344 (Univ. California Press, Berkeley, 1990).
9. Galton, P. M. Notes on the Melanorosauridae, a family of large prosauropod dinosaurs (Saurischia: Sauropodomorpha). *Geobios* **18,** 671–676 (1985).
10. Gauffre, F. X. The most recent melanorosaurid (Saurischia, Prosauropoda), Lower Jurassic of Lesotho, with remarks on the prosauropod phylogeny. *N. Jb. Geol. Paläont. Mh* **11,** 648–654 (1993).
11. Barrett, P. A sauropod dinosaur from the Lower Lufeng Formation (Lower Jurassic) of Yunnan Province, People's Republic of China. *J. Vert. Paleontol.* **19,** 785–787 (1999).
12. Dong, Z., Zhou, S. & Zhang, Y. The dinosaurian remains from Sichuan Basin, China. *Palaeontol. Sinica C* **23,** 1–145 (1983).
13. He, X., Wang, C., Liu, S., Zhou, F., Liu, T. Cai, K. & Dai, B. A new species of sauropod from the Early Jurassic of Gongxian County, Sichuan. *Acta Geologica Sichuan* **18,** 1–7 (1998).
14. Zhang, Y. *The Middle Jurassic Dinosaur Fauna from Dashanpu, Zigong, Sichuan* vol. 1 1–89 (Sichuan Publishing House of Science and Technology, Chengdu, 1988).
15. Upchurch, P. The phylogenetic relationships of sauropod dinosaurs. *Zool. J. Linn. Soc.* **124,** 43–103 (1998).
16. Wilson, J. A. & Sereno, P. C. Early evolution and higher-level phylogeny of sauropod dinosaurs. *Soc. Vert. Paleontol. Mem.* **5,** 1–68 (1998).
17. Bonaparte, J. F. Evolucion de las vertébras presacras en Sauropodomorpha. *Ameghiniana* **36,** 115–187 (1999).
18. Bonaparte, J. F. Los tetrapodos del sector superior de la formacion Los Colorados; La Rioja, Argentina (Triasico superior). *Opera Lilloana* **22,** 1–183 (1971).
19. Wellnhofer, P. Prosauropod dinosaurs from the Feuerletten (Middle Norian) of Ellingen near Weissenburg in Bavaria. *Rev. Paléobiologie vol. spéc.* **7,** 263–271 (1993).
20. Sues, H. D. in *The Dinosauria* (eds Weishampel, D. B., Dodson, P. & Osmolska, H.) 143–147 (Univ. California Press, Berkeley, 1990).
21. McIntosh, J. S. in *The Dinosauria* (eds Weishampel, D. B. , Dodson, P. & Osmolska, H.) 345–401 (Univ. California Press, Berkeley, 1990).
22. Upchurch, P. The evolutionary history of sauropod dinosaurs. *Trans. R. Soc. Lond. B* **349,** 365–390 (1995).
23. Ellenberger, P. Contribution à la classification des pistes de vertébrés du Trias. Les types du Stormberg d'Afrique du Sud (I). *Palaeovertebrata Mém. Extr.* 1–104 (1972).
24. Haubold, H. *Saurierfährten* (A. Ziemsen, Wittenberg-Lutherstadt, 1984).
25. Thulborn, T. *Dinosaur Tracks* (Chapman and Hall, London, 1990).
26. Buffetaut, E. & Suteethorn, V. in *Biogeography and Geological Evolution of SE Asia* (eds Hall, R. & Holloway, J. D.) 83–90 (Backhuys, Leiden, 1998).
27. Gierlinski, R. & Sawicki, R. New sauropod tracks from the Lower Jurassic of Poland. *Geol. Quart.* **42,** 477–480 (1998).
28. Avanzini, M., Frisia, S., Van den Driessche, K. & Keppens, E. A dinosaur tracksite in an early Liassic tidal flat in northern Italy: paleoenvironmental reconstruction from sedimentology and geochemistry. *Palaios* **12,** 538–551 (1997).

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Biochemical evidence of cannibalism at a prehistoric Puebloan site in southwestern Colorado

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The existence of cannibalism is one of the most controversial issues in the archaeology of the American Southwest. Disarticulated, cut-marked and heat-altered human remains from non-burial contexts at prehistoric Puebloan (Anasazi) archaeological sites in the Four Corners region of the American Southwest have been interpreted by some scholars as evidence of cannibalism[1]. Osteological studies indicate that many of the disarticulated