

propagate away from the wells and disturbs a larger and larger volume, the probability increases that fluid pressure will encounter a larger fault and induce a larger-magnitude earthquake. The absence of earthquakes in regions above the critical pressure threshold may result from either a lack of faults or lack of well-oriented, critically stressed faults. Alternatively, fluid flow may preferentially migrate along bedding structure (Fig. 2A).

Though seven earthquakes were recorded in 2006 to 2009 near the base of the SE OKC wellbores (10), the main swarm began ~15 km to the northeast (fig. S9), despite the high modeled pressure perturbation near the wells. Earthquakes in 2009 primarily occurred, within location uncertainty, near injection wells or on the nearest known faults to the northeast of the wells (fig. S9). Focal mechanisms near the swarm onset indicate fault planes at orientations favorable to failure (19) (Fig. 2, inset B). Faults subparallel to the north-northwest-south-southeast-trending Nemaha fault would not be well oriented for failure in the regional ~N70E stress regime (25) and would require substantially larger pressure increase to fail. Recent earthquakes near the fault may be evidence for continued pressure increase. This 50-km-long segment of the Nemaha fault is capable of hosting a *M*7 earthquake based on earthquake scaling laws (20), and the fault zone continues for hundreds of kilometers. The increasing proximity of the earthquake swarm to the Oklahoma City metropolitan area.

Our earthquake relocations and pore pressure models indicate that four high-rate disposal wells are capable of increasing pore pressure above the reported triggering threshold (21–23) throughout the Jones swarm and thus are capable of triggering ~20% of 2008 to 2013 central and eastern U.S. seismicity. Nearly 45% of this region's seismicity, and currently nearly 15 *M* > 3 earthquakes per week, may be linked to disposal of fluids generated during Oklahoma dewatering and after hydraulic fracturing, as recent Oklahoma seismicity dominantly occurs within seismic swarms in the Arbuckle Group, Hunton Group, and Mississippi Lime dewatering plays. The injection-linked seismicity near Jones occurs up to 35 km away from the disposal wells, much further than previously considered in existing criteria for induced seismicity (13). Modern, very high-rate injection wells can therefore affect regional seismicity and increase seismic hazard. Regular measurements of reservoir pressure at a range of distances and azimuths from high-rate disposal wells could verify our model and potentially provide early indication of seismic vulnerability.

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29. Monthly average volume was calculated by using reported volumes for any month with nonzero volume in data available from 1995 through 2012 (15). Injection rates over 90% larger than the median monthly value in a given year for each well were removed from calculations to remove data entry errors.

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#### SUPPLEMENTARY MATERIALS

[www.sciencemag.org/content/345/6195/448/suppl/DC1](http://www.sciencemag.org/content/345/6195/448/suppl/DC1)  
Materials and Methods  
Figs. S1 to S10  
Tables S1 to S9  
References (30–41)

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## DINOSAUR EVOLUTION

# A Jurassic ornithischian dinosaur from Siberia with both feathers and scales

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Middle Jurassic to Early Cretaceous deposits from northeastern China have yielded varied theropod dinosaurs bearing feathers. Filamentous integumentary structures have also been described in ornithischian dinosaurs, but whether these filaments can be regarded as part of the evolutionary lineage toward feathers remains controversial. Here we describe a new basal neornithischian dinosaur from the Jurassic of Siberia with small scales around the distal hindlimb, larger imbricated scales around the tail, monofilaments around the head and the thorax, and more complex featherlike structures around the humerus, the femur, and the tibia. The discovery of these branched integumentary structures outside theropods suggests that featherlike structures coexisted with scales and were potentially widespread among the entire dinosaur clade; feathers may thus have been present in the earliest dinosaurs.

The origin of birds is one of the most-studied diversification events in the history of life. Principal debates relate to the origin of key avian features such as wings, feathers, and flight (1–9). Numerous finds from China have revealed that diverse theropods possessed feathers and various degrees of flight capability (4–9). The identification of melanosomes in non-avian theropods (10, 11) confirms that fully birdlike feathers originated within Theropoda at least 50 million years before *Archaeopteryx*.

But were feathers more widespread among dinosaurs? Quill-like structures have been reported in the ornithischians *Psittacosaurus* (12) and *Tianyulong* (13), but whether these were true feathers, or some other epidermal appendage, is

unclear. Bristlelike epidermal appendages occur in pterosaurs, some early theropods (14), and extant mammals (“hairs”), and so the *Psittacosaurus*

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and *Tianyulong* filaments might have evolved independently of the feathers of theropods.

Here we report a new ornithischian dinosaur, *Kulindadromeus zabaikalicus*, with diverse epidermal appendages, including grouped filaments that we interpret as avianlike feathers. This suggests that all Dinosauria could have had feathers and that feathers arose for purposes of insulation and signaling and were only later co-opted for flight (10, 11).

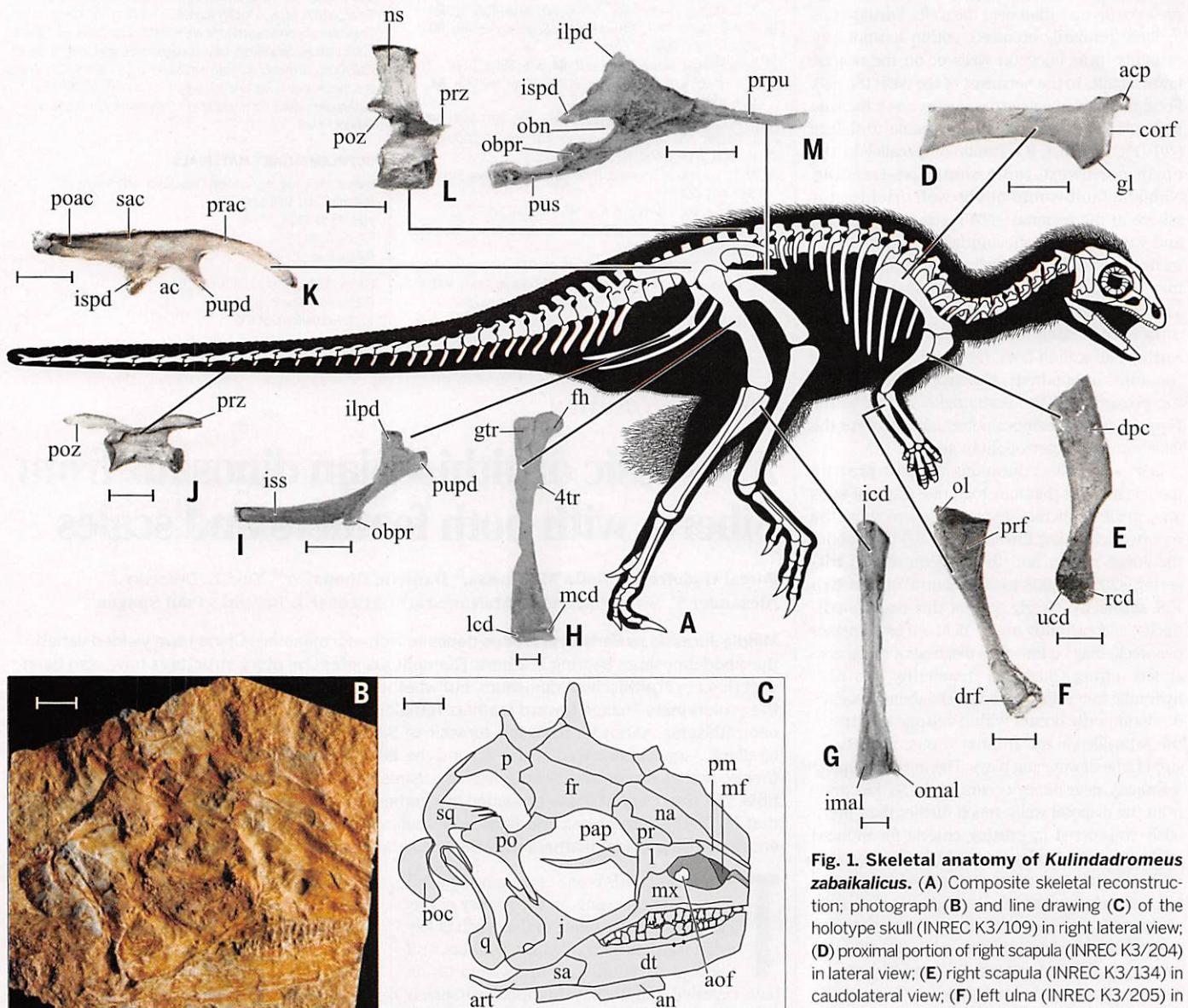
The new dinosaur comes from the Kulinda locality (Cherynshevsky District of Chita Region,

southeastern Siberia, Russia; fig. S1), from the base of the Ukureyskaya Formation, dated as Middle to Late Jurassic (15). The dinosaur bones are associated with abundant, well-preserved fossils of plants, insect larvae, and freshwater crustaceans that suggest deposition in a low-energy, probably lacustrine, freshwater environment. The sequence includes tuff deposits and ignimbrites that indicate local volcanic activity (15).

The description of *Kulindadromeus zabaikalicus* (15) is based on six partial skulls and several hundred disarticulated skeletons unearthed

from two neighboring monospecific bone beds. Each individual skeletal element is represented by a single morphotype, and all of the observed morphological differences can easily be explained by ontogenetic and intraspecific variation, as confirmed by the detailed study of the partial skeletons (15). Therefore, there is no indication that more than one basal ornithischian is present. Many of the bones are strongly iron-stained, suggesting partial replacement during diagenesis.

*Kulindadromeus zabaikalicus* is differentiated from all other dinosaurs by the following



**Fig. 1. Skeletal anatomy of *Kulindadromeus zabaikalicus*.** (A) Composite skeletal reconstruction; photograph (B) and line drawing (C) of the holotype skull (INREC K3/109) in right lateral view; (D) proximal portion of right scapula (INREC K3/204) in lateral view; (E) right scapula (INREC K3/134) in caudolateral view; (F) left ulna (INREC K3/205) in medial view; (G) right tibia (INREC K3/207) in caudal view; (H) right femur (INREC K3/206) in cranial view; (I) right ischium (INREC K3/124) in lateral view; (J) distal caudal vertebra (INREC K3/202) in right lateral view; (K) mirror image of left ilium (INREC K3/113) in lateral view; (L) dorsal vertebra (INREC 3/112) in right lateral view; (M) mirror image of left pubis (INREC K3/114) in lateral view. Scale bars, 10 mm. Abbreviations: ac, acetabulum; acp, acromial process; an, angular; aof, antorbital fossa; art, articular; cor, coracoid facet; dpc, deltopectoral crest; drf, distal radial facet; dt, dentary; fh, femoral head; fr, frontal; gl, glenoid; ilpd, iliac peduncle; imal, inner malleolus; ispd, ischial peduncle; iss, ischial shaft; j, jugal; l, lacrimal; lcd, lateral condyle; mcd, medial condyle; mf, maxillary fenestra; mx, maxilla; na, nasal; obn, obturator notch; obpr, obturator process; ns, neural spine; ol, olecranon process; omal, outer malleolus; p, parietal; pap, palpebral; pm, premaxilla; po, postorbital; poac, postacetabular process; poc, paroccipital process; poz, postzygapophysis; pr, prefrontal; prac, preacetabular process; prf, proximal radial facet; prpu, prepubic process; prz, prezygapophysis; pupd, pubic peduncle; pus, pubic shaft; q, quadrate; qj, quadratojugal; rap, rostral ascending process; rcd, radial condyle; sa, surangular; sac, supraacetabular crest; sq, squamosal; ucd, ulnar condyle; 4tr, fourth trochanter.

characters (Fig. 1, and figs. S4 to S7): maxilla with rostral ascending process much lower than caudal ascending process and maxillary fenestra larger than antorbital fenestra; jugal with notched postorbital ramus; postorbital with dorsoventrally expanded caudal ramus; dorsoventrally slender postacetabular process on ilium; and deep extensor fossae on metatarsals II to IV (15).

It was a small, 1.5-m-long bipedal herbivore, with a short skull, plant-eating teeth, elongate hindlimbs, short forelimbs, and an elongate tail (Fig. 1). Phylogenetic analysis (figs. S10 and S11) (15) recovers *Kulindadromeus* as a basal member of Neornithischia [all genasaurians more closely related to *Parasaurolophus walkeri* than to *Ankylosaurus magniventris* or *Stegosaurus stenops* (16)] and the sister taxon for Cerapoda [*Parasaurolophus walkeri*, *Triceratops horridus*, their most recent common ancestor, and all descendants (16)].

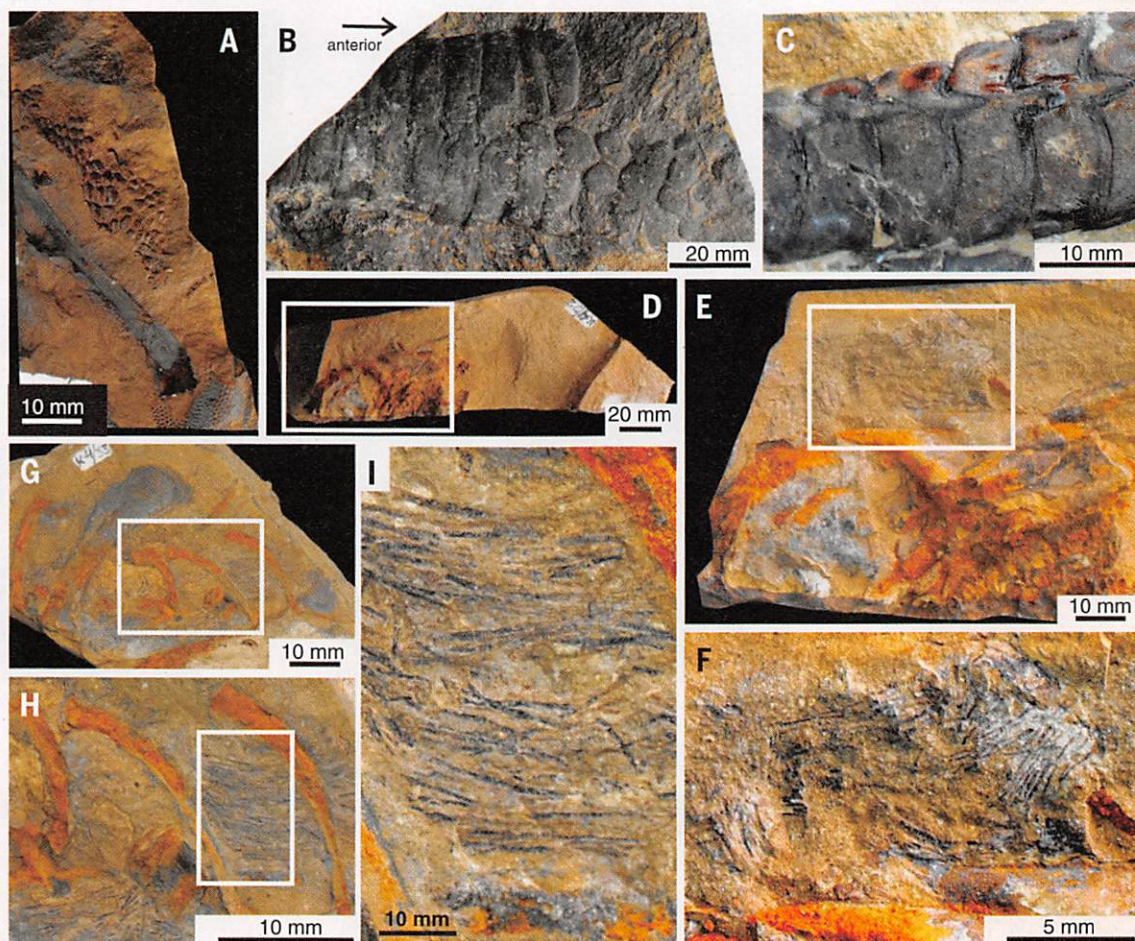
The key features of *Kulindadromeus* relate to its integument. Numerous, varied, exceptionally preserved integumentary features are associated, often in direct connection, with the bones and vary in morphology among different body regions. They comprise three types of scales and three types of featherlike structures.

Small (<3.5 mm long) imbricated and hexagonal scales, resembling the scutella in modern birds (17), are associated with the distal parts of the tibiae in *Kulindadromeus* (Fig. 2A and fig. S8E). Smaller (<1 mm) rounded and non-overlapping scales occur around the manus, tarsus (Fig. 2A and fig. S8E), metatarsus, and pes (fig. S8F), resembling the reticula along the plantar face of the pes in modern birds (17). The tail of *Kulindadromeus* is covered by at least five longitudinal rows of slightly arched scales (Fig. 2, B and C, and fig. S8, A to D). The largest scales (~20 mm long and 10 mm wide) occur along the proximal part of the tail. The caudal scales of *Kulindadromeus* are thin (<100  $\mu\text{m}$ ), unornamented, and slightly imbricated, each scale covering part of the adjacent distal one (Fig. 2C and fig. S8, B to D). They are clearly different from the thicker, sculptured, and nonoverlapping osteoderms in thyreophoran ornithischians (18) and from the proportionally thicker and smaller scales in iguanodontian ornithopods (19), more closely resembling epidermal scales. The preservation of the scales as carbonaceous remains suggests that they are unlikely to be osteoderms, because the bones

(which also comprise calcium phosphate in vivo) display a quite different preservational pathway. Each scale forms a triangular anterior spur that covers the preceding one, so that adjacent elements are interconnected by a clip-like system. Proximally, at the level of the base of the tail (Fig. 2C), the scales become progressively smaller and more rounded and do not overlap.

Monofilaments are widely distributed around the thorax (Fig. 2, G to I), on the back, and around the head (Fig. 2, D to F). Those above the head are thin (~0.15 mm in diameter), short (10 to 15 mm long), and curved, with no preferred orientation. The thoracic and abdominal filaments are wider (0.2 to 0.3 mm) and longer (20 to 30 mm). These monofilaments are shorter and thinner than the long bristlelike structures on the proximal part of the tail in *Psittacosaurus* (12) and the filamentous structures in *Tianyulong* (13). They more closely resemble the monofilaments in the basal coelurosaur *Sinosauropteryx* (20) and are similar to morphotype 1 in a recent evolutionary model of feathers (21).

*Kulindadromeus* also shows compound, non-shafted integumentary structures along the humerus and femur (Fig. 3, A to F, and fig. S9).



**Fig. 2. Epidermal scales and featherlike structures of *Kulindadromeus zabaikalicus*.** (A) Scales around the distal tibia and the tarsus (INREC K4/57); (B) double row of scales above the proximal part of the tail (INREC K4/94) in dorsal view; (C) close-up of the left row of caudal scales (INREC K4/117) in dorsal view; (D) partial skull (INREC K4/22) in right lateral view, with (E and F) detail of areas indicated in (D) and (E) showing filamentous structures; (G) left part of ribcage (INREC K4/33), with (H and I) detail of areas indicated in (G) and (H) showing filamentous structures.

These occur as groups of six or seven filaments that converge proximally and arise from the central regions of a basal plate. Individual filaments are 10 to 15 mm long. Those on the humerus are wider (0.2 to 0.4 mm) and straighter than those on the femur (0.1 to 0.2 mm). These groups of filaments are similar to feather morphotype 3 (21, 22) and resemble the down feathers of some modern chicken breeds, such as the Silkie, which are devoid of barbules (17). The basal plates are also larger on the humerus (3 to 4 mm wide) than on the femur (2 to 3 mm); they are arranged in a hexagonal pattern, but

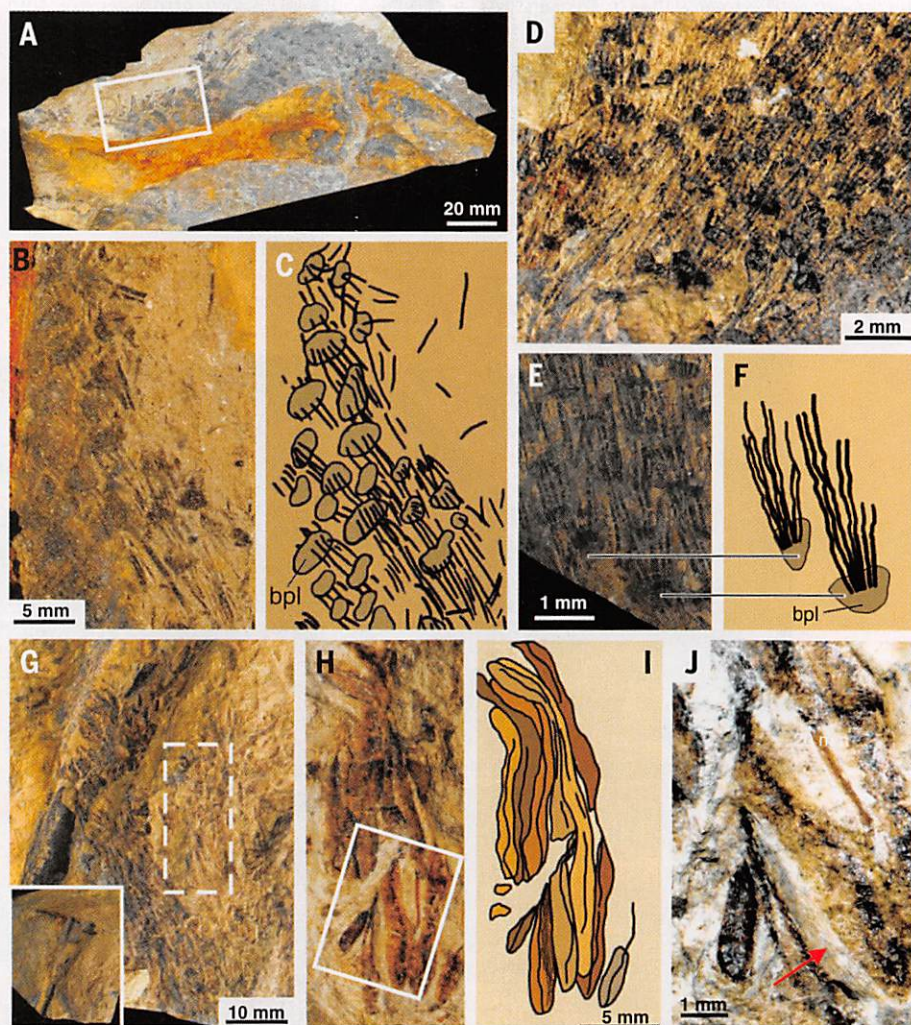
they remain distinctly separated from each other, contrasting with the contiguous distribution of the scales on the distal forelimb, hindlimb, and tail in *Kulindadromeus* and also with the feathered scales that cover the tarsometatarsus of some living birds (17). Whether the basal plates represent modified scales or calamus-like structures remains unclear and requires further investigation.

An additional integumentary morphotype occurs along the proximal part of the tibia in *Kulindadromeus* (Fig. 3, G to J): Clusters of six or seven ribbon-shaped elements appear more or

less bundled together proximally, close to the bone surface. Each individual element is 15 to 20 mm long and 1.5 to 3 mm wide, with a dark median axis along its length (Fig. 3, H to J). Careful removal of a thin superficial carbonaceous sheet reveals the presence of ~10 thin (50 to 100  $\mu\text{m}$ ) internal parallel filaments within each ribbon-shaped element (Fig. 3J). This is an arrangement that has never previously been reported and that could represent a third feather-like morphotype in *Kulindadromeus*.

The presence of both simple and compound filamentous structures in *Kulindadromeus*

**Fig. 3. Featherlike structures in *Kulindadromeus zabaikalicus*.** (A) Right humerus and proximal part of right radius and ulna (INREC K4/115), with detail (B) and interpretative drawing (C) of compound structures around the right humerus; (D and E) compound structures around femur (counterpart of INREC K4/116) with (F) interpretative drawing of (E); (G) ribbonlike structures around proximal part of tibia (INREC K4/44); the inset shows the slab at lower magnification. (H) Detail of area indicated in (G) with interpretative drawing (I) and further details of ribbonlike structures (J); the superficial carbonaceous sheet has been removed during preparation, revealing an internal structure of thin parallel filaments (red arrow). Abbreviation: bpl, basal plate.



**Fig. 4. Reconstruction of *Kulindadromeus zabaikalicus*.** A basal ornithomimid dinosaur, with feathers and scales, from the Middle to Late Jurassic of southeastern Siberia. [Drawing by Pascale Golinvaux (Royal Belgian Institute of Natural Sciences)]

