Fig. 5. (**A**) Scaling of brain vault size (width measured at the level of anterior squamosal/parietal suture) relative to skull size (measured at the distance between the left versus right temporomandibular joints). This shows that allometry of small size of *Hadrocodium*, by itself, is not sufficient to account for its very large braincase. *Had-rocodium's* brain vault is larger (wider) than expected for the crown-group mammals with similar skull width from the allometrical regression. By contrast, all contemporaneous mammaliaforms (triangles: *Sinoconodon*, *Morganucodon*, and *Haldanodon*) with the postdentary trough and meckelian groove have smaller (narrower) brain vaults than those living mammal taxa (and *Hadrocodium*) of comparable skull size. The brain vault is narrower in nonmammaliaform cynodonts (squares: *Chaliminia*, *Massetoganthus*, *Probelesodon*, *Probainognathus*, and *Yunnanodon*) than in mammaliaform stem taxa and much narrower than expected for crown group mammals of similar size. The allometric equation (natural logarithmic scale) for the brain vault width (Y) to the skull width at the level of TMJ (X) for species in the mammalian crown groups (circles: 37 living and 8 fossil species): $Y = 0.98X - 0.31$ ($R^2 - 0.715$). Data from cynodonts, mammaliaforms, and *Hadrocodium* are added second arily for comparison with the regression of extant and fossil species of mammalian crown group. (**B**) Estimated body-size distributions of mammaliaform insectivores in the Early Jurassic Lufeng fauna [following method of Gingerich ([50])]. The estimated 2-g body mass of *Hadrocodium* is in strong contrast to its contemporary mammaliaforms of the Late Triassic and Early Jurassic, such as *Sinconodon* (from ~13 to ~517 g, based on skull length from 22 to 62 mm) and *Morganucodon* (from 27 to 89 g, based on skull length from 27 to 38 mm). This wide range of body sizes indicates a trophic diversity in the paleoguild of triconodont-like insectivores ([53], [54]) in the Lufeng mammaliaform fauna.
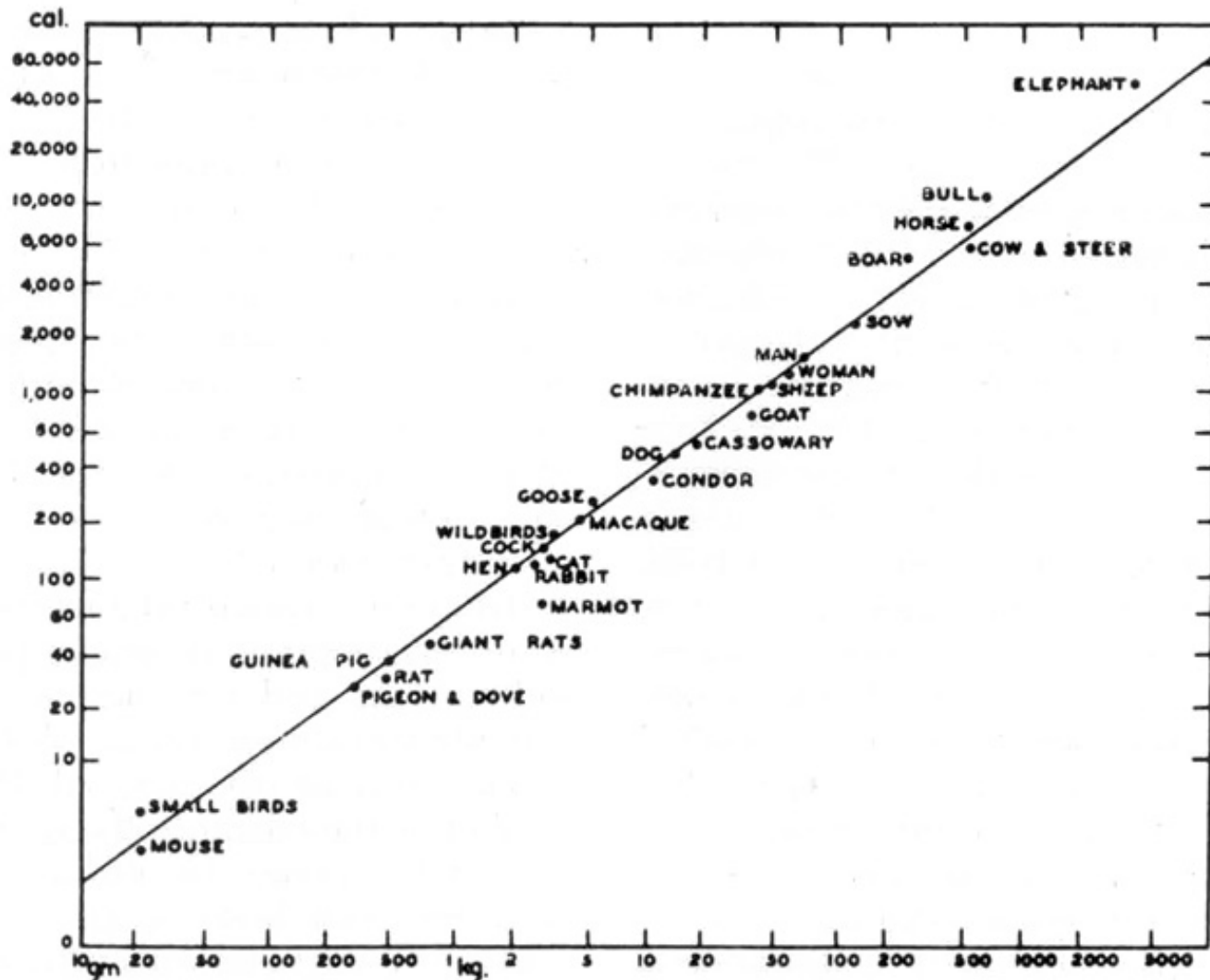
Figure 5–16. Double logarithmic plot of average total heat production and average body weight of birds and mammals. (From Benedict, F. G., Carnegie Inst. Washington Publ. *503*:1–215, 1938.)
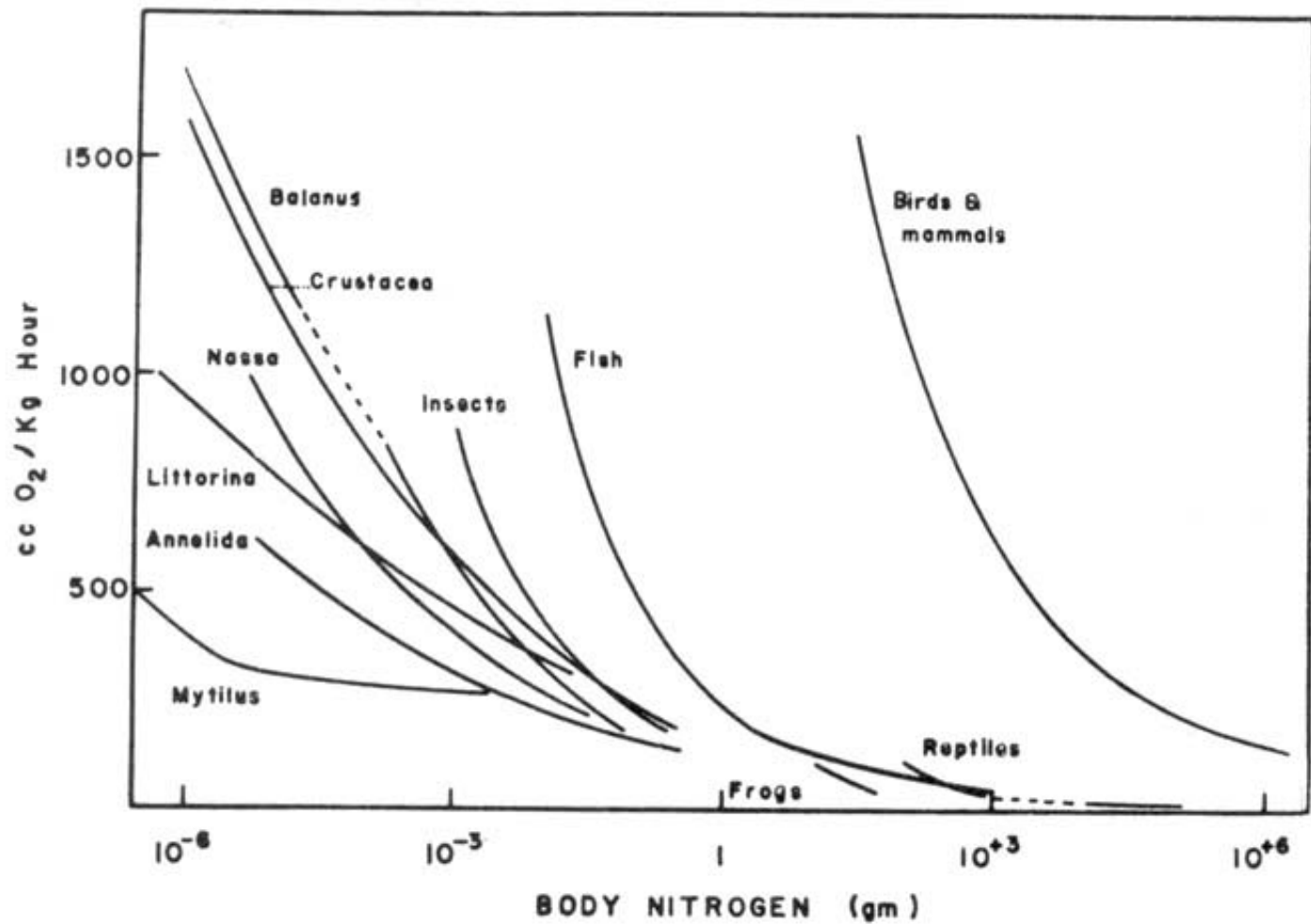
Figure 5–17. Comparison of metabolic rates of various animals as functions of body nitrogen. (From Zeuthen, E., C. R. Lab. Carlsberg, Ser. Chim. *26*:17–161, 1947.)

Fig. 1. *Hadrocodium wui gen. et sp. nov.* (IVPP 8275). (**A**) Lateral and (**B**) ventral views of restored skull. (**C**) Dentition (lateral view restoration). (**D**) Occlusion [based on scanning electron microscope (SEM) photos]. (**E**) Wear of molars (shaded areas are wear facets). The main cusp A of the upper molar occludes in the embrasure between the opposite lower molars. Abbreviations.: an, angular process (dentary); bo, basioccipital; bs, basisphenoid; c, canine; ce, cavum epiptericum; co, coronoid process (of dentary); dc, dentary condyle; er, epitympanic recess; f, frontal; fc, foramen cochleare ("perilymphatic foramen"); fst, fossa for stapedial muscle; fv, fenestra vestibuli; hp, hamulus (of pterygoid); I/i, upper and lower incisors; in, internal nares; iof, infraorbital foramen; J, jugal; jf, jugular foramen; L, lacrimal; lt, lateral trough; M, molar;
mx, maxillary; n, nasal; oc, occipital condyle; P, premolar; Pa, parietal; pcd, postcanine diastema; pgd, postglenoid degression; pr, promontorium (petrosal); ptc, posttemporal canal (between petrosal and squamosal); px, premaxillary; sm, septomaxillary; so, supraoccipital; sof, spheno-orbital fissure; sq, squamosal; tmj, temporomandibular joint (dentary/squamosal jaw hinge); v3, foramen for the mandibular
branch of the trigeminal nerve (v); xii, hypoglossal nerve (xii). Molar cusps following ([11]): A, B, and C, main cusps of upper molars; a, b, c, d, and e, cusps of the lowers
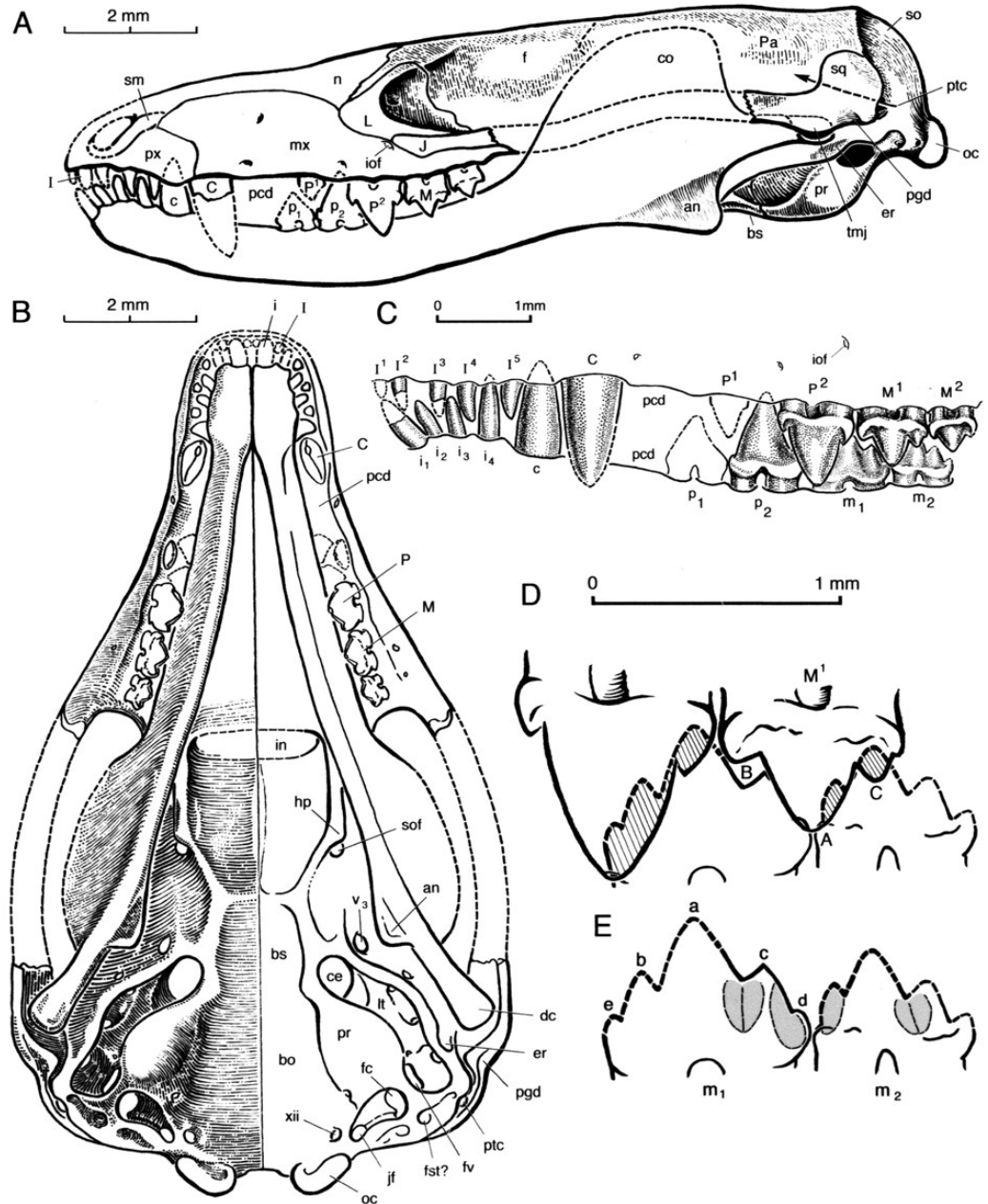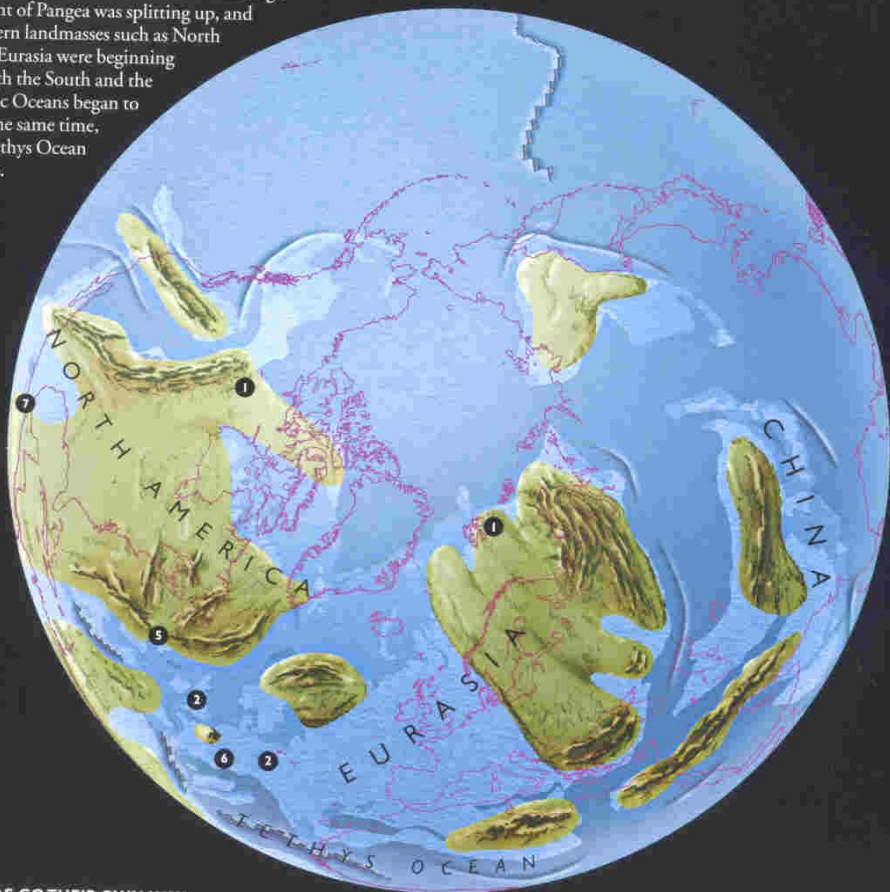
Fig. 3. Correlation of the expanded brain vault and the loss of the postdentary trough and medial concavity of mandibular angle in *Hadrocodium* and more derived mammals. (I, Left) Internal view of dentaries (standardized to one jaw length, scales differ among taxa); the postdentary trough, the medial concavity, and the meckelian sulcus on the mandibular angle are colored in blue. Abbreviations: cma, medial concavity of the mandibular angle; pdt, postdentary trough. (II, Middle) Dorsal view of the cranium (crania of different sizes are standardized to the same width between the left and right temporomandibular joints; scales differ among taxa); the areas in red represent the approximate extent of the brain endocasts. (III, Right) Measurement of the brain vault size (cranial width at the squamosal-parietal suture) relative to the width between the two TMJs; value on bar represents the width of brain vault in percentage of total skull width at the TMJs. *Hadrocodium* (85%) and mammalian crown groups (60% to 87%) with larger brain vaults show the separation of the middle ear ossicles from the mandible. *Hadrocodium* has a larger brain vault than expected for living mammals of its skull size (see allometry regression in Fig. 5B) and is similar to living mammals but different from other contemporaneous mammaliaforms. All primitive mammaliaforms [(A) to (C)] in the basal part of the tree have the postdentary trough and medial concavity of mandibular angle (for postdentary "ear" elements), as well as small brain vault (43 to 58%). The 58% value for *Morganucodon*, although larger than *Haldanodon* and *Sinoconodon*, is far below the ~75% expected for extant mammals of similar skull size (Fig. 5A). (**A**) *Sinconodon*. (**B**) *Morganucodon*. (**C**) *Haldanodon* [after (23)]. (**D**) *Hadrocodium* (brain endocast outline based on the exposed borders on the right side). (**E**) Monotreme *Ornithorhynchus*. (**F**) Monotreme *Tachyglossus*. (**G**) Multituberculate *Chulsanbaatar* [after (36)]. (**H**) Marsupial *Didelphis* [after (33)]. (**I**) Placental *Asioryctes* [after (31)].
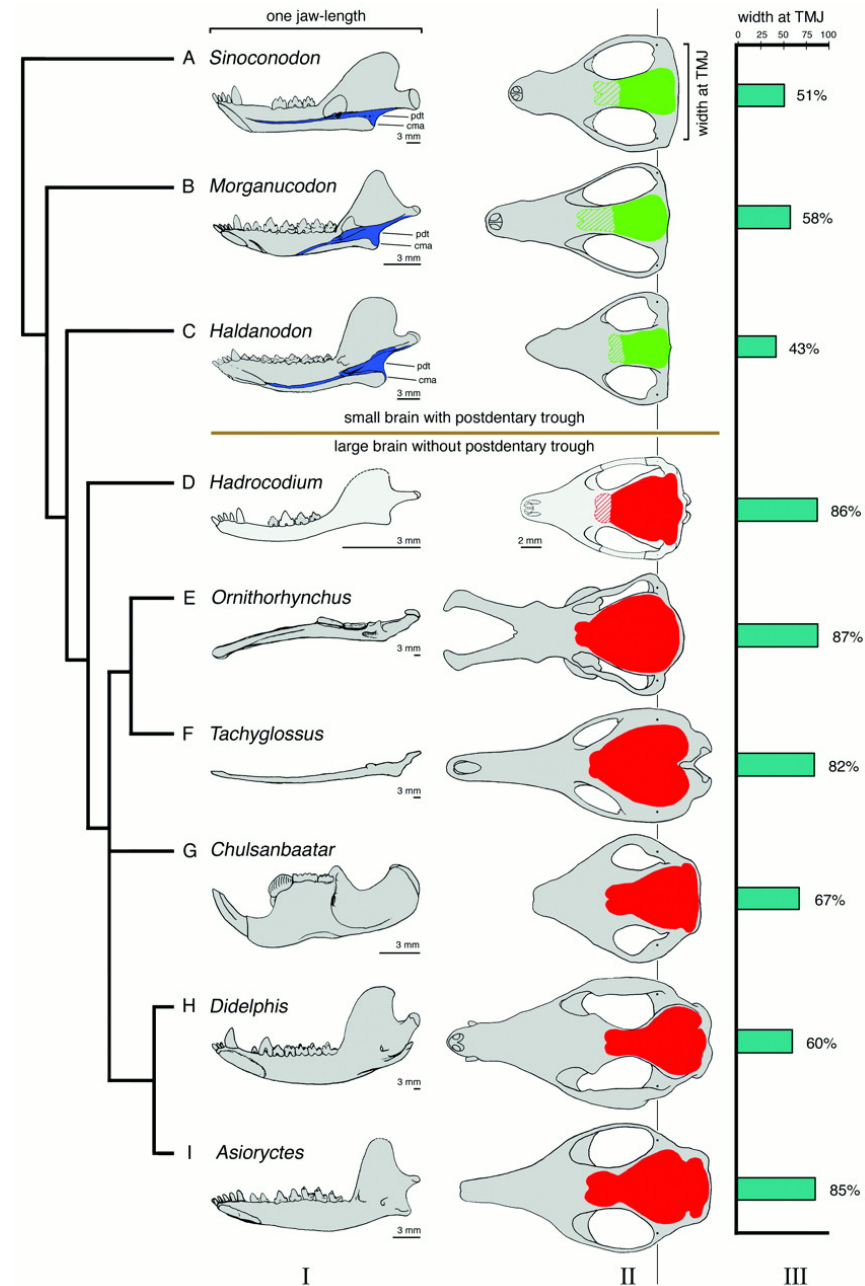
Jurassic Times

Seen from above the poles, the Earth 170 million years ago, during the Jurassic period, was a warmer, less varied place than it is today. There were probably no ice caps at the poles for much of the period, and the mild conditions made for much higher sea levels, resulting in a smaller area of dry land but extensive shallow continental seas, which teemed with life. The huge supercontinent of Pangea was splitting up, and familiar modern landmasses such as North America and Eurasia were beginning to appear. Both the South and the North Atlantic Oceans began to open up. At the same time, the ancient Tethys Ocean began to close.

I. WARM POLES

Although no evidence has been found for polar icecaps during the Jurassic period, there was almost certainly winter snow and ice. Dinosaur and plant fossils found in Siberia and Alaska suggest that even lands close to the poles had relatively mild climates. The types of plant fossils, especially, reveal that annual temperatures averaged between 35° and 45°F (2 to 8°C). Even though the world was warm, the short days of the polar winter would still have meant that plant food was scarce for parts of the year.

7. THE AMERICAS GO THEIR OWN WAY

During the Jurassic period, the landmasses of North and South America began to split, having previously both been part of Pangea. In the west, rising sea levels resulted in a new sea separating the two continents, while farther east, the Tethys Ocean extended to form the Gulf of Mexico. Marine lifeforms flourished on developing reefs in the shallow seas around the Americas, especially in subtropical regions.

6. NAMING THE JURASSIC

The Jurassic period is named for the limestone hills of the Jura located between France and Switzerland. This limestone formed from the sediment that accumulated in the shallow seas covering the area during that time, and contains an abundance of marine animal fossils, especially ammonites.

development of an ear that allowed them to distinguish sounds in a more complex way than reptiles. The small cynodonts were able to burrow, and this life in dark places led to the evolution of whiskerlike structures around the head, designed for feeling a way through tunnels.

animals. *Megazostrodon*, found in southern Africa, was the size and shape of a shrew, small enough to curl up in a matchbox. Its body was long and low, with a flexible backbone and long limbs, which were held out to the side in a primitive squatting posture that is still assumed by some small mammals today.

cavity infilled with opal, a silica mineral similar in composition to flint.

SOUTH AFRICAN INSECT-EATER
Megazostrodon, from late Triassic strata in southern Africa, was 5 inches (12 centimeters) long. This insect-eating, shrewlike animal may have been nocturnal.

RATLIKE MAMMAL
Ptilodus was a primitive rodentlike mammal that lived in early Tertiary times in North America. It belonged to an extinct group of mammals called the multituberculates and probably ate nuts and seeds.
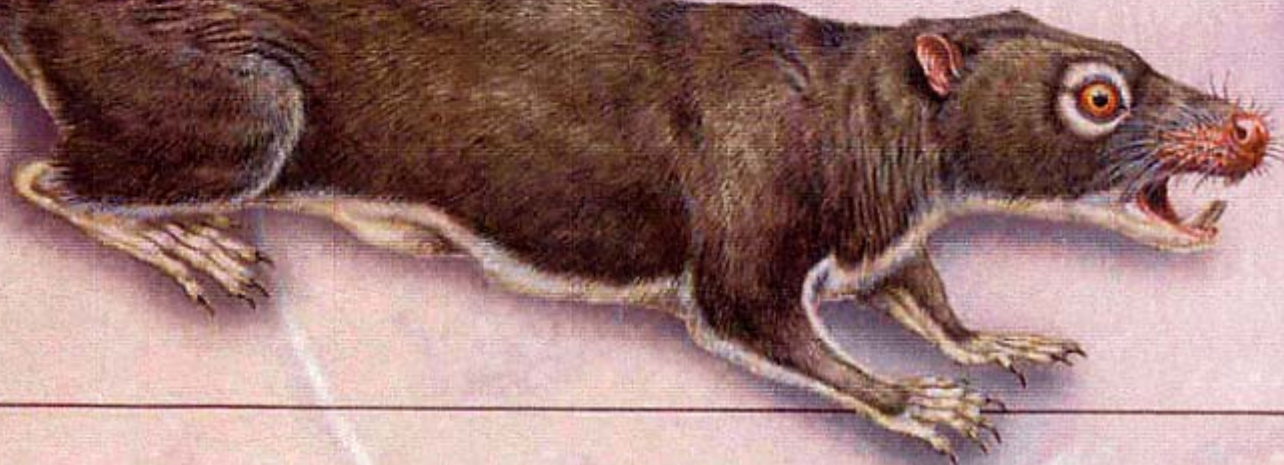
centimeters) long. The reconstruction above is based on an understanding of other primitive primates.

(15 centimeters) and was found in early Jurassic strata in both England and China. It reflected all the mammalian traits of *Adelobasileus* but had a more advanced ear structure.

The teeth of *Morganucodon*, in particular, were typically mammalian. The juvenile milk teeth were followed by a single set for adult life, unlike reptiles whose teeth are replaced several times in a lifetime. The cheek teeth were also developed into premolars and molars, as in all later mammals. Chewing involved a triangular movement of the lower jaw rather than the simpler up and down, back and forth movement of the advanced cynodonts. The teeth suggest that *Morganucodon* was carnivorous, probably feeding on insects and worms at night, when predatory lizards were less active.

The morganucodonts were agile animals capable of fast movement but not sustained running. Their nocturnal habits required them to generate body heat internally. This was achieved by means of their teeth and jaws, which worked to break down food before it reached the stomach, allowing the rapid release of energy from a high-protein diet. To conserve body heat during the night, they would have needed a covering of hair, but so far the fossil record has not revealed this critical soft-tissue evidence. As a group, these small mammals survived for 40 million years.

Altogether within the Mesozoic era, while the dinosaurs dominated the land, 20 or more families of mammals evolved to live in a hidden coexistence with the massive reptiles.

MONGOLIAN PLACENTAL MAMMAL
One of the earliest placental mammals (which could bear well-developed live young) was *Zalambdalestes* (above). This shrewlike animal lived in Mongolia in late Cretaceous times and, like the living elephant shrew, had long back legs.

ELEPHANT SHREW
The fossil record of *Elephantulus* (right) and other elephant shrews extends back to early Tertiary times. They used to be regarded as primitive insectivores, but surprisingly they are closer related to the elephants.