FIGURE 1.1 Differences in postures of a dinosaur and a large modern reptile. (A) Skeleton of the Late Cretaceous ornithopod *Edmontosaurus annectus* from Alberta, Canada. Posterior view of the rear limbs leaving a trackway, showing the typical dinosaurian trait of legs held underneath its body (erect posture). Specimen in the Royal Ontario Museum of Toronto, Ontario. (B) American crocodile, *Crocodylus acutus*, in Costa Rica, showing a sprawling posture and also leaving a trackway. This same typical reptilian posture can change to a semi-erect posture by the crocodile standing up or walking. Photo by Nada Pecnik, from Visuals Unlimited.

FIGURE 1.2 Geologic time scale used as a standard by geologists and paleontologists worldwide. Largest units of geologic time are eons, followed (in order of most inclusive to least inclusive) by subdivisions eras, periods, and epochs. Figure is not scaled according to amounts of time.

FIGURE 1.3 Cladogram of the major dinosaur clades covered in this text, using Saurischia and Ornithischia hip structures as a basis for dinosaur classification.

FIGURE 1.4 Triassic and Jurassic formations of Canyonlands National Park, eastern Utah, an area well known for both dinosaur body fossils and trace fossils. Notice the lack of convenience stores and coffee shops in the field area.

FIGURE 1.5 Photograph from the film *The Valley of the Gwangi* (1969), set in the early twentieth century western USA, with cowboys attempting to capture a large theropod. From Horner and Lessem (1993), *The Complete T. Rex*, Simon & Schuster, NY, p. 87. (Dave Allen/PhotoFest).

FIGURE 1.6 Comparison of photograph and line drawing of a skull of the Late Jurassic theropod *Allosaurus fragilis* from the Morrison Formation (Late Jurassic) of Utah, USA, showing more easily discernable anatomical details in line drawing. Skull is a replica, formerly on display in the Western Colorado Museum of Paleontology, Grand Junction, Colorado, USA.

FIGURE 1.7 A classic painting by Charles R. Knight of the Late Jurassic sauropod *Apatosaurus* (more popularly known as *Brontosaurus*) in an aquatic habitat. First published in *The Century Magazine* (1904) in the article "Fossil Wonders of the West: The Dinosaurs of the Bone-Cabin Quarry, Being the First Description of the Greatest Find of Extinct Animals Ever Made," written by Henry Fairfield Osborn. Transparency No. 2417(5), courtesy of the Library, American Museum of Natural History.

FIGURE 2.1 Hominid footprints overprinting other hominid footprints, suggesting that one hominid purposefully stepped into the footprints of another preceding it. Cast of original trackways, which were preserved in 3.5 million-year-old volcanic ash in Laetoli, Tanzania.

FIGURE 2.2 Scientific assessment of the skull of *Coelophysis baurii*, a Late Triassic theropod. (A) Skull of adult *Coelophysis*, showing qualitative traits (two holes in rear right side of skull, prominent eye socket, sharp teeth); Denver Museum of Science and Nature. (B) Bar graph of skull lengths (n = 15) for *Coelophysis bauri*, arranged in order of increasing length. Based on data from Cope (1887) and summarized by Colbert (1990).

FIGURE 2.3 Example of the difference between fact and hypothesis, as well as description and interpretation. Facts: Two features occur on the surface of a rock in Big Bend National Park in western Texas, USA. Both features show semi-circular and crescentic lines emanating and expanding from a point, but one feature is larger than the other and the larger one is also concave, whereas the smaller one is convex. Hypotheses to explain the features:

1 They are completely unrelated forms of unknown origin;

2 They are odd patterns made in the rock when it fractured on this surface and their similarity in form is a result of the uniformity of the rock, which controlled the fracturing;

3 They are plant leaves that were bent upward and downward in the sediment soon after they were buried in the sediment that later formed the rock;

4 They are trace fossils made by animals that lived long ago in the sediment, where the animals were progressively feeding out from a central point but one went up and the other went down;

5 They are the outside and inside imprint of animal bodies, where the animals were similar but just had different sizes at the time they were buried;

6 They are carvings made in the rock by Native Americans, before Europeans settled in the area, that symbolize the light coming from the sun (the larger one, because it gives more light) and the moon (the smaller one because it gives less light, and also carved in opposite relief to the "sun" to symbolize the opposites of night and day).

FIGURE 2.4 Comparison between *Archaeopteryx*, a Late Jurassic bird, and *Compsognathus*, a Late Jurassic theropod, as an approximate example of a transition between fossil forms as predicted by Darwin's hypothesis of natural selection. Reprinted by permission. From Paul (1988), *The Predatory Dinosaurs of the World*, Simon & Schuster, NY, p. 115.

FIGURE 2.5 Field occurrence of dinosaur bone, Morrison Formation (Late Jurassic), western Colorado, USA. Notice its fragmentary nature and lack of resemblance to specimens seen in mounted displays of dinosaurs in museums.

FIGURE 2.6 Students on a field trip examining possible fossil finds in Tertiary Period rocks of central Georgia, USA. Their descriptions and hypotheses were independently tested through peer review (with each other), then presented as a single hypothesis in modified form to an expert (the author of this textbook), who conditionally accepted their hypothesis but then presented it to another expert (another geologist at the field site) who was more of an expert on the rocks in that area than the author. This geologist reconfirmed the hypothesis of the students: they had found fossil plant leaves. All of this process, from discovery to reconfirmation, took about 15 minutes.

FIGURE 2.7 Diagrams showing how quantitative data can be summarized into histograms with curves approximating the distribution of the values. (Left) Normal distribution. (Right) Skewed distribution. The horizontal axis (abscissa) is in order of increasing value, whereas the vertical axis (ordinate) is in number of observations or data points.

FIGURE 2.8 Sketch of a suspected small dinosaur track from the Middle Jurassic Sundance Formation of Wyoming, with measurements included and indicators of where measurements were taken on the specimen. An observer may have a different definition of "width" and "length" of a track that would be difficult to determine through only a verbal description, whereas the sketch shows clearly what was measured.

FIGURE 3.1 Sketch of probable dinosaur bone *Megalosaurus*, described by Robert Plot in 1677 in *Natural History of Oxfordshire*.

FIGURE 3.2 William Buckland (top) and remains of the first named dinosaur fossil, the lower jaw of *Megalosaurus* (bottom). From Colbert, E. H., 1984, *The Great Dinosaur Hunters and Their Discoveries*, Dover Publications, N.Y., plates 3 and 4.

FIGURE 3.3 The Mantells, Gideon Algernon (left) and Mary Ann (right), who probably were not co-discoverers of *Iguanodon*. From Psihoyos and Knoebber (1994), *Hunting Dinosaurs*, Random House, N.Y., p. 10.

FIGURE 3.4 Sir Richard Owen, inventor of the term "dinosaur". From Psihoyos and Knoebber, 1994, *Hunting Dinosaurs*, Random House, N.Y., page 11.

FIGURE 3.5 Edward Hitchcock, describer of numerous examples of Late Triassic and Early Jurassic dinosaur tracks from the Connecticut River Valley, and dinosaur tracks figured in his 1858 publication. From Amherst College Archives and Special Collections, Negative Collection, Box 1, fig. 69, and Box 3, figs 4a–5a.

FIGURE 3.6 Edward Drinker Cope (left) and Othniel Charles (O.C.) Marsh (right), productive yet antagonistic contemporaries in dinosaur studies. Reprinted from *Science*, 1897 and 1889, respectively.

FIGURE 3.7 Barnum Brown (left) and Henry Fairfield Osborn (right) in the field at Como Bluff, Wyoming, in 1897, with a sauropod (*Diplodocus*) limb bone in the foreground and Late Jurassic Morrison Formation cropping out nearly everywhere else. Negative No. 17808, Photo. Menke. Courtesy Dept. of Library Services, American Museum of Natural History.

FIGURE 3.8 Bar graph showing decreased productivity of dinosaur bones from the Bone Cabin Quarry in number of specimens collected versus year. Data from Colbert (1968).

FIGURE 3.9 Franz Nopcsa, dinosaur paleontologist, Transylvanian nobleman, linguist, spy, and motorcycle enthusiast, shown here in Albanian costume and carrying optional field gear. From Kubacska, András Tasnáde, 1945. Verlag Ungarischen Naturwisenschaftlichen Museum, Budapest/Dover Publications.

FIGURE 3.10 Outcrop of Morrison Formation (Late Jurassic) with extremely abundant dinosaur bones, discovered by Earl Douglass in 1909, Dinosaur National Monument, near Jensen, Utah.

FIGURE 3.11 Map of Howe Quarry, showing horizontal distribution and concentration of dinosaur bones in the quarry area. Squares represent approximately meter squares. Neg. No. 314524. Courtesy Department of Library Services, American Museum of Natural History.

FIGURE 3.12 Boheti bin Amrani at Tendaguru of what is present-day Tanzania, uncovering a sauropod rib during one of the German expeditions to the region. Dr. Bernard Krebs, Lehrstuhl für Paläontologie der Freien Universität, Berlin/Dover Publications.

FIGURE 3.13 Roy Chapman Andrews (right), in the Bain-Dzak area, Mongolia, with Late Cretaceous dinosaur eggs in front of him and his bandit-prevention device behind him. Negative No. 410760, Photo. Shackelford. Courtesy Department of Library Services, American Museum of Natural History.

FIGURE 4.1 Section of a geologic map, which also has contour lines of a topographic map. The contour lines show elevation changes in a landscape, and closely spaced lines indicate relatively steeper elevation changes than widely spaced lines. Rock formations are mapped on the basis of their outcrop patterns, and letter symbols on the map correspond to the age and name of the formation (i.e., Jm is the Morrison Formation, which is Jurassic). US Geological Survey Map GQ 57, 1955.

FIGURE 4.2 Idealized diagram of basic field relations of rocks that can be used to determine relative ages, using original horizontality, superposition, lateral continuity, inclusions, cross-cutting relationships, and biologic succession. Phenomena are labeled from oldest (1) to youngest (19).

FIGURE 4.3 Fault cross-cutting thick stratigraphic sequence of the Santa Elana Limestone (Late Cretaceous) in Big Bend National Park, Texas. Students for scale.

FIGURE 4.4 Labeled unconformity near Morrison, Colorado (adjacent to Red Rocks Amphitheatre), separating the Fountain Formation (Pennsylvanian Period, about 300 Ma) from a 1.7 billion-year-old Precambrian metamorphic rock (gneiss); the surface represents a lost record of about 1400 million years.

FIGURE 4.5 Igneous rock cross-cutting sedimentary rock (Pen Formation) in Big Bend National Park, Texas. The sedimentary rock has fossils indicating that it is Late Cretaceous, about 70 Ma. The cross-cutting igneous rock should be younger, and it is. Radiometric dates derived from it and related rocks in the region indicate that they were formed in the Tertiary Period. English professor for scale.

FIGURE 4.6 Exponential loss of a parent element (^{238}U) through time, showing changes in ratio with relation to the daughter element (^{206}Pb) with each half-life. Note that the plot follows a curved line, not a straight line.

FIGURE 4.7 Map view of lithospheric plates involved in plate tectonics. Reprinted by permission from R. Cowen, *History of Life*, p. 98. (© 1995 Blackwell Science, Inc., Malden, MA.)

FIGURE 4.8 The rock cycle as explained through plate tectonics, showing relationship of lithosphere and asthenosphere, as well as convergent, divergent, and transform-fault boundaries.

FIGURE 4.9 (*opposite*) Steps in excavation of a vertebrate fossil, in this case a partially exposed skull and other bones of a metoposaur, a large amphibian that lived at the same time (and in this case, the same region) as early dinosaurs, Chinle Formation (Late Triassic), Arizona. (A) After cleaning the area, workers estimated the extent of the fossil and dug around the defined area. (B) Digging of the rock underneath the fossil established a pedestal. (C) One worker placed wet paper towels on the top to cushion and separate the fossil from the plaster. (D) Another worker placed the plaster-soaked burlap strips for the jacket all around the pedestal. The workers then waited until the next day for the plaster to have hardened before breaking the pedestal, turning over the rock, and jacketing the underside.

FIGURE 4.10 Pelvis of *Apatosaurus* from the Morrison Formation (Late Jurassic), western Colorado, still partially encased in its protective jacket and in a preparatory lab associated with the former Museum of Western Colorado, Grand Junction, Colorado. Notice the plastic model sauropod in the background, ready to help with estimating the weight of the original animal (Chapter 1).

FIGURE 4.11 *Tyrannosaurus rex* mount, which uses artificial casts of the bones and thus allows for the unusual pose of the display; Denver Museum of Science and Nature, Colorado. Author (imitating the pose in the foreground) for scale.

FIGURE 5.1 Orientation terminology as applied to anatomical features in vertebrates, using the skeletons of the Early Cretaceous theropod *Deinonychus antirrhopus* (left) and a modern human *Homo sapiens* (right).

FIGURE 5.2 Left-lateral view of pelvic bones in relation to acetabulum and proximal end of femur for typical saurischian (left) and ornithischian (right) hips in dinosaurs.

FIGURE 5.3 Different types of vertebrae along axial skeleton in the prosauropod *Plateosaurus* from the Late Triassic of Germany: 10 cervical, 15 dorsal, 3 sacral, 50 caudal.

FIGURE 5.4 Cranial bones in *Allosaurus fragilis*: compare with Figure 1.6.

FIGURE 5.5 Pectoral girdle of the Late Cretaceous hadrosaur *Edmontosaurus* of North America. Denver Museum of Science and Nature, Denver, Colorado.

FIGURE 5.6 Scapula and its articulation with the humerus and glenoid.

FIGURE 5.7 Phalangeal formula applied to a human hand as an example.

FIGURE 5.8 Characters for dinosaurs involving the appendicular skeleton. (A) Sacrum, proximal end of the femur, and the fit of the latter into the acetabulum. (B) Tibia, showing two traits of dinosaurs: cnemial crest and astragalus.

FIGURE 5.9 Lateral view of right hind limbs in digitigrade mode. (A) Modern canine. (B) Modern human. (C) Early Cretaceous theropod *Giganotosaurus* of Argentina. Fernbank Museum of Natural History, Atlanta, Georgia.

FIGURE 5.10 Hadrosaur skin impression, Late Cretaceous of North America. Mesa State Community College Museum, Tucumcari, New Mexico.

FIGURE 5.11 Restoration of skin and musculature for: (A) Late Triassic theropod *Coelophysis bauri* of North America: Denver Museum of Science and Nature; (B) Late Jurassic sauropod *Apatosaurus louisae* of North America: Dinosaur National Monument, Utah.

FIGURE 5.12 Hypothetical evolution of mice and how their synapomorphies (novelties) would contribute to their cladistic classification.

FIGURE 5.13 Currently accepted cladogram for dinosaurs, beginning with Chordata and ending with the Saurischia and Ornithischia and main monophyletic groups within these clades.

FIGURE 6.1 Main originators of the hypothesis of natural selection, Charles Darwin (left) and Alfred Russel Wallace (right). From Ridley (1996), *Evolution*, 2e, Blackwell Science, Inc., Malden, MA, pp. 9 and 10.

FIGURE 6.2 Hypothetical example of changes in genotype frequencies in the ceratopsian *Centrosaurus* with a dominant allele (H) for a smaller-horned phenotype. (A) First generation, with one parent homozygous dominant and the other homozygous recessive. (B) Second generation, with both parents heterozygous.

FIGURE 6.3 Continental landmasses during the Mesozoic showing how dinosaur populations became increasingly isolated through time. (A) Late Jurassic (about 140 Ma). (B) Late Cretaceous (about 80 Ma). From Cowen (1995), *History of Life*, 2e, Blackwell Science, Inc., Malden, MA, p. 82, figs. 5.13 and 5.14.

FIGURE 6.4 Components of an amniotic egg, including the eggshell, allantois, yolk sac, amnion, and embryo. Such eggs are a defining character of the clade Amniota, and by extension of dinosaurs. After Cowen (2000), *History of Life*, 3e, Blackwell Science, Inc., Malden, MA, p. 147, fig. 9.12.

FIGURE 6.6 *Dimetrodon*, a Permian synapsid and pelycosaur that was carnivorous, but definitely was not a dinosaur. Denver Museum of Science and Nature, Denver, Colorado.

FIGURE 6.5 Three skull types, with positions of temporal fenestra outlined, characterizing the Anapsida, Synapsida, and Diapsida in the context of a cladogram, showing their hypothesized evolutionary relationships.

FIGURE 6.7 *Thalassomedon*, a Late Cretaceous plesiosaur, a marine reptile and an example of a euryapsid. (Euryapsids, and all marine reptiles, were not dinosaurs.) Denver Museum of Science and Nature, Denver, Colorado.

FIGURE 6.8 Skull of *Euparkeria*, a basal archosaur from the Early Triassic of South Africa, which was not a dinosaur. From Cowen (2000), *History of Life*, 3e, Blackwell Science, Inc., Malden, MA, p. 182, fig. 11.13.

FIGURE 6.9 Cast of *Postosuchus*, a large rauisuchian from the Late Triassic of the southwestern USA: Mesalands Dinosaur Museum, Tucumcari, New Mexico. Despite its very fierce appearance, *Postosuchus* was not a dinosaur.

FIGURE 6.10 Cast of the pterosaur *Anhanguera* from the Early Cretaceous of Argentina: Fernbank Museum of Natural History, Atlanta, Georgia. *Anhanguera*, alas, was also not a dinosaur.

FIGURE 6.11 Cast of the small dinosauromorph *Marasuchus* from the Late Triassic of Argentina: Sam Noble Oklahoma Museum of Natural History, Norman, Oklahoma. *Marasuchus* is not a dinosaur, but is very, very close to being one. Length about 40 cm.

FIGURE 6.12 Three Late Triassic fossil archosaurs proposed as primitive dinosaurs. (A) *Eoraptor lunensis*. (B) *Herrerasaurus ischigualasto*. (C) *Staurikosaurus pricei*. Modified from Paul (1988), Sereno et al. (1993), and Sereno (1994).

FIGURE 7.1 Crocodile toothmarks in hadrosaur dorsal vertebra, Aguja Formation, Late Cretaceous, west Texas. Whether these trace fossils represent predation or scavenging of the hadrosaur is currently unknown. Photograph by Stephen W. Henderson.

FIGURE 7.2 Common sedimentary environments, showing which ones had relatively low to high preservation potential for dinosaur body and trace fossils. Environments include glacial, alluvial, lacustrine, fluvial, paludal, estuarine, deltaic, coastal, tidal, and shallow marine.

FIGURE 7.3 Taphonomic information derivable from an opossum (*Didelphis marsupialis*) on Sapelo Island, Georgia. Opossum was observed dead in the road at 8:00 a.m., July 31, 2004, and seemed freshly killed at the time; hypothesized cause of death was from being struck by an automobile. At 4:00 p.m. that same day, seven black vultures (*Coragyps atratus*) were seen around the body; their tracks and a drag mark ending with the body confirmed that it had been moved about 3 meters from the spot where it was originally sighted. Body had been almost completely eviscerated; internal organs and musculature were more than 90% gone. Tire tracks and crushed bones indicated that several vehicles had run over the body both before and after scavenging. Flies were on the body and a noticeable odor was present, the latter probably as a by-product of aerobic bacteria. Temperature was about 30°C, with nearly 100% humidity.

FIGURE 7.4 Pockmarks in sauropod bone from the Late Jurassic of Utah, interpreted as trace fossils formed through beetles gnawing on exposed bones.

FIGURE 7.5 Dinosaur bones demonstrating their behavior as sedimentary particles. Suspension – astralagus; Saltation – scapula; Traction – humerus. Floating sauropod (with an apparent density of less than 1.0 g/cm^3) for scale.

FIGURE 7.6 Sandstone bed formed from filling of a river channel and containing dinosaur bones near Morrison, Colorado.

FIGURE 7.7 Hypothetical rose diagrams of bone orientations from one flow direction (left) and variable flow directions (right) with femur used to point in direction of flow.

FIGURE 7.8 Map view of crevasse splay laterally adjacent to stream channel (compare with Fig. 3.11).

FIGURE 7.9 *Protoceratops* (left) and *Velociraptor* (right) in close proximity to one another (nicknamed "The Fighting Dinosaurs") from the Late Cretaceous of the Gobi Desert, Mongolia. These specimens likely represent rapid burial and autochtonous fossils. Transparency No. 18973, Courtesy Department of Library Sciences, American Museum of Natural History.

FIGURE 7.10 How an external mold and cast could have been made of a dinosaur body, preserving skin impressions (such as seen in Fig. 5.10).

FIGURE 8.1 African elephants (*Loxodonta africanus*) mating, providing a model for mating positions of some large quadrupedal dinosaurs. The male is located posterodorsally with respect to the female. W. M. Colbeck/OSF/Animals Animals.

FIGURE 8.2 Shapes, sizes, and dimensions of dinosaur eggs. From left to right, sphere, prolate spheroid, oblate spheroid, semiconical; axes and measurements associated with prolate spheroid.

FIGURE 8.3 Cross-section of eggshell microstructure, showing (from inside to outside) eisospherite layer (with shell membrane) and exospherite layer (with mammillary layer, column layer, and cuticle layer).

FIGURE 8.4 Differences in proportions of cancellous and compact bone in the diaphyses and epiphyses (respectively) of a limb bone.

FIGURE 8.5 Annuli (unvascularized area) and lines of arrested growth (LAGs) in ornithopod limb bone.

FIGURE 8.6 General tooth shapes typically associated with certain clades of dinosaurs (but with some exceptions as noted in the text). (A) Leaf-like (prosauropods, ornithopods, thyreophorans). (B) Peg-like (sauropods). (C) Conical (some theropods).

FIGURE 8.7 Estimates of dinosaur biomass in two different Mesozoic deposits as determined by predator/prey ratios and using different sources of data. (A) Bone data (based on a Late Creteceous deposit). (B) Track data, normalized for biomass (based on a Late Jurassic tracksite). Data from Lockley (1990).

FIGURE 8.8 Evidence of brooding and association of embryo with the theropod *Oviraptor*. (A) Skeleton of adult *Oviraptor* (missing its skull) on egg clutch. (B) *Oviraptor* embryo recovered from an egg that was previously interpreted as belonging to the ceratopsian *Protoceratops*. Both specimens recovered from Late Cretaceous strata in Mongolia. Transparencies 5789 (5) and K17685 (Photo. Mick Ellison). Courtesy of the Library, American Museum of Natural History.

FIGURE 9.1 Cladogram for Theropoda and Herrerasauridae, showing relationships of major clades and outgroups. Note that an alternative cladogram would have herrerasaurids as an outgroup sharing a common archosaur ancestor with dinosaurs, but outside of the Dinosauria.

FIGURE 9.2 Important characters for Clade Theropoda: lachrymal bone, five sacral vertebrae, manus with unguals and reduction or loss of digits IV and V, curved and long femur, long and bilaterally symmetrical pes with digits II to IV and digit I separate from pes, and cervical and caudal vertebrae processes.

FIGURE 9.3 Right manus of Late Jurassic *Allosaurus fragilis* with digits I to III (from top to bottom) and right human hand for scale. Dinosaur National Monument, Vernal, Utah.

FIGURE 9.4 Feathers associated with four limbs of *Microraptor*, an Early Cretaceous feathered theropod species from China. Reprinted by permission from Macmillan Publishers Ltd: Nature, Xu et al. "Four-winged dinosaurs from China", Vol. X, 2001.

FIGURE 9.5 Early Cretaceous neoceratosaur and abelisaurid *Carnotaurus* of Argentina, showing cranial ornamentation typical of ceratosaurs. Museo de Ciencias Naturales, Madrid, Spain.

FIGURE 9.6 Tetanurans as represented by allosaurids. (A) *Giganotosaurus*, a carcharodontosaurine of the Early Cretaceous of Argentina. (B) *Yangchuanosaurus*, a sinraptorid of the Late Jurassic of China. The former is on permanent display at the Fernbank Museum of Natural History, Atlanta, Georgia; the latter is currently on display in the atrium of Hartsfield-Jackson International Airport, Atlanta.

FIGURE 9.7 "Pinched" metatarsal in pes of *Tyrannosaurus*, a character of the clade Arctometatarsalia.

FIGURE 9.8 *Troodon*, a relatively small tetanuran with a relatively large brain for a dinosaur. Temporary display on loan from the Museum of the Rockies, at the Fernbank Museum of Natural History, Atlanta, Georgia.

FIGURE 9.9 *Deinonychus*, a Late Cretaceous dromaeosaur of the western USA. (A) Skeletal reconstruction of *Deinonychus*. (B) Close-up view of the upraised digit I of left pes. North Carolina Museum of Natural History.

FIGURE 9.10 *Acrocanthosaurus*, an Early Cretaceous allosaurid from Texas. (A) Skeletal reconstruction: North Carolina Museum of Natural History. (B) Large theropod track affiliated with *Acrocanthosaurus*, preserved in limestone but slightly submerged in Paluxy River, eastern Texas. Human footprint in river mud (right) for scale.

FIGURE 9.11 "Before" and "after" depictions of *Tyrannosaurus* foot anatomy. (A) "Before" of a large, fleshy foot represented by a probable *Tyrannosaurus* track (left foot) from the Upper Cretaceous Raton Formation, New Mexico. Cast at University of Colorado, Denver. (B) "After" ventral (sole) view of *Tyrannosaurus* foot (left again) without the flesh from the viewpoint of being stepped on. Specimen part of skeletal mount in Denver Museum of Science and Nature. Note the corresponding position of the hallux in both track and foot.

FIGURE 9.12 *Crylophosaurus ellioti*, an Early Jurassic carnosaur from Antarctica. Auckland Museum, Auckland, New Zealand.

FIGURE 9.13 Large theropod trackway from the Upper Jurassic Morrison Formation of Colorado. (A) Overview of trackway showing pace and stride lengths; dinosaur ichnologist for scale. (B) Close-up of one track in sequence with pressure-release structure evident in left upper (outer) edge of track, indicating a pushing of the sediment by the theropod as it shifted from the left to the right foot.

FIGURE 9.14 The Late Cretaceous tetanuran and tyrannosaurid *Albertosaurus*, showing its jaws filled with prominent, recurved, and serrated teeth ideally suited for slicing and dicing flesh and bone. Royal Ontario Museum, Toronto, Ontario, Canada.

FIGURE 9.15 The formidable *Utahraptor* and its raptorial digit II ungual, skeletal mount with claw raised on left pes. Note its similarity to *Deinonychus* in both form and inferred function. College of Eastern Utah Prehistoric Museum, Price, Utah.

FIGURE 10.1 Cladogram for Sauropodomorpha, with major clades (Prosauropoda, Sauropoda) and clades within Prosauropoda and Sauropoda.

FIGURE 10.2 Important characters for Clade Sauropodomorpha: distal part of the tibia covered by an ascending process of the astralagus, short hind limbs in comparison to the torso length, spatula-like teeth with bladed and serrated crowns, 10 elongated cervical vertebrae along with 15 dorsal vertebrae (25 presacrals), large digit I on manus.

FIGURE 10.3 (A) Skull of Late Triassic prosauropod *Plateosaurus* of Germany. Anatomical features of the skull. (B) Complete specimen; Naturhistoriches Museum Basel, Basel, Switzerland. See Figure 5.3 for overall anatomy.

FIGURE 10.4 Skulls of the Late Jurassic diplodocids *Apatosaurus* (left) and *Diplodocus* (right) showing dorso-ventral positioning of nares in relation to the anterior portion of their skulls. Dinosaur National Monument, Vernal, Utah. Contrast with skull of *Plateosaurus* in Figure 10.3.

FIGURE 10.5 *Diplodocus*, the Late Jurassic sauropod that inspired a pub song. (A) Skeletal reconstruction; Denver Museum of Science and Nature. (B) Left pes and ankle of *Diplodocus*, showing the large ungual on digit I.

FIGURE 10.6 *Amargosaurus*, an Early Cretaceous sauropod from Argentina with unusually long vertebral processes. Trelew Museo de Paleontológica, Trelew, Argentina.

FIGURE 10.7 Cast of nearly complete juvenile *Camarasaurus* from the Late Jurassic of Utah, USA. Dinosaur Adventure Museum, Fruita, Colorado.

FIGURE 10.8 Cast and reconstruction of the Late Cretaceous titanosaurid *Argentinosaurus*, which may have been the largest dinosaur (but it had a lot of competition). Fernbank Museum of Natural History, Atlanta, Georgia.

FIGURE 10.9 The Middle Jurassic cetiosaurid *Bellusaurus*, a smaller sauropod than most. Temporary display at Fernbank Museum of Natural History, Atlanta, Georgia.

FIGURE 10.10 Egg clutch of titanosaurids from the Late Cretaceous of Patagonia, Argentina. Temporary display at Fernbank Museum of Natural History, Atlanta, Georgia.

FIGURE 10.11 Sauropod trackways in the Late Jurassic Morrison Formation near La Junta, Colorado, showing parallelism and indicating probable herding behavior.

FIGURE 11.1 Important characters for Clade Ornithopoda: offset tooth row; occlusal surface higher than jaw joint; crescent-shaped paraoccipital process; premaxilla with an elongate process.

FIGURE 11.2 Cladogram for Ornithopoda, showing hypothesized relationships between Heterodontosauridae, Iguanodontia, and other ornithopods.

FIGURE 11.3 Skull of the Early Jurassic *Heterodontosaurus*, a heterodontosaurid of South Africa. From Cowen (2000), *History of Life*, 3e, Blackwell Science, Inc., Malden, MA, p. 220, fig. 12.10. (After Charig and Crompton.)

FIGURE 11.4 *Thescelosaurus*, a non-iguanodontian ornithopod from the Late Cretaceous. Auckland Museum, Auckland, New Zealand.

FIGURE 11.5 The diminutive ornithopod *Othniela* of Late Jurassic in western North America. Specimens in the Denver Museum of Science and Nature, Denver, Colorado.

FIGURE 11.6 *Camptosaurus*, a common iguanodontian of the Late Jurassic in western North America. Specimen in the College of Eastern Utah Prehistoric Museum, Price, Utah.

FIGURE 11.7 Representative genera of a hadrosaurine and lambeosaurine from western North America and China. (A) *Edmontosaurus*, a Late Cretaceous hadrosaurine of western North America; Denver Museum of Natural History, Denver, Colorado. (B) *Tsintaosaurus*, a Late Cretaceous lambeosaurine of China; Fernbank Museum of Natural History, Atlanta, Georgia.

FIGURE 11.8 Large track, preserved as positive relief as a natural cast on the bottom of a bed, attributed to a hadrosaurid in the Laramie Formation (Late Cretaceous) near Golden, Colorado. Note that the "heel" portion of the track was obscured by a log that was under the hadrosaurid's foot, providing evidence that the hadrosaurid was walking through a formerly forested area.

FIGURE 11.9 The hadrosaurid *Maiasaura* with its nest and juveniles, based on associated body and trace fossil material from the Late Cretaceous Two Medicine Formation of Montana. Fernbank Museum of Natural History, Atlanta, Georgia; restoration on loan from the Museum of the Rockies, Bozeman, Montana.

FIGURE 11.10 Morphologically similar but differently sized Late Cretaceous hadrosaur tracks, interpreted as representative of growth stages. Casts of original tracks put together for comparison, Dinosaur Track Display, University of Colorado, Denver.

FIGURE 11.11 Abundant iguanodontian tracks on a bedding plane of the Lower Cretaceous Dakota Formation, Morrison, Colorado. Note the parallel movement of one larger individual next to a smaller individual.

FIGURE 12.1 Cladogram showing interrelationships between basal thyreophorans (*Scelidosaurus*, *Scutellosaurus*, and *Emausaurus*) and other clades within Thyreophora, particularly Ankylosauria and Stegosauria.

FIGURE 12.2 Defining character traits of Clade Ankylosauria: broad, armored skull with deeply inset cheek teeth; synsacrum; horizontal ilium; closed acetabulum; and body armor.

FIGURE 12.3 Closely spaced osteoderms of a typical Late Jurassic ankylosaur, which likely provided some excellent protection against predators from the same time. College of Eastern Utah Prehistoric Museum, Price, Utah.

FIGURE 12.4 Late nodosaurid skull, showing typical traits for a skull of its clade: laterally placed nares, hornless, and a rounded shape. Compare with skull of *Gargoyleosaurus* in Figure 12.6. College of Eastern Utah Prehistoric Museum, Pice, Utah.

FIGURE 12.5 Tail club of the Late Cretaceous ankylosaurid *Ankylosaurus*, composed of paired osteoderms. Denver Museum Science and Nature, Denver, Colorado.

FIGURE 12.6 *Gargoyleosaurus parkpini*, a Late Jurassic ankylosaurid from the Morrison Formation of Wyoming, USA. Denver Museum of Science and Nature, Denver, Colorado.

FIGURE 12.7 Ankylosaur track (probably the pes) in the Lower Cretaceous preserved as natural cast on bottom of a stratum and cross-cut by a theropod track; Cañon City, Colorado.

FIGURE 12.8 *Stegosaurus stenops*, the most famous of thyreophorans and stegosaurs. (A) Juvenile specimen (a rare find), Denver Museum of Science and Nature, Denver, Colorado. (B) Cast of adult *S. stenops*, Fernbank Museum of Natural History, Atlanta, Georgia.

FIGURE 12.9 *Tuojiangosaurus*, a Late Jurassic stegosaur from China. Temporary display at Fernbank Museum of Natural History, Atlanta, Georgia.

FIGURE 12.10 Porous and venous texture associated with dorsal osteoderm on *Stegosaurus*, indicating high degree of vascularization. Close-up of specimen in Denver Museum of Science and Nature, Colorado.

FIGURE 13.1 Cladogram showing interrelationships between clades of Marginocephalia, particularly Pachycephalosauria and Ceratopsia.

FIGURE 13.2 Character traits of Marginocephalia: narrow shelf of bone on the parietal and posterior part of the squamosal; abbreviated posterior portion of premaxillary; and shortened pubis accompanied by widely spaced hip sockets.

FIGURE 13.3 Typical ceratopsian lower jaws. (A) Dentary and predentary of *Protoceratops*, Late Cretaceous of Mongolia; Dinosaur Adventure Museum, Fruita, Colorado.
(B) Unidentified ceratopsian dentary and predentary, Late Cretaceous, western North America; College of Eastern Utah Prehistoric Museum, Price, Utah.

FIGURE 13.4 Ceratopsian track interpreted from the Laramie Formation (Late Cretaceous) near Golden, Colorado.

FIGURE 13.5 Skulls of Late Cretaceous pachycephalosaurids. (A) *Stegoceras* as represented only by its fused frontal and parietals forming a high dome, a typical trait of pachycephalisaurids; College of Eastern Utah Prehistoric Museum, Price, Utah. (B) *Pachycephalosaurus*, showing deeply inset cheek teeth, domal dorsal surface, and fringing osteoderms on dentary (ventral), nasal (anterior), and squamosals (posterior). Specimen is cast of original, Denver Museum of Science and Nature, Denver, Colorado.

FIGURE 13.6 *Pachycephalosaurus*, reconstructed as an entire skeleton but with little more to inspire this other than a very bony skull. North Carolina Museum of Natural History, Raleigh, North Carolina.

FIGURE 13.7 Comparative anatomy between skulls of two small ceratopsians. (A) Early Cretaceous psittacosaurid *Psittacosaurus* of Asia, the oldest known ceratopsian and namesake of its clade. (B) Late Cretaceous neoceratopsian *Protoceratops*, also of Asia.

FIGURE 13.8 Cast of skull for the Late Cretaceous neoceratopsian (and ceratopsid) *Torosaurus latus*, from the Hell Creek Formation of South Dakota, a candidate for the largest skull possessed by any land animal. Utah Field House of Natural History, Vernal, Utah.

FIGURE 13.9 *Chasmosaurus*, a Late Cretaceous neoceratopsian and ceratopsid of North America. (A) Frontal view, showing legs positioned underneath the plane of the body (erect posture). Cast of skeleton, College of Eastern Utah Prehistoric Museum, Price, Utah. (B) Lateral view.

FIGURE 13.10 *Styracosaurus*, a Late Cretaceous ceratopsian from North America that apparently could never have had enough horns. Dinosaur Adventure Museum, Fruita, Colorado.

FIGURE 13.11 Impression of palm frond in Upper Cretaceous Laramie Formation, which co-occurs with ceratopsian tracks in the same part of the formation and thus indicates a co-occurrence with a potential ceratopsian food source; Golden, Colorado.

FIGURE 14.1 Measurable parameters that can be derived from a well-preserved dinosaur track and trackway, assuming bipedalism. Note diagonal pattern to the trackway, which is typical for those made by dinosaurs.

FIGURE 14.2 Manus–pes placement in typical walking pattern by quadrupedal animals. (A) Manus–pes pair from dog (*Canis domesticus*) trackway preserved in modern sidewalk, Emory University, Atlanta, Georgia. (B) Manus–pes pair from iguanodontian trackway in Lower Cretaceous bedding plane near Morrison, Colorado.

FIGURE 14.3 Different pressure-release structures caused by different behaviors, transmitted by the right foot of the same person walking in firm sand. (A) Moving straight forward. (B) Making an abrupt right turn.

FIGURE 14.4 Different pressure-release features caused by displacement of sediment from movement of a dinosaur. (A) Large theropod track in sandstone, Late Jurassic, Utah. (B) Sauropod track in sandstone, Late Jurassic, Utah. Theropod was moving straight forward, whereas sauropod had began to make an abrupt right turn.

FIGURE 14.5 Differences in tracks as a function of substrate firmness, illustrated by a juvenile human female, weighing about 30 kg, making a trackway on a beach where tracks "disappear" in the middle because of firmer sand in that area.

FIGURE 14.6 Typical track morphologies interpreted for theropods, ornithopods, prosauropods, sauropods, ankylosaurs, stegosaurs, and ceratopsians.

FIGURE 14.7 Plot of relative stride length versus dimensionless speed for different animals based on data derived from living cursorial vertebrates in terrestrial environments. (After Alexander, 1976, 1989.)

FIGURE 14.8 How varying depths of tracks and preservational modes can result in a track assemblage on a bedding plane where the tracks are not contemporaneous.

FIGURE 14.9 Sauropod track on top of a gastropod (snail) shell, preserved in shallow-marine limestone from the Late Jurassic of Switzerland. View is from underneath, which means that the gastropod was stepped on by the sauropod.

FIGURE 14.10 Nest types associated with modern reptiles, shown in cross-sectional view. (A) Mound nest. (B) Hole nest.

FIGURE 14.11 Dinosaur egg clutch of the Late Cretaceous theropod *Troodon* associated with a nest structure (not shown). Orientation implies that eggs were moved by the mother after egg-laying. Cast of original clutch from Museum of the Rockies, Bozeman, Montana; the clutch is upside-down for display purposes.

FIGURE 14.12 Four sets of toothmark rows on left ilium of a Late Jurassic sauropod, *Apatosaurus*. Toothmark spacing corresponds with tooth row of *Allosaurus*, a large theropod found in same-age strata of *Apatosaurus*. All sets begin at distal part of bone as scrape marks that trend caudally; feeding was performed through pulling of muscles from insertion point on ilium on a carcass lying on its right side. The allosaur was taller than the width of the recumbent apatosaur so that it could move its head horizontally for this "nipping" motion. Rightward trend of scrape marks suggests that allosaur was on the dorsal side of the apatosaur. Specimen in the Dinosaur Adventure Museum of Fruita, Colorado.

FIGURE 14.13 Typical gastroliths with rounded and polished appearance, from the Lower Cretaceous Cedar Mountain Formation of Utah. Denver Museum of Science and Nature, Denver, Colorado.

FIGURE 14.14 Coprolite containing abundant ground-up conifer remains attributed to the hadrosaurid *Maiasaura*, Upper Cretaceous Two Medicine Formation, Montana.

FIGURE 15.1 Cladogram showing the lineage within Theropoda leading to Aves (birds) and subsequent clades nested within Aves.

FIGURE 15.2 A few characters defining Aves (birds): (A) reduction of caudal vertebrae into a pygostyle; (B) forearm more than 90% of the length of the humerus and forelimb considerably longer (more than 120%) than the hindlimb; (C) anisodactyl foot, with a reversed hallux adapted for perching. Notice also the keeled (carinate) sternum and elongated coracoids.

FIGURE 15.3 The Late Jurassic bird *Archaeopteryx lithographica* of the Solnhofen Limestone, Bavaria, Germany. Compare with Figure 2.4. Humboldt Museum für Naturkunde, Berlin/Peabody Museum of Natural History, Yale University.

FIGURE 15.4 Anatomy of a typical flight feather.

FIGURE 15.5 *Confuciusornis sanctus*, an Early Cretaceous bird from China. (A) Fossil specimen, with carbonized margin indicating presence of feathers. (B) Reconstruction of living animal. Note the prominent digits on the wings, indicating a primitive condition. Naturhistoriches Museum Basel, Basel, Switzerland.

FIGURE 15.6 Skeleton of *Hesperornis regalis*, a Late Cretaceous diving bird recovered from marine deposits in Kansas, and artistic reconstruction behind it. Note the vestigial wings, indicating secondary flightlessness in a Cretaceous bird. Sam Noble Oklahoma Museum of Natural History, Norman, Oklahoma.

FIGURE 15.7 Track of greater rhea (*Rhea americana*), a large ratite native to Patagonia, Argentina. Notice its close anatomical resemblance to Mesozoic theropod tracks depicted and described in previous chapters, with prominent digits II–IV, phalangeal pads, and well-developed claws.

FIGURE 15.8 Skeleton of the frightening Tertiary ratite *Diatryma* of North America. Be aware of its anatomical similarity to theropod skeletons from Chapter 9. Sam Noble Oklahoma Museum of Natural History, Norman, Oklahoma.

FIGURE 15.9 *Dinornis*, a recently extinct genus of moas, which were a group of ratites native to New Zealand. (A) Skeleton of adult *Diornis maximus*; bust of Sir Richard Owen (Chapter 3) for scale. (B) Egg of *D. giganteus*, with a calculated volume of about four liters (!). Auckland Museum, Auckland, New Zealand.

FIGURE 15.10 Variety of nests constructed and used by modern birds. (A) Ground scrape with a clutch of eggs on a sandy beach made by American oystercatcher (*Haematopus palliatus*), Georgia, USA. (B) Large and elaborate stick nest of osprey (*Pandion haliaetus*), Florida, USA. (C) Hole nest (burrow) in semi-consolidated sand with vegetation stuffed inside, made by kotare (kingfisher: *Halcyon santus*), North Island, New Zealand. (D) Nesting colony of takapu (Australasian gannet: *Morus serrator*) showing regularly spaced nest mounds formed by guano, North Island, New Zealand.

FIGURE 15.11 Altricial juveniles of magnificent frigatebirds (*Fregata magnificens*), which have 1.7–2.4 m wingspans as adults but are completely dependent on their parents for the first year of life, despite approaching their sizes. Notice their eerie resemblance to non-avian theropods, downy feathers and all. San Salvador, Bahamas.

FIGURE 15.12 Wood-boring activities of birds related to nesting and feeding. (A) Hole nest in tree trunk made by pileated woodpecker (*Dryocopus pileatus*); Idaho, USA. (B) Oak acorns (*Quercus* sp.) wedged in holes made by acorn woodpecker (*Melanerpes formicivorus*) in trunk of ponderosa pine (*Pinus ponderosa*); California, USA.

FIGURE 15.13 Evidence of unsuccessful predation of a modern avian dinosaur: a footless laughing gull (*Larus altricilla*) on a beach in Georgia, USA. This observation was confirmed by examination of its trackways, which showed well-defined right-foot tracks alternating with impressions made by the metatarsal nub of the left leg.

FIGURE 16.1 The coelacanth *Latimeria chalumnae*, regarded as a "living fossil" because of how its lineage survived from the Cretaceous Period to now.

FIGURE 16.2 Mass extinctions of marine genera during the Phanerozoic Eon, plotted as percentage of genus extinctions versus geologic time. Adapted from data by Sepkoski (1994).

FIGURE 16.3 Pangea, the supercontinent caused by the uniting of Laurasia and Gondwana at the end of the Permian Period, which was a time of the greatest of all mass extinctions. Reprinted by permission from Scotese, C. R., 2001. Atlas of Earth History, Volume 1, Paleogeography, PALEOMAP Project, Arlington, Texas, 52 pp.

FIGURE 16.4 Age subdivisions of the Late Cretaceous, terminated by the Maastrichtian Age.

FIGURE 16.5 Iridium-bearing clay layer and its geochemical signature from the K–T boundary at Gubbio, Italy. Iridium concentration in parts per billion (ppb) throughout the clay layer. After Cowen (2000), *History of Life*, 3e, Blackwell Science, Inc., Malden, MA, p. 284, fig. 18.1.

FIGURE 16.6 K–T boundary in Recife, Brazil, one of more than 100 such boundaries in the world that show elevated amounts of iridium, yet far removed from Gubbio, Italy.

FIGURE 16.7 Map, based on a gravity field, of probable impact structure associated with the end of the Cretaceous Period, Chicxulub, Mexico. Reprinted courtesy of Virgil L. Sharpton, University of Alaska, Fairbanks.

FIGURE 16.8 Paleogeographic map of the end-Cretaceous, showing continental landmasses relative to one another at the time the dinosaurs went extinct. Reprinted by permission from Scotese, C. R., 2001. Atlas of Earth History, Volume 1, Paleogeography, PALEOMAP Project, Arlington, Texas, 52 pp.

FIGURE 16.9 Maastrichtian dinosaurs that lived during that age, all of which became extinct by its end.

FIGURE 16.10 Bald eagle (*Haliaeetus leucocephalus*), a modern predatory theropod of North America that was considered an endangered species and is now protected in the USA. PhotoDisk.

FIGURE 16.11 Invasive species in terrestrial habitats thought to be responsible for decimating modern bird populations, the mammal *Felis domestica*, which is proliferated in those habitats by another species of mammal, *Homo sapiens*.