In Pagel, M., ed., 2002, *Encyclopedia of Evolution*, Oxford University Press, Oxford, v. 2, p. 1090-1093.

STRATIGRAPHY

The basic principles of understanding earth history and the rock record are known as *stratigraphy*, literally "the study of layered rocks." Although stratigraphy originally developed as a method of describing and interpreting layered sedimentary rocks (rocks such as sandstone and

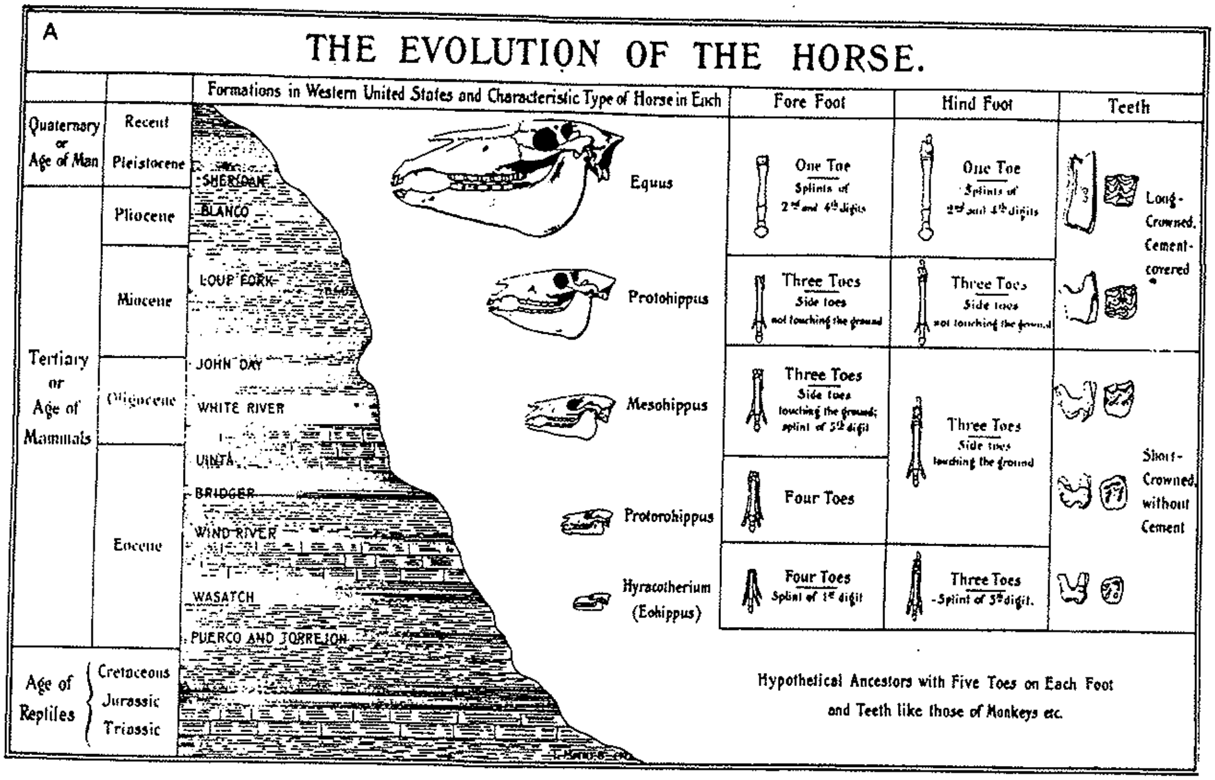

FIGURE 1. Early Representation of Horse Evolution Emphasizing the Linear Transformation in Form Through Time. The old names of the fossil-bearing beds are shown on the left, in stratigraphic order, demonstrating exactly where this sequence of horse fossils can be found. Courtesy the Library, American Museum of Natural History.

limestone formed by or from preexisting deposits), by the late twentieth century its scope had broadened to include layered igneous rocks (rocks cooled from magmas such as lava flows and volcanic ash falls) and even intrusive igneous rocks—any rocks that demonstrate a sequence of geologic events. Based on stratigraphic principles, geologists have been able to reconstruct the past 4.5 billion years of earth history in surprising detail.

There are two primary means of determining the age of events in the geological past. A geologist can determine the relative sequence of events (event A is younger or older than event B), or the numerical age (i.e., this rock is so many millions of years old) of a rock unit, the latter primarily by radioisotopic dating of igneous rocks. (Numerical dating is erroneously called "absolute dating" in older books.)

The basic principles of relative dating were first proposed by Nicholaus Steno in 1669. In Steno's time, most scholars thought of the rocks of the earth's crust as having been created exactly as they then appeared, some 6,000 years previous. They were puzzled by the occurrence of fossils in solid rocks, and thought that the fossils might have grown in the rocks by supernatural

Flood. Steno realized that the presence of fossils in sedimentary rocks showed that these rocks had not always been solid, but were once composed of loose sedimentary materials (sand, mud, lime) that consolidated around the fossils and later turned into stone. From this insight, Steno derived several principles of relative dating that are the foundation of stratigraphy. The most important of these is the principle of superposition. If sedimentary rocks are deposited as layers of sand or mud, one on top of the other, then the layers on the top of the stack will be younger than those toward the bottom. This is analogous to a stack of papers on a desk that have accumulated for a long time without being shuffled. Those at the bottom of the stack were left there some time ago, while those at the top were placed there most recently.

Dating Methods. The fundamental method of determining the age of geological events is relative dating, using the principle of superposition. This was the way that geologists worked out the sequence of strata in Europe that is the basis of our modern timescale. However, at the same time, they found that many rock units were similar in appearance and hard to distinguish from one

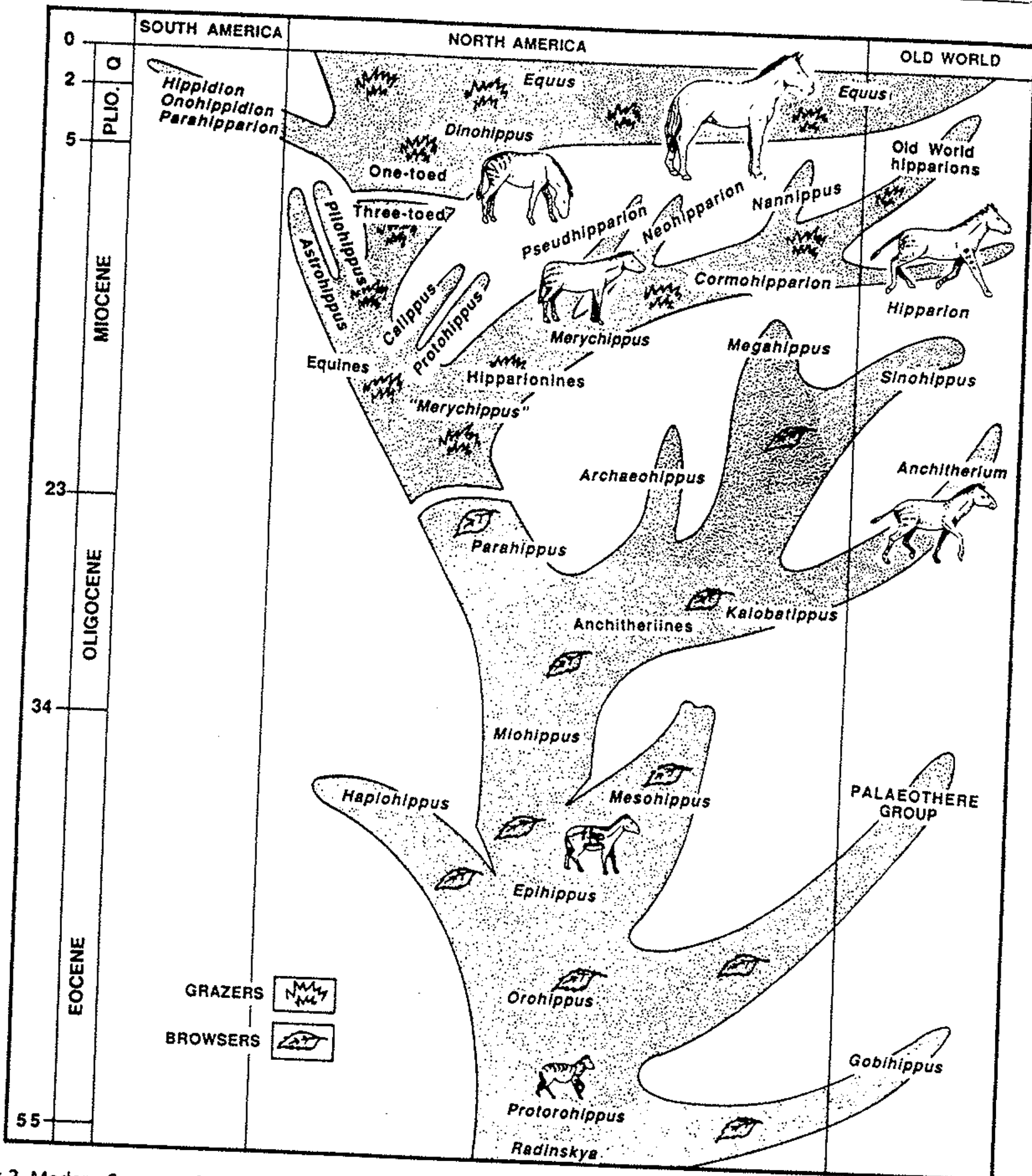

FIGURE 2. Modern Concept of Horse Evolution.
Shown are much more complex, bushy, branching pattern as we discover more horse fossils. Donald Prothero.

English canal engineer William Smith realized that each rock unit in his English succession contained its own distinctive assemblage of fossils, and that each rock unit could also be recognized by its fossil content. The fact that fossils change continuously through time is known as faunal succession and is the basis for biostratigraphy, the scientific study of the distribution of fossils in rock sequences. Biostratigraphy is the only practical means of dating most sedimentary rocks. Rock types may change over distance, or become difficult to distinguish, but distinctive assemblages of fossils are unique to certain segments of geologic time and can be used around the world to recognize that time interval. Most paleontologists employed by oil companies are biostratigraphers using fossils to date and correlate rocks as precisely as possible.

When the timescale developed in the early 1800s, no one could tell the age and duration of the different geological periods. Some geologists thought that the age of the earth was nearly infinite (Hutton noted that there was "no vestige of a beginning"), but other scientists gave the earth only 20 million years or less for its entire history. The discovery of radioactivity in 1896, however, provided the first method of obtaining a numerical age for geological events. When a radioactive atom, such as uranium or rubidium, spontaneously decays by nuclear reactions, it gives off heat, radioactive particles, and leaves a nonradioactive daughter atom. The rate of this nuclear reaction is well known, and half of the original parent atoms decay to their daughter atoms in a fixed interval of time, known as a half-life. If we can measure the ratio of parent to daughter atoms, we can determine when this atomic decay reaction began and date the material that contains these atoms. However, this system only works for minerals that have cooled down from a very hot state (igneous or high-grade metamorphic minerals), locking in the parent atoms at the time of their crystallization. Thus, it is inapplicable to normal sedimentary rocks, which are formed from preexisting grains eroded from other rocks and not from a molten state. To determine the age of sedimentary rocks, the geologist needs interbedded igneous rocks (such as ash falls or lava flows), which give numerical ages in certain parts of the sedimentary sequence, or cross-cutting igneous dikes, which bracket the age of the rocks through which they cut and which cut across them.

Stratigraphy and Evolution. Although evolutionary biologists have been able to determine much about the process of evolution from studying living organisms, the fossil record is the only direct evidence for how evolution actually occurred. In the early days of stratigraphy, geologists attempted to explain the change in fossils through the rock strata as the result of creatures killed by successive floods (not mentioned in the Bible). But by the 1830s, so many different extinct faunas had been described that it was no longer possible to explain the change in fossils through time by biblical stories.

In 1859 Charles Darwin published his theory of evolution by natural selection, and revolutionized biology. Ironically, Darwin's book had relatively few examples from the fossil record to support his theory of evolution, and his chapters on the subject were largely apologies for the incompleteness of the fossil record. But in 1861 *Archaeopteryx*, the transitional fossil between reptiles and birds, was described, and paleontologists soon began to amass more and more examples of evolutionary transformations in the fossil record. In the 1870s Kowalevsky and Marsh described the evolutionary history of the horse (Figure 1), which remains a classic example of evolution to this day. The oldest horses are primitive, tiny four-toed beasts with low-crowned teeth from rocks 55 million years old. Larger animals with three toes and longer legs are found in 30-million-year-old strata, while modern horses have long one-toed legs and very high-crowned teeth. Although the general outline of horse evolution is still valid, in the twentieth century many more horse fossils were found that made the picture much more complex. Instead of a single lineage getting larger and more advanced, we now know that horse evolution was highly branched, with multiple lineages of horses living at any given time (Figure 2). During the Miocene epoch, horses became even more diverse, with some lineages retaining the old low-crowned teeth for eating leaves, while many others evolved higher-crowned teeth for eating gritty grasses. Even the loss of side toes occurred in several different lineages, and one-toed horses evolved at least twice. About 10 million years ago, there were at least twelve different lineages of horses living at the same time. At the end of the last ice age, many of the different lineages of horses became extinct, so that only a single genus of horse (*Equus*) survives, divided into a number of species of zebras, asses, and wild and domestic horses.

[*See also* Geology; Paleontology.]

BIBLIOGRAPHY

Berry, W. B. N. *Growth of Prehistoric Time Scale.* 2d ed. Palo Alto, Calif., 1987. An excellent account of the historic development of the understanding of geologic time.

Dalrymple, G. B. *The Age of the Earth.* Palo Alto, Calif., 1991. A thorough account of the attempt to date the earth, and how modern methods of radioisotopic dating work.

Eicher, D. L. *Geologic Time.* 2d ed. Englewood Cliffs, N.J., 1976. A good introductory-level paperback text on geologic time and stratigraphic principles.

Prothero, D. R. *Interpreting the Stratigraphic Record.* New York, 1990. A college-level textbook on the principles of stratigraphy.

Prothero, D. R., and R. H. Dott, Jr. *Evolution of the Earth.* 6th ed. New York, 2001. A college textbook in historical geology, with chapters on evolution and stratigraphic principles.

Schoch, R. M. *Stratigraphy: Principles and Methods.* New York, 1989. A more advanced college-level textbook on the principles of stratigraphy.

— Donald R. Prothero