Geological time scale

The history of the Earth can be displayed in the form of a calendar which is based on the observation of rocks formed through time. Depending on the location, the formation of rocks has recorded different (regional) histories describing the magmatic, tectonic, hydrospheric, or biospheric evolutions, and thus different calendars have been generated. Geologists (stratigraphers) are attempting to unify these different calendars. Stratigraphers define rock units bracketed between two boundaries that can be correlated worldwide. The succession of these modern units is the global geological time scale.

Stratigraphical units. In general, the evolution of the Earth is continuous, so fixing the location of the unit boundaries can be achieved only through convention (decisions are made under the aegis of the International Commission on Stratigraphy). Stratigraphers use a variety of tools for characterizing the age of a rock, including physical ages, fossils, magnetism, and chemical properties, all of which have evolved through time. There are three intervals in the history of the Earth (Archean-Proterozoic, Phanerozoic, Plio-Quaternary) with each one showing distinct material available for characterizing rocks; thus, there

Eon	Era	Period	Ma
PHANEROZOIC	PALEOZOIC	CAMBRIAN	540
PROTEROZOIC	NEO-PROTEROZOIC	NEOPROTER. III	650
		CRYOGENIAN	850
		TONIAN	1,000
	MESO-PROTEROZOIC	STENIAN	1,200
		ECTASIAN	1,400
		CALYMMIAN	1,600
	PALEO-PROTEROZOIC	STATHERIAN	1,800
		OROSIRIAN	2,050
		RHYACIAN	2,300
		SIDERIAN	2,500
ARCHEAN	NEOARCHEAN		2,800
	MESOARCHEAN		3,200
	PALEOARCHEAN		3,600
	EOARCHEAN		–4,550 +20/–80

Fig. 1. Agreed-upon geological time scale of the pre-Phanerozoic history of the Earth. The beginning of the Earth is estimated to be 4,470 to 4,570 Ma, with a preferred age at 4,550 Ma.

are three successive kinds of geological time scale. In the earliest time scale, during Archean and Proterozoic eons, fossils are rare or absent in most rocks, and the major tool is the physical dating process based on naturally unstable isotope decay used by geochronologists. For this interval of time, the boundaries of the calendar units are defined by selected numerical ages (**Fig. 1**). These ages are conventionally abbreviated Ma (Mega anna, or million years, following recommendation of the Subcommission on Geochronology).

During the Phanerozoic Eon certain animals and plants elaborated skeletons or exoskeletons that, when preserved as fossils, provide an additional means of time correlation (**Fig. 2**). Up to about 5 Ma, these fossils become the major tool for determining the relative age of a rock. Together with other physicochemical characteristics, fossils allow a definition of stages which cover an average duration of about 5 Ma each. For the last 5 Ma, Plio-Quaternary time, there is evidence that the evolution of the environment on Earth is diversified and well represented in the geological record.

Most stratigraphical tools can be used continuously in this young interval, each tool providing a specific time scale. Because several tools can often be used to characterize (that is, to date) a single rock, it is easy to connect all these time scales. A variety of easily interchangeable time scales are useful. However, the absolute time dimension for all time scales can be calibrated only by using geochronology. The progress toward a common terminology and geological time scale benefits from three factors: better definition of the conventional units, better geochronological calibration, and a potential for extrapolating between calibrated ages.

Geochronological calibration. Progress in geochronological calibration benefits from both new technology and new geochronological information. During the 1990s, the precision and reproducibility of the measurements obtained using mass spectrometry have increased significantly. This improvement offers the possibility of dating minute quantities of certain material with remarkable precision. Using the uranium-lead (U-Pb) dating method, the age of a single crystal of zircon, 200 micrometers in length and 10 μm in diameter, can be measured. More significantly, several portions of this same crystal can be dated separately, allowing for verification of the internal consistency of the data obtained from the single crystal. For the potassium-argon (K-Ar) dating method, developments in the irradiation techniques which transform the original potassium into argon allow single biotite mica flakes 500 μm in diameter and 10 μm thick to be dated. Laser heating can also give several ages obtained from different points of a single crystal.

Explosive volcanic eruptions producing ash clouds blown over large areas are common. The ability to date small quantities of material has led to the search for minor volcanic events within the stratigraphical record. This advance is important because the same volcanic material covers both marine and continental areas, sometimes at the scale of a continent, allowing correlation of distant deposits. In addition, there is great interest in this method since explosive volcanism often scatters a variety of minerals, including uranium-bearing and potassium-bearing ones. Thus, the geochronologist can perform measurements on independent isotopic systems in order to make a reciprocal check of the validity of the calculated ages. The calibration of the geological time scale is mostly realized through the study of crystal-bearing volcanic dust discovered in sediments. Precise dating can also be achieved through a variety of other datable materials. For example, a few tens of milligrams of microtektite particles (scattered in wide areas when an asteroid collides with the Earth) can be dated. Another example is calcite crystallized in paleosols during cyclic deposition in shallow basins. Because this calcite is associated with organic matter which favors uranium enrichment, and is formed essentially at the time of deposition, calcite crystals become a potentially datable material using uranium-lead methods.

Two examples of refinement. One example of recent refinement concerns the dating of the Eocene-Oligocene boundary. That boundary has long been known as the *Grande Coupure* (great break) in the history of European land-mammal evolution. There have been a few European studies which documented an age at about 34 Ma. But the age of the boundary was assumed to be about 37–38 Ma by some North American geologists. Paleontologists did not like the latter age because, in North America, the 38-Ma-old mammals were dated using contemporaneous volcanic flows and seemed less evolved than those known to be at the stratigraphical boundary in Europe. The problem was solved due to a better boundary stratotype discovered near Ancona in east-central Italy. Minerals sampled from several layers of volcanic dust interbedded in the marine deposits of the stratotype were dated. The results indicated an age of about 33.7 ± 0.5 Ma for the boundary. This result confirmed the later of the two previous proposals demonstrating that the evolution of mammals in Europe and North America was synchronous.

Another significant example of the beneficial combination of improved stratigraphical definition and modern geochronological dating is given by the Precambrian-Cambrian boundary. The base of the Cambrian (and of the Phanerozoic Eon) had long been placed at the first occurrence of skeletalized fossils including trilobites (arthropods). Later, a Tommotian pretrilobitic stage was added below it in view of the presence of older faunal remains, such as archaeocythids (calcitized spongelike forms), which have been well documented on the Siberian Platform. Before 1980, the earliest skeletalized faunas were estimated to be between 570 and 590 Ma. However, independent geochronological data were gathered from northern France, southern Britain, Morocco, and Israel in the early 1980s. These data were

				Ma	+/−
CENOZOIC	QUATERNARY			1.75	0.05
	NEOGENE	PLIOCENE		5.3	0.15
		MIOCENE	MESSINIAN	7.3	0.15
			TORTONIAN	11.0	0.3
			SERRAVALLIAN (+LANGHIAN)	15.8	0.2
			BURDIGALIAN	20.3	0.4
			AQUITANIAN	23.5	1
	PALEOGENE	OLIGOCENE	CHATTIAN	28	1
			RUPELIAN	33.7	0.5
		EOCENE	PRIABONIAN	37.0	1/0.5
			BARTONIAN	40	1
			LUTETIAN	46.0	1/0.5
			YPRESIAN	53	1
		PALEOCENE	THANETIAN	59	2
			DANIAN	65.0	0.5
MESOZOIC	CRETACEOUS	LATE	MAASTRICHTIAN	71.5	0.5
			CAMPANIAN	83	1
			SANTONIAN	87	1
			CONIACIAN	88	2
			TURONIAN	92	2
			CENOMANIAN	96	2
		EARLY	ALBIAN	108	3/1
			APTIAN	113	3
			BARREMIAN	117	5/2
			HAUTERIVIAN	123	6/2
			VALANGINIAN	131	4
			BERRIASIAN	135	5
	JURASSIC	LATE	TITHONIAN	141	?/5
			KIMMERIDGIAN	146	—
			OXFORDIAN	154	5
		MIDDLE	CALLOVIAN	160	2
			BATHONIAN	164	2
			BAJOCIAN	170	4/3
			AALENIAN	175	3
		EARLY	TOARCIAN	184	3
			PLIENSBACHIAN	191	—
			SINEMURIAN	200	4/?
			HETTANGIAN	203	3
	TRIASSIC	LATE	RHETIAN	—	—
			NORIAN	220	—
			CARNIAN	230	6
		MIDDLE	LADINIAN	233	5
			ANISIAN	240	5
		EARLY	OLENEKIAN	—	—
			INDUSIAN	250	3

Era	Period	Epoch	Stages	Ma	+/−
PALEOZOIC	PERMIAN	LATE	(TATARIAN)	255	
			(KAZANIAN)	258	
		EARLY	(KUNGURIAN)	265	
			(ARTINSKIAN)	275	
			(SAKMARIAN)	285	
			(ASSELIAN)	295	5
	CARBONIFEROUS	LATE (SILESIAN)	(GZHELIAN)	—	—
			(KASIMOVIAN)		
			(MOSCOVIAN)		
			(BASHKIRIAN)		
			(SERPUKHOVIAN)	325	5
		EARLY (DINANTIAN)	(VISÉAN)	345	—
			(TOURNAISIAN)	355	5
	DEVONIAN	LATE	FAMENNIAN	370	5
			FRASNIAN	—	—
		MIDDLE	GIVETIAN	380	—
			EIFELIAN	390	5
		EARLY	EMSIAN	400	—
			PRAGIAN	—	—
			LOCHKOVIAN	410	8/5
	SILURIAN	PRIDOLI		415	—
		LUDLOW		425	5
		WENLOCK		430	6
		LLANDOVERY		435	6/4
	ORDOVICIAN	ASHGILL		445	4
		CARADOC		455	5
		LLANVIRN		465	5
		ARENIG		480	5
		TREMADOC		500	
	CAMBRIAN	LATE		—	—
		MIDDLE		520	—
		EARLY	(LENIAN)	525	5
			(ATDABANIAN)		
			(TOMMOTIAN)	530	5
			("PALEOCAMBRIAN")	540	5
PRECAMBRIAN					

Fig. 2. Simplified geological time scale of the Phanerozoic Eon. From about 120 possible stages, only one-fourth are formally defined in modern terms. Among others, many are mostly used regionally (in parentheses) with less precise boundaries and content compared to formal ones. Stages are not shown for some epochs for which no realistic subdivision can be recommended today. Ages given in two columns are shown without error bar when they are obtained from an interpolation procedure. For some boundaries, the error bar is asymmetrical; for example, the Aptian-Albian boundary has a preferred age at 108 Ma, but this age is constrained only between 111 and 107 Ma. (*After G. S. Odin, Geological Time* Scale, *C. R. Acad. Sci., 318:59–71, 1994*)

obtained from levels located below the first occurrence of trilobites in the different countries. The data showed that trilobites were younger than 530 (±10) Ma. In the following years, older faunas known as small shelly fossils contemporaneous with trace fossil assemblages were discovered in China, Australia, the Siberian Platform, and Canada. A modern Precambrian-Cambrian conventional boundary was definitely fixed in 1992 at the base of this fauna in Canada. From new geochronological information obtained from volcanic zircon sampled from the above locations, an age of 540 (±5) Ma was documented for that boundary. This has been of great consequence, considering that the end of the Cambrian is about 500 Ma. The apparently extraordinary radiation of skeletalized metazoans observed within the Cambrian took only a few tens of millions of years (instead of 100 Ma as thought in the mid-1980s). This extraordinary radiation must be compared to the evolution observed over the next 500 Ma during which no new important phyla were created. Two examples that help provide better understanding of geological phenomena connected to the precise dating of geological strata are the short duration of the important biological cuts occurring at the Permian-Triassic (Paleozoic-Mesozoic) boundary and the Cretaceous-Palaeogene (Mesozoic-Cenozoic) boundary.

Extrapolation procedures. The direct geochronological calibration method will never allow for the continuous calibration of every point of geological history, since datable material is much too scarce in rocks. However, continuous dating can be refined through the use of interpolation procedures between geochronologically calibrated points. This principle consists in combining those tie points with a continuous geological phenomenon. Commonly used phenomena are rhythmic sedimentation and the oceanic record of past magnetic fields. When the rhythmic deposition of sediments can be related to the orbital (Milankovitch) parameters of the Earth, the time scales of which are reasonably well understood, the duration of deposition can be estimated when combined with nearby measured ages.

Another procedure considers the aperiodic change (reversal) of the direction of the Earth's magnetic field that is recorded in the oceanic plates being continuously formed at midocean ridges (separating two tectonic plates). For a given plate, the distance between two magnetic reversals is proportional to the time durations between reversals and spreading rate (which can be calculated from two geochronologically dated points). Thus, geological ages can be calculated for each point of the record, though with some degree of uncertainty.

The geological time scale is gradually becoming unified through an internationally agreed upon scale which is replacing a variety of regional scales. It is ironic that such an important improvement in calibrating this vast expanse of time is linked to the discovery of volcanic dust interbedded in sedimentary rocks.

For background information *see* ARCHEOLOGICAL CHRONOLOGY; DATING METHODS; FOSSIL; GEOCHRONOMETRY; GEOLOGICAL TIME SCALE; INDEX FOSSIL; RADIOCARBON DATING; ROCK AGE DETERMINATION; SEDIMENTARY ROCKS; STRATIGRAPHIC NOMENCLATURE; STRATIGRAPHY in the McGraw-Hill Encyclopedia of Science & Technology.

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