The Geological Society of America Geologic Time Scale

INVITED REVIEW

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ABSTRACT

The Geological Society of America has sponsored versions of the geologic time scale since 1983. Over the past 30 years, the *Geological Society of America Geologic Time Scale* has undergone substantial modifications, commensurate with major advances in our understanding of chronostratigraphy, geochronology, astrochronology, chemostratigraphy, and the geomagnetic polarity time scale. Today, many parts of the time scale can be calibrated with precisions approaching less than 0.05%. Some notable time intervals for which collaborative, multifaceted efforts have led to dramatic improvements in our understanding of the character and temporal resolution of key evolutionary events include the Triassic-Jurassic, Permian-Triassic, and Neoproterozoic-Phanerozoic boundaries (or transitions). In developing the current *Geological Society of America Time Scale*, we have strived to maintain a consistency with efforts by the International Commission on Stratigraphy to develop an international geologic time scale.

Although current geologic time scales are vastly improved over the first geologic time scale, published by Arthur Holmes in 1913, we note that Holmes, using eight numerical ages to calibrate the Phanerozoic time scale, estimated the beginning of the Cambrian Period to within a few percent of the currently accepted value. Over the past 100 years, the confluence of process-based geological thought with observed and approximated geologic rates has led to coherent and quantitatively robust estimates of geologic time scales, reducing many uncertainties to the 0.1% level.

INTRODUCTION

One of the most important aspects of research in the geosciences is connecting what we examine in the rock record with ages of events and measured rates and durations of geologic processes. In doing so, geoscientists are able to place estimates on the rates of climate and evolutionary changes, use astronomically forced depositional processes to tell time within sedimentary basins, examine the ways in which tectonic processes change crustal and mantle structure and influence landscape evolution and global climate patterns, and assess the temporal relations among magmatism, fluid-rock interaction, and base/precious metal mineralization in many settings. A key requirement is establishing accurate ages of rocks that are directly associated with or bracket a geologic event or process. With efforts to estimate the chronology of geologic events beginning well over two centuries ago, this was commonly accomplished by establishing a relative geologic time scale using the ranges of fossils and stratigraphic relationships. Beginning in the early twentieth century, the relative geologic time scale was calibrated using numerical information.

A geologic time scale is the ordered compilation of numerical ages and relative age determinations based on stratigraphic and other principles. Numerical ages, formerly called "absolute ages" (Holmes, 1962), form a chronometric time scale typically expressed in thousands (ka) or millions (Ma) of years; relative ages form a chronostratigraphic time scale. A geologic time scale is an invaluable tool for geoscientists investigating virtually any aspect of Earth's development, anywhere on the planet, and at almost any time in Earth's history.

This paper describes the history of the development of the *Geological Society of America Geologic Time Scale* and provides a brief history of geologic time scales and their components. We also discuss important advances made over the past few decades in establishing both numerical and relative ages, describe selected proxies for time in the rock record, and note and comment on some future challenges. This paper is intended to provide a general overview of geologic time scales. The most comprehensive treatment of the geologic time scale is contained in the recent publication of Gradstein et al. (2012), the most current definitive work on the geologic time scale from a global perspective. This book is the most recent in the series of major publications by The Geological Society of London (Harland et al., 1964) and subsequently Cambridge University Press (Harland et al., 1982, 1990; Gradstein et al., 2004; Ogg et al., 2008) and Elsevier (Gradstein et al., 2012). The current *Geological Society of America Geologic Time Scale* (Fig. 1) incorporates information presented in the International Commission on Stratigraphy's International Chronostratigraphic Chart (Cohen et al., 2012) and in Gradstein et al. (2012). Numerical dates used for boundary positions are from Gradstein et al. (2012). The Geological Society of America (GSA) does not directly "maintain" an international geologic time scale. Rather, the society provides a geologic time scale in a concise, logically organized and readable format that is largely based on the work of the International Commission on Stratigraphy (ICS) and related groups and publications. GSA follows the work and recommendations of these groups in promoting a better understanding and use of geologic time through its time scale. Many of these organizations include geoscientists who are GSA members or members of the associated societies of GSA.

History of Chronometric-Chronostratigraphic Geologic Time Scales

> *"For it was evident to me that the space between the mountain ranges, which lie above the City of Memphis, once was a gulf of the sea, like the regions*

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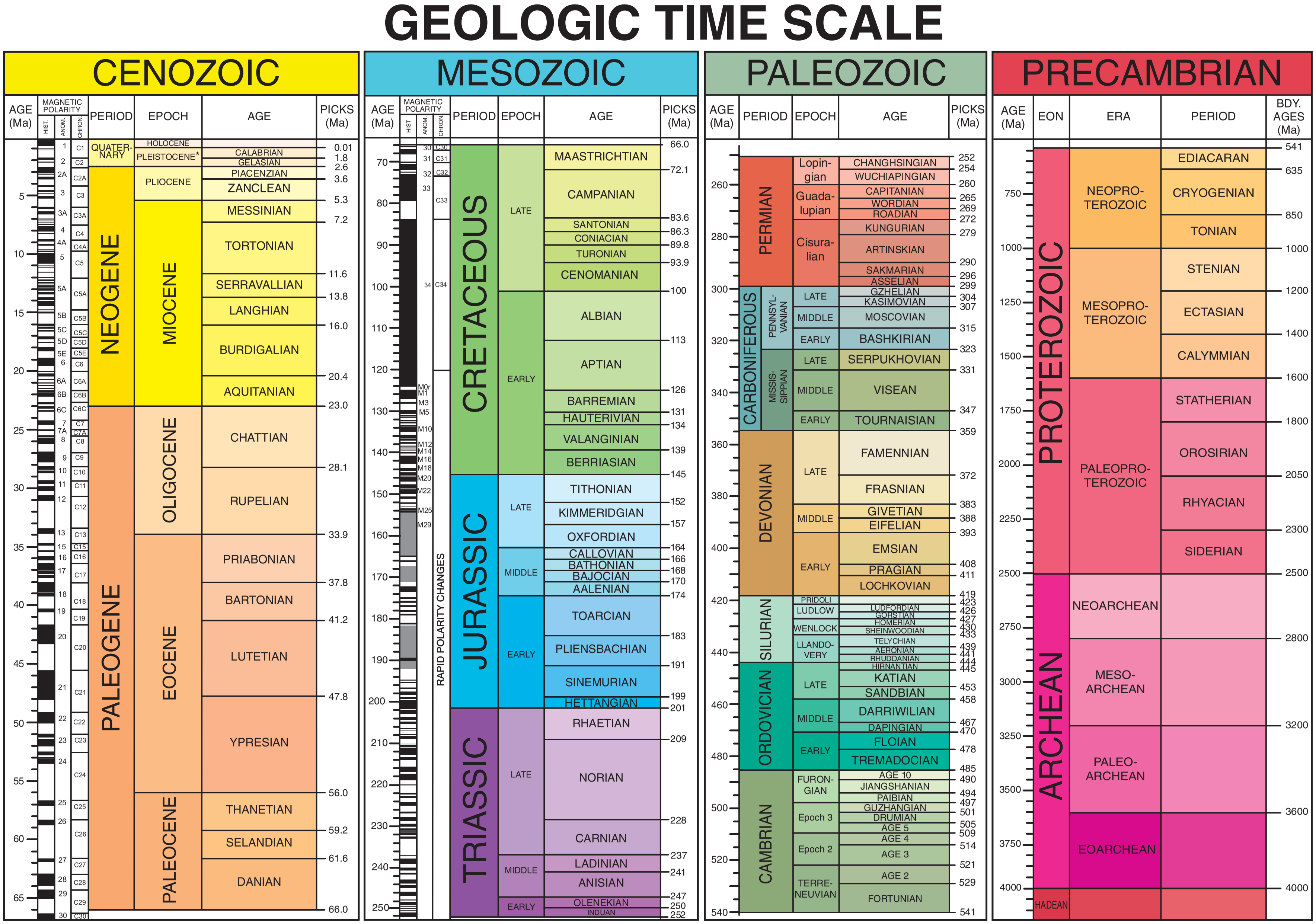

Figure 1. *Geological Society of America Geologic Time Scale*. The Cenozoic, Mesozoic, and Paleozoic are the Eras of the Phanerozoic Eon. Names of chronostratigraphic units follow the usage of the Gradstein et al. (2012) and Cohen et al. (2012). Age estimates of boundary positions follow Gradstein et al. (2012) but are rounded to the nearest whole number (1 Ma) for the pre-Cenomanian, and rounded to one decimal place (100 ka) for the Cenomanian to Pleistocene interval. Numbered series and stages of the Cambrian are provisional. The Pleistocene is divided into four ages, but only two are shown here. What is shown as Calabrian is actually three ages: Calabrian from 1.8 to 0.78 Ma, Middle from 0.78 to 0.13 Ma, and Late from 0.13 to 0.01 Ma.

> *about…Ephesos and the Plain of the Maiander, if it be permitted to compare small things with great. And small these are in comparison, for of the rivers, which heaped up the soil in those regions none is worthy to be compared in volume with a single one of the mouths of the Nile, which has five mouths."*
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> —Herodotus, likely the world's first geologist, fifth century B.C., in his *Histories, 2.10.0-2.*

The quest to understand geologic time has been integral to the geosciences for over 200 years. James Hutton first formally presented the scientific hypothesis that Earth is ancient in a reading at the Royal Society of Edinburgh on 4 April 1785. He concluded his revolutionary text, *Theory of the Earth*, which was based on his lectures to the Royal Society of Edinburgh and published in 1788, with the now-famous and often-quoted sentence concerning the natural history of the Earth: "The result, therefore, of our present enquiry is, that we find no vestige of a beginning,—no prospect of an end" (p. 304). His work in part inspired the great advances in the geosciences over the following century, over many parts of the world, and, after the discovery of radioactivity, prompted the initial attempts to quantify the age of the planet Earth and geologic time.

The first attempts by geologists to quantify the chronostratigraphic time scale and to establish some bounds on the age of Earth fall under the category of "hourglass" methods. The two most important of these involved considerations of the thickness of sedimentary strata and the salinity of the oceans. Both of these approaches relied on using estimated rates of geologic processes to establish a more quantitative time scale. For the first hourglass, the rates of sediment accumulation were compared to thicknesses of sedimentary strata of known chronostratigraphic age to compute the duration of deposition of the rock unit. The second method relied on understanding the input from streams to the oceans to compute an overall age for the oceans. In both cases, these were very rough approximations of the duration of processes, because the estimates of rates were inexact. Importantly, these estimates indicated that the Earth was much older than was accepted at the time. This was also true of estimates by Thomson (see below). Remarkably, during the second half of the nineteenth century, prior to the discovery of radioactivity, a number of workers recognized astronomically forced sedimentary deposits and used them as a means to calibrate geologic time (reviewed in Hilgen, 2010). The first attempts were built on the astronomical theories for ice ages, and they used eccentricity maximums to tune deposits of the last glaciation but were also tuning Miocene and Cretaceous sedimentary rocks (Hilgen, 2010).

The discovery of radioactivity, and, more specifically, the relation between radioactive parent elements and their intermediate and ultimate daughter products through a fundamental half-life of radioactive decay, was the seminal event that led to establishing the numerical ages of geologic materials and ultimately developing the first chronometric time scale. The first attempt was by Arthur Holmes (1913) in his book *The Age of the Earth*. Holmes (1913, Chapter X) extensively reviewed the early methods of geochronology using U as the parent element. Work at that time showed that the decay of U produced He as a by-product and probably had as its ultimate daughter the element Pb. The half-life of U and thus production rates of these elements were roughly established by the time of Holmes' (1913) publication. At the time of Holmes' work, it was simply the ratio of U to He or Pb that was measured—the discovery that elements had multiple isotopes was reported separately in the same year (Soddy, 1913; Thomson, 1913). Holmes (1913) reviewed all available age determinations for U-Pb and U-He that had bearing on tying numerical age estimates to meaningful geologic ages. In this effort, he noted that U-He age estimates were typically too young, represented minimum ages, and were most useful for younger (Cenozoic) rocks. Holmes established the pre-Cenozoic time scale using a total of five U-Pb determinations. Of these, only three were from rocks of Phanerozoic age: an age of 340 Ma for the end of the Carboniferous, 370 Ma for the end of the Devonian, and 430 Ma for the end of the Ordovician. Ultimately, Holmes used five U-He and five U-Pb dates to calibrate his geologic time scale. The ages of other parts of the chronostratigraphic time scale not covered by available age estimates were approximated by using compilations of sediment thicknesses. Holmes concluded this chapter by stating (p. 165):

> *"Most of the available evidence drawn from radioactive minerals has now been passed in review. As yet it is a meager record, but, nevertheless, a record brimful of promise. Radioactive minerals, for the geologist, are clocks wound up at the time of their origin. After a few years' preliminary work, we are now confident that the means of reading these time-keepers is in our possession. Not only can we read them, but if they have been tampered with and are recording time incorrectly, we can, in most cases, detect the error and so safeguard ourselves against false conclusions."*

Besides establishing a rough time scale, this work was radical in that it expanded the age of Earth beyond any previous estimate. Up until that time, the particularly influential work of Lord Kelvin had placed an upper limit of ca. 40 Ma on the age of Earth (Thomson, 1865). In his first edition of *On the Origin of the Species by Means of Natural Selection*, Charles Darwin provided a crude estimate of the age of Earth of several hundred million years based on both geology and his assumption of phyletic gradualism. Interestingly, estimates of the duration of the Phanerozoic incorporating radiometric ages in the work of Holmes (1913) at ~550 Ma (inferred from Holmes' fig. 17) and Barrell (1917, p. 892) at ~552 Ma are well within a few percent of the currently accepted value.

The time scale was greatly refined by Holmes in the second edition of his book (Holmes, 1937). At that time he used almost 30 U-He, U-Pb, and Th-Pb age determinations. Because of the recognition of multiple isotopes, geochronology relied not just on determining the parent-daughter ratio, but in the cases of the U-Pb and Th-Pb decay systems, the actual atomic mass and, to some extent, the isotope ratios of the daughter products (Holmes, 1937, Chapter V). Holmes continued to refine the time scale over the next 25 years. Concurrently, analytical methods increased in their precision while the number of elements and thus minerals used for isotopic age determinations increased. For example, Kulp (1961) primarily incorporated K-Ar dates as numerical estimates for his compilation of the time scale. A subsequent symposium in honor of Holmes resulted in a major effort toward developing a geologic time scale by a broader community of geoscientists (Harland et al., 1964). In the symposium volume, the authors reviewed all of the significant aspects of and developments with the geologic time scale from numerical dates, to hourglass methods, and stratigraphic constraints. In all, over 300 dates were used to construct a Phanerozoic time scale.

Over the next 20 years, the standardization of isotopic decay constants by Steiger and Jäger (1977) and major improvements to the chronostratigraphic time scale, fostered by the International Union of Geological Sciences (IUGS) through the International Commission on Stratigraphy (ICS) and its subcommissions, greatly advanced the geologic time scale. In particular, the efforts of the ICS established worldwide standard definitions of the relative geologic time scale. ICS has and continues to establish global chronostratigraphic standards known as global boundary stratotype section and points (GSSPs) (see following discussion). The work of IUGS and ICS has culminated in more refined geologic time scales for the Phanerozoic published by Harland et al. (1982), Odin (1982), and numerous other authors. The initial GSA time scale (Palmer, 1983) relied heavily on the contributions by these authors. A major treatment, including the statistical assessment of uncertainties of the estimated boundary ages, was presented by Harland et al. (1989). Considerable progress was made over the next 15 years, with the next major and comprehensive revision to the geologic time scale published by Gradstein et al. (2004). This publication fully integrated the advances made in global stratigraphy through the work of the ICS, including astrochronology, and took advantage of considerably more precise radioisotope geochronology including ^{40}Ar/^{39}Ar step heating and single-crystal laser methods as well as U-Pb zircon dating methods.

History of the *Geological Society of America Geologic Time Scale*

Besides being the 125th anniversary of the Geological Society of America, 2013 marks the 30th anniversary of the *Geological Society of America Geologic Time Scale*, the 50th anniversary of the publication of the Vine-Matthews-Morley-Larochelle hypothesis that marine magnetic anomaly patterns adjacent to mid-ocean ridges were a record of the polarity reversal history of the geomagnetic field and thus that the ridges were sites of ocean-floor spreading (Vine and Matthews, 1963), the 100th anniversary of the first geologic time scale presented by Holmes (1913), and the 225th anniversary of Hutton's *Theory of the Earth* (1788). The GSA time scale grew out of the Decade of North America Geology (DNAG) project (Palmer, 1983), which had as its goal a synthesis of the geology then known of the North American continent. Before that time, geologic information on North America had been scattered through the literature. With a few exceptions (e.g., Eardley, 1951; King, 1959), little in the way of comprehensive summaries of the geology of North America existed. A necessary prerequisite for discussing the geology of the continent was a common chronostratigraphic vocabulary and internally consistent sense of both the relative and numerical ages of geologic and evolutionary events. This provided ages of specific stratigraphic units addressed in the multivolume compilation involving scores of authors that resulted from the DNAG project. The DNAG project was the first detailed synthesis of North American geology following widespread acceptance of plate-tectonic theory and provided a sense of the evolution of the continent in the context of global events. Before the DNAG compilation could proceed very far, a uniform geologic time scale had to be adopted, and it was the first major product of the DNAG initiative. This inevitably led to advancement of a version of the geologic time scale that was North American–centered but with more far-reaching consequences. With progress of the DNAG project and considerable changes in chronostratigraphic nomenclature taking place internationally, refinements of the time scale were inevitable, and updated versions were published as GSA's *1999 Geologic Time Scale* (Palmer and Geissman, 1999) and *2009 Geologic Time Scale* (Walker and Geissman, 2009). What set the original DNAG time scale apart from earlier versions of time scales published in textbooks and summary papers was the overt application of integrated stratigraphic and magnetostratigraphic data sources (including both relative and numerical age dating techniques used to assemble the time scale) and the style of presentation.

The rationale behind and history of the work to develop the first *Geological Society of America Geologic Time Scale* itself were described by Palmer (1983) and Walker and Geissman (2009). Allison ("Pete") Palmer was the Centennial Science Program Coordinator for GSA's DNAG project, and was charged with compiling the results of the efforts of the Time Scale Advisory Committee, consisting of Z.E. Peterman, J.E. Harrison, R.L. Armstrong, and W.A. Berggren. Pete Palmer had a clear passion for the work and devoted considerable energy to the project. An innovative contribution was the attempt to organize the time scale onto a single 8.5 by 11 inch sheet of paper using the "tools of the trade" in those days—Mylar, zipatone letters, a Leroy lettering machine, and a lot of patience. His efforts resulted in a unique layout for the time scale, in which each era of the Phanerozoic, and all of the Precambrian, was given identical column length. Scaling of the magnetic polarity time scale to fit this format required numerous trials. When Jim Clark, the director of publications for GSA, suggested that the geologic time scale should also be published as a pocket wallet card, the effort became even more challenging. A key concern by both the advisory committee and Palmer was whether the time scale should be North American centric or global. The advisory committee and Palmer recognized the likely pitfalls and hurdles associated with trying to develop a global time scale and set as a goal trying to develop a "common vocabulary" for North America, still a sufficiently great challenge. In discussions with Palmer (2012, personal commun.), he emphasized the difficulties with defining the base of the Ordovician (which has more recently been solved with the definition of an Ordovician GSSP). The final product (Palmer, 1983) served the intended purpose well. "There were no naysayers, and no major disagreements," stated Palmer. "The basic subdivisions were all accepted."

RECENT ADVANCES AND THEIR IMPACT ON THE GEOLOGIC TIME SCALE

Here, we review some of the key advances that have led to changes and refinements of the geologic time scale. These include, of course, changes in stratigraphic and geochronologic approaches that are at the heart of a combined chronometric/chronostratigraphic time scale, but also astrochronology, which is revolutionizing the time scale effort, chemostratigraphy and related rock magnetic stratigraphy, and the geomagnetic polarity time scale (see Table 1 for brief descriptions of these methods).

Advances in Stratigraphy—The International Commission on Stratigraphy

Leading the way in the advancement of chronostratigraphic information is the International Commission on Stratigraphy, including the many subcommissions formed by the ICS. These groups actively promote the acquisition and dissemination of information vital to making informed decisions about stratigraphic boundary positions and numerical calibrations of those positions. A major goal of the ICS is to develop an unambiguous, globally applicable nomenclature for geologic time units and their chronostratigraphic equivalents, a common language in which concepts are identical for all localities across the globe. This effort is part of a larger project to develop unambiguous chronostratigraphic units for the entire geologic time scale (Gradstein et al., 2004, 2012; Ogg et al., 2008; Cohen et al., 2012). The main driving forces for the refinements and restructuring to the chronostratigraphic side of the geologic time scale are changes in philosophy about how stratigraphic units are defined, as well as high-resolution studies utilizing chronostratigraphic proxies, including biostratigraphy, chemostratigraphy, magnetostratigraphy, rock magnetic stratigraphy, and astrochronology/orbital tuning.

Over the past several decades, different stratigraphic philosophies have been applied to definitions of chronostratigraphic units. Definitions in many places around the world were commonly based on the unit-stratotype concept, in which a type section serves as the standard of reference for the definition and characterization of a unit (Salvador, 1994). The lower and upper boundaries of a unit are normally specified by reference to a type section. Beginning in the 1970s, the concept of a boundary-stratotype was promoted. Under this concept, only the base of a chronostratigraphic unit is formally defined, and it is marked by a point in strata (Salvador, 1994),

TABLE 1. TIME DETERMINATION METHODS

Methods	Definition and application
Astrochronology	Study of cyclical variation in properties present in sedimentary rock sequences interpreted to represent a response to Earth orbital parameters deriving from interaction with the Sun, Moon, and other planets. Variations can be expressed in physical sedimentary patterns (e.g., bed thicknesses) or chemical characteristics. Can be used for establishing durations in the Cenozoic and in older time intervals if calibrated by geochronologic results and for direct dating in rocks younger than ca. 35 Ma.
Chemostratigraphy	Study of chemical and isotopic variations in sedimentary sequences interpreted to reflect changes in seawater chemistry or catastrophic events (e.g., Ir anomaly at the end of the Cretaceous). Detailed variations in chemical signals may reflect astronomical forcing and can be used as a dating tool when signal changes at a high rate (Cenozoic Os and Sr). Can also be used for relative time by correlation of major unique signatures.
Geochronology	Study of radioisotopes and their decay products. Time measured by the ratio of radioisotopes to decay products using a decay constant. This is a numerical dating method.
Magnetic polarity stratigraphy	Study of the polarity record of Earth's magnetic field as reflected in the paleomagnetic signatures of stratified rocks. This gives relative ages and allows for correlation of sequences. It can approximate a numerical method if one or, ideally, many parts of a sequence can be tied to a numerical age.
Rock magnetic stratigraphy	Study of the variations in the magnetic mineralogy (concentration and mineral phases) assumed to be originally deposited with the sedimentary sequence. At a fine-scale examination (e.g., bed or even lamina), this method can be a component of astrochronology.
Stratigraphy	Study of stratigraphic successions by using the physical arrangement of layers and sequences (lithostratigraphy) as well as the fossil content (biostratigraphy). This is a relative dating and correlation method.

which is known as a GSSP, or global boundary stratotype section and point, more popularly referred to as a "golden spike."

Originally, the boundaries of most geologic time units were drawn at positions in the stratigraphic record where some sizable biotic change, widespread geologic event such as a glacial advance or retreat, or an orogenic episode was recognized. Some of the formal nomenclature of the geologic time scale reflects this practice: "Phanerozoic" means "visible life," Paleozoic, Mesozoic, and Cenozoic mean "ancient life," "middle life," and "recent life," respectively. Informal terms applied to geologic time units, such as the "age of bryozoans" for the Ordovician, the "age of coal swamps" for the Carboniferous, the "age of dinosaurs" for the Mesozoic, and the "age of mammals" for the Cenozoic, reinforce this approach to characterizing the progression of geologic time. This broad-brush view may have some merits, but to a large extent, the apparent distinctions between strata contained in superjacent chronostratigraphic units have been enhanced by evolutionary overturns (extinctions, followed by recoveries and changing patterns of ecologic dominance) and unconformities of varying scale. Boundaries drawn at such horizons are almost certain to be in stratigraphic gaps. In the past, chronostratigraphic units based on the unit-stratotype concept were often drawn at previously unrecognized gaps in the stratigraphic record. To be useful, a globally synchronous boundary must be drawn at a horizon in a continuous succession of strata to ensure that there are no gaps in the succession. A boundary-stratotype–based chronostratigraphic unit is defined only at the base, so the "top" is automatically defined by the base of the overlying unit, and there can be no gap in between. GSSPs are defined according to the boundary-stratotype concept. By definition, every GSSP marks the base of a chronostratigraphic unit. Also by definition, the chronostratigraphic unit subjacent to each GSSP includes all strata known and unknown up to that horizon, so there can be no gap between adjacent chronostratigraphic units.

High-resolution stratigraphic studies today, often enhanced with continuous drill cores, are the norm, so more detailed information is available now than when early versions of the geologic time scale were assembled. The resulting details are not always clear, and unambiguous sets of data in some cases have shown that geoscientists were sometimes mistaken in their assumptions of isochronous events. The first appearance of trilobites was once used through much of the world as the marker for the base of the Phanerozoic. Today, we recognize that the appearance of trilobites on separate paleocontinents was not synchronous, making such an inferred singular "event" unsuitable on its own as a definitive correlation tool. High-resolution chronostratigraphic studies using multiple methods in combination now give us the ability to pinpoint an exact datum in strata where a boundary can be drawn. For example, the base of the Cenozoic coincides with the base of an iridium-bearing clay layer, as first demonstrated at Gubbio, Italy (Alvarez et al., 1980). On a global scale, numerous other stratigraphic tools (among them, the biostratigraphic ranges of nannoplankton and foraminiferans, spores and pollen, ratios of stable isotopes of carbon and oxygen, and magnetic polarity stratigraphy) provide information that adds to the anomalous concentration of iridium at that single datum to help define its singular position. Geochronology also can be used to identify the base of the Cenozoic with great precision (ca. 66.0 Ma), adding to the broad range of techniques that can be used to identify the boundary horizon globally.

Most GSSPs in the Phanerozoic have been defined to coincide with an evolutionary event, normally the evolutionary first appearance of a recognizable guide fossil. For at least one chronostratigraphic unit, this approach is impractical, in part because some available time proxies exceed biostratigraphy in their ability to provide high-resolution stratigraphic information. The base of the Holocene Series/Epoch, for example, has been defined at a point reflecting a distinct switchover in deuterium content of glacial ice in Greenland. That point essentially coincides with the onset of warming at the end of the Younger Dryas and a change in thickness of glacial ice layers, reflecting increased dust content associated with the warming interval. Chemostratigraphy, particularly using $\delta^{13}C$, provides high-resolution stratigraphic information for parts of the Paleozoic that have been challenging to define on the basis of biostratigraphic evidence alone. To date, stable isotope data have not been used as a primary tool for defining a chronostratigraphic unit, but biostratigraphically calibrated isotopic excursions, particularly in $\delta^{13}C$, have some advantages in successions where the biostratigraphic data are inconclusive at a detailed scale (e.g., Maloof et al., 2010; Korte and Kozur, 2010). As we achieve a more highly calibrated record, assuming global synchroneity of the Carbon record, for example, may not remain valid. Since the completeness of sections is variable, it may be that no single proxy will resolve all issues making the use and integration of multiple proxies required.

The application of the GSSP approach has helped stabilize the geologic time scale by adoption of chronostratigraphic nomenclature ratified by specialists the world over. Changes to the time scale resulting from these advances are numerous and some time periods have been dramatically restructured through formal decisions on boundary positions. The Cambrian System/Period, for example, now has a ratified base that is stratigraphically well below its position in 1983, and the ratified base of the Ordovician System, which marks the top of the Cambrian, is above its position in 1983. The 1983 position of the Cambrian base, following Harland et al. (1982) was at the base of the Tommotian Stage as used in Siberia and, at that time. Today, that position is within provisional Stage 2 of the Cambrian System and estimated to be about 525 Ma (570 Ma by 1983 standards). The horizon is well within what was in 1983 considered to be Proterozoic strata. The base of the Ordovician, after formal definition, is at a horizon near 485 Ma (504 by 1983 standards).

Formal decisions on chronostratigraphic boundaries have in some instances led to changes in the way we subdivide systems/periods. Largely as a result of the addition of a thick stratigraphic section below its traditional base, the Cambrian is now subdivided into four series/epochs rather than the traditional three, and the resulting names for the epochs are derived from localities, not relative stratigraphic position. The Silurian Period is also subdivided into four epochs, the names of which are derived from localities. The Permian Period is subdivided into three epochs, and their names are likewise derived from localities rather than relative stratigraphic position. The Cenozoic Era has been considerably reorganized. It now consists of three periods, Paleogene, Neogene, and Quaternary. Strata traditionally assigned to the uppermost Pliocene Series/Epoch (Neogene System/Period) are now assigned to the Gelasian Stage/Age, which belongs in the Pleistocene Series/Epoch (Quaternary System/Period). As a result, the Quaternary is 43% longer today than it was prior to addition of the Gelasian Stage/Age. Importantly, the base of the Holocene Series/Epoch has been defined, and its beginning is dated at 11,700 yr b2k (before A.D. 2000). Terms such as Tertiary, Recent, and Anthropocene have been dropped from the geologic and chronostratigraphic vocabulary as they no longer have any internationally sanctioned standing.

Advances in Geochronology and the EARTHTIME Effort

The past decade has seen dramatic advances in high-precision geochronology. These advances have been used to develop time lines for Earth history and deconvolve complex tectonic and magmatic events. Importantly, the application of high-precision geochronology to sedimentary sequences has allowed researchers to determine the age, duration, and possible synchroneity of global events such as extinctions, rates of biological evolution and changes in biodiversity, and the age and duration of stable isotope anomalies that reflect major changes in seawater and atmospheric chemistry. This mainly results from dramatic increases in the precision of radioisotopic dates, especially using ^{40}Ar/^{39}Ar (feldspars) and U-Pb (zircon) methods. These increases have been stimulated by new laboratory methods, new generations of mass spectrometers, and scientific projects that demand the highest possible precision. The U-Pb method can be applied to rocks from as young as 600 ka, to as old as the oldest known mineral grains on the planet (ca. 4.4 Ga zircon), to meteorites. The ^{40}Ar/^{39}Ar method is mainly used for rocks that range in age from younger than 600 ka through the Paleozoic, and even in some cases Archean rocks and meteorites. However, ^{40}Ar/^{39}Ar systematics are typically disturbed by metamorphism in rocks exposed to greenschist and higher grades of metamorphism. For rocks younger than 600 ka, ^{40}Ar/^{39}Ar and U-series geochronology are best applied. The time interval reflecting recent landscape evolution and erosion is best evaluated using several different terrestrial cosmogenic nuclides.

As precisions improved (e.g., <0.1% for U-Pb zircon methods), it was apparent that there were both intertechnique and interlaboratory systematic errors for the U-Pb and ^{40}Ar/^{39}Ar methods. Thus the EARTHTIME project (http://www.earth-time.org/ and European sister organization http://earthtime-eu.eu/) was initiated to develop a community-driven approach to the calibration of Earth history using ^{40}Ar/^{39}Ar and U-Pb methods. The project organized all the major geochronology laboratories in the world in a collaborative effort to eliminate both interlaboratory and intertechnique biases and to critically assess both accuracy and precision associated with numerical ages. The ultimate goal is to calibrate Earth history, and the effort has already produced remarkable cooperation among geochronologists and the rest of the earth science community, especially paleontologists, astrochronologists, and stratigraphers. This has also spawned a new generation of students who range from conversant to full practitioners of radioisotope geochronology and paleontology, stratigraphy, and astrochronology. A critical element of this globally collaborative approach is the need for transparency for all laboratory techniques, from sample preparation to data acquisition and data reduction to data reporting and archiving.

The first step for the U-Pb community was to eliminate a large source of interlaboratory bias caused by the fact that each laboratory used a different isotopic tracer. Enriched tracers are added to U-bearing accessory minerals prior to dissolution to allow the U/Pb ratio of the mineral to be determined. Tracers used by different laboratories when EARTHTIME began included both ^{208}Pb and ^{205}Pb that were mixed with ^{235}U or ^{233}U + ^{235}U or ^{233}U + ^{236}U. Two isotopes of U allow mass-dependent fractionation to be evaluated during the run, greatly reducing one of the biggest sources of uncertainty in U isotopic analyses. In addition, there are a few tracers containing ^{233}U-^{235}U-^{202}Pb-^{205}Pb that allow correction for fractionation of the Pb isotopes as well. It was decided that the community needed a single mixed tracer for all laboratories interested in the EARTHTIME goal (producing the highest-precision geochronology to establish a calibrated time line for Earth history) and one was mixed, calibrated, and sent to several laboratories (Condon et al., 2007).

At about the same time, U-Pb zircon geochronology was forever changed by the development of a method that eliminates open-system behavior (usually Pb loss) from zircon. The method was developed by James Mattinson (Mattinson, 2005) and involves high-temperature annealing of grains followed by partial dissolution. Mattinson was able to show that the high-U parts of the grains that are most susceptible to Pb loss can be preferentially removed, leaving relatively low-U domains with no evidence of Pb loss.

EARTHTIME workers did a series of blind tests where unknown zircons and synthetic U-Pb solutions were sent to a number of laboratories with the EARTHTIME tracer. The first blind test was done without the tracer, and dispersion was close to 1%. The second test was done using the EARTHTIME tracer, and the synthetic solutions indeed greatly decreased interlaboratory variability, and at least six laboratories now agree at the 1‰ level. Finally, the community seeks to have common open-source data acquisition and reduction protocols that can evolve as new ideas are developed. The same approach can be and is being used for all techniques from ^{14}C to terrestrial cosmogenic nuclides (http://www.physics.purdue.edu/primelab/CronusProject/cronus/).

The ^{40}Ar/^{39}Ar community is working in parallel on developing neutron fluence monitors, including independent assessment of their age, other age standards, and data acquisition of fluence monitors. This community also has run two blind tests. The first test, involving five samples, indicated considerable dispersion among laboratories but no systematic bias. In the second test, all five samples were sent for one irradiation and then distributed, eliminating differences in reactors and irradiation protocols. The results were similar to the first with ~2% dispersion among laboratories, and this is much greater than the reported analytical precisions (mostly 0.1%–0.5%). There are several potential explanations, including differences in the data acquisition and reduction protocols in each laboratory (currently there is not a common platform), nonlinearity of the mass spectrometer source/detector systems, and different systems for cleaning sample gas using getters. A new approach to solving this problem is under way. A pipette system filled with gases of a known isotopic composition will travel to participating laboratories to eliminate issues associated with sample heterogeneity. There will be three gasses in the pipette experiment; one will be air, and the other two will be aliquots of a large natural sample of biotite irradiated different times such that the ratio of ^{40}Ar*/^{39}Ar is ~23.6 between the two experiments. An important aspect of the pipette experiment is that each canister will have three calibrated pipette volumes of 0.1, 0.2, and 0.4 cm^3, allowing for varying the amount of gas delivered as 0.1, 0.2, 0.3 (0.1+0.2), 0.4, 0.5 (0.1+0.4), 0.6 (0.2+0.4), and 0.7 cc. Furthermore, it will be possible to mix these gases with the same volume increments to produce intermediate values. This approach should better elucidate the sources of interlaboratory dispersion. We are highly optimistic that within a few years, the ^{40}Ar/^{39}Ar community will have eliminated interlaboratory bias and have internal errors of ~0.3%, if not lower.

As EARTHTIME community members have attempted to improve precisions of radioisotopic dates, there has been a much deeper appreciation of the ways in which to quantify most sources of uncertainty and to fully propagate associated errors. This in turn has led to new protocols for data acquisition, reduction, and archiving through open-source software (Bowring et al., 2011; McLean et al., 2011), resulting in more accurate uncertainties in calculated U-Pb dates. Archiving of data will be achieved through a collaboration with EarthChem (at http://www.geochron.org), where data may be uploaded directly from the software and will allow future recalculation of dates as "constants" such as the ^{238}U/^{235}U ratio in zircons (e.g., Hiess et al., 2012), U and K decay constants, and tracer calibration changes due to new measurements in any laboratory while preserving the original uploaded data. This will allow any time scale to be updated using published and recalculated dates. The ^{40}Ar/^{39}Ar community is also working toward a common platform for data reduction and is linked to EarthChem for archiving of data through current data reduction software.

Advances in the Geomagnetic Polarity Time Scale—Developments and Integration with the Geologic Time Scale

> *"The critical thing at that meeting was that I met Brent Dalrymple for the first time. He told me in private discussion between sessions, 'We think that we've sharpened up the polarity reversal scale a bit, but in particular we've defined a new event—the Jaramillo event.' I realized immediately that with that new time scale, the Juan de Fuca Ridge could be interpreted in terms of a constant spreading rate. And that was fantastic, because we realized that the record was more clearly written than we had anticipated. Now we had evidence of constant spreading; that was very important.*
>
> *"I realized at once, having poured over the problem for so long and so recently, that with this revised time scale it would be possible to interpret the Juan de Fuca anomaly sequence with an essentially constant rate of spreading. To me, at that instant, it was all over, bar the shouting."*
>
> —Frederick J. Vine, recalling his meeting of Brent Dalrymple at the 1965 GSA Annual Meeting, November, Kansas City, in Glen (1982) and Oreskes (2001), respectively.

It has been 50 years since the publication of the seminal contribution by Fred Vine and Drummond Matthews (Vine and Matthews, 1963) in which marine magnetic anomaly patterns were interpreted in the context of seafloor spreading and mid-ocean ridges (the Vine-Matthews-Morley-Larochelle hypothesis). It was the recognition that Earth's magnetic field was capable of reversing its polarity, and in fact had done so numerous times, that allowed their hypothesis to be proffered. This was at a point in the early stages in the history of the development of the geomagnetic polarity time scale and magnetic polarity stratigraphy, as the "ordering of sedimentary or igneous rock strata into intervals characterized by the direction of magnetization of the rocks, being either in the direction of the present Earth's field (normal polarity) or 180° from the present field (reverse polarity)" (Opdyke and Channell, 1996). It was also at a point soon after the general acceptance of the fact that the geomagnetic field was capable of reversing its polarity—a concept that for decades met with considerable argument and debate in the scientific community. The first report of a magnetization in a rock (the natural remanent magnetization, NRM) with a direction reverse to that of the present geomagnetic field of Earth was that of Brunhes (1906), who examined Pliocene lava flows from central France. Several other studies over the ensuing decades reported magnetizations reverse to that of the present field, the most notable of which is that by Matuyama (1929), who suggested the possibility that the polarity of the geomagnetic field was age dependent. With the development of magnetometers with sufficient sensitivity to measure the NRM of sedimentary rocks, magnetic polarity stratigraphy began to blossom in the late 1940s and early 1950s. The earliest such study in North America was that by Torreson et al. (1949), which demonstrated that magnetizations of reverse polarity were retained in rocks as old as the early Mesozoic. Numerous studies further enforced the hypothesis that Earth's field had reversed its polarity in the past.

These emerging data served to enforce the need to settle the controversy concerning the possibility that the field was capable of reversing polarity, as workers recognized the potential of Earth's polarity history for establishing an independent scale of geologic time. In support of the field reversal hypothesis, there was a growing body of data showing positive "baked contact" tests, where the magnetization in a host rock immediately adjacent to an intrusive igneous rock, or below a lava flow, was similar if not identical to that in the igneous rock, and thus of the same polarity. In his classic early text on paleomagnetism, Irving (1964) described the ideal baked contact test (his fig. 7.22, p. 172) that, once and for all, would convincingly demonstrate that reverse polarity magnetizations in rocks were truly a geomagnetic field phenomena, rather than some form of "self-reversal" characteristic of a complicated magnetic mineralogy that is not common to most rocks. As Opdyke and Channel (1996) noted, the geomagnetic field reversal hypothesis was gaining considerable support by this time. First, all rocks of late Pleistocene and Holocene age were of normal polarity. Second, reverse polarity magnetizations were common to rocks of early Pleistocene age. Third, magnetizations with directions that were "transitional" between normal and reverse polarity were identified in both sedimentary and igneous rocks; their presence would be consistent with changes in polarity states occasionally being recorded. Fourth, self-reversal mechanisms were identified in laboratory experiments, but in only a few types of rocks; the overwhelming majority of experiments demonstrated that most rocks acquired a thermoremanent magnetization that replicated the ambient field. Finally, many baked contact tests, including some involving the nearly ideal field conditions postulated by Irving (1964), provided strong support for dual polarities of the geomagnetic field.

As described in *The Road to Jaramillo* (Glen, 1982), tremendous competition and excitement raged between teams of geochronologists/paleomagnetists from laboratories at the U.S. Geological Survey at Menlo Park and University of California at Berkeley and their Australian counterparts at the Australian National University. The important geochronologic method of potassium/argon age dating was being perfected, and the "race" was on to establish a more refined polarity time scale, based on isotopic age determinations of the very rocks examined for polarity information. By 1963, the combined geochronologic and magnetic polarity data were sufficiently compelling in their internal consistency to allow Vine and Matthews to formulate and have accepted for publication their now famous explanation of mid-ocean ridges and their importance. In the context of both the geomagnetic polarity time scale and global tectonics, the Vine and Matthews (and Morley/Larochelle) hypothesis of seafloor spreading was certainly not immediately embraced by the broad community. Skeptics noted the fine structure of marine magnetic anomaly patterns adjacent to crests of mid-ocean ridges and pointed out inconsistencies between anomaly patterns and the current, yet quickly evolving, polarity time scale. Much of that skepticism disappeared following the Doell and Dalrymple (1966) paper in *Science*, in which they demonstrated that the last ~1 m.y. of Earth history was not of entirely normal polarity, but rather consisted of some 700 ka of normal polarity, followed by an interval of ~100 ka of reverse polarity, an ~150 ka interval back to normal polarity, and a several 100 ka interval of reverse polarity, which characterized what was then the early Pleistocene. They named the short time interval of normal polarity the Jaramillo "event," after Jaramillo Creek in the Valle Grande of the Jemez Mountains, north-central New Mexico, and also described the longer intervals of constant polarity as magnetic epochs (e.g., Brunhes normal, Matuyama reverse, Gauss normal, and Gilbert reverse). As noted previously herein, Fred Vine first learned of this new observation in November 1965. By spring 1967, the hypothesis of seafloor spreading, and its many implications, had risen in status to the theory of plate tectonics.

At the time of publication of the *1983 Geologic Time Scale* (Palmer, 1983), our understanding of the geomagnetic polarity time scale had evolved by incremental refinements from a chronology of the last few million years of Earth history to an increasingly robust definition of Earth's polarity history back to the Middle Jurassic. How this happened in considerably less than 20 years involved additional high-quality radioisotopic dates obtained from igneous rock sequences with well-defined polarity records, improved magnetic polarity stratigraphy records, including those from deep-sea sediments, determination of the approximate ages of boundaries between some specific polarity epochs, and a global integration of marine magnetic anomaly data into an interpretable record of polarity changes, eventually back to the Middle Jurassic. These efforts were summarized by Berggren et al. (1985a, 1985b) and Kent and Gradstein (1986). Having several key numerical age estimates of polarity boundaries allowed for further refinements to the magnetic polarity time scale based on the marine magnetic anomaly record (Cande and Kent, 1992, 1995) and better recognition of the fact that seafloor spreading rates were not constant among ocean lithosphere plates and that they have not been constant since the early Mesozoic.

Since 1983, the geomagnetic polarity time scale has been extended to the base of the Triassic and in fact the very latest Permian using magnetic polarity stratigraphy records from continental and marine sedimentary rocks, in combination with high-resolution geochronologic data, biostratigraphy, and cyclostratigraphy, where possible. It may be possible to extend an accurate, chronologically defined polarity time scale into the latest Mississippian, prior to the Permian-Carboniferous Reverse Superchron. This superchron is perhaps the singular most unusual feature of the geomagnetic field during the entire Phanerozoic, as we have little evidence to contradict the likelihood that the field was exclusively of reverse polarity for some 55 Ma. The termination of the reverse superchron, originally named the Kiaman Magnetic Interval by Irving and Parry (1963), is close to the Wordian-Capitanian boundary (ca. 265 Ma). The base of the superchron, however, is less well known. Opdyke et al. (2000) argued that it might lie in lowermost Pennsylvanian strata. For most of the remainder of the Paleozoic, the magnetic polarity record is relatively ill defined, as noted by several workers and summarized by Opdyke and Channell (1996). The exception to this statement is an interval (superchron) of reverse polarity in the Early to Middle Ordovician that may be some 30 Ma in duration. Pavlov and Gallet (2005) proposed the name of "Moyero" for the superchron, based on the location in Siberia where a first complete record of the interval was identified. They also noted that the Middle Cambrian was a period of high polarity reversal frequency. Subsequent work by Pavlov et al. (2012) has further documented the chronostratigraphic framework for the Moyero superchron.

Two important time intervals in Earth history for which considerable effort has been made to understand and define, at very high resolution, the magnetic polarity time scale are the Late Triassic to earliest Jurassic and the late Middle Permian to earliest Triassic. Both of these time intervals include major extinction events and the development of large igneous provinces, the Central Atlantic magmatic province, and Siberian flood basalts, respectively.

The magnetic polarity record of the Triassic, and particularly the Late Triassic, has evolved considerably since early work by Keith Runcorn and colleagues in the 1950s. The seminal work by Paul Olsen and Dennis Kent and colleagues on the continuously cored Upper Triassic sequence of the Newark Basin (Kent et al., 1995; Olsen et al., 1996a, 1996b) provided a high-resolution, astrochronologically tuned polarity record for the ca. 25+ Ma. time interval obtained, which has been incorporated into the GSA geologic time scale. This advance permitted far more robust correlations of magnetic polarity data obtained from marine sections that preserved more complete records of evolutionary change during the latest Triassic to earliest Jurassic transition. This time interval (late Rhaetian to earliest Hettangian) is dominantly of normal polarity. Importantly, as summarized by Lucas et al. (2011), individual sections across the boundary have revealed between two and four reverse polarity zones inferred to be of short duration, and thus microzones. If possible, the precise correlations of these microzones, in marine and continental sections, across the Triassic-Jurassic boundary may ultimately prove invaluable in understanding the timing of end-Triassic vertebrate extinctions and the evolution of Jurassic recovery faunas.

Several recently obtained magnetic polarity stratigraphy records from both marine and terrestrial strata across the Permian-Triassic boundary interval show that both the end-Permian ecological crisis as well as the conodont-calibrated biostratigraphic Permian-Triassic boundary both followed a key polarity reversal from a relatively short interval (subchron) of reverse polarity to a considerably longer interval (chron) of normal polarity (Li and Wang, 1989; Scholger et al., 2000; Szurlies et al., 2003). An excellent example of the importance of integrating biostratigraphic, cyclostratigraphic, and magnetic polarity stratigraphic records is the principally continental Permian (Rotliegend and Zechstein Groups) and immediately overlying epicontinental Triassic (Buntsandstein Group) strata from Western and Central Europe, which have yielded high-quality magnetic polarity stratigraphic records. In combination with cyclostratigraphic records, Szurlies et al. (2003, 2012) estimated that the normal polarity chron containing both the end-Permian crisis and the biostratigraphic Permian-Triassic boundary was ~0.7 Ma in duration.

Chemostratigraphy

Chemostratigraphy is the study of variations in the primary chemical and isotopic compositions of sedimentary rocks with time. A variant of chemostratigraphy is rock magnetic stratigraphy, where variations in the concentration and/or mineralogy of magnetic phases are determined in sedimentary sequences (e.g., Evans and Heller, 2003; Kodama et al., 2010). Ideally, in chemostratigraphic and rock magnetic stratigraphic approaches, it is assumed that the chemical/rock magnetic signals preserved within sedimentary rocks provide a proxy for global seawater chemistry and/or environmental conditions at the time of, or shortly after, deposition. However, postdepositional processes can overprint primary signals, and much care must be taken to avoid interpretation of signals that have been modified by postdepositional processes as primary. If one assumes that the variation in seawater chemistry is a global and homogeneous signal, then one of the main uses of chemostratigraphy is to correlate stratigraphic variability in chemistry between packages of sedimentary rocks across a basin and/or around the globe. The relative temporal framework provided by chemostratigraphic correlation is enhanced using biostratigraphy, magnetostratigraphy, floating astrochronology (see following section), and calibration of chemical signals with numerical time using either well-established boundaries (e.g., extinctions, isotopic anomalies) or accurately dated volcanic rocks. Most recently defined GSSPs are at horizons close to some well-established chemostratigraphic shift that can be correlated between sections (Gradstein et al., 2012). In strata that are devoid of recognizable guide fossils, chemostratigraphic correlation has been essential to unraveling the chronology of Earth history. Study of the Neoproterozoic has benefited greatly from applying stable isotope chemostratigraphy to chronostratigraphic correlation (e.g., Knoll and Walter, 1992; Halverson et al., 2005).

A major complication to detailed chemostratigraphic correlations across large distances is that it is unlikely that multiple depositional areas capture the same complete and continuous record of sediment accumulation. In addition, accumulation rates between locations often vary significantly. In detail, these factors result in different structures of chemical variability, requiring care in comparing records. Nonetheless, average global curves for some elements have been compiled and appear to work quite well (e.g., Halverson et al., 2005; Saltzman, 2005; Zhu et al., 2006). Some stratigraphic positions, such as the base of the Cambrian (Corsetti and Hagadorn, 2000; Amthor et al., 2003; Bowring et al., 2007; Babcock et al., 2011), and the base of the Oligocene (Zachos et al., 2001), as well as some geologic events such as the end-Permian extinction (e.g., Shen et al., 2011; Cao et al., 2009) are marked by sharp, short-lived perturbations in seawater chemistry that can be used to correlate disparate sections.

Light stable isotopes and, in particular, variations in $^{13}C/^{12}C$ and $^{18}O/^{16}O$ are the most widely applied chemostratigraphic tools, largely because of their relative low acquisition costs. The smooth trends in their global values over long periods of time, punctuated by large, mostly short-lived and globally synchronous perturbations, aid in correlation. Also used is the heavier system of $^{87}Sr/^{86}Sr$, although data acquisition is more time consuming and expensive. Rock magnetic stratigraphy may utilize several rock magnetic parameters, including but not limited to bulk magnetic susceptibility, intensity of anhysteretic remanent magnetization (ARM), intensity of isothermal remanent magnetization (IRM), including saturation IRM (SIRM), and S-ratios (IRM acquired by first saturating the sample in a high field and then applying a backfield IRM in a field of –300 mT; this is divided by the SIRM).

Isotopes of Carbon

It is generally assumed that the carbon isotopic composition of carbonate rocks (expressed as $\delta^{13}C_{carb}$) is set during equilibrium precipitation from seawater and reflects the isotopic composition of the contemporaneous dissolved inorganic carbon reservoir, which is in turn set by the relative fraction of inorganic to organic carbon burial (e.g., Kump and Arthur, 1999). Excursions from $\delta^{13}C_{carb} = 0$ (e.g., Shields and Veizer, 2002; Maloof et al., 2010; Zachos et al., 2001) can be used for global correlation, especially when calibrated with high-precision geochronology. For the Neoproterozoic, the large amplitude of well-documented global $\delta^{13}C_{carb}$ excursions has led to controversy over the canonical interpretation of these records. Like the Phanerozoic, positive excursions are thought to reflect enhanced organic carbon burial. The cause of the negative excursions is debated, and hypotheses include reconstitution of organic carbon (e.g., Rothman et al., 2003; Fike et al., 2006) and catastrophic methane release (e.g., Kennedy et al., 2001).

Isotopes of Oxygen

Secular variations in marine $^{16}O/^{18}O$, denoted as $\delta^{18}O$, have been a very important chemostratigraphic tool, especially in paleoclimate studies over the last 55 Ma (e.g., Zachos et al., 2001). The basis for the method is that ^{16}O is preferentially enriched in water vapor leaving the oceans, resulting in seawater that is relatively enriched in ^{18}O. Organisms that precipitate shells as well as $CaCO_3$ reflect the oxygen isotope composition of seawater. When the continents have ice sheets, the ice is enriched in ^{16}O from precipitation, and the oceans are depleted in ^{16}O, so that the $\delta^{18}O$ is increased. During times of no ice, precipitation is mixed back into the oceans, and there is little change in $\delta^{18}O$. Temperature also controls the $\delta^{18}O$ of precipitation, with higher fractionations correlated with lower mean annual temperatures. It has long been appreciated that the oxygen isotope record shows cyclic variation, and Emiliani (1955) was the first to argue that these variations over the past 55 Ma have been the result of oscillations between glacial and interglacial stages. Thus, the oxygen isotopic composition of minerals precipitated from seawater can be used to infer ice volumes and ocean temperatures.

Variations in the oxygen isotopic composition of foraminifera have played an important role in the calibration of the astronomical time scale, related to the periods of orbital eccentricity, obliquity, and precession (see detailed discussion in the following section). Tilt and precession control the seasonal variations in solar radiation. This has led to dramatic variations in the temperature of the Northern Hemisphere over the last 25 ka. Using the variations in oxygen isotopes of calcite in foraminiferan shells, it is possible to reconstruct past ice volumes and temperatures. Ice volume depends largely on the amount of summer radiation at high latitudes in the Northern Hemisphere. Most of the variation in $\delta^{18}O$ can be related to orbital forcing of summer radiation. During glaciations, there is less seasonal variability, the Earth-Sun distance is high, and Earth's orbit is characterized by high eccentricity and low tilt. During interglacial periods, there is strong seasonality, the Earth-Sun distance is lower, and Earth's orbit is characterized by low eccentricity and high tilt. These orbital variations have led to the recognition of ~50 different episodes of growth of continental ice or ice ages over the past 3 Ma and a way to calibrate the astronomical time scale.

Oxygen isotopic studies of older rocks are also of value and have been used with great success in the Cretaceous. Unusually fresh foraminifera from the Demerara Rise in the western tropical Atlantic record the warmest (~36 °C) sea-surface temperatures (SSTs) reported for Cretaceous–Cenozoic time (Wilson et al., 2002). This in turn supports the idea of a Cretaceous greenhouse. Other studies that have reconstructed Cretaceous paleotemperatures using oxygen isotopes include Norris and Wilson (1998), Bice et al. (2003), and Huber et al. (2002). The further back in time one goes using oxygen isotopes, the more carefully diagenetic effects must be evaluated.

Isotopes of Strontium

Over much of Earth history, the $^{87}Sr/^{86}Sr$ ratio of seawater has varied (e.g., Veizer, 1989; Halverson et al., 2007), and it can be used to evaluate the relative contributions of the major sources of dissolved Sr, namely, riverine input from chemical weathering of (1) continental rocks that range from old radiogenic Sr from shield areas and active orogens to (2) relatively unradiogenic Sr contained in weathered limestones, and (3) the hydrothermal Sr flux, which is similar to the MORB source. Samples amenable to $^{87}Sr/^{86}Sr$ analysis include calcite, dolomite, shells, and authigenic or biogenic phosphates, especially conodonts. Diagenesis and contamination by Sr residing in clay mineral lattices can perturb the primary seawater signal of $^{87}Sr/^{86}Sr$. Calcite samples must be carefully screened for high Sr concentrations, 100 ppm to >2000 ppm, and in some cases, trace elements (e.g., Brand and Veizer, 1980; Jacobsen and Kaufman, 1999).

Veizer (1989) provided a detailed review of the origins of strontium in seawater and the processes that affected the preservation of the signal, including the effects of diagenesis. He constructed the first Phanerozoic Sr seawater curve using $CaCO_3$ from rocks and shells of different ages. He argued that the rate of mixing of ocean waters and the long-residence time of strontium in seawater could potentially yield a reliable signal. He assumed that by using the least radiogenic (i.e., lowest $^{87}Sr/^{86}Sr$) ratios for a given time and using large amounts of data, one could minimize the effects of diagenesis and produce a robust estimate of the isotopic composition of seawater with time. McArthur (1994, 1998) and McArthur and Howarth (2004) have taken the lead in the development and application of the approach to age determination and standardization of the method, especially when there are large and unidirectional changes, and its integration into the process of refining the time scale.

The $^{87}Sr/^{86}Sr$ ratio of marine limestones can be used for global correlations as well as interpretations concerning the role of tectonics and climate in determining the isotopic composition of seawater. For example, the dramatic rise in $^{87}Sr/^{86}Sr$ after ca. 40 Ma (Burke et al., 1982; Palmer and Elderfield, 1985; Edmond, 1992) is attributed to the dissolved load (radiogenic and high concentrations) derived from the rising and rapidly eroding Himalayas and carried to the oceans by the Ganges and Brahmaputra-Tsangpo River systems. Raymo and Ruddiman (1992) suggested the rapid rise was related to an enhanced rate of continental weathering and thus climate. The Himalayas contain a broad range of rocks with radiogenic Sr, especially metamorphic rocks, which were likely the dominant control on the Sr isotopic composition of seawater at that time (Harris, 1995). It remains unclear whether this trend can be used in deep time to fingerprint the rise of ancient mountain ranges or to make inferences about climate. However, for rocks with good radioisotopic and biostratigraphic control, such a rise can be used as a chronometer with precisions of ~1 Ma or better. Very detailed and precise strontium isotope records exist for the Cenozoic (e.g., Paytan et al., 1993) and Mesozoic (McArthur et al., 2001), but the resolution of the record decreases further back in Earth history (Veizer et al., 1999; Shields and Veizer, 2002; Halverson et al., 2007).

Chemostratigraphy in the Precambrian

The most recent addition of a new geologic period occurred in 2004 (Knoll et al., 2004) when the Ediacaran Period was defined with a GSSP in southern Australia. This period brackets the period of time from one of the last major ice ages (Marinoan) to the base of the Cambrian. Because of the dearth of fossils with well-known ranges in this period and the global nature of the bounding events, carbon isotope chemostratigraphy (Ediacaran-Cambrian transition) and the signal of deglaciation (Cryogenian-Ediacaran boundary) were used to define the newest period (Knoll et al., 2004, 2006). These global isotope excursions, interpreted to be isochronous, and events such as the global glaciations that characterize the Neoproterozoic offer much hope for further subdivision of Earth history.

In summary, several chemostratigraphic methods provide very powerful tools for global correlation between radioisotopic tie points. Moreover, in addition to providing a framework for relative time, chemostratigraphic variations are ultimately driven by evolving seawater composition, and thus, when integrated with the fossil and tectonic records, great insight may be gained in understanding the history of oceanic circulation and timing of major changes in ocean chemistry.

Astrochronology

There are significant gravitational interactions between Earth and the Sun, Moon, and other planets. Earth's orientation relative to the Sun changes in a quasi-periodic fashion as a result of interactions between Earth's axial precession and the variable shape of its orbit induced by motions of other planets (Berger and Loutre, 1990; Laskar et al., 2004; Hinnov and Hilgen, 2012). The interactions result in cyclic oscillations in the eccentricity of Earth's orbit and in the tilt and precession of Earth's axis. Orbital eccentricity variations have periods of ~100,000 years and 405,000 years, whereas the tilt variation has a period of 41,000 years, and the "climatic precession" has a period of ~21,000 years, and apart from the 405,000-year cycles, there are multiple periods for each of these modes. These in turn cause variations in solar radiation reaching Earth's surface, which result in climatic variations, called Milankovitch cycles. The climatic variations are recorded as cyclically deposited sediments, which can be tuned to the calculated Milankovitch cycles together with stratigraphic correlation tools, principally biostratigraphy and magnetostratigraphy.

This has developed into the use of "target curves," which provide numerical age calibration, with no reliance on radioisotopic geochronology, by matching local cyclostratigraphic records with a highly constrained model of the astronomical parameters or the climatic expression of those parameters such as variations in solar insolation (the target curve). In the past decade, dramatic improvements in understanding solar system dynamics have resulted in the extension of sophisticated models that predict the climatic and sedimentologic response of Earth to the astronomical parameters at least as far back as 40–50 Ma (Laskar et al., 2011).

A similar approach for older rocks that cannot be directly referenced to the late Cenozoic allows the use of "floating" segments of cyclically deposited sedimentary rocks to estimate the amount of time between two stratigraphic horizons. There are many examples of spectacular cycles preserved in both marine and continental sedimentary rocks that are defined by, for example, color, geochemistry, rock magnetic properties, sedimentary structures, and organic carbon content. The signal is measured and assigned relative ages using magnetic polarity stratigraphy and biostratigraphy, and then, if possible, calibrated in numerical time with high-precision geochronologic information on volcanic ash beds. These sections can be used to correlate with other sections that may not have cyclostratigraphy but include the same biostratigraphy or magnetic polarity stratigraphy. When combined with geochronology of volcanic horizons, one can use the cycles to interpolate time with higher precision than with geochronology alone or linear interpolation assuming constant sediment accumulation rates. This has been used for sequences in the Cretaceous (e.g., Meyers et al., 2012) and in much older strata, such as those deposited near the Triassic-Jurassic transition (e.g., Whiteside et al., 2007) and in the Carboniferous (Davydov et al., 2010).

The target curve and floating curve calibration approaches have been important for developing an astronomical time scale in the construction of the global geologic time scale back to 250 Ma (Gradstein et al., 2012). The astronomical time scale alone has a resolution of 0.02–0.40 m.y. for cyclostratigraphy in Neogene and Quaternary sections, and at the low end, it is comparable to radioisotopic dating but completely independent. For older rocks, the astronomical time scale can provide age models between radioisotopically dated tie points allowing fine-scale resolution in thick sequences lacking other geochronologic proxies.

Parallel improvements in both $^{40}Ar/^{39}Ar$ and U-Pb geochronology have made it possible to pursue the intercalibration of radioisotopic dating and astrochronology (e.g., Kuiper et al., 2008; Meyers et al., 2012). When successful, this integration allows for unprecedented accuracy and precision in the measurement of geologic time. The basic approach is to use high-precision geochronology of volcanic ash beds with both U-Pb and $^{40}Ar/^{39}Ar$ techniques to yield an estimate of the duration between each dated deposit. Despite the complexities involving systematic differences between U-Pb and $^{40}Ar/^{39}Ar$ dates, the age difference between each deposit should be the same but likely with different uncertainties. Then, the floating astronomical model for the time interval can be used for a much higher-resolution age model. Ideally, bedded sedimentary rock sequences with orbitally influenced cycles occur nearby or between the dated ash beds, so that one can be sure the floating time scale can be applied to a particular interval. This is a rare occurrence but allows an opportunity to directly intercalibrate two independent radioisotopic chronometers against an astrochronologic age model (Meyers et al., 2012).

Another important application was reported by Kuiper et al. (2008), who used $^{40}Ar/^{39}Ar$ geochronology to determine the age of the Fish Canyon sanidine by astronomically calibrating high-precision dates on ash beds and arriving at a value of 28.201 ± 0.046 Ma. Meyers et al. (2012) directly tested this by comparing U-Pb and $^{40}Ar/^{39}Ar$ dates from the same bentonites and concluded that the pairs of dates, using an assumed age for Fish Canyon sanidine of 28.201 Ma, were the same within uncertainty. They integrated the $^{40}Ar/^{39}Ar$ dates from three bentonites and the orbital time scale with uncertainties of thousands of years to confirm that 28.201 Ma is the best age estimate for Fish Canyon sanidine. Renne et al. (2010, 2011) arrived at a slightly older age estimate (28.291 Ma ± 0.036) by comparing pairs of U-Pb zircon and $^{40}Ar/^{39}Ar$ dates from rocks from a wide range of ages with the Fish Canyon sanidine age proposed by Kuiper et al. (2008). In future intercalibration studies, the sources of uncertainty associated with the radioisotopic ages (analytical, tracer solution, or age of neutron fluence standard, and decay constants), as well as uncertainties in the astrochronology, must be considered.

A Geologic Time Scale 2012 (Gradstein et al., 2012) uses "absolute" astronomical calibrations based on solar system dynamics for the Neogene, and "floating" astronomical calibrations tied to radioisotopically dated stratigraphic points for the Paleogene and all three Mesozoic periods. The geologic time scale includes absolute astronomical calibrations for the entire Cenozoic Era and Cretaceous Period; floating astronomical calibrations make up 85% of the Jurassic and 75% of the Triassic time scales.

The eccentricity of Earth's orbit has a major variation with a period of 405,000 years. Shorter astronomical cycles with precession and obliquity periods are used to calibrate Neogene and younger rocks. However, because the solar system exhibits chaotic diffusion, we can expect that their periods will change with time beyond 50 m.y., and the short cycles cannot be used to calibrate the older (>50–60 Ma) rock record. The 405,000-year eccentricity cycle remains more stable through geologic time because it results from interactions of Jupiter and Venus. Workers are now using floating cyclostratigraphic records that contain what they interpret to be the 405,000-year cycle to calibrate the geologic time scale dating back to at least the end of the Paleozoic era (ca. 252.2 Ma) and beyond.

There is potential to use the floating curve approach to greatly increase the precision of the geologic time scale. For example, Davydov et al. (2010) used U-Pb geochronology in the Donets Basin to confirm that individual high-frequency Carboniferous cyclothems and bundles of cyclothems into fourth-order sequences are the eustatic response to orbital eccentricity (100 and 405 ka) forcing. They produced a continuous age model for Pennsylvanian strata of the basin during this key interval of Earth history characterized by a major ice age. Detailed biostratigraphy will allow the export of this age model to sections throughout Euramerica.

This approach has also been used in the remarkable sedimentary sequence of dominantly lacustrine facies of the Newark Basin, where investigation of the continuous sequence obtained by a series of drill cores has allowed unprecedented resolution of a floating astronomical time scale for over 5800 m of composite stratigraphy integrated with magnetic polarity stratigraphy that includes 59 magnetozones and a sampling density of about every 20 ka (Kent and Olsen, 1999; Olsen et al., 2011). Vertebrate biostratigraphy and geochronology of the section are sparse, although several Central Atlantic magmatic province intrusions and lava flows at ca. 201.4 Ma, near the end-Triassic extinction, are used as an upper tie point. There is a pronounced 405 ka cyclicity, and it has been used for speculations on the tempo and mode of dinosaurian origin, diversification, and rise to ecological dominance (Olsen et al., 2011).

A good example of combining magnetic polarity information and geochronology and testing the results against astrochronological models was recently published by Tsukui and Clyde (2012). In this paper, a highly resolved, previously obtained geomagnetic polarity time scale for the early-middle Eocene was combined with $^{40}Ar/^{39}Ar$ sanidine age determinations on 23 discrete ash-fall tuffs and other chronostratigraphic information, including polarity data, to support a revised paleomagnetic time scale for the early to middle Eocene. The age calibration model suggests an approximate 2 Ma duration for the early Eocene climatic optimum, which in turn coincides with the inferred age of the Wasatchian-Bridgerian faunal transition. Compared with a previous astrochronological model, the revised time scale is consistent with an age for the Paleocene-Eocene thermal maximum of 56.33 Ma. Ultimately, terrestrial sequences with relatively high accumulation rates and high-precision geochronology can better resolve the age and duration of polarity chrons, and can be compared with astrochronologic data from more continuous marine sedimentary deposits.

In summary, the integration of high-precision, high-accuracy geochronology with refined astrochronological models and stable isotope, chemostratigraphic, and magnetostratigraphic observations will allow us to better understand the role of climate and ocean-atmosphere interactions on biological evolution.

OUTSTANDING ISSUES

Stratigraphic Challenges

The search for satisfactory horizons to use for marking GSSPs in the Phanerozoic has been a long protracted process, and many refinements in strategy and technical methods have been introduced since the time that the first GSSP, which marked the base of the Devonian, was ratified in 1972. With the appearance of new information (particularly detailed chemostratigraphic data) and reevaluation of sections, some early decisions as to specific time boundaries now seem less well justified, and may merit reexamination. One example is the basal Cambrian GSSP. Because of problems associated with global correlation of the Cambrian/Paleozoic-Phanerozoic base using the biostratigraphy of trace fossils, chemostratigraphy has emerged as the de facto means of characterizing and correlating that horizon globally (Bowring et al., 2007; Babcock et al., 2011). The Ediacaran-Cambrian boundary in Newfoundland is based on trace fossil assemblages and has no body fossils and has no rocks suitable for geochronology or chemostratigraphy. It remains uncertain whether the negative $\delta^{13}C$ excursion used to approximate the boundary does in fact coincide with the Cambrian GSSP.

Up to the present time, boundary positions in the Archean and Proterozoic have mostly used purely chronometric boundaries called global standard stratigraphic ages (GSSAs), based on geochronologic data, rather than points in sections or GSSPs. The one exception is the terminal system/period of the Proterozoic, the Ediacaran. Ultimately, it will be desirable, if possible, to replace GSSAs with GSSPs that have well-calibrated numerical ages.

The recent definition of the base of the Holocene Series using signals of climatic change (Walker et al., 2009), rather than biostratigraphic markers, represents an important turning point in philosophy about GSSP definition. Some nonbiostratigraphic proxies are superior to biostratigraphic tools in certain parts of the geologic column, and it is likely that nonbiostratigraphic correlation techniques will play an increased role in the definition of GSSPs in the future, particularly those that will be defined in the pre-Phanerozoic.

Geochronology and Resolving Discrepancies between U-Pb and ^{40}Ar/^{39}Ar Methods

Ultimately, the geoscience community will succeed in building a time scale that can seamlessly use both high-precision ^{40}Ar/^{39}Ar data and U-Pb geochronologic data. The concern that we presently face, however, is one that has been recognized for some time, and that is the systematic bias between U-Pb and ^{40}Ar/^{39}Ar dates, which in some cases approaches ~1%, with U-Pb dates being consistently older. The causes of this systematic bias are not clear and likely include inaccuracies in the decay constants for both systems, inaccuracies in the age of fluence monitors used in ^{40}Ar/^{39}Ar geochronology, an inaccurate assumed value for the ^{238}U/^{235}U ratio in zircons (Hiess et al., 2012), and the possibility that in some volcanic rocks the U-Pb system in zircon does not record the time of emplacement but rather a short period of pre-eruptive residence. Because all ^{40}Ar/^{39}Ar approaches are relative dating methods, the age of the fluence monitor must be independently determined, and sanidine from the Fish Canyon tuff is the most commonly used. Renne et al. (2010, 2011) inverted data sets of U-Pb zircon and ^{40}Ar/^{39}Ar dates to arrive at a more accurate estimate of the age of Fish Canyon sanidine. This is a promising approach as we acquire many additional high-precision ^{40}Ar/^{39}Ar and U-Pb data sets on the same samples from several different localities representing more and more of geologic time. The estimate of the assumed age of the Fish Canyon sanidine has varied from ca. 27.7 Ma to 28.29 Ma (Renne et al., 2010, 2011). Many workers in the community are using 28.201 Ma as the preferred age, as determined by astronomical calibration (Kuiper et al., 2008), as in many cases it appears to result in good agreement between ^{40}Ar/^{39}Ar and U-Pb determinations. The community is making great progress, but more work remains to be done.

Our goal was to provide a synopsis of the history of the *Geological Society of America Geologic Time Scale* and the many different facets of deep time investigations that have led to refinements in geologic time scales. This overview highlights the continued importance of integrated efforts to better understand the Earth-life record of deep time on a global scale. A crucial aspect of progress in geochronology is the use of highly characterized mineral standards that span a range of ages. EARTHTIME is actively seeking out standard samples that range in age from less than 1 Ma to well over 500 Ma that can be analyzed for both ^{40}Ar/^{39}Ar and U-Pb (Schoene et al., 2005; Renne et al., 2010). Mineral separates will be distributed to participating laboratories, and, after analyses are completed, the results will be published. Ideally, when a U-Pb laboratory publishes a study, they will also publish data for one or more standards run during the same interval as the study, as is currently done in many ^{40}Ar/^{39}Ar laboratories.

The *Geological Society of America Geologic Time Scale* and Its Future

Palmer's seminal work on the *Geological Society of America Geologic Time Scale* (Palmer, 1983) was important for the development of time scales in general. This model has been adopted by the ICS in the presentation of their geologic time scale (International Commission on Stratigraphy, 2012). The 1983 *Geological Society of America Geologic Time Scale* was constructed with an emphasis on North American geology. The Geological Society of America will continue to follow the ICS and other efforts such as Gradstein et al. (2012) in updating the chronostratigraphic scale and integrating it with the chronometric one, and the GSA will maintain its presentation of the time scale as a service to its membership, the larger scientific community, and the public to promote the scientific and educational goals of the society.

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