Time-scale construction and periodizing in Big History: From the Eocene-Oligocene boundary to all of the past

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ABSTRACT

The Ancona Penrose Conference of October 2007 dealt with the current state of understanding of the late Eocene and the Eocene-Oligocene boundary, ~34 million years ago, a critical but very brief interval in Earth history. In this paper, we place that brief interval and the lessons from the conference in the broadest possible context by viewing them in the light of “Big History.” This new intellectual concept maintains that there may be value in considering the entire past, from the big bang until today, as a single unit of study. At this very early stage in the study of Big History, not even the most fundamental questions have been well formulated, let alone answered. As a first cut, Big History can be divided into regimes by considering the disciplines that study it: cosmic history (studied by cosmology and astronomy), Earth history (studied by geology), life history (studied by paleontology and evolutionary biology), and human history (studied by archaeology and historiography). These disciplines differ in terms of problems, techniques, and intellectual traditions. If we seek a common basis for a finer subdivision, the changes in utilization of the energy that have driven historical changes would seem like a good candidate. In two thought-provoking papers in 2007, Robert Aunger proposed “periodizing” all of history by placing divisions between periods when new methods of utilizing concentrated energy came into being, e.g., cellular metabolism or human agriculture. Aunger draws a parallel between this periodization of Big History and the establishment of the geological time scale. In this paper, we carefully consider this parallel and conclude that periodizing history on the basis of energy use or any other conceptual scheme is quite different from the division of Earth history into the intervals that yielded the geological time scale. Both are important but they have different purposes. Time-scale construction is a procedure that ties history to the rocks that record the history. It is a necessary step in reconstructing Earth and life history but is neither necessary nor possible in studying
the history of cosmos or humanity. In contrast, periodizing history into intervals provides a conceptual framework on which to hang a growing understanding of history. We conclude that it is important to differentiate between (1) time-scale construction, (2) correlating events, (3) dating events, and (4) periodizing history. In this light, Auinger’s focus on changes in energy use remains an instructive way of periodizing history, but it must be clearly differentiated from time-scale construction.

**Keywords:** Earth history, big history, time scale, periodization, Eocene, Oligocene.

**INTRODUCTION:**

**THE ANCONA PENROSE CONFERENCE**

The Ancona Penrose Conference of October 2007 dealt with the current state of geological and paleontological understanding of the late Eocene and of the Eocene-Oligocene (E-O) boundary, ~34 million years before present (Ma). This was a critical time in Earth history, in which a long-enduring warm, “hothouse” climatic phase shifted over into the cold, “icehouse” glacial phase that has persisted until the present time. The beginning of the shift is marked by the “Oi-1” oxygen-isotope shift, which reflected that climate change and occurred shortly after at least two large extraterrestrial impacts and a marked increase in the flux of extraterrestrial dust particles reaching Earth. Many technical questions were considered at the conference—how to read the stratigraphic record of these events, how to divide up the chronology of this part of Earth history, and how to interpret the causal relationships.

**THE EOCENE-Oligocene INTERVAL IN THE CONTEXT OF BIG HISTORY**

We do not intend to debate the specific questions considered at the conference, but rather to show how they fit into a very much broader context. Earth history, of which the Eocene-Oligocene interval is a significant detail, deals with only a small part of everything that has happened in the past. Taking the broadest possible viewpoint, there is currently an effort by a small community of scholars and scientists to develop a coherent history of everything that has ever happened. Pioneered by the historian David Christian, who gave it the name “Big History,” this approach deals with the combined history of cosmos, earth, life, and humanity. It is clear from this subdivision of Big History that, in practice, it cannot really deal with everything that has ever happened, but only with the parts that we have the practical possibility of studying—mostly what has happened in the visible parts of the cosmos and on this specific planet.

Christian (2004) and Brown (2007) offered narrative accounts of all of Big History, while Spier (1996) provided a thoughtful introduction to some of the fundamental questions and concepts in this emerging field. Big History is an intellectually rich concept that is seen differently by investigators from different fields. The Christian, Brown, and Spier books are centered on a human focus. Chaisson (2001, 2006) and other astronomers see the field from a cosmological perspective, in which Big History has been called “cosmic evolution.”

Earth and life history, the middle levels in the Big History spectrum, have long been seen as unified by geologists and paleontologists. The findings of these two fields are closely related, and they combine to present an integrated view of the biological and geological evolution of planet Earth. Furthermore, geologists and paleontologists have long recognized that their combined field of earth and life history is conditioned by cosmic evolution and provides the setting for human history, so the concept of Big History has long been inherent, if seldom specifically recognized, in the work of geologists and paleontologists, for example, Cloud (1978).

The findings of geologists and paleontologists come primarily from the historical record preserved in rocks, and largely from sedimentary rocks, because solids remember, while liquids and gases forget. Reading the rock record of Earth and life history is dependent on the construction of the geologic time scale. This task is not necessary in other regimes of Big History, where the information is not extracted from rocks. In the present paper, we explain in some detail this central effort required to understand Earth and life history.

The geologic time scale has been constructed over the last two hundred years, and its subdivisions are continually being improved and refined, while the ages in years that have been attached to it over the last half-century are constantly being made more accurate and precise. The Ancona Penrose Conference dealt both with the most recent improvements in the Eocene-Oligocene portion of the geologic time scale, and with the growing understanding of the trends and events in the history of Earth and life in that interval.

Some of the points made in this paper will seem obvious to any geologist or paleontologist. They are included and discussed at length because the paper is a summary of the lessons learned by Earth scientists during the setting up and refining of the geologic time scale, and it is intended to be useful to scholars from other fields who may be trying to bridge the disciplinary boundaries that compartmentalize Big History.

We wish to stress here a critical point that will be developed in this paper: the ongoing task we refer to as “time-scale construction” is essential to the entire enterprise of reading the rock record of Earth history and of life on Earth, but it is neither possible nor necessary in cosmic history, or in human history based on written documents. Time-scale development is completely
different from what we shall call “periodization,” which is the procedure of identifying and naming coherent intervals within any of the regimes of Big History. Periodization gives rise to names like “Renaissance” and “Hadron epoch,” which serve entirely different purposes than do the intervals in the geologic time scale. The situation is confusing because “periods,” which are one of the kinds of subdivision in the geologic time scale, are not established by “periodizing” history. This kind of confusion caused by the differing usage of the same word in different fields of study is a typical problem in the early stages of developing an interdisciplinary field like Big History (Alvarez, 1991).

DIVIDING UP BIG HISTORY

In an infant discipline like Big History, a critical task is simply to formulate the questions that are to be asked. Without research-grade questions, Big History could turn out to be no more than a useful way to organize an overview course for undergraduate students. Whether it also becomes a vibrant scholarly field will depend on whether challenging questions can be asked that will attract the attention and activity of scholars and scientists from its component disciplines. Spier (1996) made an initial effort in this direction.

One such question concerns how Big History as a chronological record might be divided up into coherent intervals to clarify understanding and guide research. At this point we see two potentially useful ways to divide and subdivide the time scale of Big History. The coarser division is based on the major historical entities and thus on the scholarly disciplines that study them. A finer subdivision might be based on innovations in the way concentrated energy is used to drive the processes that generate history.

The Major Regimes of History

Spier (1996) recommended using the usefully vague word “regime” as a term with which to divide up Big History in various ways. He defined regime (p. 4) as “a more or less regular but ultimately unstable pattern that has a certain temporal permanence.” It is worth noting that a particular regime may occur at different times in different places, e.g., biological regimes in different parts of the Earth or on different planets. We suggest that a reasonable first-cut organization of Big History would be to divide it into a few major regimes that correspond to historical entities and, equivalently, to scientific and scholarly fields of study.

One such organization would have four major regimes, reflecting the historical objects of interest: cosmic history would deal with the history of the Universe and the Milky Way Galaxy from the big bang to the present, as studied by cosmology and astronomy. Earth history would study the planet Earth, and perhaps the rest of the solar system, from its origin to the present time, corresponding to the fields of geology, the other earth sciences, and planetary science. Life history would treat the evolution of organisms from the origin of life to the present, thus including the subject matter of paleontology and evolutionary biology. Human history would have a poorly defined beginning and correspond to the subject matter of archaeology and of historiography (history in the strict sense). This division is slightly problematic, because human history and archaeology have similar subject matter but different methods, whereas geology and paleontology have different subject matter but similar methods.

In other cases, perhaps it would be useful to identify six major regimes, to better correspond to the disciplines involved. In this arrangement, cosmic history could be divided into big bang history, where theoretical physics is of central importance, and post–big bang history, which is in the purview of astronomy, while human history could be separated into archaeology-based preliterate human history and document-based literate human history. Clearly, there is no “correct” division, simply divisions that are useful for certain purposes. In a table presented later in this paper, we use the six-regime division because we are interested in the kinds of techniques used by the scholarly and scientific disciplines that study these regimes.

It is interesting to note that although the history of the big bang ended after only a few minutes or a few hundred thousand years, depending on how its end is defined, none of the other major historical regimes has ended. Cosmic history continued after the appearance in our solar system of solid planets; Earth history continued after the origin of life, and all continue now along with human history.

The subdivision into four or six major regimes leads to the question of what changes mark the transition from each stage of Big History to the next. In each regime, different sets of rules and information govern historical change. The fundamental rules are the laws of physics, but with variations. In cosmic history, subsequent to the high-energy physics conditions of the big bang, change is governed by the physical laws of gravity and of gases and plasmas. In Earth history, the laws of condensed-matter physics and of chemistry come into play. In life history, the rules of organic chemistry, the complexity of biochemistry, and the information stored in deoxyribonucleic acid (DNA) are central. However, as mentioned already, Earth and life history are closely related and mutually interacting, dealing with the combined geological and biological evolution of Earth. In human history, new kinds of information are stored in brains and documents, while social interactions, the laws of which, if any, seem still to be obscure, enter the picture. The complexity of organization and of interactions seems to increase along this sequence (Chaissin, 2001, 2006; Christian, 2008), although both have proven difficult to quantify.

Periodizing History According to Changes in the Use of Energy

In two recent and thought-provoking papers, Aunger (2007a, 2007b) suggested a coherent way to periodize Big History all the way back to the big bang at ca. 13.7 Ga, at a finer level than our four or six major regimes. Noting that Big
History has been marked by a set of transitions in the ways in which concentrated energy is utilized in driving historical processes, Aunger chose these transitions as the boundaries between regimes that he called “periods.” This is an important concept: stars, planets, organisms, and human societies require very different material resources, but they all require sources of concentrated energy, so energy use provides a possible unified basis for subdividing all of Big History. Taking the hierarchical structure of the geological time scale as a model, Aunger proposed a set of “eons,” “eras,” and “periods.” The resulting periodization is shown in Figure 1.

Although as geologists we are flattered by the choice of the geologic time scale as a model, we find three aspects of this approach that deserve comment. First, it is ironic that although the hierarchical units in this periodization are based on the units in the geologic time scale, from which the names of the three levels of units are taken, geology and the evolution of the Earth itself are omitted, with the periods passing directly from “Galaxy” to “Cell.” Judging by the subdivision of the “Terrestrial Eon,” Earth is seen as a relatively inert stage upon which the drama of life and humanity are played out. As a result, the long and fascinating history of the Earth itself that geologists have uncovered is not considered.

In a second, related observation, this compilation omits several geological events of the type used by Aunger to periodize the rest of Big History—it omits the innovations in energy use made possible by the formation of a solid planet like the Earth in orbit around a star like the Sun. We prefer to include these innovations in the interest of portraying a richer Earth history, although Aunger’s approach of reducing the absolute number of events in the interest of simplicity and clarity is equally valid. Our additional thermodynamic innovations include (1) conversion of gravitational potential energy to heat through the accretion of the planetesimals, and the sinking of its iron component to the center of the planet, forming the core; (2) the driving of most of the internal processes within Earth, first by the heat released by accretion and core formation, then by radioactive decay, and then with additional latent heat from freezing of the liquid iron outer core to form the solid iron inner core; (3) heating of the Earth’s surface by solar radiation, which drives most of the surface processes on Earth, such as erosion, sediment transportation and deposition, and the ocean-atmosphere-climate system; (4) the use of solar energy to produce biomass through photosynthesis, and the use of that stored solar energy in the complex food chains that power a large part of the biosphere; and (5) tides within the oceans and the solid Earth. We recognize that Earth and the Solar System are not the first places in the universe where these innovations will have occurred, but since Big History can only deal with the history for which we have a record, the energy innovations made possible by formation of Earth should be considered in periodizing all of history.

Third and most fundamental, this energy-based subdivision of Big History entangles two different procedures involved in reconstructing and understanding the past.

The first procedure involves choosing or developing a chronological framework, a way of ordering historical events in a time sequence. With events or objects ordered sequentially in a chronological framework, it is possible to judge proposed causal relationships. The ideal chronological framework would be simply to have all events dated in years (Christian, 2008). In cosmic history, it is often possible to date an observed event like a distant supernova in years, and in human history, many documents carry dates in years. However, this is not the case in Earth and life history, where events are most often recoded in rocks. Consequently, it has been necessary to go through the intermediate step of constructing a time scale tied to the rock record. Now, with many kinds of sophisticated radiometric dating available, the geologic time scale is being calibrated in years.

A second procedure commonly used for understanding the past involves identifying historical intervals that have some kind of coherence. This appears to be what Aunger has done in identifying his energy use–based intervals (Fig. 1). Following Aunger and accepted usage in human history, we call this procedure “periodization.” For the interdisciplinary communication that will be necessary if Big History is to emerge as a valid field, it is important to keep separate the procedures of time-scale construction and periodization that are entangled in Figure 1. The rest of the present paper explores these themes in depth.

![Figure 1](image-url)
HISTORICAL PROCEDURES IN SCHOLARSHIP AND SCIENCE

To make possible the kind of interdisciplinary conversation needed in Big History, it is critical for participants in each of the relevant disciplines to understand the special conditions and terminology of the other disciplines. In this discussion, we will consider each of these main concepts as they apply to each of the four main regimes of Big History, drawing lessons mainly from Earth and life history, where our expertise lies. It will be seen that students of each of the regimes face complex problems that may be quite different from regime to regime. Table 1 provides an overview of the considerations presented here.

Chronological Framework and Time-Scale Construction

In trying to understand what has happened in the past and in seeking causal relationships and a general understanding of history, one first needs a chronological framework for ordering, correlating, and then comparing the ages of different events. Each historical discipline has developed such a framework, but they are not all the same.

Human History

In historiography based on written documents, it is often possible to use calendar years as a chronological framework, but this entails the problem of choosing the starting point. Counting backward from the present is not an option in human history, for the present is changing as the research is being done (in contrast to Earth history, where these changes in the present are smaller than the resolution of the dating). Dates in human history are thus counted backward and forward from a standard starting point—B.C. (or BCE) and A.D. (or CE) in the most widespread system. These dates are essentially conventional, since the birth date of Jesus is not known, and since other traditions such as the Islamic world use other starting points. In addition, for early written documents, it can be difficult to date these sources accurately, so, for example, one sees Egyptian history based on the “low chronology” or the “high chronology.”

Because individual years are so closely spaced, historians commonly refer events to centuries or millennia. Thus, historical treatments are full of references to the second millennium B.C., the mid–twelfth century A.D., or the late nineteenth century. Anticipating a problem that will arise in Earth history, these millennium and century intervals are generally not bounded by significant events, so the French Revolution occurs in the late eighteenth century, but not at the end of that century. Millennia and centuries are thus neither time-scale units like those of geology, nor conceptual periodizations; they are simply coarser divisions, or approximations, of the chronological framework in years.

The preliterate history of humans is of necessity based on archaeology, yielding situations quite analogous to geology and paleontology, where history is recorded in stratified sedimentary deposits, and where artifacts play the role of fossils. Just as the early geologists could only divide up Earth history on the basis of characteristic fossils, archaeologists were forced to divide the history they were uncovering into units based on the type of artifacts—units like the Stone Age, the Bronze Age, or subdivisions thereof, for example, the Paleolithic or the Late Helladic IIA, an interval in the Greek Bronze Age.

It was clear early on that this was an unsatisfactory procedure because new technologies diffused slowly through the ancient world, so that the Bronze Age began earlier in Turkey than it did in Italy. This is inherent to fossil- or artifact-based chronologies and analogous to the diachronous first appearance of species of fossil organisms. Establishing the sequence of artifacts is an additional procedure that is aided when archaeologists encounter situations where long intervals of time are recorded by successive cities at the same site, such as Troy or the Mesopotamian tells, or in trash dumps that were in long-continued use and are full of pottery fragments (Potter, 1976). These situations are analogous to the stratigraphic sections studied by geologists, but often archaeologists deal with sites representing only brief time intervals. The development of radiocarbon dating has made it possible to put numerical dates on the succession of observed archaeological events, although radiocarbon years require a not-yet-fully determined correction for conversion to absolute years.

Earth and Life History

Although human history merges insensibly back into prehuman Earth history, the development of a chronological framework for Earth history has been completely different from that of written human history. The effort to understand Earth’s past in a scientific way began with the discovery by Steno (1669) that the sequence of rock layers deposited one on top of the other carries a stratigraphic record of Earth history (Cutler, 2003). Steno recognized in Tuscany that the sea had twice covered parts of what is now dry land (Alvarez, 2009, ch. 5), but in the absence of any other way to date these inundations, he could only attribute them to the universal ocean of Genesis before the creation of the land, and to Noah’s flood.

The first serious attempt to develop a time scale corresponding to the rocks seen in the field was made by Giovanni Arduino (1714–1795), who used the terms Primary, Secondary, Tertiary, and Quaternary, from oldest to youngest (Cita, 2009). Primary and Secondary fell into disuse long ago, there is currently debate whether to discontinue the use of Tertiary (Salvador, 2006), and the definition of Quaternary is under review (Gradstein et al., 2004, p. 28, 411).

The development of the modern time scale for the stratigraphic record of Earth history was made possible, beginning around 1800, by the careful study of fossils. Even then, it was a clear observational fact that the shapes of fossils have changed through the time represented by layers of rock. The changes in fossils allow the time correlation of rocks in distant places and thus the placing of rocks in their correct chronological order, even if they do not happen to lie in contiguous stratigraphic
<table>
<thead>
<tr>
<th>Regime</th>
<th>Discipline</th>
<th>Time-scale construction based on solid rocks or artifacts</th>
<th>Chronology in units of time (years, etc.)</th>
<th>Methods for determining age in units of time</th>
<th>Periodization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big bang history</td>
<td>Cosmology, physics</td>
<td>Not needed—dates are computed</td>
<td>Years, minutes, seconds, or negative log seconds, after instant of big bang. (Time runs forward from t = 0 = instant of big bang.)</td>
<td>Calculations based on principles of physics.</td>
<td>Terms are apparently used informally and inconsistently (e.g., Primordial era, Hadron epoch or Hadron era).</td>
</tr>
<tr>
<td>Cosmic history</td>
<td>Astronomy, cosmology</td>
<td>Not needed—dates are based on distance or computation</td>
<td>Billions of years ago, back to big bang at ca. 13.7 billion years ago (Time runs backward from the present.)</td>
<td>Age is related to distance, which can be determined by red shift of light. History of stars is inferred from observing stars in many stages of evolution and from physical calculations.</td>
<td>Terms are apparently used informally and inconsistently (e.g., Primordial dark age, Stelliferous era).</td>
</tr>
<tr>
<td>Earth history</td>
<td>Geology</td>
<td>Phanerozoic Eon/Eonotheum* Cenozoic Era/Eothem* Paleogene Period/System* Eocene Epoch/Epoch* Priabonian Age/State* (An example of the hierarchical structure.)</td>
<td>Millions or billions of years ago (Ma, Ga), back to origin of Earth at 4.56 Ga. (Time runs backward from the present.)</td>
<td>Various methods based on radioactive decay (K/Ar, U/Pb, U/Th, Rb/Sr, etc.); counting of orbital cycles, varves, etc.</td>
<td>Geologists and paleontologists generally use the well-defined, agreed upon time-scale divisions, finding them more precise than periodizations like &quot;late heavy bombardment,&quot; &quot;time of banded iron formations,&quot; or &quot;assembly of Pangea.&quot;</td>
</tr>
<tr>
<td>Life history</td>
<td>Paleontology, evolutionary biology, paleoanthropology</td>
<td>Same as for Earth history; relative dating is based on fossils.</td>
<td>Same as for Earth history.</td>
<td>Same as for Earth history.</td>
<td>Same as for Earth history.</td>
</tr>
<tr>
<td>Human archaeology</td>
<td>Archaeology</td>
<td>Paleolithic, Late Bronze Age, etc., based on materials used for, and styles represented by, artifacts recovered in excavations. No global system because of diachronous appearances.</td>
<td>Years, centuries, or millennia before the present. Sometimes in uncorrected radiocarbon years. (Time runs backward from the present.)</td>
<td>Various methods based on radioactive decay (especially radiocarbon); counting of tree rings; dated inscriptions on archaeological materials.</td>
<td>Sometimes periodized in terms of building styles, agricultural practices, or social organization, but none of these can be global.</td>
</tr>
<tr>
<td>Human history</td>
<td>Historiography</td>
<td>Not needed—dates are based on documents.</td>
<td>Years before or since an arbitrary starting point with labels like B.C. (=BCE), A.D. (=CE), AH, Hebrew, or Roman calendars, etc. (Time may run forward or backward.)</td>
<td>Dates, or references to events, in written documents, which may be difficult to calibrate in older documents.</td>
<td>Historians commonly use numbered centuries, which are in fact precisely defined units of time, chronologically specified terms such as dynasties, or poorly defined, regional terms, like World War II, Renaissance, or Baroque.</td>
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</tbody>
</table>

*The first term refers to a time interval, and the second refers to the rock deposited during that time interval.
sequences. The philosophical context of these discoveries was reviewed by Allègre (1992); this context emerged through debates over whether geologic time was infinite or finite, whether Earth history has been cyclic or trend-like, and whether it has always changed slowly and gradually, or has been punctuated by occasional catastrophes (Eldridge and Gould, 1972; Gould, 1987).

The pioneering stratigraphic geologists in the early nineteenth century found that different parts of the geologic record of Earth history—the geologic column—are preserved in different places in the world. As they worked out the sequence of fossils, they named parts of the geologic column in ways that reflect those places, but with no guiding principles or system. Thus, we have the Devonian named for Devonshire, the Permian for ancient Perm in Russia, the Lutetian for the Roman town that is now Paris, and the Jurassic for the Jura Mountains. In a more whimsical mood, the Ordovician and Silurian are named for pre-Roman British tribes that lived where rocks of those ages are exposed. Sometimes intervals were named for the dominant kind of rock in a region where that time interval was studied; this is the origin of Carboniferous for a coal-rich interval, and the Cretaceous, from the Latin name for chalk, or even Triassic, for a German region where rocks of that age occur in a triad of distinctive layers. Some units were named in a semisystematic way, including the rocks that were the subject of the Ancona Penrose Conference—Eocene meaning the dawn of the recent, Oligocene meaning less recent.

The geologic time scale was thus built up in a disorderly way, which is understandable, since those who built it were exploring deep time with no guiding principles because no one had done this before. The time scale was gradually refined during the nineteenth and twentieth centuries (Fig. 2).

The intense research in many parts of the world that produced the time scale made it clear that the fossil organisms upon which the time scale was based have changed, or evolved, over geologic time, and this made it possible to correlate rocks over long distances. Evolution in this sense is an observable fact. In 1859, the geologist Charles Darwin explained the evolutionary changes in organisms as the result of descent with modification resulting from natural selection. Thus, the fundamental paradigm in modern biology was largely an outcome of research aimed at building a geologic time scale, although insights from other fields also contributed.

Fossils allowed the division of the most recent part of Earth history into the Paleozoic, Mesozoic, and Cenozoic Eras, along with a hierarchy of finer subdivisions. Below the oldest Paleozoic layers—a period called the Cambrian—were rocks lacking fossils, which therefore could not be dated or fitted into a detailed succession. These rocks were called Precambrian, and their history remained intractable until the development of radiometric age dating in the mid-twentieth century.

By the 1960s, it had become clear that different stratigraphic traditions in different countries were making it hard to compare and integrate the findings of geologists and paleontologists around the world. Further progress in dating and interpreting the rock record of Earth history would require standard procedures to be adopted on a global basis. A major effort in geological diplomacy, in which Hollis D. Hedberg repeatedly circulated questionnaires among prominent stratigraphers around the world and gradually widened the areas of agreement, eventually produced the International Stratigraphic Guide (Hedberg, 1976; Salvador, 1994).

A critical problem at that time was the way in which to tie the intervals in the time scale to the rock record itself. In nineteenth-century work, an investigator would find a region with abundant, fossil-rich rocks representing some part of geologic time and would use those fossils to define a time interval—the
Triassic Period, for example. Rocks anywhere else that carried those typical fossils would be identified as Triassic in age. As work progressed, the order of these periods became evident, for in undeformed areas, rocks with Jurassic fossils rest on top of those with Triassic fossils. As the time scale became more detailed, the problem arose of defining the boundaries between adjacent time intervals. It was clear that the time intervals needed to be tied to the rock record, and so the concept of a type section, or stratotype, emerged. However, if the top and the bottom of the Triassic were picked in a type section in Germany and the top and bottom of the Jurassic were established in Switzerland, for example, it was unlikely that the top of the type Triassic and the base of the type Jurassic would be exactly the same age; probably there would be either a gap or an overlap in time.

Largely through the work of Hedberg and others interested in the problem (Ager, 1973), a solution was developed that has become the basis of the modern time scale. In this procedure, only the lower boundary of a time interval is tied to the rock record. This boundary is formally established at a specific level in a specific exposure of stratified sedimentary rocks. The top of a time unit is not defined anywhere in the rock record, but is considered to be the same as the base of the next younger unit. The defined position of the lower boundary of a unit is often informally called a “golden spike,” but the formal term is “global stratotype section and point” (GSSP), where the stratotype section is the exposure of rocks chosen for defining the lower boundary of a time unit, and the point is the specific level in that section where the formal boundary is placed (Fig. 3).

International working groups were set up to identify possible GSSPs and choose the best one for defining each stage, where a stage is defined as a subdivision of an epoch (Fig. 3). The base of a time interval is placed at the base of its lowest stage. This was the context of the Ancona meeting. The GSSP for the base of the Rupelian stage, and the equivalent Eocene-Oligocene boundary, had been established in an abandoned quarry at nearby Massignano in 1992 (Fig. 4). The 2007 meeting was held to consider the accumulated research on this part of the time scale since the boundary had been formalized (Fig. 5).

Obviously, there is a great deal of investigation, argument, advocacy, and negotiation involved in choosing each of the dozens of GSSPs. This crucial work is now well advanced, although not yet complete. For an online list of the GSSPs for all recognized stages and their current status, see http://www.stratigraphy.org/gssp.htm. For an example of the intensely detailed work that goes into proposing a GSSP, see Coccioni et al. (2008), who documented a candidate GSSP for the base of the Chattian, the upper of the two Oligocene stages, in the same part of Italy where the base of the Oligocene was previously established at Massignano. Formal ratification of several GSSPs is anticipated, based on discussions at the International Geological Congress at Oslo in August 2008.

The history of this critical work in geological time-scale construction has been reviewed in general by Walsh et al. (2004) and for the Neogene stages of the Mediterranean area by Cita (2009). Generally, it has worked extremely well, although technical debates continue, for example, whether a GSSP should

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Figure 3. Current status of the geologic time scale and the global stratotype sections and points (GSSPs) for the Upper Cretaceous and Paleogene. This diagram is not scaled with time; instead, each stage has an equal-sized box. This figure combines information from Gradstein et al. (2004) and the web site of the International Commission on Stratigraphy (http://www.stratigraphy.org/gssp.htm) as of April 2008.

Figure 4. View of the Massignano quarry near Ancona, Italy, with bedding dipping gently to the left. The position of the global stratotype section and point (GSSP) that defines the base of the Oligocene, and thus the Eocene-Oligocene boundary, is marked. The inset close-up shows the actual physical spike driven into the rock at the GSSP.
Figure 5. Detailed stratigraphy of the Massignano global stratotype section for the Eocene-Oligocene boundary (after Montanari and Koeberl, 2000, p. 260–261), which may be consulted for the genus names and the references cited in the figure. The star marks the global stratotype section and point (GSSP).
be placed at a level corresponding to a major event in Earth history (a “golden event”), or at a minor but easily correlated event like the appearance or disappearance of a widespread and abundant fossil species, which must then be considered to have occurred globally at the same time.

The critical point from the foregoing discussion is that, unlike the human history based on often-datable written documents, Earth and life history are based on the rock record, which cannot be directly calibrated in years. The subdivision of rock-based Earth history has been carried to a detailed and sophisticated level, and currently these intervals of the rock record are being dated in years using isotopic methods. A similar situation prevails in the human prehistory based on archaeological excavations, and yet this time-scale construction has no analogue in either document-based historiography or in cosmic history.

**Cosmic History**

Cosmic history was the most recent major regime for which it was determined that there actually is a significant history to be understood. The expansion of the universe was discovered in the 1920s, and through the middle of the twentieth century this was explained in two mutually contradictory ways—the big bang hypothesis and the steady-state hypothesis. Both hypotheses were developed theoretically until the discovery of the cosmic microwave background radiation in the 1960s definitively confirmed a prediction of the big bang theory, demolished the steady-state hypothesis, and rendered cosmic history significant and interesting. Ferris (1988) has reviewed these developments.

Much is now understood about cosmic history, and the sources of that information are quite unlike the sources of information about the history of Earth, life, and humanity. In part, cosmic history can simply be observed with telescopes. Observations of galaxies billions of light years away show us the conditions of those objects billions of years ago. Although there is no way to observe our own planet or solar system far back in time, the distant observations illustrate what the universe in general was like in remote times.

Telescopes make it possible, however, to infer the early history of our sun and solar system, by observing nearby protostars and very young stars. Spectacular images from the Hubble Space Telescope and other observatories (http://apod.nasa.gov/apod/astropix.html) show brand-new stars accreting from giant clouds of dust and gas, lighting up from thermonuclear fusion, and blowing away the residual dust and gas. Geological understanding of the very early history of Earth in the context of the solar system has been greatly enhanced by these astronomical images.

Our knowledge of the big bang itself has come from an interplay between theoretical calculations based on high-energy physics and astronomical observations, especially of the cosmic microwave background radiation.

None of these sources of information on cosmic history requires or is susceptible to the kind of time-scale construction that geologists, paleontologists, and archaeologists have had to use to understand the rock record. Cosmic history has always been dated, as well as possible, in years. Even when it sounds like cosmic history is being divided into units like those of the geologic time scale (for example, the Radiation Era), this is a completely different kind of historical procedure, which we treat later under “Periodizing history.”

**Correlating Events**

In rock- and sediment-based history, it is often useful to correlate events, that is, to determine that they are the same age, or that one is older than the other, whether or not the events can be dated in years. Clearly, this is important in trying to establish causal relationships. Correlation is one of the two main uses of fossils in geology; the other being environmental reconstruction.

Beginning in the 1960s and 1970s, a new correlation technique was developed based on the measurement of remnant magnetization in rocks. Paleomagnetists discovered that Earth’s magnetic field has reversed many times in the past, and it has been possible gradually to work out the sequence of geomagnetic reversals recorded in rock sequences. Earth’s magnetic field collapses during a geomagnetic reversal and then regrows in the opposite direction, so these events must be synchronous worldwide, making them an ideal basis for correlating distant rock sequences. If an event is recorded in one place in rocks with normal magnetic polarity (normal is the polarity of today’s Earth) and an event is recorded elsewhere in reversely polarized rocks, they cannot be the same age. The “fingerprint” of long and short, normal and reversed polarity zones has been recovered from the continuous magnetic record in ocean crust (Glen, 1982), so if enough polarity zones can be identified in a section of layered rocks to recognize the fingerprint, the rocks can be correlated to the seafloor record and thus to other rock sequences.

The modern time scale (Gradstein et al., 2004) shows the history of geomagnetic reversals along with the fossil-based subdivisions, and both are dated in years as well as possible. This development (Lowrie and Alvarez, 1981; Glen, 1982) has no obvious analogue in either human or cosmic history.

**Dating Events**

At the beginning of the twenty-first century, we find ourselves in a situation never before experienced, in which all the major regimes of Big History can place their findings in a chronology based on years. Years form the ideal basis for chronology because the orbital period of Earth circling the Sun has been essentially constant since nearly the beginning of the solar system, unlike the length of the day, which progressively slows because of tidal friction, and because they can be understood intuitively.

Christian (2008) writes of a First Chronometric Revolution marked by the invention of writing, which allowed events of the past to be preserved with more or less accurate dates for longer than was possible using only memory and legend. He points out that as a result, history based on written documents came to be perceived as the only way there was to know and date the past.
Christian calls the current situation, in which all of the past can be known and studied, the Second Chronometric Revolution. This has led to the slightly touchy problem that various sciences now claim to be doing history, which may distress some historians. In cases where this distinction may cause discomfort, it may be useful to think of history based on written documents as history sensu stricto, and the broader view of the past to which various sciences are contributing, as history sensu lato.

Christian (2008) gives a useful overview of the various methods by which ages in years are determined for geological and paleontological materials. The most important, of course, is radioactive decay. Many different radioactive isotopes have been exploited because their half-lives and useful materials have made them applicable to a wide range of geological time scales and problems. For age calibration of the geological time scale in cases like the Eocene and Oligocene under consideration at the Ancona Penrose Conference, probably the most useful is $^{40}$Ar/$^{39}$Ar. This system is based on the decay of potassium to argon and is measured on volcanic mineral grains that were erupted explosively and carried by wind, in this case, to the (then submerged) part of Italy where the Eocene and Oligocene sediments were accumulating. These mineral grains were too hot before eruption to retain any daughter argon, but after eruption, they cooled, began to accumulate radiogenic argon, fell to the ocean, and sank to be incorporated in the accumulating sediment, all in a geological instant. Their radiometric age thus gives the age of the fossils in the layer where they are found or of any other stratigraphic feature, such as magnetic polarity reversals or chronostratigraphic signatures. This approach, which has been referred to as “integrated stratigraphy,” was pioneered in the Tertiary portion of the northeastern Apennine pelagic succession, providing unprecedented precision and accuracy in the calibration of the geological time scale (Montanari et al., 1985, 1988, 1991, 1997).

Christian (2008) also lists other techniques by which ages in years can be determined to calibrate Earth and life history: dendrochronology, counting of annual layers in glacial ice and in the sediments of periglacial lakes (varves), thermoluminescence, electron-spin resonance, fission-track dating, and genetic dating methods. Yet another technique that is having a major impact on the dating of the geological time scale is cyclostratigraphy (Kuiper et al., 2008). This method is based on finding rhythms in pelagic sediments, such as cyclic oscillations in the proportions of detrital clay and biogenic calcium carbonate, which reflect plankton productivity controlled by cyclic climate changes. In turn, these climate changes are responses to oscillations in the three main parameters of Earth’s orbit and spin, with periods of ~20,000 yr (precession of the spin axis), 40,000 yr (obliquity of the spin axis), and 100,000 yr (eccentricity of Earth’s orbit). These orbital rhythms, known as Milankovitch cycles after the Serbian engineer and mathematician who first calculated them in the late 1930s (Milankovitch, 1941), control the changing amount of solar energy that reaches Earth’s surface at any given latitude and time. These changes in energy have an effect on the production of primary biogenic carbonate and, ultimately, on the type of sediment deposited in marine pelagic basins (especially marl versus limestone). In addition to calcium carbonate, other proxies are used today to resolve orbitally forced climate cycles, including stable carbon and oxygen isotopes, magnetic susceptibility, and the relative abundances of different types of microfossils, e.g., rhythmically alternating radiolarian-rich layers and foraminifera-rich layers (Mitchell et al., 2008).

The history of the orbital parameters of Earth was recently calculated astronomically with extreme precision at 1000 yr intervals back in time to 100 Ma by Laskar et al. (2004). This reference curve makes it possible to calibrate with high precision the orbital cyclicity recorded in pelagic sediments. The marine carbonate succession of the northeastern Apennines of Italy, which represents a nearly 200 m.y. time interval from the Early Jurassic to the Pliocene, provides an ideal situation for applying high-resolution cyclostratigraphy. The Miocene succession exposed on the cliffs along the Conero Riviera, near Ancona, has been subjected to high-resolution cyclostratigraphic analysis (Cleaveland et al., 2002; Mader et al., 2004; Hilgen et al., 2005), leading to a highly precise astrochronological calibration of this portion of the geological time scale. The Eocene-Oligocene succession exposed at Massignano and elsewhere in this region (Premoli Silva et al., 1988; Montanari and Koeberl, 2000) is also being dated by the cyclostratigraphic method, providing not only an ever more accurate calibration of the geologic time scale, but insights into the response of the marine biota to climate changes and extraterrestrial events such as impacts and comet showers as well (Jovane et al., 2006; Brown et al., this volume; Hyland et al., this volume).

Thus, the cyclostratigraphic approach, combined with integrated stratigraphy, is leading toward a realistic goal of a geologic time scale with events calibrated to an accuracy of around 1000 yr—a time resolution previously almost inconceivable.

Periodizing History

The whole purpose of time-scale development and of correlating and dating the past must be to understand history. In human history, we would like to know the social and environmental factors that drove historical change, as well as the human choices that were made and their historical consequences. In Earth and life history, we want to understand the evolution of Earth and of life on Earth that led to the world we know today. In cosmic history, we would like to know how the initial conditions at the time of the big bang led to a universe that developed as it has. In Big History, we hope that it may be possible to discern the structure and character of all of the past, and to recognize the nature and timing of the first-order changes that have produced the major regimes of history.

It would not be easy to discern the structure underlying a continuous written narrative with no chapter breaks, no headings or subheadings, and no separation into paragraphs. It is thus imperative for writers to provide these markers and breaks, to make the reader’s job easier. Analogously, when historians study the past,
they generally impose breaks or separations on their narrative. Within the field of human history, there is a long tradition of making these separations, and it is called “periodizing” history. However, as David Christian (2008, personal commun.) points out, “periodization is much more than a matter of making life easier for the reader. It is fundamental to understanding the past as it entails an attempt (which may or may not succeed) to separate the trivial from the significant, and to identify the large changes. It has to be done because history without periodization is a meaningless jumble of information.” Periodization is intimately related to the questions that are chosen for study. It is, however, a controversial procedure to which philosophically minded historians have given a great deal of thought (Gerhard, 1973–1974).

Examples of periodization are everywhere at hand. Ancient Egyptian history is conventionally divided into the Old, Middle, and New Kingdoms, separated by the First and Second Intermediate Periods. These are our divisions, not theirs; surely Sesostris III did not think of himself as a Pharaoh of the late Middle Kingdom. Indian history is summarized as a sequence of Kingdoms and Empires. Chinese history is conventionally presented as a chronology of dynasties. European history is usually divided into a sequence something like the following: Roman Empire, Early Middle Age, High Middle Age, Late Middle Age, Renaissance, Reformation, and so on.

Periodization is probably unavoidable if we are to gain any understanding of history. The problem is that the choice of periods and breaks between periods is very subjective. Where should one place the division between the Late Middle Age and the Renaissance? A historian of Italy with a particular interest in art and literature might place the break at the beginning of the Florentine humanist movement around 1400. A historian of Iberia interested in the end of the Late Middle Age and in exploration might place the break at some critical discovery of the Portuguese, perhaps Gil Eannes finally passing the longtime barrier of Cape Bojador on the Saharan coast of Africa in 1434, or at Spain’s miracle year of 1492. Historians of Germany, France, or England would make other choices, but to historians of China, India, Africa, Mexico, or Peru, the transition from the Middle Ages to the Renaissance is completely irrelevant. It seems clear that such periodizations are useful but rather subjective, and they are virtually impossible to correlate worldwide. In view of this inherent subjectivity, it is difficult to imagine the world’s historians undertaking to agree on a standard periodization, nor would it be either necessary or desirable.

A central point of the present paper is that periodization in this sense is completely different from the time-scale development that has been necessary in order for geologists and paleontologists to decipher the rock record of Earth and life history, and yet they are commonly confused because, at first glance, the geological periods and other ranks of time-scale division look like periodized intervals. For example, the Wikipedia article on “Periodization,” as of April 2008, states, “Periodization from the sciences includes the geologic Cretaceous or Jurassic periods, while examples from human history include the Baroque Period, the Age of Anxiety, and the Harlem Renaissance.” This ignores the difference that Cretaceous and Jurassic are objective time-scale divisions formally tied to the rock record and agreed to at the highest level of international scientific cooperation—or will be, when the bounding GSSPs are agreed upon, probably in the next couple of years (http://www.stratigraphy.org/gssp.htm), whereas the Baroque Period, the Age of Anxiety, and the Harlem Renaissance are subjective terms, although they may be very useful and may reflect a great deal of scholarship. We seek to make this difference clear with the following examples.

EXAMPLES

Historiography: The Second World War

In his thoughtful and influential little book, The Nature of the Stratigraphical Record, Ager (1981, p. 71–73) drew an analogy between establishing a unit in the geological time scale and trying to define the Edwardian Era. This analogy clearly illustrated the problems in choosing the beginning and end of a geological time interval and in recognizing it from the material remains that may be preserved. However, we would note two critical differences. First, defining geological periods like the Devonian or Permian on the basis of the rock record was an essential step in establishing the chronology of Earth history; nothing could be understood until that was done. Defining the Edwardian Era can be an aid in understanding what was happening at that time—it is an example of periodizing history—but it was not necessary in order to establish a chronology, because the dates in years were already there, although the archaeological study of earlier human history would be more analogous to the geological procedure. Second, once the GSSPs that define the limits of the Devonian and Permian were placed in the rock record, those geological periods were precisely defined. It is difficult to imagine an analogous procedure for precisely defining the beginning and end of the Edwardian Era.

For another example, consider the Second World War, for which the age of almost every critical event is known not just to the year, but to the day or even the hour. Time-scale construction is not necessary for establishing chronology, but periodizing is helpful in understanding what happened. Periodization will be arbitrary and designed for the purpose of a particular study. For example, did the Second World War begin in 1939, when Germany invaded Poland, or was it then a regional conflict only? Did it begin when the conflict widened to include Britain and later the Soviet Union, or when it became truly global with the entry of Japan and the United States? Did it end with the surrender of Germany, or of Japan? Or did it continue seamlessly into the Cold War? Perhaps each historian will structure the Second World War differently, for the purposes of a particular study, as Winston Churchill did in the titles of the six volumes in his study of the war: “The Gathering Storm,” “Their Finest Hour,” “The Grand Alliance,” “The Hinge of Fate,” “Closing the Ring,” and “Triumph and Tragedy.”
Cosmic History: The Early Galaxies

As an example of how astronomers can literally see ancient history, consider the Hubble Ultra Deep Field (Beckwith et al., 2006), an image of a tiny portion of the sky, covering 11 arcmin², made with a 1,000,000 s exposure using the Hubble Space Telescope. The HUDF image (www.aip.de/groups/galaxies/sw/udf/swudfV1.0.html) contains at least 10,000 objects, almost all of them galaxies, with the wavelength of their light shifted toward the red because of motion away from us. The red shifts increase with distance—which is the signature of the expansion of the universe—and the greater the distance, the longer it has taken the light to reach us. Thus, in the most distant objects astronomers are seeing galaxies as they were when the universe was very young. Red shift is measurable; converting it to age is somewhat model dependent, but in some objects in the HUDF image, we are clearly seeing galaxies as they were in the first billion years after the big bang, 13.7 billion years ago. Beckwith et al. (2006) observed that distant, young-universe galaxies have ragged, irregular shapes, contrasting with the elegant spirals and ellipses of closer galaxies, which we see as they were after galactic shapes had had time to evolve, pulling together gravitationally into spirals and ellipses.

The HUDF early galaxies represent an intermediate step between the original slight fluctuations in the density of the universe immediately after the big bang, which are another example of observed history, seen as patchiness in the cosmic background radiation (http://antwrp.gsfc.nasa.gov/apod/ap050925.html), and the present universe of discrete, gravitationally organized galaxies.

Earth and Life History: Mass Extinctions

The geologic record bears witness to mass extinctions of fossil organisms. Six great extinctions are recorded since the appearance of an abundant fossil record at the beginning of the Cambrian, ca. 540 Ma, and there have been several minor extinctions as well. The early stratigraphers used these extinctions as natural breaks between periods when they set up the time scale. They did this work well, and four of the six great extinctions currently recognized (end Ordovician, end Permian, end Triassic, end Cretaceous) are at or very close to modern geologic period boundaries. In the absence of a method for dating rocks in years, it was possible to interpret these extinctions as due to missing rock record, since an originally gradual evolutionary change will appear sudden where a hiatus has removed the record. Darwin, influenced by the then-current doctrine of uniformitarianism, chose this interpretation—Natura non fecit saltum (Nature does not make jumps); it was perhaps his greatest mistake, for we now know from places with demonstrably continuous sedimentation that at least some of the mass extinctions took place suddenly (Alvarez, 1997).

A brief review of three of the extinctions throws light on the interplay between time-scale development and periodization. A minor extinction can be seen around the Eocene-Oligocene boundary on a graph of the number of marine fossil genera recorded in the literature, plotted to substage (Sepkoski, 1997), but it is not easy to locate with precision in the rock record, even in an intensely studied section like the Massignano stratotype. The clearest event at Massignano is the extinction of the Hantkeninidae, a family of planktic foraminifera, and this level was selected as the GSSP for the Eocene-Oligocene boundary because of the utility of these floating microorganisms for correlation. However, there is no corresponding extinction in two other well-represented fossil groups, the benthic foraminifera and the calcareous nannofossils (Fig. 5). Furthermore, this GSSP does not correlate with either of two indicators of extra-terrestrial influences—a level of impact debris or an anomaly in helium isotopes that marks an input of extraterrestrial dust (Farley et al., 1998), nor does it correlate with the striking cooling event and increase in global ice volume recorded by oceanic isotopic event 1, labeled O1 (Miller et al., 2008). Thus, for the Eocene-Oligocene boundary, the time scale is well defined, but it does not quite match any of the interesting events that might be taken as periodization boundaries.

The most recent of the great mass extinctions, the Cretaceous-Tertiary (K-T) boundary, at 65.5 Ma in the 2004 time scale, is unique in being extremely abrupt and synchronous in a number of groups of organisms, and in correlating precisely in time with evidence for a very large impact (Smit and Romein, 1985; Alvarez, 1997; Arenillas et al., 2006). Hundreds of excellent stratigraphic sections on land and in deep-sea cores are available for studying this event worldwide (Claeys et al., 2002). The GSSP for the K-T boundary has been placed at the base of a thin clay layer carrying the geochemical evidence for the impact, at a stratotype at El Kef in Tunisia. This is a unique case of a precise match between the time-scale boundary and a critically important periodization boundary.

The greatest of the mass extinctions, close to the Permian-Triassic boundary (251 Ma in the 2004 time scale) has been harder to study because useful stratigraphic sections are very rare, occurring almost exclusively in China. The extinction is fairly abrupt, yet at the well-studied Meishan section in China, it is spread over ~25 m of section, corresponding to more than a million years (Jin et al., 2000). The extinction is recorded primarily in marine invertebrate fossils, which are less useful for long-range correlation than are conodonts—the microscopic jaws of otherwise soft-bodied, swimming vertebrates, which largely escaped the extinction (Sepkoski, 2002). The gradual character of the mass extinction and the greater utility of conodonts for correlation have led to a surprising situation in which the GSSP for the base of the Triassic has been placed at the first appearance of the fossil conodont Hindeodus parvus, slightly above the level of what has long been called the Permian-Triassic extinction. Thus, by definition, the greatest mass extinction in life history took place very late in the Permian, but not at the Permian-Triassic boundary. Nothing could show more clearly the difference between time-scale construction and periodization!
CONCLUSION

We conclude that it is important for historians of all kinds to distinguish carefully between dating events and establishing time scales, on the one hand, and periodizing, or dividing the past into manageable and useful chunks, on the other. Certainly, some of the concepts and distinctions we have discussed are subtle and slippery, and we hope this paper may generate discussion and exchange between the component disciplines of Big History and will lead to the sharpening and clarification of these important differences.

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