THE CHARACTER OF EARTH HISTORY

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ABSTRACT
The patterns of human history can provide an original key to the interpretation and understanding of the much longer history of the earth. Some of the fundamental processes that regulate the evolution of the earth display a repetitive, cyclical behavior, whereas others are characterized by irreversible, unidirectional trends. Both processes, i.e. cycles and trends, may be seen as long-term patterns in earth history. These patterns may coexist, and may be modulated by occasional, but extremely important, chance events. It has been suggested that the interplay between chance events and long-term patterns is a feature in human history; in this paper we propose that the same character applies to earth history as well. This suggestion is illustrated with geological examples: we discuss the tectonic evolution of mountain belts that display components of both cyclical and unidirectional trends. We then provide an example of a dramatic, important chance event, namely the impact of a large meteorite on the earth’s surface that caused the Cretaceous–Tertiary boundary mass extinction 65 million years ago.

Keywords: earth history, geology, mass extinction, tectonic evolution.

1 INTRODUCTION
In a small thoughtful book called The Landscape of History, Gaddis [1] has considered the character of human history and the ways in which historians seek to understand it. Gaddis frequently uses analogies from earth history and from the scientific approach of geologists, and it seems reasonable to turn this approach around and to look at the character of earth history as illuminated by insights from human history. What, if anything, can we say about the character of the history through which our planet has evolved over the last 4.5 billion years?

2 TRENDS AND CYCLES IN HISTORY
In his book, Time’s Arrow, Time’s Cycle, Gould [2] pointed out that a critical 18th and 19th century debate centered around the question of whether earth history should be thought of primarily as displaying unidirectional trends, or as being fundamentally characterized by cycles. A similar dichotomy has always pervaded presentations of human history. Religious interpretations of history range from the endless cycles of Hinduism to the brief creation-to-judgment trend of fundamentalist Christianity. The views of secular historians show a similar range, from the inescapable cycling of civilizations in Toynbee’s [3] A Study of History to the directionality implicit in the titles of Gibbon’s [4] The Decline and Fall of the Roman Empire and Spengler’s [5] The Decline of the West, or its optimistic antithesis, McNeill’s [6] The Rise of the West. Probably few serious historians would accept a black and white choice between polar opposites, but would look for a more subtle interplay between cyclical and unidirectional factors to generate the extravagant complexity of unfolding human history. Historians would also look for the historical consequences of critical events, and the historical role of exceptional individuals that is the province of the historiographical subdiscipline of biography.

What is the situation in earth history? Has modern geology reached a conclusion on the debate that so engaged the founders of our science? Paralleling the study of human history, we are being forced toward more nuanced interpretations than the original arrow–cycle dichotomy. We are also coming to realize that great events play a fundamental role in determining the character of earth history, and we should furthermore consider whether there have been any constants in earth history.
The earth’s water cycle was known in general form at least as far back as Dante Alighieri [7]. The more subtle pattern of changes known as the rock cycle was one of the great discoveries by early geologists – the understanding that there are many possible pathways of change between sedimentary, metamorphic, and igneous rocks, allowing earth materials to cycle in various ways between these different states. This limited version of the rock cycle was expanded during the plate tectonic revolution into the concept of the Wilson cycle of continental assembly and disassembly, and ocean growth and destruction, driven by a deeper and more fundamental cyclical convective overturn of the mantle. The implication would seem to be that earth history is fundamentally cyclical.

However, seen in full-earth context, the rock cycle became a central feature of earth’s behavior only after the first-order, irreversible trends of earth’s accretion and organization, particularly its differentiation and the solidification of the mantle (although not the core), were completed. Furthermore, the cumulative effect of the rock cycle, through much iteration, is to mediate the irreversible, arrow-like conversion of mantle peridotite into continental crust and nearly pure quartz sandstone. Seen in this broader context, earth history is fundamentally arrow-like. Complicating this question about cycles and trends in earth history is the difficulty of rigorously defining what constitutes either a cycle or a trend. Since definition is difficult, we now consider a case study of cycles and trends in geology.

3 CYCLES AND TRENDS IN THE TECTONIC EVOLUTION OF THE APENNINE MOUNTAINS

The repeated opening and closing of ocean basins and the consequent fragmentation and reassembly of continents have long supported the concept of the Wilson cycle – of periodic reversals in the polarity of orogenic events [8]. An orogenic cycle may be viewed as two extensional deformation stages, pre-orogenic and post-orogenic, separated by an intervening stage of syn-orogenic contraction of the earth’s continental lithosphere. This sequence of alternating deformations has characterized the history of many mountain ranges and is particularly clear in the study of the peri-Mediterranean orogenic belts such as the Alps and the Apennines [9]. The evolution of these mountain belts can thus be viewed as fundamentally cyclical.

However, when seen in a broader perspective, the architecture of these mountain ranges shows a record of the overprinting of structures formed at successive times, increasingly complicating the rock record as time passes – an evolving architecture that cannot be undone. In this perspective, the history of these mountain ranges seems better described by a unidirectional trend than by a cycle.

To explore the interplay of these two aspects of tectonic evolution, let us now examine one example where both repetitive cycles and unidirectional trends are preserved in the rock record. This example comes from the mountains southeast of Spoleto, in the Umbria–Marche Apennines of Italy (Fig. 1a), which provide an excellent example of how both cycles and trends may be recognized in tectonic evolution. These mountains are a classical area for both stratigraphic and tectonic studies [10–15] and were mapped in detail in the late 1970s [16].

The outcropping rocks belong to a sequence of Mesozoic–Tertiary marine sediments that were deposited mainly under pelagic conditions on an attenuated, subsiding, northward-pointing spur of the African continental crust known as the Adriatic Promontory. This episode of crustal stretching, mainly accommodated by the development of synsedimentary normal faults (pre-orogenic normal faults in Fig. 1b), occurred as the Adriatic continental margin was drifting away from its European counterpart due to the opening of the Tethys Ocean in Jurassic time [17]. Local effects of crustal stretching continued on the Adriatic margin into the late Cretaceous–early Tertiary time interval, as indicated by important stratigraphic variations [14] and by the coeval occurrence of minor extensional synsedimentary structures [18].
Figure 1: (a) Tectonic sketch map of the Umbria–Marche province of the northern Apennines of Italy. (b) Simplified structural map of the mountains that extend southeast of the city of Spoleto (modified after Decandia [16]): the effects of (i) pre-orogenic extension, (ii) syn-orogenic folding, thrusting, and strike–slip faulting, and (iii) post-orogenic extension are shown. (c) Geological cross-section (A–A’ trace in b) across the Spoleto overthrust (modified after Decandia [16]).

In late Tertiary time, the overall tectonic regime changed, the Tethys Ocean closed, and the Adriatic–African continental margin eventually collided with that of Europe [19]. During this event the Mesozoic–Tertiary sediments, previously deposited on the subsiding Adriatic continental margin, were compressed and thickened, and the Alpine mountain range was formed. The Apennines have a more complex history, but for the sake of simplicity their development may be regarded here as fundamentally similar to that of the Alps. The main product of this orogenic episode in the Spoleto Mountains is a spectacular structure along which the local stratigraphic sequence has driven over itself for a horizontal distance of at least 5 km (Fig. 1b). This structure, known in the literature as the Sovrascorrimento di Spoleto (Spoleto overthrust), was first described by Verri [10] and Lotti [11], who correctly ascribed its development to a process, later known as thrusting, that plays a fundamental role during compressional orogenesis. This process, whose effects had been just discovered in the Caledonides of northwest Scotland [20] and soon after recognized in the Swiss Alps [21], represents the main mode through which the earth’s crust thickens as a consequence of continental collision. The development of the Spoleto overthrust was accompanied by intense folding of the sediments, and by the upward propagation of accessory, minor thrust faults across them (Fig. 1c).
From the late Pliocene time onward, a new change in the tectonic regime, from contraction to extension, led to the opening of the Tyrrenian Sea. As a consequence, the easternmost portion of the Apennines in the Umbria–Marche region experienced post-orogenic extension, with the development of a new system of normal faults that dissected the mountain belt and overprinted all previously formed structures (Fig. 1b and c).

In summary, the stratigraphic and tectonic history of the Spoleto Mountains can be considered as resulting from two episodes of extension, respectively, pre- and post-orogenic, separated by an intervening stage of syn-orogenic contraction (Fig. 2). This history of alternating extensional and contractional deformations is closely reminiscent of an orogenic cycle [8].

However, when seen in detail, the structure of the Spoleto Mountains displays evolutionary features that deviate from the simple notion of repetitive orogenic cyclicity. The pre-orogenic palaeogeographical template, largely inferred from thickness and facies stratigraphic variations of Mesozoic sediments, appears dominated by an approximately north–south (N–S) trending (in present-day

![Figure 2: Tectonic evolution of the Spoleto Mountains, inferred from sequential restoration of the cross-section of Fig. 1c. The deformation history is characterized by two extensional phases, pre-orogenic (a) and post-orogenic (b) respectively, separated by an intervening episode of syn-orogenic contraction (c).](image-url)
coordinates) central trough that hosts a complete sedimentary sequence up to 500 m thick (Fig. 2a). This passes laterally on both flanks into coeval, but very thin (less than 100 m thick), discontinuous sequences that were deposited on elongated seamounts (Fig. 2a). These stratigraphic differences occur across two main synsedimentary normal faults that dip away from the seamounts toward the central trough [16]. The reconstructed structural geometry of the basin, inferred from the stratigraphic relationships of coeval Mesozoic sediments, is thus quite simple (Fig. 2a).

As mentioned earlier in this section, the Mesozoic–Tertiary stratigraphic sequence, with its inherited thickness and facies variations, is doubled by the Spoleto overthrust that was developed during the main syn-orogenic contractional event. The original geometry of the Spoleto overthrust, inferred from partial cross-section restoration (Fig. 2b), was quite simple. However, this originally simple geometry was complicated, during syn-orogenic deformation, by the development of subsidiary folds and upward-propagating thrusts. In addition, the fold-and-thrust architecture was further complicated by the development of a southwest–northeast (SW–NE) trending, right-lateral strike–slip fault (Fig. 2b), called the Schioppo Fault by Decandia [16]. This structure (see also Fig. 1b for location) belongs to a regional tectonic lineament, known as the Valnerina Line, consisting of alternating SW–NE trending faults that connect N–S trending, west-dipping thrust faults. The Valnerina Line, of probable late Messinian–early Pliocene age, developed during the last stages of syn-orogenic deformation [16]; it reactivated a pre-orogenic stratigraphic boundary of Late Cretaceous–Eocene age, that was first described by Renz [13].

The onset of post-orogenic extensional deformation, probably active since the late Pliocene time, resulted in the development of a complex array of SW–NE and northwest–southeast trending normal faults that overprint all pre-existing structures (Fig. 2c) and control the present morphology and landscape of the area. The present structural geometry of the Spoleto Mountains, as achieved by the superposition of structures that originated during pre-orogenic, syn-orogenic, and post-orogenic phases (Figs 1c and 2c), is very complicated. Sequential restoration of the effects of each deformation phase, expressed in cross-section view, shows that the geometry of the investigated area was quite simple at the end of the pre-orogenic event (Fig. 2a), became quite complicated due to the overprint of syn-orogenic contraction (Fig. 2b), and eventually was extremely complicated because of the development of normal faults during the unidirectional trend of increasing complexity.

In summary, the geological history of the Spoleto Mountains preserved in the rock record can be described in terms of alternating extensional and contractional events (Fig. 2), a model in broad agreement with the concept of the Wilson cycle. However, the local structural evolution appears better described in terms of a unidirectional and irreversible trend, from simple to complex geometries (Fig. 2a–c). Perhaps a useful way to incorporate these apparently contrasting behaviors in a synthetic description is to think of the geological evolution of mountain ranges, such as the Spoleto Mountains in the Umbria–Marche Apennines, in terms of a spiral-like conceptual model that accounts for, and brings together, both cyclical and unidirectional components.

4 THE ROLE OF GREAT EVENTS IN EARTH HISTORY

Since earth history seems to involve both cycles and trends, interwoven in a nearly inextricable fashion, the cycle–arrow dichotomy may not be the most fruitful way to consider the character of the earth’s past. Thinking on the broadest scale about all of earth history, perhaps a more realistic view would be to recognize (1) an initial event in which a chance supernova triggered the condensation of a molecular cloud, at least part of which collapsed to form the solar system, with the formation and ignition of the sun and the accretion of the earth from planetesimals, (2) a set of rapid evolutionary changes during Hadean and Archean time, in which the young earth melted (from the kinetic energy of the impacting bodies that built up the earth) and differentiated into core, mantle, and primitive continents, and (3) a
very long time of stability, or quasi-constancy, representing Proterozoic and Phanerozoic time, during which cyclical processes gradually brought about further irreversible changes.

This sequence – initial triggering event, then rapid evolutionary adjustment trends, then long enduring quasi-constancy – is a pattern that may be recognized in a variety of historical episodes. In cosmology it is seen in the initial Big Bang event, followed by the evolutionary growth of galaxies, and then by the long-continued cycling of star birth and star death during which the elements heavier than helium are slowly produced and distributed by supernova explosions.

The trigger–adjustment–stability pattern may be applicable to life history as well. Gould [22] argues that fundamental evolutionary change in the earth’s biota has not come about through gradual modification, but rather in discrete, event-triggered decimations followed by short response periods of diversification, and that this happened three times in the late Precambrian and Cambrian ages, setting up the general character of multicellular life on earth. Mass extinction events later in the history of life seem to have triggered very quick evolutionary developments (as in the rapid Paleocene appearance of new taxa that followed the sudden Cretaceous–Tertiary (KT) mass extinction), leading to normal, slow biological evolution (in this case, from the Eocene to the present). The most recent of the mass extinctions, at the KT boundary 65 million years ago, brings into focus another aspect of the character of history – the role of contingent events.

5 THE ROLE OF CONTINGENT EVENTS

An impact trigger for the KT mass extinction was proposed by Alvarez et al. [23] on the basis of an iridium anomaly found at Gubbio in the Apennine Mountains, and through the 1980s a variety of supporting evidence was reported by various research teams (reviewed by Alvarez [24]). In 1991 the largest impact crater yet found on the earth was recognized, with its center at Puerto Chicxulub, beneath the Tertiary limestones and dolomites of the Yucatán peninsula [25]. The discovery of the tsunami-reworked Chicxulub ejecta precisely at the KT boundary at Arroyo el Mimbral, 800 km away, showed that the Chicxulub Crater dates from the time of the mass extinction [26]. Although the dating of the crater has been debated, new micropaleontological evidence confirms that it is exactly the same age as the KT mass extinction [27].

The impact-triggered mass extinction was a great event in earth history, especially from our viewpoint as large mammals. Dinosaurs had been the dominant large land animals for roughly 150 million years prior to their elimination in the KT mass extinction. Mammals that had long coexisted with dinosaurs, but only as small land animals, evolved to large sizes shortly after the disappearance of the dinosaurs. We owe our existence as large land animals with advanced intelligence to the impact that removed the dinosaurs.

It is thus interesting to consider the remarkable improbability of that impact. One can get a rough idea of how small a target in space the earth is by looking at similar-sized Venus, a bright but tiny dot in the night sky. Looking more closely it is clear that the KT impact could only happen when the orbit of the impacting bolide (asteroid or comet) was aligned so that it passed through a band one earth diameter wide, centered on the orbit of the earth. Comet and asteroid orbits move around through time as a result of gravitational perturbations due to the planets, so the situation where the bolide orbit intersects that of the earth is only temporary. Furthermore, the impact could only happen when the earth and the bolide were in the position where their orbits intersected, at exactly the same time. The velocity of the earth in its orbit around the Sun is about 30 km/s (2π × 150 × 10⁶ km/year), and the earth’s diameter is about 12,750 km. Thus the time window for the bolide to impact the earth is about 7 min (12,750 km/30 km/s). Clearly, if the bolide had been a few minutes ahead or behind in its orbital position, there would have been no impact. A few minutes out of the 4.5 billion years of solar system history, and there would have been no mass extinction; dinosaurs would probably have
continued to be the largest animals on earth, mammals would probably have remained small, and intelligent human beings would not have evolved.

The extreme improbability of the impact-triggered mass extinction that made possible our emergence as human beings is a reminder of the interplay between chance events and long-term patterns – between contingency and continuity – as a feature in the character of history. Gaddis [1] has stressed the importance of this interplay in the unfolding of human history. It has received less attention as a feature in earth history.

6 PUNCTUATION OF HISTORY BY GREAT EVENTS

One can identify patterns of trigger, adjustment, and stability in human history as well as in earth history; for example, the trigger event of the French Revolution followed by dramatic changes until 1815, then the Victorian century of relative stability until a new trigger event occurred in 1914. A similar pattern is seen in the birth, growth, and maturity of each organism. Whether or not the trigger–adjustment–stability sequence is a rule of history, it is clearly a template onto which numerous historical dramas can be fit with fair comfort. It makes some physical sense as the response of a system to a perturbation, as seen very simply in the behavior of a stringed musical instrument, with impulse, transient, and then gradually decaying tone.

The hypothesis that history has seen many trigger–adjustment–stability episodes is distinctly different from the alternative concept that the rate of historical change has been increasing in exponential fashion ever since the Big Bang. The latter view has been put forward, for example, by Kurzweil [28] with regard to biological evolution and human technology. Kurzweil argues that we are close to a complete merger of technology and human intelligence (what he calls the ‘singularity’) and that the rate of change will continue to accelerate even after that merger. The view we have put forward here suggests, instead, that the singularity, if it happens, will not be followed by further acceleration, but rather by a complex adjustment period leading to an extended period of stability.

Critical geological triggering events introduce into earth history a factor similar to what was once called the great-man theory of human history, a view that is currently in some disfavor among historians. The concept is that the activities – the deeds or thoughts – of a single exceptional individual may derail and rechannel long-established historical trends which, in the absence of that person’s influence, would have led to entirely different outcomes. Geology, also, was once saddled with a uniformitarian prejudice against considering the role of critical events, but that has receded and now we can comfortably study the effects of great geological events. An event worth considering is the evolution of oxygen-producing photosynthesis among primitive blue-green algae early in the Precambrian period. This is one of several biological ‘inventions’ suggested by Fischer [29] to have set the earth’s biota and its environmental conditions on the particular trajectory they have followed, and not on some equally possible but completely different one. Was there some nameless micro-organism, utterly lost in deep time, whose chance evolution of photosynthesis is responsible for earth having an oxygen-rich atmosphere and not some equally possible but completely different chemistry? The great bacterium theory!

Purely physical great events would include (1) the late Cenozoic tectonic closing of the circum-Antarctic oceanic pathway, which short-circuited the oceanic gyres that formerly brought equatorial Pacific, Indian, and Atlantic water south to warm Antarctica, thus thermally isolating the Antarctic continent and allowing it to be covered by continental glaciers, and (2) the tectonic closing of the Mediterranean in the late Miocene that led to the Messinian salinity crisis and the extraction of a large mass of salt and other evaporates from the world’s ocean. And of course (3) the KT boundary impact, resulting in a complete redirection of biological history, is a prime example of a great geologic event.
The questions that arise from this philosophical approach to the nature of earth history will include the following:

1. Should we distinguish between (a) events that are physically required but unpredictable in timing and location, such as the mantle plumes required to release earth’s internal heat, or the plate-boundary changes required by spherical geometry; (b) events which are only statistically inevitable, such as the impact of large asteroids and comets; and (c) events that occur because nonlinear break points have been reached?

2. Is there a serious distinction to be made between (a) times of rough constancy in which driving forces for change are simply not present, and (b) other times when driving forces are present but are temporarily held in check by buffering systems, such as the thermal buffer resulting from the freezing of the liquid iron core, or the chemical buffer that prevented the accumulation of large amounts of oxygen in the atmosphere until most of the earth’s reduced iron had been oxidized and sedimented? Are there interesting analogs to buffered constancy in human history, such as the forced stability of the Roman Empire after the reforms of Diocletian?

Let us discuss the past with our counterparts in the History Department. We have been separate for too long.

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