TIME IN THE GEOLOGICAL PAST OF EARTH

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Keywords: Geological time, sedimentary record, fossil record, geological processes, cycles, catastrophic events, stratigraphy, time correlation, radiometric dating, geochronology, geological timescale

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1. Geological Time: A Summary

Human inquiries into geological history have suggested essentially new concepts of time and rates of change. Geological investigations and the discovery of natural radioactivity brought a numerical meaning to the idea of geological time. Paleontology revealed the minor position occupied by man on the enormous scale of life history. Modern humans have resided on Earth for but a brief moment of some 150 000 years, which represents about a few thousandths of one percent of geological time. In Earth's history, the time dimension has been involved in exogenous and endogenous geological processes and biotic evolution. All these, consisting substantially of chemical evolution, brought Earth from its heterogeneous, formless, and lifeless beginning to its present state as a highly organized, complex, inhabited world.

Estimates of the age of Earth have been increasing constantly, from less than several thousand years up to the present-day estimate of 4.5 billion years. The maximum figure does not seem likely to increase very much more, however. In our geological concept, time began with the origin of the earliest rocks or rock particles of the present lithosphere. Relative chronology established on lithostratigraphic and biostratigraphic principles has developed greatly since the nineteenth century. The discovery of radioactivity, however, generated a new geoscientific discipline called geochronology, which deals with the absolute chronology of Earth's history. Absolute chronology arises from data based upon physically done time-related changes in the isotopic composition of geological materials.

It is forcefully demonstrated that nothing is permanent in Earth's history but change. More importantly, this change is neither simply linear or "steady-state," nor perfectly cyclic as envisioned at the end of the of 19th century. The change called evolution by current science is cumulative, irreversible, and cannot be foreseen as a whole although it involves a number of predictable cyclic and/or quasicyclic phenomena. In evolution, longer periods of relative calm have been punctuated by sudden, episodic changes, sometimes on catastrophic scales. Despite some remaining doubts, a detailed and integrating study of the geological and biological past make it possible to extrapolate many aspects of Earth's history and to suggest some implications for the future of humans and their environment.

Figure 1. Time. St. Augustine developed a solid framework by dividing all time into past, present, and future. The historians of the nineteenth century, with their obsession with the ends of civilization, taught us to comprehend any social, political, or cultural change from the point of history. Geology as originally historical science helped to develop the sense of time we are almost automatically using now.

Several other contributions of this Theme deal with geological time. The general overview is given in chapter "History of Earth," but more detailed division including stratigraphy can be found in individual sections of this chapter (see e.g. "Palaeozoic History" and other chapter. The very beginnings of "time" are described in contribution "Historical Overview of the Universe" and the following "Early Earth".

2. Reconstruction and Relative Dating of Earth History

2.1. Early Ideas and Basic Principles

Until the late eighteenth century, the biblical Genesis seemed to explain well all questions concerning the age and history of Earth. An age of some 6000 years was accepted for Earth, in agreement with Scriptures. Even the presence of abundant fossils of apparently marine creatures in strata strewn over the land seemed to offer proof of the biblical Deluge. Only a few people questioned conventional conformist geological thoughts and they did so at no small risk. At the beginning of the sixteenth century, when Leonardo da Vinci observed fossiliferous beds in northern Italy, he suggested that there were many floods rather than a single world-wide deluge. Nicholas Steno (1669) observed stratified shell-bearing rocks beneath the site of ancient Rome, which were used in construction of buildings and thus must have been older than the city. He recognized that sediment particles settle down from a fluid in proportion to their relative weight and mass, the larger ones first. Any change in the size of particles would then cause horizontal layering or stratification of the sediment accumulations. He inferred that the characteristics of different strata reflected changes of such conditions as currents, storms, wind, or temperature. Sedimentary strata consisting of particles and shells must have been deposited particle by particle and layer by layer, one on top of another. He postulated that in a sequence with many layers of stratified rocks, a given layer must be older than any overlying layers. Steno's conclusions provided the ultimate bases of interpretation of Earth history. They are now called the *principle of superposition*, which says that in any succession of strata not severely deformed, the oldest stratum lies at the bottom, with successively younger ones above (this is the basis of relative ages of all strata and the fossils they contain), and the *principle of original horizontality*, which says that since the sedimentary particles settle from fluids under gravitational influence, the resulting stratification must be more or less horizontal, and steeply inclined strata have therefore suffered subsequent disturbance. At about the same time, British scientist Robert Hooke suggested that fossils might be useful for making chronological comparisons of rocks of similar age, rather as ancient coins were used to date human historical events in Europe. Hooke speculated that species had a fixed "life span," for many of the fossils he studied had no living counterparts. His assumption forecasted the phenomenon of species extinction. Until the late eighteenth century, however, natural scientists were engaged in a different battle. Deluge enthusiasts, known as diluvialists, still held such amazing ideas as the suggestion that the Flood had first dissolved antediluvial matter, except fossils, and then reprecipitated the sediments in which the fossils became encased as they settled out of the turbulent waters. In this context, in 1709, Swiss professor J. Scheuchzer interpreted a giant salamander skeleton as the fossil remains of a man (child) drowned by the Deluge. In the late eighteenth century, however, knowledge of Earth materials grew rapidly with pioneer geological mapping. Just before 1800, William Smith, a British civil engineer involved in land surveying, recognized a widespread regularity in the rock succession and the proven great utility of fossils. Smith traced and mapped different strata according to their color, mineral compositions, and distinctive fossils. He recognized many strata over long distances by their fossils and his map was accompanied by a table of strata. Meanwhile, in France, Georges Cuvier and Alexandre Brogniart also proved that there is a definite relationship between fossil occurrences and the succession of sedimentary deposits. Simultaneous efforts stimulated by the need to construct geological maps led to the widespread recognition of fossils as a most powerful tool in sedimentary rock correlation. Mapping geologists organized rock bodies into units on the basis of their lithological properties (lithostratigraphical classification) and/or their contained fossils (biostratigraphical classification). Two important and closely related principles were discovered: the *principle of fossil succession*, which says that in a succession of fossil-bearing strata, obviously the lowest fossils are oldest, and the *principle of fossil correlation* (principle of identical fossils), which says that strata containing assemblages of identical fossils are of like age. Application of the latter principle involves the concept of what we now call index fossils, i.e., fossils that are particularly useful for the correlation of strata (see section 2.5.2). The apparent and evidently abrupt changes of fossil faunas and floras observed by Cuvier and Brogniart in sedimentary successions of the Paris Basin have been explained as evidence of a series of catastrophic extinctions of organisms caused by violent oscillations of the sea. Cuvier and Brogniart's catastrophic theory was an attempt at a reasonable interpretation of the Judeo-Christian tradition of a single Deluge in the light of contemporary scientific knowledge.

Counter to Cuvier's catastrophism, however, there was a general and gradual tendency for younger fossils to be progressively more like living organisms, while no modern forms occurred in older rocks. Georges de Buffon convinced some of his fellow scientists and philosophers that some evolution must have occurred. He noted that modifications of organisms are due to inheritance of characters and changes caused by the environment which, in turn, produced a natural descent that resulted in life as we see it today. Despite further attempts (particularly those of B. Lamarck) the true theory of evolution, however, was not formulated until Charles Darwin's (1859) formulation of the *theory of the origin of species by means of natural selection* as expounded in his "Origin of Species". Sooner or later the concept of biological evolution as an irreversible or unidirectional trend of development and systematic change through time would receive support from increasing knowledge of Earth's fossil record, despite Darwin's belief that geology does not reveal a finely graduated organic chain because the record is too imperfect. For almost the next century, the fossil record offered the most impressive evidence of gradual evolution and, in turn, Darwin's theory served as a theoretical basis for stratigraphic considerations. O. C. Marsh's study of the evolution of the horse became a classic example of organic evolution evidenced in the fossil record. The wide application of biostratigraphy was further strengthened when L. Dollo formulated the *principle of irreversibility of biological evolution* early in the twentieth century.

2.2. Uniformitarianism and Catastrophism

Ancient people were impressed only by rapid and violent geological processes. Consequently, a particular view of Earth developed very early and gradually earned for itself the name of catastrophism. According to this view, which dominated human thought until 1850, most changes occurred suddenly, rapidly, and devastatingly. The biblical great Deluge may be considered the most famous example of such a supposed catastrophe. Other comparatively minor catastrophes included volcanic eruptions at Pompeii, Krakatoa (1883), and Thera (1470 BC), and earthquakes at Lisbon (1755). Baron G. Cuvier provided the scientific background for catastrophic views, making very detailed studies of the sediments and fossils of the Paris Basin and recording sudden and frequently repeated changes in environments and extinctions of animals and plants. In England William Smith came to very similar conclusions.

When geology was established as a vigorous intellectual pursuit around 1800, however, an alternate concept developed of change in the planet. The new noncatastrophic or "uniformitarian" conception argued that many of the past changes imprinted in the rock record could be easily explained by the same common processes now observed to operate upon the planet. A noncatastrophic view of change required only a limited role for exceptionally sudden events like earthquakes, volcanic eruptions, floods, and avalanches. The great problem for uniformitarianism was always the amount of time needed to explain what was known to have happened in the history of Earth (including the evolution of all its biota) if one could only consider present processes. James Hutton (1785) recognized this right from the outset with his famous aphorism "no vestige of beginning, no prospect of an end". Charles Lyell (1830–1833) instead wanted an empirical theory founded on observation and practical experience that did not depend on any preconceived ideas from the Bible or elsewhere and which provided a methodology—a means of explaining geological phenomena. Charles Darwin's theory of evolution by natural selection was also completely uniformitarian in attitude. A corollary of uniformitarianism was the inescapable implication that Earth must be much more than a few thousand years old in order to allow enough time for all observable ancient changes to have occurred in noncatastrophic ways. The entirely uniform rates or conditions of geological and biological changes presumed by uniformitarianists are in contradiction with all we know now about the very different world of the early Precambrian, for instance. See chapter "Evolutionary Mechanisms and Processes"

Figure. 2. Mesozoic sandstones in Hradcany, Northern Czech Republic.
The layer is a basic unit of geological time. The basic concept is that the lower layer is older than the upper one.

Nearly two centuries later science merged some of the ingenious ideas of both uniformitarianism and catastrophism. Some processes forming Earth's face developed in the course of its geological history. Both the lithosphere and atmosphere and, later, the hydrosphere developed substantially until the early- to mid-Palaeozoic when plants and animals invaded landwards on a massive scale. Entirely different endogenous and exogenous conditions formed the very distinctive rock suites of the Early Proterozoic and Archaean ages. Evolution has even been considered in terms of geological processes forming Earth's surface and interior.

Rare catastrophic happenings played a major role in working out the stratigraphical record as we find it today. The hurricane, the flood, the volcanic explosion, or the tsunami may do more in an hour or a day than ordinary natural processes have achieved in a thousand years. This forces the conclusion that sedimentation in the past has often been very rapid indeed.

Continuity and the gradualness of many sediment-forming processes cannot be denied at all, but one must always distinguish between the nature of the process and the nature of the record. It is evident from the stratigraphical record that long periods of regular sedimentation may be partially or entirely overprinted by the effects of more-or-less periodical catastrophes. Also, the abruptness of some of the major changes in the history of life lead modern science to adopt some aspects of a neocatastrophist attitude to the fossil record. Modern science is faced with increasing evidence of sudden past catastrophic changes of various sizes which are termed events in the broader sense.

Annually, the world experiences approximately 150 major earthquakes, 20 volcanic eruptions, and countless floods. None of these violent events can be considered unusual since the planet is envisaged as dynamic, ever-changing, and evolving under the influence of many complex physical, chemical, and biological processes. The resulting changes are in part nonrecurring or irregular, and in part regular, recurring, or cyclic in character. Changes do not take place gradually but in sporadic bursts, as a series of minor local catastrophes separated by periods of relative calm.

2.3. Geological Catastrophes and Events: Particular Historical Geological Phenomena

Apart from natural catastrophes recorded by humankind, such as devastating volcanic eruptions, earthquakes, tsunamis, or floods, Earth has experienced dramatic and relatively sudden changes of a much larger scale during geological history. While sudden and brief devastation is usually simply called a catastrophe, the specific terms "geological event," "biological event," or just "event" were introduced to designate those happenings which have been deeply incised in the world's record of geological and biological history. The duration of an event may vary considerably, from days and even hours (like the duration of a catastrophe) to several hundred thousand years. We must bear in mind that the complex stories of some very ancient glaciations, marine transgressions, and/or regressions look like simple and relatively short happenings from a present-day perspective. The time resolution decreases down through the geological past.

In 1980, L. W. Alvarez and his fellows introduced the idea that the great world-wide extinction among marine and terrestrial faunas some 65 Ma ago can be explained by the disastrous impact of a huge celestial body. This idea was based upon detailed observations of drastic faunal extinction (such renowned groups as ammonoids or dinosaurs disappeared once and for all) and sedimentary change in the Cretaceous/Tertiary boundary beds, and also upon a prominent increase of extraterrestrial iridium content in the basal Tertiary sediment. Indeed, probability calculations indicate that at least one large meteorite or comet with a mass of 1×10^{18} tons or more and an impact energy of 1×10^{25} J should have hit Earth during the Phanerozoic (i.e., during the last 545 Ma). The idea of the extraterrestrial-body impact was then also applied to some other stratigraphic boundaries at which prominent biotic and sedimentary changes have been observed. See chapter “Past Global Crises” and. “Cosmic Influences on Earth”. See "Asteroid Impact".

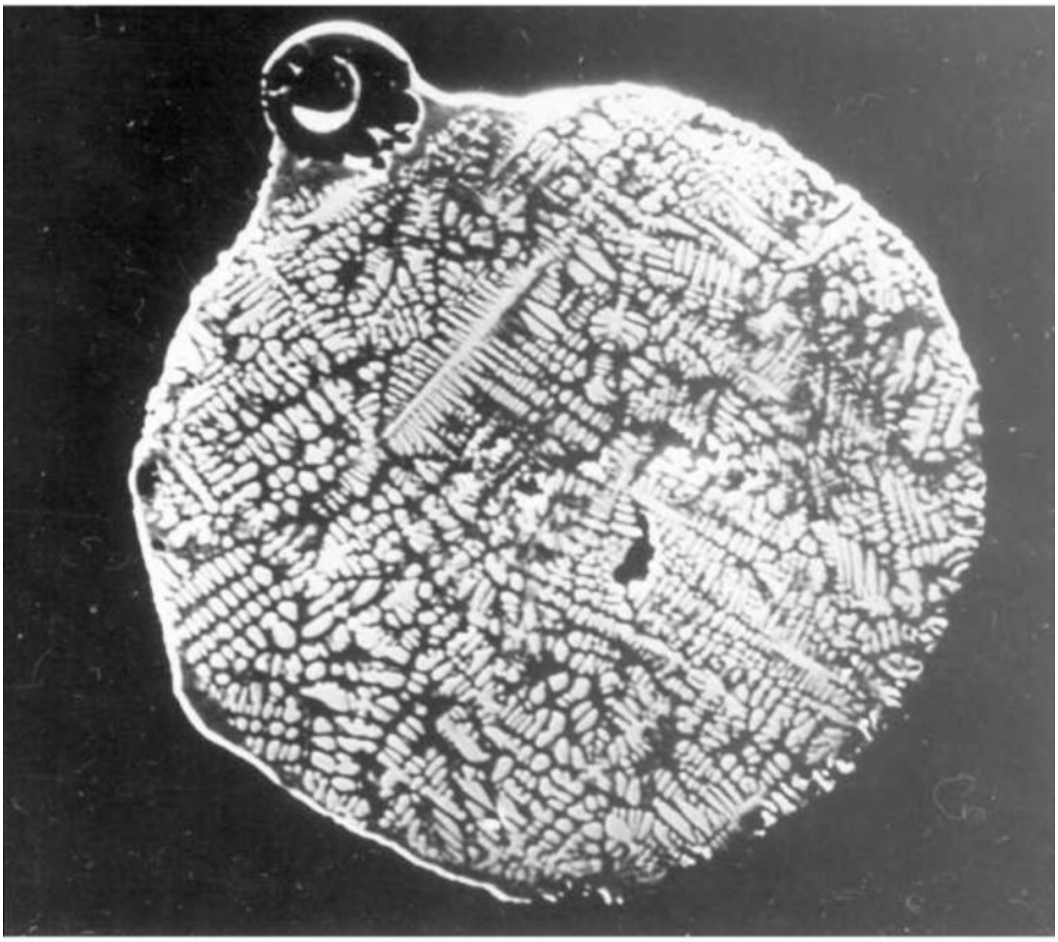

Figure 3. Westphalian period coal seam.
The cosmic microspherules are abundant at certain layers like in this Westphalian period coal seam (Carboniferous, Kladno district, Central Bohemia, Czech Republic). They often indicate the impact of a large meteorite. The cross section of the spherule displays dendritic magnetite in glassy matrix, notice the small, hollow microspherule of a different origin melted on the surface of the bigger particle.

Apart from impacts of celestial bodies, which must have had enormous and sudden effects on the entire surface of Earth (heating and evaporization of the ocean, formation of a giant tsunami wave, devastation of dry land surface, "nuclear" winter), a number of other exceptional, relatively sudden, and widespread changes have been classified as geological events. These events manifest themselves by drastic changes in the fossil biota, extinction of whole groups of animals, sudden changes in paleogeography and sedimentary facies. G. Einsele and A. Seilacher enlarged the concept of an event and recognized a wide spectrum of minor events which are recorded in local sediment strata.

The wide spectrum of geological events is classified according to the mechanism, duration, and consequences of the events.

(i) Biological events belong among those best recorded and most widely employed in relative dating and stratigraphic correlation. They manifest themselves principally as sudden and global extinctions among fossil faunas and floras although rapid biotic radiations, often following extinctions, are also considered biological events along with local extinctions and migrations. Biological events may represent both mass kill due to an extraterrestrial-body impact, and comparatively slow processes related to sea-level changes ranging from 1×10^3 to 1×10^6 years.

The most prominent of global extinctions are considered to be the Ordovician/Silurian Boundary Event, Late Devonian Frasnian/Famenian Boundary Event, Paleozoic/Mesozoic (i.e., Permian/Triassic) Boundary Event and the Cretaceous/Tertiary boundary event cited above. Less universal extinctions affecting only certain biota and fossil groups on a more-or-less global scale appear to be rather frequent in the fossil record, having a recurrence interval of approximately 1×10^6 years. For more detailed explanation see individual sections of chapter "History of Earth".

(ii) Magnetic events involve inversions of Earth's magnetic field. They are of great importance for the precise relative correlation of rocks, but their bearing on other environmental changes and biotic evolution is not well understood so far. Magnetic reversal may last for thousands of years.

(iii) Chemical events principally comprise changes in paleotemperature-related ratios of stable isotopes (^{18}O:^{16}O, ^{13}C:^{12}C) in limestones and fossil shells and also marked variations in the amount of trace elements, like strontium, boron, manganese, and iridium. Some chemical changes and anomalies recorded in sedimentary rock successions manifest environmental changes (climate and salinity changes) while Ir anomalies are regarded as powerful evidence of meteoritic impact.

(iv) Sedimentological events are of various types and durations. Some of them result from catastrophic processes such as earthquakes, cataclysmic eruptions, or particularly violent hurricanes, while others reflect relatively sudden tectonic deformations and related sea-level changes. In principle, particular sediments account for extraordinary events. Thus tempestites or storm sandstones have been deposited by extraordinary winter storms or hurricanes, homogeneous beds of tsunamites have been deposited by earthquake-triggered tsunamis, and turbidites result from gravity currents which may have been initiated by volcanic eruptions or earthquake shocks. Tephra accumulations result from cataclysmic eruptions, thick accumulations of fluvial gravels (inundites) may result from rather local although exceptional floods, anoxic black shales in open shelf sediments reflect so-called anoxic events and account for climatic and/or sea-level changes.

The time required for the formation of sedimentological events ranges from minutes (storms, earthquake-related tsunamis and gravity currents, meteoritic impacts, and many of their effects) and weeks (floods) to thousands of years (changes in sedimentation, onset of anoxic sedimentation).

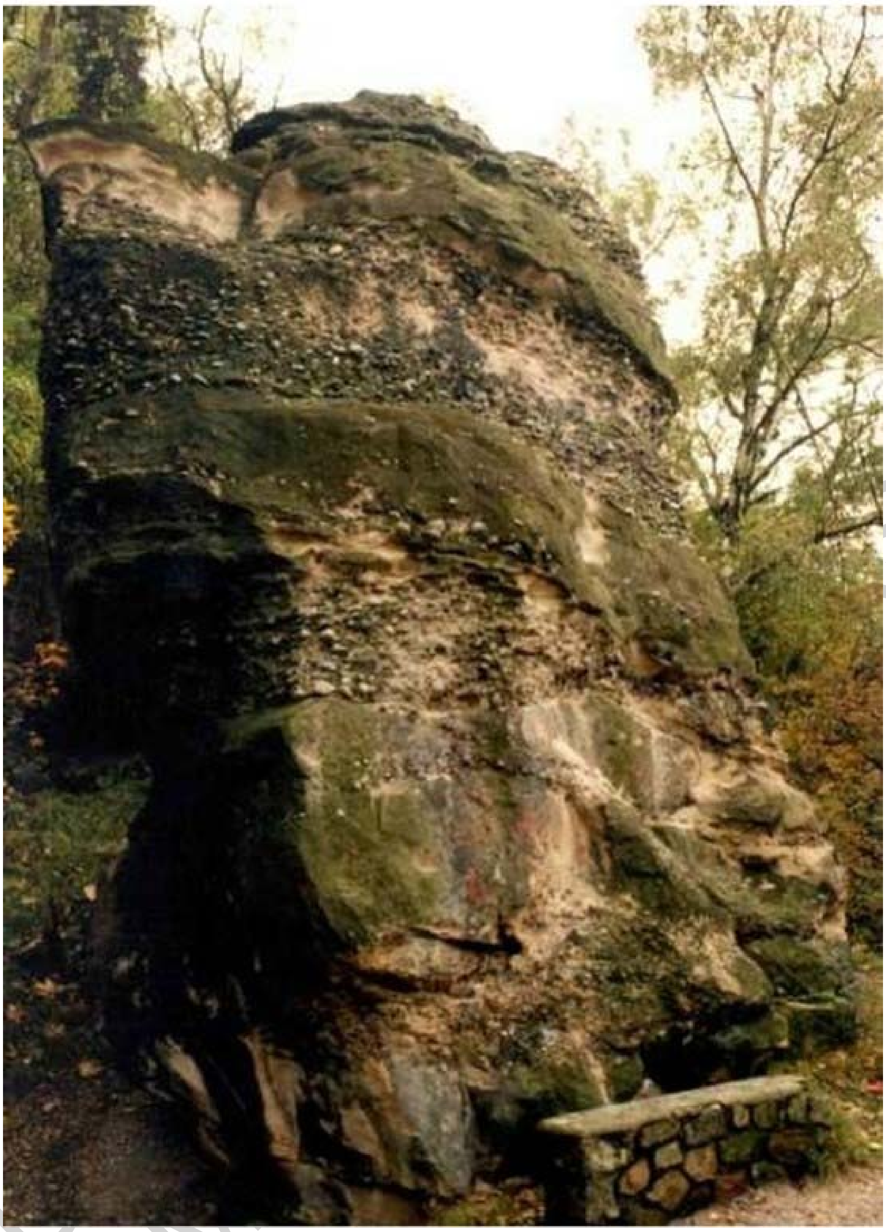

Figure 4. Alternating layers of conglomerate and arcose.
The alternating layers of conglomerate and arcose are interpreted as the wash-down episodes into otherwise shallow lake basin in Carboniferous (Hostibejk, Central Bohemia, Czech Republic).

(v) Climatic events are of varying duration and manifest themselves through changes of water temperature and agitation, salinity, specific isotopic, and chemical changes (see iii) as well as through prominent changes in fossil faunas and floras. Arid conditions are marked by terrestric red-beds. Glaciations may be recorded due to eustatic regressions (in which water is incorporated in continental ice sheets) and the presence of specific glacial sediments. Of these, glacimarine diamictites (poorly sorted, laminated gravel–sand–mud marine deposits with abundant ice-rafted pebbles) and varvites (rhythmically seasonally laminated clays typical of periglacial lakes) are the best known.

(vi) Volcanic events can be of great significance though across a limited area. Exceptional cataclysmic eruptions with huge tephra production can be used in the stratigraphic correlation of distant areas. The volcanic ash from Thera has been identified and radiometrically dated in the ice core from Greenland, as well as in archeological sites of Egypt. The time correlation may indeed be extremely precise, since the volcanic ash may circulate in the atmosphere for days to months and, rarely, for a few years. None of the volcanic events experienced by human beings, however, is even comparable to the processes which formed the Dekkan (India) or Siberian plateau basalts.

(vii) Seismic events may cause landslides and rockfalls in the terrestrial environment. Tsunamites and various dense current (turbidite) deposits are common in marine sediments of tectonically active zones.

(viii) Tectonic events include both local deformations of Earth's crust leading to diachronic sedimentation and global changes in sea-floor spreading manifested by sea-level changes. Large-scale oscillations in sea level (with amplitude of more than 100 m) can be attributed to tectonic rather than climatic events, although some exceptions are possible.

(ix) Cosmic events are not well known since their recurrence interval may be extremely long and little is understood about the resulting effects. Devastating impacts of a number of celestial bodies of various diameter have been identified on Earth's surface. The impact structure responsible for the Cretaceous/Tertiary great extinction event was found at Yucatan Peninsula (Mexico). Impacts may manifest themselves as a series of the events listed above (seismic, climatic, volcanic, chemical, sedimentological, biological).

Of all the events which are useful for stratigraphy, i.e., for relative time correlation, large oscillations in sea-level stands are of the greatest importance. Transgressive and regressive events can be caused mainly by sudden climatic and tectonic changes, and in special cases also by volcanic and cosmic events, facies changes, and anoxic events. On the other hand they are the likely cause of a majority of faunal extinctions. Global correlation of great transgressions and regressions based principally on stable cratonic margins of several continents led to the compilation of a curve which is believed to record real global changes in sea-level stands. Major eustatic fluctuations represent major turning points in Phanerozoic Earth history, being associated with major faunal and floral changes.

In turn, many of the biological events discovered to date are connected with sedimentological and facies changes (sudden appearance of black shale, for instance). Such biological and sedimentological events may occur in a particular part of a biozone. Thus they are shorter than the biozone and can be used to refine a chronological correlation, particularly when the event can be traced globally within relevant facies.

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Biographical Sketch

Petr Štorch was born on 9 February 1956 in Prague and graduated from the Faculty of Sciences of Charles University in 1980. A few months after he achieved the RNDr. degree, he acquired a position in the Department of pre-Variscan Formations of the Czech Geological Survey. His research has been focused on stratigraphy, palaeontology, and sedimentary geology of the Ordovician and Silurian of the Bohemian Massif. He took part in several mapping projects of the Geological Survey, in biostratigraphical syntheses and IGCP projects. His Ph.D. (CSc.) thesis on stratigraphy, correlation, and facies distribution in the Late Ordovician and Early Silurian of the Barrandian area, supervised by Dr. Vladimír Havlí�ek, CSc, was defended in 1991. In 1989, he took the position of head of the Geological Survey Museum. Three years later, an appointment to the position of the head of the Department of Documentation temporarily reduced his reseach plans. Soon after, however, he left the Czech Geological Survey and took a research position in the Institute of Geology of the Academy of Science of Czech

Republic. Besides his main interests in Upper Ordovician and Silurian graptolites and stratigraphy, his research has extended to the Late Ordovician glaciation, related palaeoenvironmental changes, and infaunal extinctions and recoveries. His past and present reseach projects have dealt with, in particular, Lower Silurian graptolites and stratigraphy in central and southwestern Europe—once a part of northwestern Gondwana. At present the project on Lower Silurian graptolites and stratigraphy of North Africa (Libya, Algeria, Tunisia, and Niger) is in progress.