EARTH SYSTEM: HISTORY AND NATURAL VARIABILITY

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Summary

"The Earth is all the home I have".
W.E. Aytoun

The Earth is one of the planets in the solar system, the third closest to the Sun and the fifth largest in diameter. It is the only planet known to support higher forms of life and civilization capable of self-reflection. The Earth is the home of innumerable plants, creatures and human beings, which are connected by an intricate web of mutual relations and feedback. The Earth is an almost spherical body with an equatorial radius of about 6378 km. Its outstanding feature is the presence of liquid water. Water is not only crucial for life but its cycle keeps the surface in a state of constant change due to erosion and sedimentation. In comparison to the other terrestrial planets of the solar system, the Earth undergoes constant morphological changes which are caused by internal and external forces and influenced by the evolution of the biosphere. Therefore the Earth is often called the living planet. The complex, ever-present abiotic and biotic evolution is a major resource of the Earth, because it affords the potential for changes to occur. The Earth is the only terrestrial planet whose future is unpredictable.

The aim of this essay is to guide you through the history of the Earth system, considered as "the open system comprising the atmosphere, oceans, life, soils and crust, bounded by outer space and the molten inner Earth," and to give you a sense of its richness,

interconnectedness and beauty. The data collected here may help us to understand our planet, its resources and biomes not only for the sake of science but also with a view to the future and survival of all forms of life. This text takes the form of a mosaic of basic descriptions together with selected, more detailed "case studies" excerpted from the theme articles. As the general characteristics of the Earth system alone might be rather obvious and superficial, we plunge more deeply below the surface of definitions in the cases of the deep Earth structure, history, climate, the emergence of life, global cycles and biodiversity. All these subjects are treated from a central perspective: What is the nature of the Earth system and what are its thresholds? Are we not transgressing them at this very time?

"Because we love this world and we are afraid to lose it…"

1. Introduction: Earth as One of the Planets in the Solar System

"Everything changes in the course of time".
Aristotle

The people of the Earth have ever wondered about the origins of the Earth, Life and humankind. Mythical explanations provide more or less accurate insights into the functioning of the deepest layers of the human mind, whereas hypotheses in the natural sciences are based on observations and the evidence of physical nature. Not until the Greek philosophers do we find any written documentation of observed natural phenomena. The Greeks were aware that the surface of the Earth is changing continuously. Xenophanes and Herodotus observed fossils and inferred that they were once living organisms in a sea that had covered even the high mountains. Aristotle [384-322 BC] summarized these views as follows: "*The distribution of land and sea does not endure throughout all time but it becomes sea in those parts when it was land and again it becomes land when it was sea…. As time never fails, and the Universe is eternal, neither the Tanais nor the Nile can have flowed forever…. Everything changes in the course of time."* During their travels, Roman geographers and philosophers - Seneca, Pliny the Elder and Strabo - investigated numerous geological topics such as the rise and fall of the sea and volcanism, but no consistent geological theory was formulated. The Greek texts were embellished by Arab scholars during the Dark Ages of Europe. Avicenna [980-1037] explained fossils as an unsuccessful attempt on the part of the creative force of nature to produce organic from inorganic matter. Chinese Confucian sages and later Leonardo da Vinci gave clear and accurate expositions of the origin of fossils; but the debate was just beginning.

Many names could be mentioned among the founding fathers of modern geology. James Hutton [1726-1797] advocated the idea that weathering, erosion, sedimentation and so on have been going on for ever and thus that the geological processes of ancient times are the same as those of the present. The logical consequence was that the present is the key to the past. We propose now, threatened as we are with vast climatic and environmental changes, the further step that the past might be the key to the future. William Smith [1769-1839] observed while working on a canal project that different strata were characterized by unique assemblages of fossils. He laid the basis for the concept of the geological column, a series of individual layers each of a different age and having different fossil assemblages. All the layers of the Earth could now be arranged as a "stone calendar", as the sheets of geological history.

Figure. 1. The Earth from the sky (from theme contribution "Earth as self-regulating system," written by T. Lenton)

Era	**System of period** (*rocks*) (*time*)	**Series or epoch** (*rocks*) (*time*)	**Approximate age in millions of years**
Cenozoic (*recent life*)	Quaternary (an addition to the old tripartite 18th century classification)	Holocene	0.01
		Pleistocene (most recent)	0.01 to 1.7
	Tertiary (Third, from the 18th century classification)	Pliocene (very recent)	5.0
		Miocene (moderately recent)	25
		Oligocene (slightly recent)	34
		Eocene (dawn of the recent)	54
		Paleocene (early dawn of the recent)	65
Mesozoic (*intermediate life*)	Cretaceous (chalk)		145
	Jurassic (Jura Mts., France		205
	Triassic (from three-fold division in Germany)		250
Paleozoic (*ancient life*)	Permian (Perm, a Russian province)		295
	Carboniferous (from abundance of coal)		355
	Pennsylvanian (American division)		325

		Mississippian (American division)	355
		Devonian (Devonshire, England)	415
		Silurian (an ancient British tribe, the Silures)	440
		Ordovician (an ancient British tribe, the Ordovices)	495
		Cambrian (Cambria, a Latin form of the native Welsh name for Wales)	545
Precambrian	Proterozoic	Many local system and series are recognized	2500
	Archean		3900
	Hadean		4510

Table 1. The geological column and time scale (modified according to B. Kummel 1970).

Time units	Time-rock units
Era	-
Period	System
Epoch	Series
Age	Stage
-	Zone

Table 2. Classification of stratigraphic units (B. Kummel 1970).

Every science offers some basic contribution to our understanding of the world. In the nineteenth century, geology opened the doors of perception to the depths of time. The Biblical chronology, according to which the world is about 6000 years old and underwent a major catastrophe (the "Deluge") after which stable conditions were established, had to be exchanged for a more complex model of an immensely long period of gradual evolution punctuated with sudden revolutions of the Earth's crust.

The Earth scientists of the twentieth century brought into existence several very powerful concepts that modified and expanded our view of the Universe. In almost all fields of Earth science they have gathered enough evidence to claim our world to be more complex, varied and interconnected than had ever previously been supposed. Some of the major achievements can be summarized as follows:

Plate tectonics: The Earth's crust is fragmented into a number of lithospheric plates some 150-200 km thick. The plates are in motion, in some areas converging and colliding, in other places diverging and creating separate continents or large islands. Major orogenic zones and earthquake belts are related to these movements. Prominent morphological features of the Earth such as the shapes of the continents, mountain belts and mid-ocean ridges correspond to past or present boundaries between plates. The theory of continental drift was proposed by Alfred Wegener in his book "The origins of Continents and Oceans" (1912), but inadequate evidence and insufficient data led to its general rejection at that time. The idea of continental drift has several very important consequences: (1) the materials of the Earth are gradually recycled in the Earth's convection cells; (2) the separation and divergence of continents leads to the speciation and radiation of living forms; (3) the Earth's climate depends on the size and distribution of continents. Plate tectonics thus provides the basic framework not only for the formation of the Earth's rocks and relief but also for the general evolution of life and the Earth's environments.

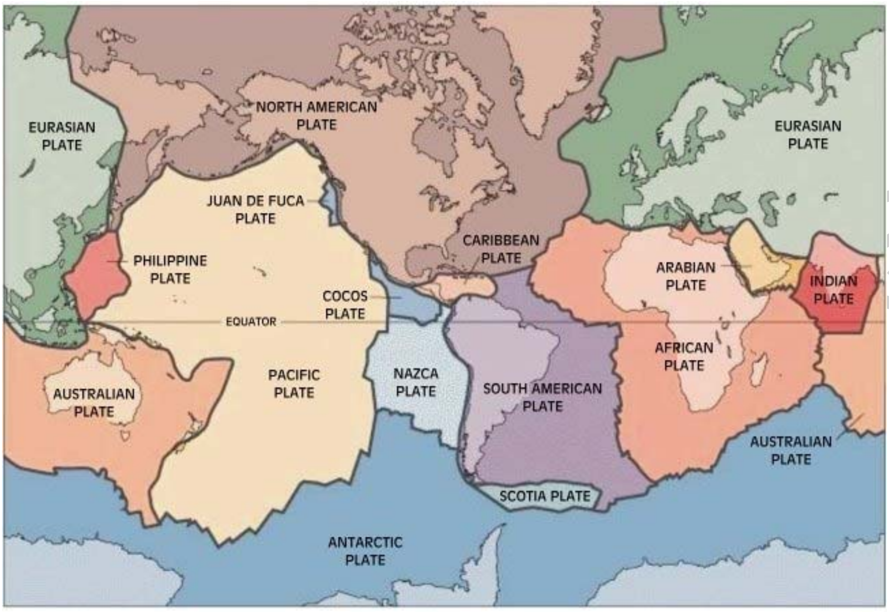

Figure. 2. Lithospheric plates of the world (from theme contribution "Internal forces and their influence on Earth's surface," written by D. Plasienka)

Planetary geology: The Apollo program, other astronomical projects and meteorite studies have helped us to understand the early development of the Earth from meteoritic material and some of the catastrophes the Earth underwent. Large meteorites have produced large craters upon collision with the Earth's surface. Meteorite impacts can cast significant quantities of material into the atmosphere. Molten blobs become streamlined in their passage before solidifying into glassy objects called tektites. Large quantities of dust would cause significant cooling and even some mass extinctions. The general features of the Earth's lithosphere, atmosphere and hydrosphere evolution can be comprehended only when compared to the other planets that "froze" in their early stages of development while the Earth experienced cycles of changes. The discovery of a "deep and hot" biosphere (that is, bacterial communities living in the fractured zones and rock pores several kilometers under the surface of the Earth) suggest on the other hand the possibility that extraterrestrial life could exist in subsurface zones of Mars, the Jovian satellite Europe and perhaps in other parts of our solar system. While the planetary sciences cast new light on terrestrial processes, study of the Earth can open up some cosmic perspectives as well. We have known since the times of Copernicus (1473-1543) and Galileo Galilei (1564-1642) that the Earth is not the center of the Universe but until recently we were not aware how minutely our big neighbor - the Universe itself - has affected some of the Earth's processes including life and climate.

Paleoclimatology: Paleoclimatology is the study of climate prior to the period of instrumental measurements. The state of the climate varies with time. The findings of glacial debris at tropical latitudes, or equatorial fossils in the arctic zone, puzzled scientists because only two explanations were possible—at the time of deposition the continent lay elsewhere or had different climatic conditions. Instrumental records span only some 200 years or less and the vast climatic past must be deduced from rock strata. Only when the causes of past climatic fluctuations are understood will it be possible to understand present changes or even to anticipate future climates. The science of global climatic and environmental change was born in the last few decades, and we know now that the climate and environment varied in the geological past more than was ever supposed. The Quaternary era that we live in is one of the periods of greatest change in the Earth's history. We recognize at least 26 major ice ages that have occurred during the last 2.7 million years, and even the individual ice ages themselves consist of a long and complex series of climatic oscillations. We should be aware that during an abrupt climatic change the mean annual temperature may drop or rise some 10 ^{o}C within 50 years, as happened several times during the last ice age.

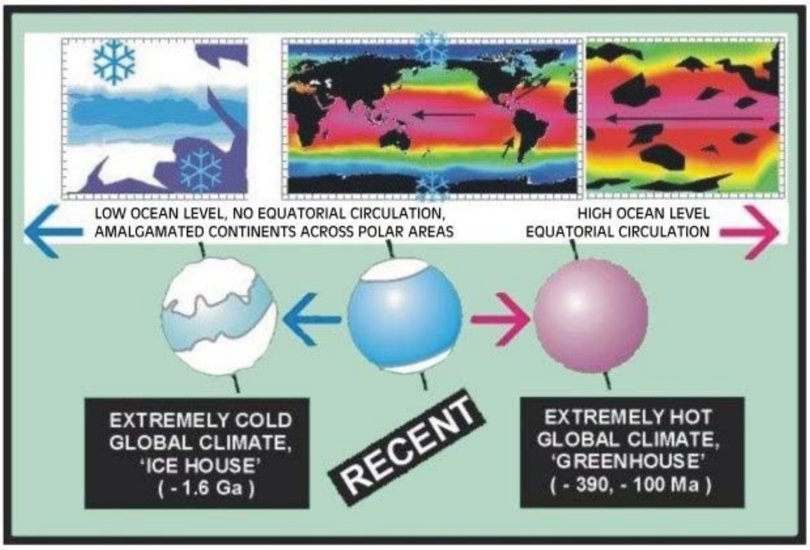

Figure. 3. The warm mode (examples: 390 and 100 million years ago) and the cold mode (example: 1.6 billion years ago) of the Earth system (from theme contribution "Past global crises," written by J. Hladil)

History of life: when we ask the familiar question "what are we and what will we become?" we usually have in mind the idea that "we are more or less what we were". We may call this tradition, roots or our biological origin but the answer is instead that we are the sum of all previous influences, inventions and reorganizations. Paleontology or paleobiology has, during the last two centuries, supplied us with a constant flow of facts and ideas about the milestones of evolution, our potential and the selective forces of nature. One of the most fascinating fields of research deals with life's ability to maintain quasi-stable climatic and atmospheric conditions in the Earth system, and with the reactions of life to catastrophes.

Investigation of crises in the past is connected with fairly new disciplines and its conclusions are sometimes controversial. However, five major mass extinctions in the Earth's history are strongly expressed in the fossil record and cannot be overlooked. These unusual extinction events lasted between 0.5 to 3.5 million years. They can be characterized by diverse environmental catastrophes, for example cataclysmic climate changes, sea-level drops and oscillations, huge volcanic eruptions, increased number of collisions with large meteorites or comets. At least five major crises must be recognized in regard to the last 550 million years and the sixth mass extinction appears to be in progress at present.

Most important (and also most striking for our humanistic understanding of nature) is the fact that the biocrises are very probably necessary for sustainable evolution, as death is for life. A biosystem which is not refreshed by some biocrisis tends to be fragile and may collapse in the face of tiny, almost unobservable triggering causes. The paleontological record of crises shows that simple restoration (conservation *ad absurdum*) of ecosystems which are disappearing naturally might be no more effective than health care for an extremely aged patient. It may be effective in the short term, but we cannot be optimistic about the final outcome. If crises and extinctions are then so necessary for biological evolution, why do we try to avoid the revolutions and violent turmoils of human society? Are we not contravening the natural course of all living beings? While answers to such questions are beyond the reach of the natural sciences, culture and religion sometimes propose an alternative stance: the constitution of human society may mean a further evolutionary step whereby catastrophes may be, at least sometimes, being replaced by less violent conflicts on a more sublimated level. Voluntary self-regulation may be the remedy by which to divert some crises.

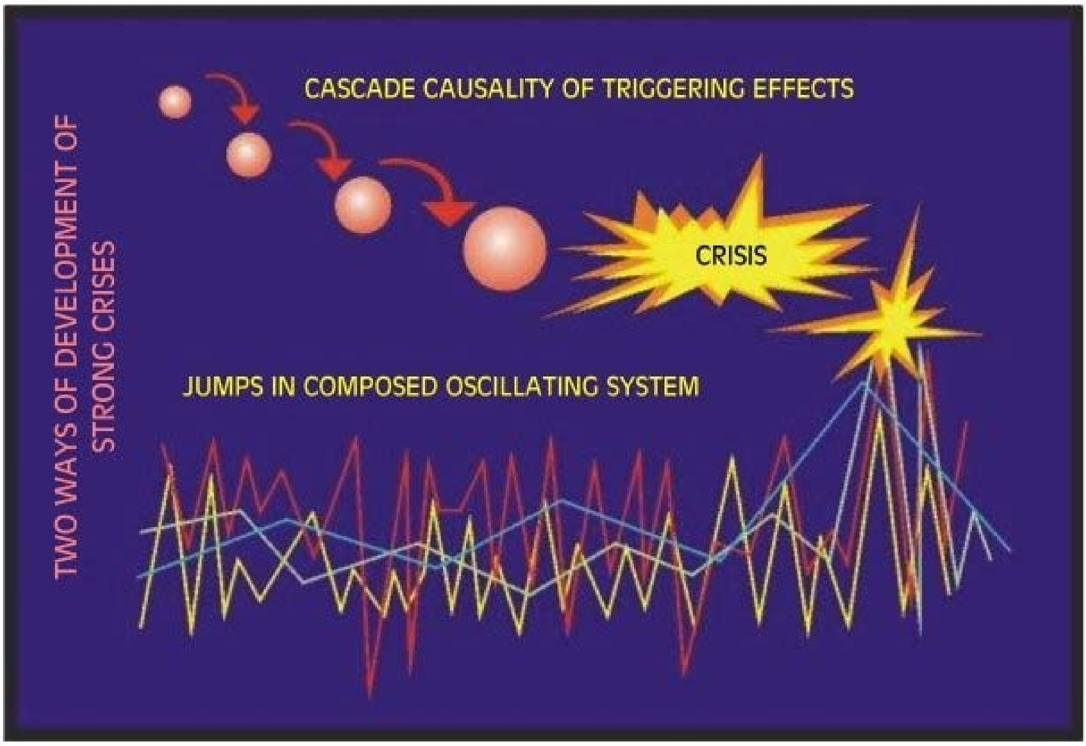

Figure. 4. Two forms of major paleoenvironmental crisis development (from theme contribution "Past global crises," written by J. Hladil)

2. Origin and history – The Earth Does not Stand Still

"Is this world to be considered merely as a machine … or as an organized body?"
James Hutton, 1785.

"Whether the causes of change do act uniformly; whether they oscillate only within narrow limits; whether their intensity in former times was nearly the same as it is now; these are precisely the questions which we wish Science to answer to us impartially and truly…" W. Whewell, 1847.

According to the solar nebula theory, the Earth and other planets in the solar system formed about 4.57 billion years ago by condensation of interplanetary dust. The Sun is a star that formed at the center of our solar system about 4.6 billion years ago. Compared to other stars in the heavens, the Sun is a rather mediocre star and is referred to as a "Yellow Dwarf".

The primordial Earth was a hostile environment, with its thin primitive crust, abundant volcanic activity and extra-terrestrial impacts. Since that time, however, the planet has evolved from its tumultuous origins to a relatively benign modern world capable of supporting diverse ecosystems. The evolutionary process has been dominated by slow progressive change involving ongoing interaction between solid earth, air, water and life. However, there is increasing evidence that rapid global change occurred in narrow time intervals and that progressive evolution was also punctuated by catastrophic events that are best represented in the geologic record as mass extinctions.

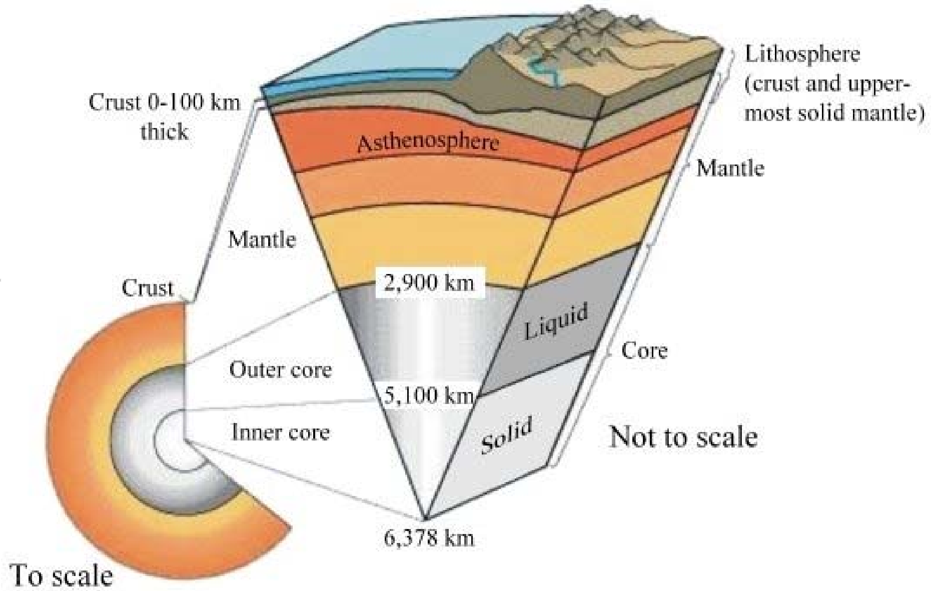

Figure 5. The internal structure of the Earth (from theme contribution "Internal forces and their influence on Earth's surface," written by D. Plasienka).

As the inner portion of the solar system cooled, small objects called planetismals formed. These objects collided with one another, and grew into protoplanets. One of these protoplanets evolved to become the Earth. Calculations indicate that the Earth's principal layers, the core, mantle and crust, formed within 20 million years of the planet's formation. The earliest atmosphere, consisting of hydrogen and helium, was lost and was replaced by an atmosphere generated by volcanoes that was dominated by water vapor, with subordinate amounts of carbon dioxide, carbon monoxide, sulfur dioxide, sulfur, chlorine, nitrogen, argon, hydrogen and no oxygen. Water vapor accumulated in the atmosphere, and turned to rain as temperatures cooled. This stripped water vapor and soluble gases such as carbon dioxide from the atmosphere. The solid Earth evolved from the primitive crust in the Hadean and early Archean eons to one which had many of the attributes of modern crust by the end of the Archean. The contrast in densities between continental and oceanic crust allowed water to accumulate in regions we now call ocean basins. The oldest marine sedimentary records indicate that oceans (and therefore the hydrological cycle) had originated by about 4 billion years ago.

The origin of life is controversial and hypotheses include the effects of lightning storms in the atmosphere, the utilization of energy adjacent to deep-sea vents, seeding from extra-terrestrial impacts (panspermy), and the formation of organisms in inter-tidal pools. Life originated early in the Archean, in the form of organisms interpreted as prokaryotes. Prokaryotes are single-celled organisms that lived in anaerobic environments and were only capable of asexual reproduction. The oldest widely accepted examples of these organisms occur in rocks that are 3.5 billion years old. As life began to proliferate, oxygen produced by photosynthesis was initially consumed by iron-rich ocean waters, which absorbed the oxygen to produce iron-rich minerals, preserved in the record as banded iron formations.

The late Archean crust consisted of granite-gneiss complexes and greenstone belts. During the Proterozoic, continents and continental shelves grew from smaller Archean nuclei to the large-scale continents of the modern era. Much of the geological history of the Late Proterozoic and Phanerozoic is influenced by the formation and dispersal of supercontinents. This includes the formation and destruction of oceans, and the distribution of mountain belts, earthquakes and volcanoes. By about 2 billion years ago, the rate of oxygen production by photosynthesis exceeded the ability of ocean waters to absorb it, and free oxygen entered the atmosphere. The presence of free oxygen in the atmosphere is supported by the sudden abundance of red continental sedimentary deposits. The resulting environmental crisis initiated a mass extinction. By 1.8 billion years ago, eukaryotes evolved that could exist in aerobic (oxygen-rich) environments. Eukaryotes were the first living forms capable of sexual reproduction.

The geologic record suggests that a supercontinent, known as Rodinia, formed about 1.0 billion years ago. About 760 million years ago, Rodinia began to fragment and the Pacific Ocean formed when Australia, Antarctica and India separated from ancestral North America, which is known as Laurentia. Towards the end of the Proterozoic, the oxygen content in the atmosphere reached at least 2%, and an ozone layer formed providing organisms with some protection from ultraviolet radiation. As ecological niches expanded, organisms became more numerous and diverse. A controversial hypothesis, called the Snowball Earth hypothesis, proposes that at various times between 750 and 580 million years ago, there were rapid oscillations in climate with average surface temperatures varying from $-50\ ^{o}C$ to $+50\ ^{o}C$. These intense climatic changes are believed to have been caused by the carbon cycle. Carbon in the form of carbon dioxide was either released as a powerful greenhouse gas in the atmosphere (resulting in the warm mode) or removed from the atmosphere and deposited in limestones (producing the cool mode).

By the end of the Proterozoic, life was relatively prolific in marine environments, and at the dawn of the Paleozoic, the first shelly fossils appeared. The fossil record of subsequent eras is far superior to that of the Proterozoic. The Paleozoic Era spans the fragmentation of a Late Proterozoic supercontinent, and ends 245 million years ago with the amalgamation of Pangea. In the Ordovician, marine life included corals, bryozoa and jawless fishes called ostracoderms. The increased protection afforded by the ozone layer allowed the colonization of land by plants and animals, such as amphibians (particularly due to luxuriant plant growth). Reptiles evolved from, and then out-competed the amphibians. By the end of the Paleozoic, the decomposition of prolific plant life in oxygen-deficient environments led to the formation of widespread coal deposits. The end of the Paleozoic era was accompanied by a mass extinction event that is most commonly attributed to the loss of habitat as Pangea amalgamated, and to enhanced volcanic activity. Marine life was more profoundly affected, with 90% of all marine species becoming extinct.

At the beginning of the Mesozoic, Pangea began to break up and the generation of continental shelves allowed surviving species to occupy the new ecological niches. Reptiles, including dinosaurs, ruled the land and sky, and flourished in the relatively warm climates. As land plants progressively diversified, herbivores and carnivores became more established. The mass extinction at the end of the Mesozoic is most popularly attributed to the fall-out of an extra-terrestrial body. Mammals were the chief beneficiary of the demise of the dinosaurs, and one family of mammals, the hominids, ultimately evolved to produce *Homo sapiens*, modern humans.

The climate deteriorated during the Tertiary period in several waves. Modern biota replaced the former species. Several important orogenetic phases caused the faulting and uplift of the Himalayan belt, the Alps, the Andes and other mountain ridges. Humans began to evolve in the late Tertiary some five million years ago. A controversial but interesting question concerns environmental changes as the possible cause of human evolution. Some of the main environmental crises such as the beginning of the Quaternary ice age cycle coincide with milestones in the evolution of *Homo sapiens*.

With regard to the future of the Earth, the geological record indicates that life in some form will survive on Earth as long as the supply of energy to the Earth's surface is maintained. There are two main sources of this energy: an internal source related to the Earth's own heat content, and an external source, solar energy. Heat flow measurements at the Earth's surface reveal that heat is escaping from the Earth into the atmosphere. This implies that the Earth is cooling down. Over geologic time heat loss has occurred continuously, but also in a concentrated fashion during volcanic eruptions. The Earth's heat was primarily generated during its formation, and the only additional modern heat source comes from radioactive decay. However, the heat production from current radioactive decay is only 12% of that in the primitive Earth. Nevertheless, radioactive decay today powers convection of the Earth's mantle, which in turn drives plate tectonics. Once this heat supply is insufficient, plate tectonics will cease, and the planet will follow the fate of Mars and become geologically dead. Calculations suggest that this will happen in about 4-5 billion years' time.

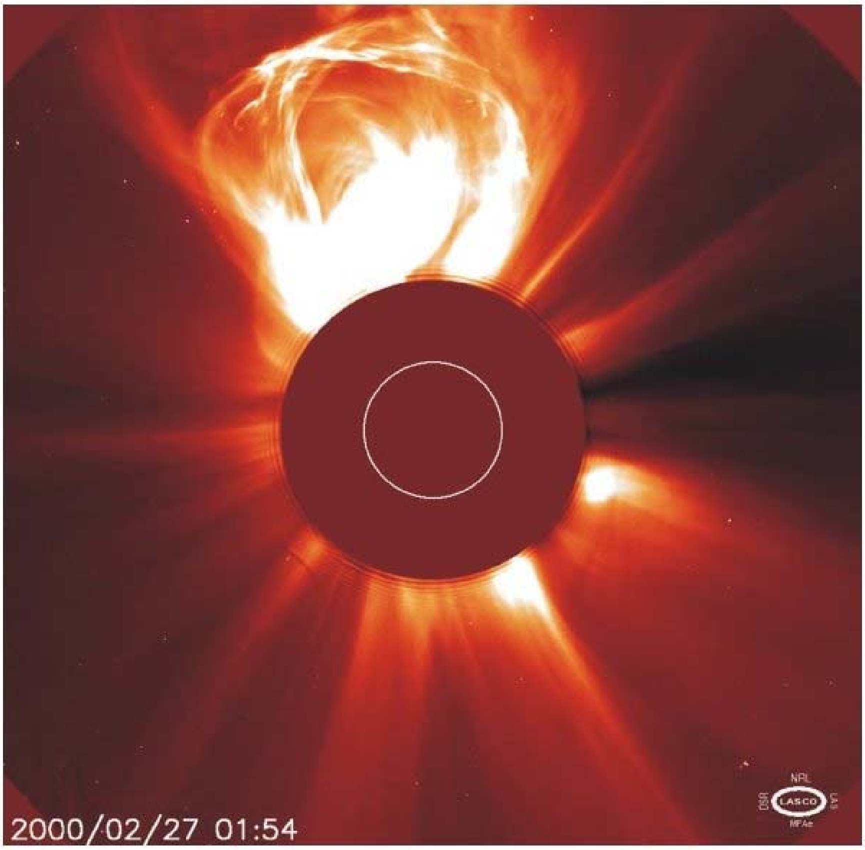

Figure. 6. The only significant external source of energy for the Earth system is the Sun. Even small variations in solar irradiation may cause vast climatic changes (from theme contribution "History of Sun," written by P. Kotrc).

The study of the Earth's history contributes to our knowledge and understanding of the world in several basic areas:

- **Mineral resources.** Geology originally developed as a practical science primarily involved in the discovery, extraction and processing of mineral resources such as fossil fuels, metals, groundwater and non-metallic raw materials.
- **Operational limits of the Earth system.** Paleoenvironmental, paleoecological and paleoclimatic studies demonstrate the diversity of the relationships among different parts of the Earth system, namely between life and the environment. They help mankind to understand the limits of the Earth system in order not to overstep them.
- **Geological hazards.** Different geological hazards such as earthquakes, mudflows and landslides can be deduced from local geological history. The consequences of climatic changes are recorded in rock strata.

- **Nature of time.** The geology of the nineteenth century helped us to perceive time as something vast, full of changes and thus challenging. It helped us to recognize past geological catastrophes and to predict some of the consequences of environmental changes.
- **Cultural and spiritual meaning.** The observation of the ever-changing, majestic face of the Earth has inspired numerous works of art. Confrontation with the Earth's grandeur may fill us with awe, respect and at the same time with caution and a concern not to affect the world we depend on too deeply.

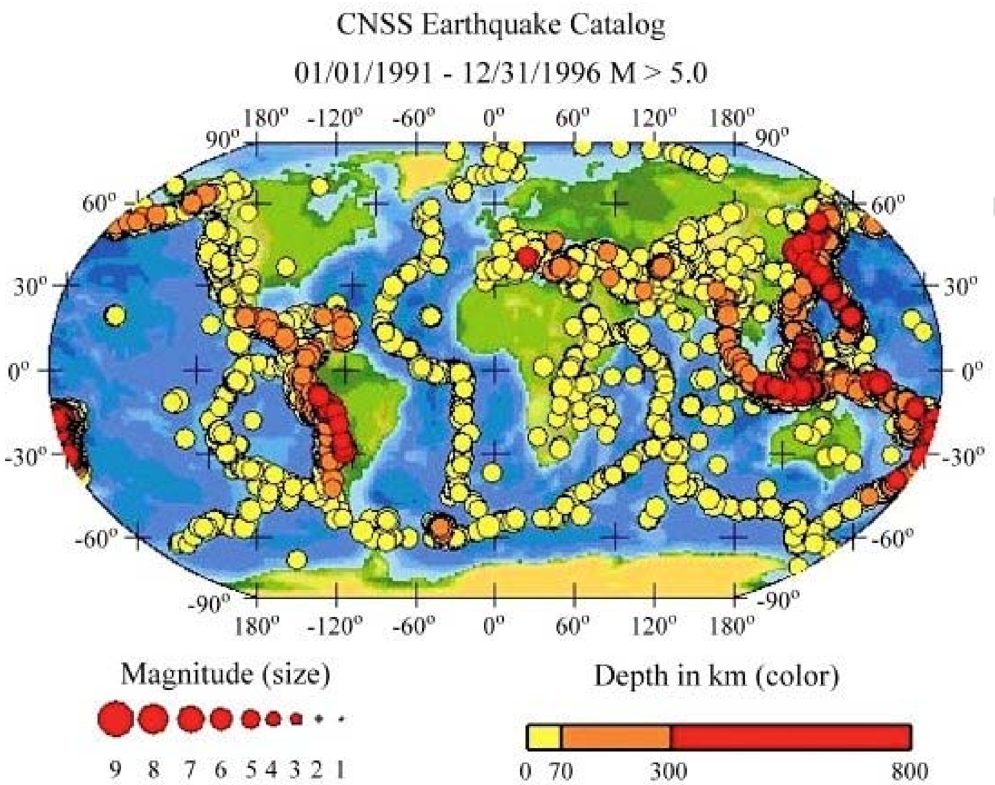

Figure. 7. The distribution of earthquakes, one of the major geological hazards, over the world (from theme contribution "Internal forces and their influence on the Earth's surface," written by D. Plasienka).

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Biographical Sketches

Vaclav Cilek studied in years 1970-74 Mining Institute in Pribram, then he joined the Department of Economic Geology of Charles University in Prague where he studied uranium deposits of Czech

Republic. However when coming in 1980 to Institute of Geology of the former Czechoslovak Academy of Science he was asked to cooperate in Interkosmos Programme that was primarily involved in the study of lunar rocks brought by Russian satellites. He spent much of his free time in caving and karst research and the study of karst infillings brought him finally in 1990 to Quaternary geology. He is principally interested in environmental changes and climatic oscillations in Holocene and in several last glacial cycles. V. Cilek teaches the courses on what he calls "Cultural geology", he is the author of about 240 papers, he participated in about 28 books including two textbooks concerning mostly the environmental topics such as atmosphere protection and landscape evolution.

Rachel H. Smith Ph.D. in the Department of Linguistics, University of Cambridge, UK, where her main area of research was the role of fine phonetic detail in spoken word recognition. She received her B.A. in Modern and Medieval Languages from the University of Cambridge in 1998, and her M.Phil. in Linguistics in 1999. She has also spent time working in Prague, Czech Republic, as a teacher of English and editor/proof-reader.