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# Earth's layers, their cycles and Earth system science

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## Abstract

Masses in the Earth's physical layers are in constant convective motion, the fluid envelopes driven by energy from the Sun, the solid Earth driven by energy from radioactive decay and primordial energy. The layers form a system of interactive components because mass and energy are continuously transferred across layer boundaries. Earth system science treats the Earth as an interactive system, thus offering a platform for collaboration of the subdisciplines of geoscience and for teaching Earth science to a broader public. Recent advances in quantifying rates and volumes of the various convection cycles have shown that prediction in the geosciences also greatly benefits from the Earth system approach. Timing of volcanic eruptions, location of subsurface resources or earthquake-prone areas, as well as past and future evolution of the climate system greatly benefit from an approach that simultaneously examines all relevant components of the Earth system. Geoscientists should strive to be recognized as experts of the system Earth analogous to physicians as experts of the human body.

Die Massen in den physischen Lagen der Erde sind in ständiger, konvektiver Bewegung, in den fluiden Hüllen getrieben durch Sonnenergie, in der festen Erde durch Energie aus der Ur-Kondensation und aus Kernzerfall. Ständiger Austausch von Masse und Energie verbindet die Lagen zu einem System interaktiver Komponenten. "Earth system science", die Wissenschaft vom System Erde, bietet ein Rahmenkonzept für alle geowissenschaftlichen Disziplinen und für die Darstellung der Geowissenschaften nach aussen, in den Schulen und in der Öffentlichkeit. Auch die Vorhersage geologischer Phänomene wird erleichtert durch den Erdsystem Ansatz, vor allem durch die jüngsten Fortschritte bei der Quantifizierung von Raten und Volumina in den Stoffkreisläufen. Vorhersagen über den Zeitpunkt von Vulkanausbrüchen, die Ortung von Rohstoffen im Untergrund, die Abgrenzung von Erdbebenzonen, oder Vergangenheit und Zukunft des Klimasystems – sie alle gewinnen durch die gleichzeitige Betrachtung aller relevanten Komponenten des Erdsystems. Geowissenschafter sollten sich profilieren als Experten des Systems Erde, so wie die Ärzte die Experten des Systems Mensch sind.

## 1. Introduction

Like most scientific disciplines, geoscience (or geology in the broad sense) is a child of the Enlightenment, with the publication of Hutton's "Theory of the Earth" in 1788 as the approximate birth date. Curiosity about the functioning of the natural world and the desire to understand its workings has been a prime driving force in our science. However, besides curiosity-driven geoscience we now see an increasing demand from society to not only describe and understand but also predict natural processes on Earth. For instance, to predict the location of hydrocarbons and ores in the subsurface or to predict catastrophic events in the form of earthquakes, floods or volcanic eruptions. Yet another task for looms on the horizon: prediction of humanity's growing impact on the natural environment requires input from geosciences. In addition, we need to convey essential knowledge about our planet to the public at large as a basis for democratic debate on important decisions in this area.

On the following pages, I argue that both tasks, the step from description to prediction as well as the responsibility to reach out to the public, are best performed in the context of Earth system science.

The layering of the solid Earth and its fluid envelopes was well recognized by the end of the 19$^{th}$ century. It was also known that the surface ocean and the lower atmosphere were in convective motion. However, the processes of the Earth's interior were essentially terra incognita. When Eduard Suess wrote the first synthesis of the regional geology of the Earth (Suess, 1888-1909), he intuitively grasped the significance of certain fundamental patterns - for instance, the difference between ocean margins of the Atlantic type where the bounding continents are fragments of a larger entity, and the Pacific type with its island arcs. However, knowledge of geodynamics was so rudimentary that Suess could only speculate about the forces that deformed the solid Earth, created mountain chains and ocean basins. The concepts of continental drift (Wegener, 1915) and plate tectonics (Hess, 1962; Isacks et al. 1968) largely closed this gap of knowledge and established convective motion also for parts of the solid Earth. The concept of Earth system science emerged in the 1970's, in the wake of plate tectonics and space exploration. Garrels and Mackenzie (1971) were among the first to clearly depict the layered Earth as a system of interacting components, albeit without using the term. The expression "Earth system science" became common in the 1980's, when studies of Earth from space documented the interaction among the outer layers and life in particularly impressive ways. Like many common terms, Earth system science is used with slightly different connotations. The original connotation refers to the entire planet from the core to the atmosphere as the Earth system (e.g. National Research Council, 1993, p.16); other users emphasize the climate-controlling components, i.e. atmosphere, ocean and the surface of the solid Earth including the biosphere (e.g. Asrar et al., 2001). In this report, Earth system science is used with its original connotation.

If one focuses on Earth's physico-chemical aspects, as I will do here, one may view the Earth as an assembly of layers, or spheres, formed by differentiation of the primordial planetary matter under the influence of gravity. In all layers except the inner core, masses are in convective motion. Motion in the outer fluid envelopes is driven by radiative energy from the Sun, motion in the inner layers by energy from radioactive decay and by primordial energy left over from the condensation process. The layers are not isolated from one another. Mass and energy are continually transferred across layer boundaries and the cycling within layers and interaction among layers form the basis for viewing the Earth as a system of interacting components. Chemical indicators, such as isotope ratios, are powerful tools for unraveling the cycles. However, the widely used term "geochemical cycling" should not distract from the fact that the principal driver for the mass movements are gradients in temperature and density.

The physico-chemical cycles and their feedbacks drove conditions at the surface of the solid Earth into a range that allowed life to evolve. Once present, organisms strongly influenced the conditions on Earth and the "biosphere" became important component of the Earth system even though it is not a physical layer.

In the past two decades, Earth system science has gained added dimension because quantitative understanding of the cycles improved to a point where the Earth's layers and their cycles frequently provide the framework for improved quantitative prediction in geoscience.

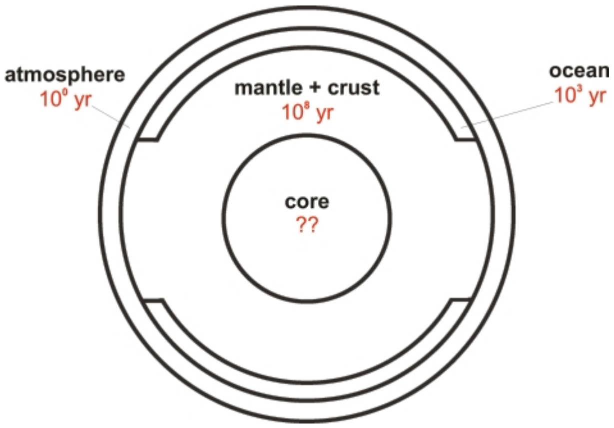


**Figure 1:** Cartoon of the physical layers of the Earth that constitute the framework for this overview. In all layers except the inner core, masses are in convective motion but the velocity of the cyclic motions differ many orders of magnitude. Red numbers – characteristic time necessary for a parcel of mass to complete a large cycle in the respective layer. Further subdivision of the indicated layers is possible but not essential in the present context. The notion of layers or "spheres" has also been extended to conceptual entities such as biosphere or anthroposphere not shown here. See text for discussion of "biosphere".

This article, then, describes the most important layers and their cycles, presents examples of geologically demonstrable interaction among layers, and finally discusses geoscientific prediction in the context of Earth systems science. All these topics are dealt with briefly and in introductory fashion. The cited references are far from exhaustive but they should be sufficient to guide interested readers to more detailed sources. Wherever possible, I referred to publications written for a broader public rather than the specialist.

## 2. Earth's physical layers and their cycles

The masses that condensed into our planet about 4.65 billion years ago soon differentiated into layers of different density under the influence of gravity. Fig. 1 shows the most important layers in cartoon-like fashion. Several aspects of this diagram merit mention. (1) Only physically identifiable layers are shown. Terms such as biosphere, anthroposphere etc. are conceptually useful but they cannot be defined as physical layers. (2) Even the pattern of physically identifiable layers is greatly simplified. Crust and mantle (and their respective subdivisions) are combined, because they closely interact in the same circulation system. (3) The ocean forms a discontinuous layer; consequently, atmosphere and solid Earth have a broad interface that represents the preferred habitat of our species. A brief overview of the cycles in the various layers is given below.

### 2.1 Atmosphere

Fig. 2 is a classic photo by the Apollo mission. The (mostly turbulent) motion of the atmosphere is visible in the cloud cover, particularly the eddies of the low-pressure cells. Cloud patterns and the colors of the continents reflect the major climate belts of the Earth: the tropical zone with speckled clouds of numerous thunderstorms and green vegetation; the two subtropical desert belts with few clouds and brown soil colors; south of the southern desert belt one recognizes the temperate climate zone with swaths of clouds indicating large frontal systems and finally the polar zone with largely clear skies over the Antarctic ice sheet. These basic climate belts are the result of two processes: (1) Solar radiation decreases from the equator to the poles and (2) the lower atmosphere forms six circulation cells, three per hemisphere, in response to the differential irradiance by the Sun. These circulation cells, commonly called Hadley cells, extend around the Earth in E-W direction and are responsible for the alternation of dry and wet climate belts at the Earth's surface (e.g. Open University Course Team, 2001). Wet climate develops where the dominant air motion is upward, desert belts form where air motion is downward. The arrows in the figure indicate only the movement in cross section. Viewed in three dimensions, the air also moves westward. The result is a spiral motion of air masses in each circulation cell.

The Hadley-cell circulation is overprinted and distorted by monsoon winds driven by the differential heating of land and sea. Monsoons are seasonally reversing winds that are most pronounced where large and high land masses lie adjacent to warm seas, e.g. around southeastern Asia.

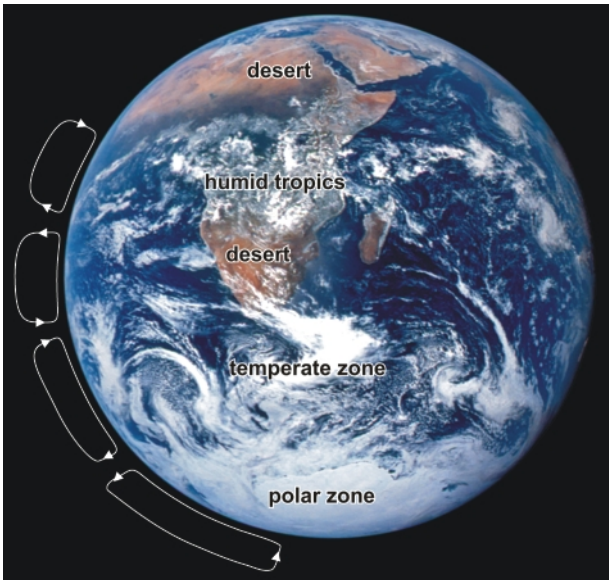


**Figure 2:** Circulation patterns of the atmosphere and climate belts at the Earth's surface can be deduced from this classic photograph of NASA's Apollo 17 mission. Cloud patterns and colors of the surface of Africa and Arabia show climate belts that extend latitudinally around the globe. They are related to circulation cells ("Hadley cells") in the lower atmosphere. Four cells are shown schematically and with great vertical exaggeration on the left. Wet climate belts in the tropics and temperate latitudes are characterized by numerous clouds and dark vegetation on land; they correspond to rising air streams of the Hadley cells. Subtropical desert belts have few clouds and show brown colors of the Earth's surface; scarcity of clouds of the dry south-polar zone is masked by the white color of the Antarctic ice sheet. Dry climates correspond to sinking air streams of the Hadley cells. (Globe image courtesy of NASA Johnson Space Center, Apollo 17 mission, Dec. 7, 1972).

There is strong evidence in the geologic record that the climate belts resulting from the Hadley-cell circulation were a common feature at least during the Phanerozoic (Scotese et al., 1999; Flügel et al., 2002). The fundamental nature of the Hadley cells is underlined by the fact that the atmosphere of Venus shows an analogous circulation pattern, albeit somewhat modified by the much slower rotation and thus smaller Coriolis effect on this planet (Svedhem et al., 2007).

## 2.2 Ocean

The ocean is not further differentiated in Fig. 2. However, the surface ocean also shows large circulation patterns overprinted by local cyclonic and anticyclonic eddies, analogous to the high and low pressure cells in the atmosphere (Fig.3). The surface circulation is complemented by a slower deep circulation that connects all major ocean basins and combines them into one global ocean circulation system (Fig. 4). At present, this circulation is mainly driven by density differences caused by differences in temperature. The cold bottom water is provided by the northern Atlantic and by the ice shelves of Antarctica. However, there were times in Earth history when salinity differences played a more important role in global ocean circulation (e.g. Brass et al., 1982; Hay, 1988).

## 2.3 Crust and Mantle

In the past 40 years, it has become clear that Earth's crust and mantle jointly participate in wide-ranging convection, the surface expression of which is plate tectonics. The motions are much slower than the circulation of ocean and atmosphere and thus not directly perceptible to the human eye. The crucial information that led to the discovery of this motion of the solid Earth is the geologic record. Fig. 5 shows the age pattern of the basaltic ocean floor – a pivotal piece of evidence for long-term movements of the solid Earth. Other compelling arguments for convection in the solid Earth are the movement of continents as indicated by paleomagnetic signals in their sediment cover and the tectonic and paleogeographic evidence for break-up and collision of continents. Most recently, space-based positioning systems started to directly measure the contemporary movement of tectonic plates (e.g. Prawirodirdjo et al., 2004). The results agree well with the geologic records.

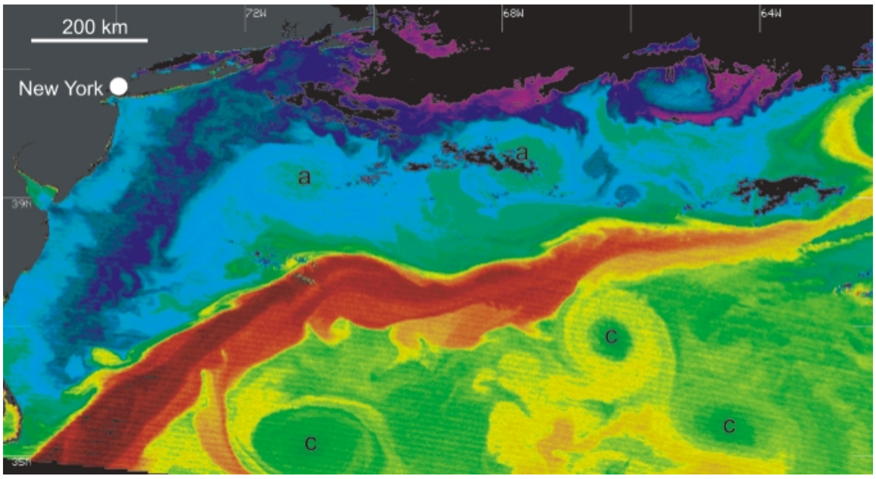


**Figure 3:** Surface circulation of the Atlantic Ocean E of the USA. Colors of surface water temperatures (red – warm) reveal a major surface current, the Gulf Stream, accompanied by spiral eddies on both sides of its main flow path. Eddies marked "c" rotate counter-clockwise and are analogs of cyclonic depressions in the atmosphere. Eddies marked "a" rotate clockwise and correspond to anti-cyclonic (high-pressure) systems of the atmosphere. (Image courtesy of Rosenstiel School Marine & Atmospheric Science, Univ. of Miami, Miami, Florida, USA).

Fig. 6 shows the plate-tectonic pattern in depth. It is based on mantle tomography, i.e. the threedimensional reconstruction of mantle properties from the observation of seismic waves by a global network of earthquake monitoring stations. Fig. 6 shows that the relatively cool Pacific crust that was subducted under America during the last 100-120 Myr extends almost to the core-mantle boundary. Similar patterns from the western Pacific confirm some subduction zones extend almost all the way to the core-mantle boundary.

Consequently, the plate motions observed at Earth's surface are part of a convective motion that mixes the entire crust-mantle domain. This does not imply, however, that all subducted plates extend to this depth. There is strong evidence that some subduction motions are blocked by shallower discontinuities (e.g. Wortel and Spakman, 2000; Faccenna et al., 2007).

Volcanic "hot spots" are the surface expression of another mixing process that affects mantle and crust. Hot-spot volcanism (e.g. Hawaii) is caused by plumes of exceptionally hot magma that rise, like columns of smoke in calm air, from great depth through the mantle to the Earth surface. Experimental mineralogy strongly suggests that these plumes originate near the core-mantle boundary (Duffy, 2008).

Mantle convection seems to be driven by heating from the core and by heat sources within the mantle caused by the inhomogeneous distribution of radioactive isotopes, especially $^{40}K$, $^{232}Th$, $^{235}U$, $^{238}U$ (e.g. Fowler, 1994).

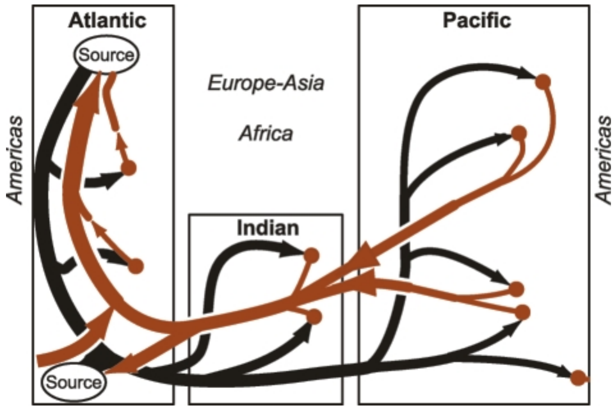


**Figure 4:** Deep circulation of the world ocean. Three major ocean basins represented by boxes, approximate position of major land mass indicated by their names in italics. Deep-sea currents (black arrows) flow from source areas in the N Atlantic and around Antarctica into all major basins. Water rises to the surface in upwelling areas (red dots) and returns to the source areas via surface currents (red arrows). (Schlager, 2005, modified after Broecker and Peng, 1982).

## 2.4 Core

Earth's core is inaccessible and poorly known. Geochemical arguments indicate that the core does not, or only to a minimal extent, participate in the convective motion of the mantle and crust. However, it is highly probable that the core donates heat to the mantle and thus partly drives mantle convection (Fowler, 1994). There is strong, albeit indirect, evidence that the outer core has a convection system of its own. The argumentation is largely based on observations of the Earth's magnetic field and runs as follows: (1) The field must originate in the core because the mantle contains too little ferromagnetic materials. (2) The changes in intensity and polarity of the field indicate that it cannot be caused by a permanently magnetized part of the core. (3) The field most probably is generated by electrical currents via the principle of a self-exciting dynamo; convection currents in the outer core seem to be the only possible mechanism to generate and maintain electrical currents (National Research Council, 1993; Fowler, 1994).

## 2.5 Biosphere

The biosphere differs fundamentally from the layers discussed above. It is not a well-defined physical layer but a conceptual "sphere of influence". The term was created by Eduard Suess as "the place on Earth's surface where life dwells" (Suess, 1875). For geochemists, the biosphere represents the total biomass on Earth, i.e. the sum of all biota.

The biosphere is very important for Earth system science, even though it is not a physical layer. There is abundant evidence that the conditions at the surface of the Earth are the result of the interaction of the physical Earth and its biota. The "Gaia hypothesis" (Lovelock and Margulis, 1974; Lovelock 2003) even postulates that Earth's biota, atmosphere, oceans and the physical land surface form a system that functions like an organism. The Gaia hypothesis may be controversial but there is broad agreement on the important contribution of life to the present conditions at the Earth's surface. It is also widely accepted that future climate change will be governed by the interaction of physico-chemical and biotic processes.

## 2.6 How fast do the layers circulate?

The velocity at which masses move in the various layers differs by many orders magnitude. Moreover, the speed of circu-

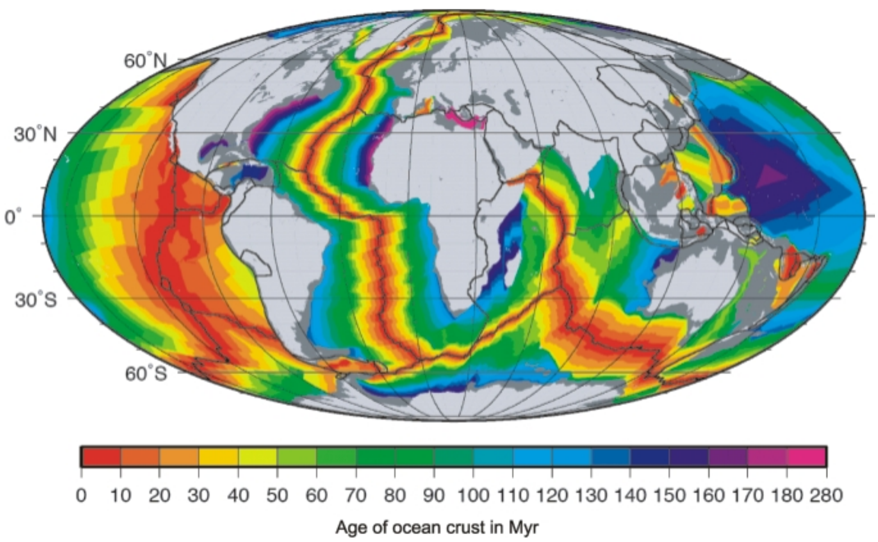


**Figure 5:** Ocean crust (colored according to age) and plate boundaries (black lines). Ages indicate that ocean crust originates at the spreading ridges and moves from there to the subduction zones where it is consumed. This pattern is a surface expression of convective motion in the mantle. In all three major oceans, the oldest crust has an age of about 150-180 Myr (Jurassic); the much higher age shown for the eastern Mediterranean is rather speculative (Müller et al., 2008).

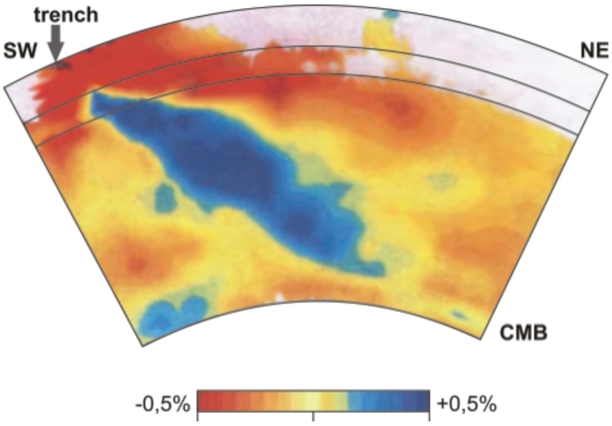


**Figure 6:** Velocity of seismic pressure waves in crust and mantle along a SW-NE section from the eastern Pacific, across Central America to the northwestern Atlantic. High velocities (blue) indicate relatively cool (subducted) material in the mantle. Note NE-dipping high-velocity zone in the extension of the present subduction zone, the Middle-America trench, at the surface; this zone probably represents Pacific crust subducted during the Cenozoic and probably Cretaceous. Subducted material extends close to the core-mantle boundary (CMB), supporting the concept of mantle-wide mixing. The apparent lack of connection between the present trench and the high-velocity zone in the mantle is caused by the large cell-size required for the calculations of deeper-mantle anomalies; regional studies using smaller cells and focusing at shallow depth clearly reveal the connection between active trench and deeper-mantle anomaly (Van der Hilst et al., 1997).

latory motion within each layer varies considerably in space and time. Thus, exact measurements of the velocity of mass movement in the various layers may only be of local significance but the principal differences among the layers are important characteristics of the Earth system. Below follows a brief summary for each layer. The estimates are crude but they suffice to show that the times required to complete a major cycle in the various layers differ by many orders of magnitude.

*Atmosphere.* Weather systems usually last for weeks and months ($10^{-2}$ – $10^{-1}$ yr). However, ashes from large volcanic eruptions as well as materials from nuclear tests have been shown to take several years to settle back down, implying a maximum cycling time in the range of $10^{0}$ yr (e.g. National Research Council, 1993; Kerr, 1994).

*Ocean.* The eddies and loops of surface circulation last somewhat longer than atmospheric weather systems but the deep circulation is orders of magnitude slower. The residence time of a water parcel in the deep circulation of Fig. 4 is in the range of 250 - 1000 years, thus in the $10^{2}$-$10^{3}$ yr domain (Open University Course Team, 2001, p.239).

*Crust-Mantle.* The rate of convection of this layer can be estimated by plate-tectonic reconstructions. The oldest segments of basaltic sea floor still preserved in situ are of Middle or Late Jurassic age. This means that the longest paths of parcels of basalt from creation at a spreading ridge to destruction in a subduction zone take about 160-180 Myr. If one assumes that the residence time in the hidden part of cycle, i.e. melting at depth and resurgence in a spreading ridge, is similar, then the characteristic duration of a loop in mantle convection would be on the order of $10^{8}$ yr. However, there is some indication that the invisible part may be in the $10^{9}$ yr range (e.g. National Research Council, 1993, p. 56).

*Core.* It seems that the information on the core presently is insufficient to justify an estimate.

This brief overview shows that the residence times of material in a typical circulation loop range from months or years in the atmosphere to hundreds of millions of years in the solid Earth. The great differences in circulation velocity are an expression of the fact that the layers are rather well defined physical entities. However, the layers are by no means isolated entities as pointed out above. We live at the intersection of solid Earth, ocean and atmosphere and directly witness the exchange among these three layers. Similar interactions, albeit at a slower pace, also occur among the components of the solid Earth in the deep subsurface. Life processes in the lower atmosphere, the ocean and the upper parts of the crust affect and modify this physical system.

## 3. Examples of connections or interactions among layers

### 3.1 Spreading ridges as ion exchangers

The spreading ridges represent a chemical connection between the ocean and the crust-mantle layer of the solid Earth. At the ridge crest, cold seawater comes in contact with hot lava and basalt. The result is a very efficient hydrothermal circulation system: cold seawater is sucked into the porous basalt on the ridge flank, it heats up, reacts with the basalt and is finally expelled in hot hydrothermal vents at the ridge crest (Fig. 7). On its way through the basalt, the water alters the rock, losing magnesium and sulfate, gaining potassium and chloride in the process. Thus the spreading ridges act as an ion exchange device. As the world's spreading ridges are over 60 000 km long and sea-floor spreading is a geologically rapid and continuous process, the chemical reactions significantly affect the

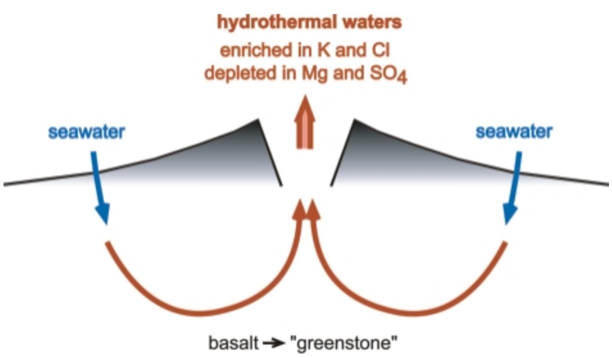


**Figure 7:** Spreading ridge as ion exchanger. Interaction between hot basalt and cold seawater leads to thermal convection whereby cold seawater enters the crust at the ridge flank and is expelled as hot hydrothermal brine at the ridge crest. Basalt and seawater react such that the water becomes depleted in magnesium and sulfate ions and enriched in potassium and chlorine. During times of rapid seafloor spreading these reactions run faster and change seawater chemistry. The change in seawater chemistry, in turn, is reflected in the mineralogy of calcareous fossils and the chemical composition of evaporites (Stanley and Hardie, 1999, modified).

composition of sea water. During times of accelerated sea-floor spreading, seawater has been richer in potassium and chlorine and lower in magnesium and sulfate than at present. Consequently, potash evaporites became enriched in KCl and depleted in $MgSO_4$; concomitantly, the mineralogy of carbonate-secreting benthos changes from predominance of magnesian calcite to pure calcite plus aragonite (Hardie, 1996). The experiment in Fig. 8 elegantly demonstrates the connection between water chemistry and skeletal mineralogy of a red alga.

The intensive hydrothermal circulation at the spreading ridges also creates important sulfidic ore deposits.

### 3.2 Plate tectonics and ocean circulation

As the ocean is not a continuous envelope over the surface of the solid Earth, the influence of surface relief of the solid Earth on ocean circulation is profound because land barriers completely block ocean circulation. The surface circulation of the ocean is driven predominantly by the Hadley cells of the atmosphere (see Fig. 2). The Hadley cells will induce globe-circling currents if no N-S barriers oppose them. If extended N-S landmasses are present, the oceanic surface currents will be bent into large circular currents called gyres. At present, gyres are dominant. However, plate tectonics has re-arranged this pattern numerous times and the sediment record indicates that the ocean has responded by switching from gyres to globe circling currents and vice versa. For instance, the only globe-circling current of the modern ocean, the circum-Antarctic current, was created in the Cenozoic by the opening of the Drake Passage between Antarctica and South America (Kennett, 1982).

### 3.3 Mountain building and climate

The connection between plate tectonics and ocean currents is unidirectional in the sense that plate tectonics moves the continents and causes the ocean currents to change.

For a long time, the interaction between mountain building and climate was believed to represent a similar chain of cause and effect – plate tectonics, driven by mantle convection, created the mountains and atmospheric circulation and precipitation patterns adjusted to the changing relief. The recent advances in measuring rates and timing of the relevant processes have drastically changed this view (Allen, 2008). There is mounting evidence for feedback also in the other direction. For instance, climate strongly influences rates of erosion and these, in turn, may determine the location of anticlines and their rate of deformation; erosion rates may even determine whether an orogen forms a bundle of subparallel mountain ranges or develops large plateaus, such as Tibet or the Altiplano in the Andes (e.g. Garcia-Castellanos, 2007). The subdiscipline of "tectonic geomorphology" systematically pursues these topics.

### 3.4 Earth's magnetic field and life

The magnetic field is an example of the effect of the Earth's core on the conditions in the outer layers. The magnetic field deflects the "solar wind", a constant stream of ionized particles from the Sun. The field is strongly deformed by the solar wind but it remains intact in the vicinity of the Earth. Several effects on life and its evolution have been proposed, among them protection of the Earth's surface from the high-energy particles of the solar wind and influence on prebiotic chemical reactions (Rochette et al., 2006). In connection with the present search for life on Mars it is worth noting that this planet presently lacks a magnetic field but probably had one during its early history.

### 3.5 Anthropogenic greenhouse effect

Another topic that benefits from analysis in the context of Earth system science is humanity's burning of fossil fuels. Our consumption of oil and gas disturbs the natural cycling of carbon between the Earth's crust and mantle and her fluid envelopes. Fig. 9 illustrates the situation. Most carbon of plants and animals is rapidly re-oxidized when the organisms die and subsequently recycled within the ocean or the soils of the solid Earth (Berner, 1999). In this way, the carbon moves in rapid cycles with characteristic residence times of $10^0$-$10^3$ yr. However, a small fraction of organic carbon is buried in sediment on the sea floor, escapes rapid oxidation and joins the slow plate-tectonic cycle of the solid Earth with a characteristic residence time of $10^8$ yr (Berner, 1999). This organic matter becomes part of the fill of sedimentary basins and a significant part diagenetically matures to hydrocarbons. The natural way to recycle these accumulations is by orogeny, uplift and surface erosion. Humanity is short-circuiting this multimillion-year process by extracting much of the Earth's hydrocarbons, burning them and pumping the resulting carbon dioxide into the atmosphere on time scales of $10^1$-$10^2$ yr. Even though the total

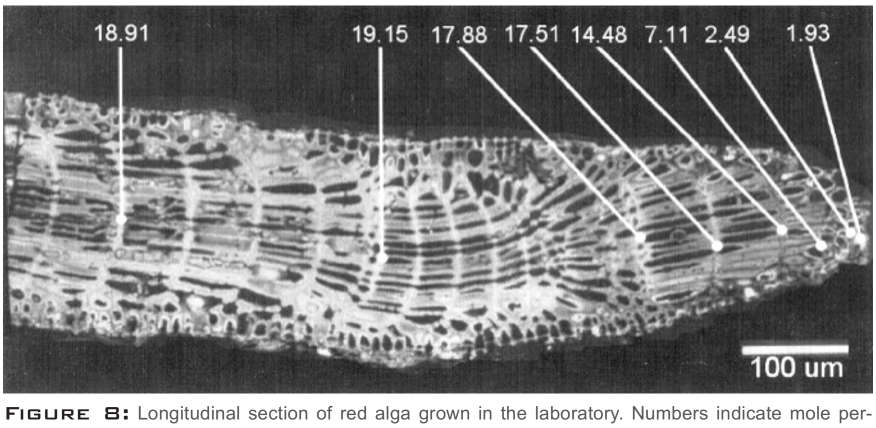


**Figure 8:** Longitudinal section of red alga grown in the laboratory. Numbers indicate mole percent of magnesium substituting for calcium in algal skeleton. Alga changes skeletal composition from magnesian calcite to pure calcite as seawater composition is changed from present day values to values inferred for the Cretaceous (Stanley et al. 2002; reprinted with permission from National Academy of Science).

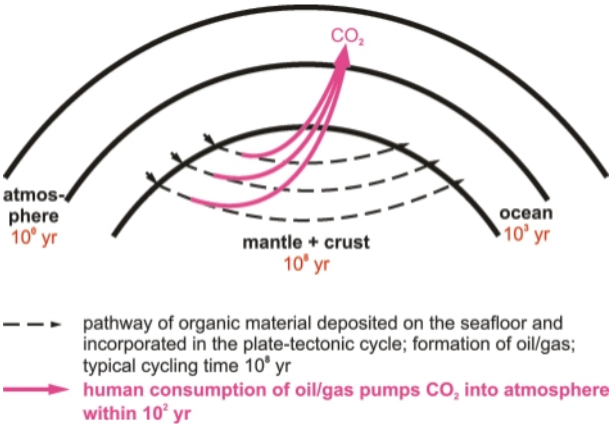


**Figure 9:** In the context of Earth system science, the anthropogenic greenhouse effect amounts to a short-circuit in the natural carbon cycle. In this cycle, carbon in organic remains is buried with other sediment at the seafloor and slowly moves through the crust or mantle as part of the plate-tectonic cycle with a typical residence time on the order of $10^8$ yr. Carbon returns to the surface by tectonic uplift and erosion. Modern industrial societies short-cut this slow cycle. They extract a significant amount of this organic matter in the form of oil and gas, burn it and pump the resulting carbon dioxide into the atmosphere within few hundred years.

mass of burned hydrocarbons is minuscule compared to the total sediment mass of the Earth, the effect is substantial for three reasons: First, we transfer the carbon into the atmosphere, the Earth layer with the smallest mass; second, the product of human interference, $CO_2$, has a large effect on the heat budget of the atmosphere; third, the atmosphere has the shortest cycling time and is the only layer that mixes on a human time scale of months and years. The consequence of these effects is that humanity is creating for itself a global problem of yet unknown proportions.

The word "unknown" in the last sentence above is not quite correct. There is broad consensus among scientists that we have begun to measurably change the temperature at the Earth's surface. However, the changes are small and human beings have a natural tendency to linearly extrapolate trends. This may be a very misleading simplification because of the highly non-linear nature of the climate system (see next chapter). Small, man-induced changes may trigger much larger responses in the natural system by letting the system cross a critical threshold. Gas hydrates may serve as an example. Under certain pressure-temperature conditions, methane and water in deep-sea sediments combine to form a solid substance, called gas hydrate. There are large volumes of gas hydrates under the ocean and they seal even larger volumes of free methane deeper in the sediment column (e.g. Mao et al., 2007). If the deep ocean water warms up, the gas hydrates may melt and release large volumes of methane that would quickly raise the temperatures at the Earth's surface (methane is a very strong greenhouse gas). Submarine landslides caused by melting of gas hydrates may release even more methane that would again quickly escape into the atmosphere. There is strong evidence that abrupt warming events in Earth history, for instance at the Paleocene/Eocene boundary, have been triggered by gas hydrates (Zachos et al., 2005). The anthropogenic greenhouse effect described above could again lead to this chain reaction.

## 4. Prediction in earth sciences

Prediction is an important task of all natural sciences and has been from the outset. Geologists, for instance, were required to make predictions about the inaccessible subsurface for exploitation of resource or underground constructions. In addition to these classic tasks, geoscientists increasingly participate in predicting future changes in the ocean-atmosphere system as humanity becomes aware of its own effect on the natural environment. Frequently, prediction in geoscience if is facilitated by conscientiously studying all relevant parts of the Earth system. Below follow some examples to illustrate this approach.

Before turning to examples of prediction in geosciences, two theoretical concepts must be mentioned – non-linear dynamics and self-organized criticality. Both concepts were developed by physicists but they are highly relevant for the geosciences, particularly for modeling and predicting natural processes.

*Non-linear dynamics and chaos.* With the advent of large computers in the 1960's it was discovered that the behavior of certain dynamical systems is extremely sensitive to initial conditions. These systems were deterministic, i.e. at any time only one thing could happen next, but did not look deterministic because their behavior could change drastically with minute chan-


**Figure 10:** Mount St. Helens (Washington, NW USA), a well-studied and continually monitored volcano in a subduction setting. Its recent eruptions have been predicted very successfully, including the catastrophic explosion in May 1980 shown here. (A) Mt. St. Helens on May 17, 1980. (B) Mt. St. Helens on May 18, 1980. Images by US Geol. Survey, Cascades Volcano Observatory, Vancouver, Washington, USA.

ges in initial conditions. Exact prediction of these systems requires infinitely precise knowledge of the initial conditions – an impossibility with natural systems. The name "*chaos*" was introduced for systems with this particular sensitivity to initial conditions. It was also shown that chaotic systems must be governed by non-linear systems of differential equations, i.e. systems of equations that do not exhibit a linear relationship between disturbance and effect. Thus the entire branch of system analysis became known as non-linear dynamics (Lorenz, 1993; Hergarten, 2002).

*Self-organized criticality (SOC).* While the concept of chaos has evolved gradually since the 19th century, the concept of self-organized criticality was introduced as a well-formulated hypothesis in one step, few decades ago (Bak et al. 1987). The hypothesis stipulates that many natural systems evolve by slow external forcing and numerous internal feedbacks and thresholds to a critical state, comparable to the critical point of thermodynamical systems, e.g. water at the freezing point. A classical example of SOC is a pile of dry, loose sand supplied from above. It will pile up in a cone and steepen its slope to the critical angle. In this condition, the addition of just one more grain will trigger avalanches of a wide range of possible sizes. The size distribution of these events will obey a power law with the largest events being the least likely. The output of SOC systems is a series of events resulting from the interplay of slow outside forcing and internal feed-backs. The concept has been used to explain the occurrence of earthquakes, landslides, turbidites and other phenomena in the geologic record (Bak, 1996; Jensen, 1998; Hergarten, 2002).

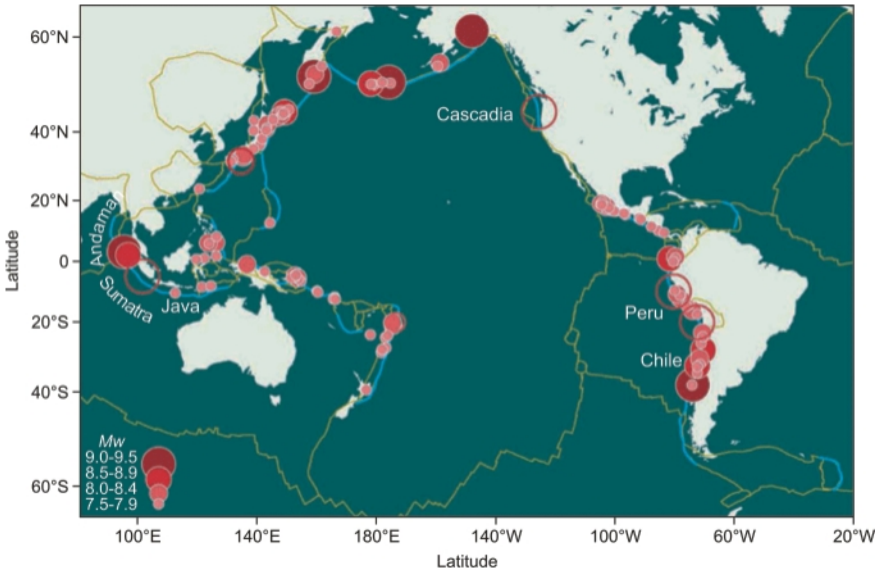


**Figure 11:** Subduction zones are areas of high earthquake risk as demonstrated by this compilation of large, subduction-related earthquakes in the Pacific and eastern Indian Ocean. Blue curves - subduction zones; light brown lines - other plate boundaries; filled circles - earthquakes of magnitude 7.5 or larger since 1900 at subduction zones; open circles - inferred largest earthquakes from 1700-1900 (incomplete sample). Prediction remains difficult but Earth system science contributes significantly to localizing the principal earthquake-prone areas. Note that most Californian earthquakes are not shown because they are related to a transform fault, not a subduction zone. (From McCaffrey, 2007; reprinted with permission from American Association for the Advancement of Science).

### 4.1 Volcanic eruptions

Predicting volcanic eruptions is, of course, a high-priority objective in all populated areas. There has been significant progress in the past halfcentury. A prominent example is Mount St. Helens in the northwestern USA (Fig. 10) where the eruptions of the past three decades have been very reliably forecast. A common denominator of this and other successful examples is the multidisciplinary approach and the broad scope of the work. Mount St. Helens is covered by a network of observation points, providing continuous measurements of the microearthquake activity, temperature and surface deformation. These data have been complemented by detailed documentation of the eruption history from the geologic record and by careful analysis of the plate-tectonic setting.

### 4.2 Earthquakes

Timely prediction of earthquakes turns out to be far more elusive than prediction of volcanic eruptions. To date, no reliable precursors have been identified and there are strong indications that earthquakes may be an example of self-organized criticality, analogous to the avalanches of Per Bak's sandpile. If this is so, then prediction of individual earthquakes would be virtually impossible (Bak, 1996). However, even for earthquakes the Earth-system approach bears fruit. Plate tectonics is rather successful in localizing the areas of frequent strong earthquakes. Particularly dangerous is the ring of subduction zones surrounding the fast-spreading ridges in the Pacific and the eastern Indian Ocean (Fig.11). This prediction is based on knowledge of the rates of subduction as well as the thermal regime in the lithosphere. Further mitigation of earthquake damage within the danger zones indicated by plate tectonics is being pursued in two ways: (1) Detailed measurements during earthquakes provide rapidly growing knowledge about the mechanics of the process that can be translated into appropriate building codes. (2) Early warning systems are based on the principle that electronic signals travel faster than ground waves of the earthquake itself, providing time for emergency measures (Yamamoto et al., 2008).

Tsunamis are a potentially devastating side effect of earthquakes. Consequently, advances and problems of earthquake prediction directly affect the prediction of tsunamis – with one crucial difference: the tsunami lies further downstream in the chain of events that starts with the rupture of a fault in the lithosphere; this fact considerably increases the time difference between the arrival of a warning message and the arrival of the tsunami wave itself. Consequently, warning systems against tsunamis can be expected to be more efficient than early-warning systems against earthquakes(e.g. Gonzalez et al., 2005).

### 4.3 "Petroleum systems" as a tool in hydrocarbon exploration

The triad of source rock, reservoir and seal was already recognized in the late 19th century as an essential prerequisite for the formation of oil/gas fields. This basic concept was steadily refined and in the 1990's the "petroleum system" became the conceptual framework for hydrocarbon exploration (Magoon and Dow, 1994). The petroleum-system approach takes the migrating fluids as the red line and attempts to quantitatively reconstruct all critical aspects of the relevant part of geologic history: the deposition of the source material, its maturation from organic-rich sediment to hydrocarbon-generating source rock, the migration path of the hydrocarbons through the overlying rocks, the formation of reservoir rock and seal, the process of hydrocarbon emplacement in the reservoir and, if applicable, its subsequent history of deformation and alteration. The task is formidable and requires quantitative insights into processes of sedimentation, organic and inorganic geochemistry and tectonics. The petroleum-systems approach reconstructs a particular chapter of Earth history in detail to predict location and quality of hydrocarbon accumulations in the deep subsurface. The exact architecture of the buried sediment bodies remains unpredictable because of the highly non-linear processes of sedimentation. However, prediction and visualization becomes possible by combining general sedimentation models with reflection-seismic images of the rocks in question (Fig. 12).

In closing, it should be mentioned that the "systems approach" guides not only the search for hydrocarbons but also the exploration for and exploitation of metallic ores. The advent of plate tectonics and the growing insights in the formation and gravitational differentiation of the Earth provided powerful concepts for genetic analysis and prediction of mineral resources (e.g. Blundell et al., 2005).

### 4.4 Source-to-sink studies of siliciclastics

Siliciclastic rocks constitute the largest fraction of the Earth's sediment mass. Unlike carbonate rocks or evaporites, the siliciclastic material is chemically very stable at the Earth's surface. Therefore, sediment mass is conserved on the way from the eroding hinterland to the ultimate resting place in the ocean. The source-to-sink approach to siliciclastic systems combines information on tectonics, sedimentology and stratigraphy with data on climate and oceanography. The approach again illustrates the trend in modern geoscience towards studying various phenomena as interacting components of a larger system (Allen, 2008). The results of this integrative approach are very promising. I illustrate them with two examples.

The 3000 km-long Ganges river system faithfully recorded climate changes during the late Quaternary (Goodbred, 2003). For instance, strengthening of the summer monsoon led to high rainfall and rapid erosion of the Himalayan catchment areas, to incision of the alluvial fans in the Himalayan foreland and to increase of deposition on the submarine Bengal fan. The climatic signals are being felt within few thousand years throughout the entire system.

Other studies reveal the stunning detail about the evolution of orogenic belts recorded in their associated sedimentary basins. The example of the Carpathians is particularly impressive in this respect because source areas in the rising orogen are very close to the depocenters and a wealth of data has been collected recently (Cloetingh et al., 2005).

### 4.5 Climate change

Climate change and our role in it may be the most formidable challenge facing humanity today. In terms of Earth system science, we are looking at interactions among atmosphere,

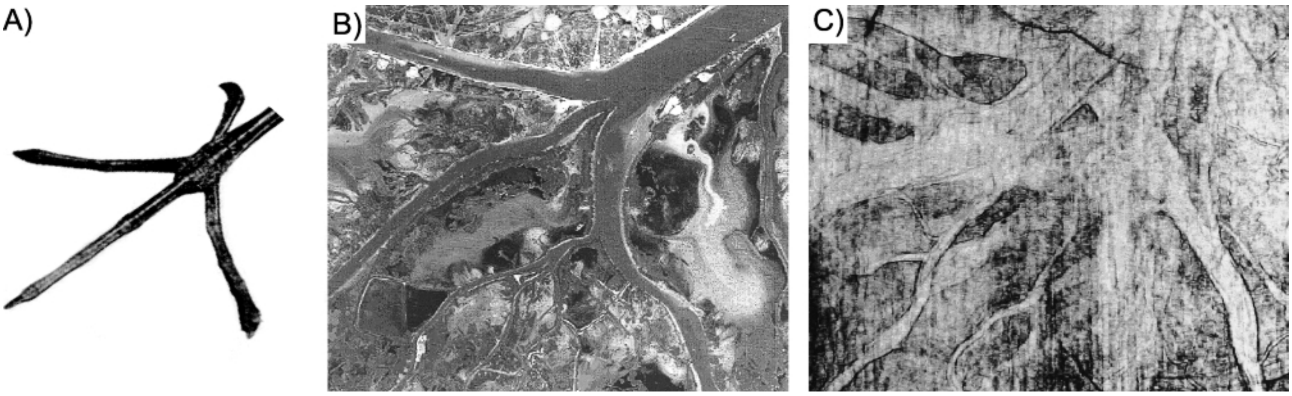


**Figure 12:** Prediction of sediment architecture in the subsurface is crucial for hydrocarbon exploration and many other human activities in the subsurface. Non-linear dynamics severely limits sediment prediction by forward modeling of processes but reflection seismics largely compensates for this shortcoming as illustrated here. A) Anatomy of real birdfoot is completely predictable if bird species is known. B) Birdfoot-like geometry of Mississippi delta may be predicted in principle from flow conditions of the river and the wave regime of the adjacent sea; however, the detailed geometry of the channel system remains unpredictable because of the highly non-linear nature of sediment transport and deposition. C) Subsurface prediction of detailed sediment architecture becomes possible by combining sedimentologic facies models with real images of reflection seismics. Shown here are channels in horizontal section of 3D seismic data (after Schollnberger, 1998; Schlager, 2000, modified).

ocean and the surface of the solid Earth. Classical geoscience can provide long-term records of environmental conditions on Earth, comparable to the medical anamnesis of a patient. These records have the advantage that they include many examples (for instance of rapid climate warming) as well as a wider range of conditions than humanity is likely to experience. All this helps with establishing a diagnosis and plan of action with regard to a system whose non-linear nature makes prediction by forward modeling rather unreliable.

Fig. 13 illustrates the use of the geologic record in the debate on anthropogenic climate change. The history of eustatic sea-level fluctuations of the past 600 kyr indicates that during two interglacials sea level had risen several meters above its present level. This observation strongly suggests that part of the extant ice mass on Earth is prone to rapid melting. Anthropogenic emissions of carbon dioxide may provide the extra push to melt this ice and induce rapid sea level rise of several meters. This scenario gains added weight from the observed variations of carbon dioxide. Over the past 650 kyr, atmospheric $CO_2$ concentrations varied approximately in the range 180 – 300 ppm and these variations closely paralleled fluctuations of sea level and temperature; since 1950, the $CO_2$ concentration has risen to 370 ppm (IPCC 2007, Fig. 6.3). This figure significantly exceeds the interglacial levels of the late Quaternary and puts the present concentration of carbon dioxide in the atmosphere and the size of terrestrial ice sheets far out of balance – further melting and concomitant sea-level rise seem virtually inevitable.

Another example is the role of scleractinian corals in the prediction of future climate change. Corals record temperature and other environmental parameters as variations of trace elements and isotope ratios in their calcareous skeletons. Many corals have annual growth bands comparable to tree rings. These annual bands and the rather precise radiocarbon age dates of the coral skeleton frequently provide environmental records with resolution of individual years or better. The coral record can be calibrated with instrumental measurements of the recent past and then extended hundreds of years into the past that is devoid of instrumental measurements. The technique has been used to predict the future trends of the Pacific's El Nino/ Southern Oscillation under the influence of anthropogenic climate change (Dunbar, 2000; Gagan et al., 2000).

## 5. Teaching Earth system science

The notion of the Earth as a system of interacting components is relatively easy to convey to high-school youth or other interested audiences. It relies on vivid and perspicuous models and images with only minimal recourse to abstract concepts. The amount of specific detail to be remembered can be kept far below what was required on the topic "Earth" during my days at high-school, 50 years ago, despite the enormous increase in knowledge. The reason for this seeming paradox is that Earth system science explains the functioning of the Earth by relying on few basic principles - gravitational pull to separate the materials according to density, thermal convection in each layer but with vastly different velocities etc. In this way, Earth systems science accomplishes two goals at once: it explains how the Earth functions now, for instance how the morphology of the Earth's surface relates to the driving forces in the interior, but it is also shows how the Earth has evolved. The latter is possible because the convection of the solid Earth is so slow that the present outline of most continents still shows

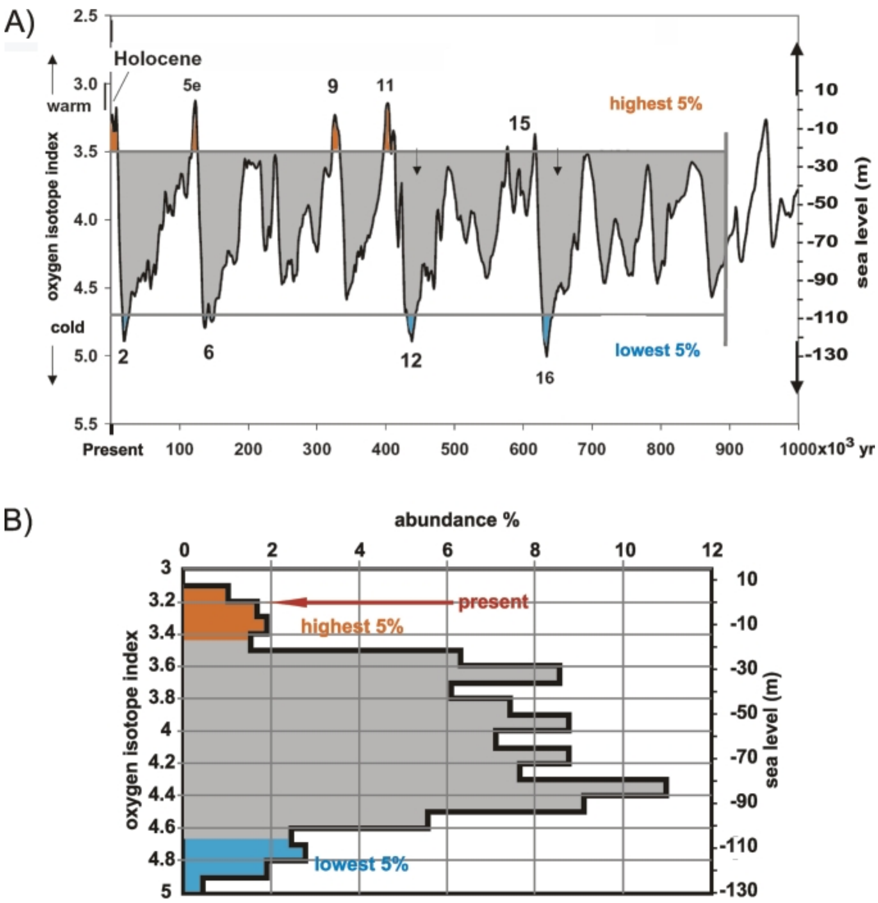


**Figure 13:** Eustatic sealevel fluctuations of the past 900 000 yr, reconstructed from oxygen isotope ratios ($\delta^{18}O/^{16}O$) of marine calcareous microfossils. (A) Sea-level curve shows that highstands comparable to the Holocene existed only for about 5% of time in the past 900 000 yr. (B) Frequency histogram of sealevel curve of (A) indicates that Holocene sealevel is high but not absolute top. It had been exceeded during two earlier interglacials, strongly suggesting that there currently exist ice sheets that may collapse and melt relatively quickly upon further warming. (Berger, 2008; modified).

how these masses originally fit together to form the supercontinent Pangaea some 250 Myr ago.

Teaching Earth system science in high-school would offer a joint introduction to the fields of physical geography and geology. However, a summary of Earth system science could also be offered to the interested public in evening courses or popular writings. The topic is urgent because of the intensifying public debate on climate change, environmental pollution and shrinking natural resources. Humanity's disturbance of the Earth system will continue to grow and this will not be without cost. The global strategies regarding climate change, pollution and resources should be based on democratic consensus of knowledgeable citizens. Teaching Earth system science in high-school and to the interested public may be an efficient step in preparing societies for the decision processes on these issues.

## 6. Medicine as a role model for Earth system science

Medicine is a system science par excellence. It relies on the fundamental sciences for most of its tools and theoretical underpinnings - X-ray or NMR scanners are pure physics, pharmaceuticals pure chemistry, - but people with health problems turn to the physician, not the physicist, for help. The reason is that the physician is perceived as the expert of the system "human body". Geoscientists need to conscientiously prepare themselves for the role of experts of the Earth system. Humanity now uses the planet so intensively that it needs scientific advice not only on finding and managing underground resources but also on predicting and managing the disturbances of the natural environment.

Geoscience should also take measure from medicine with regard to education. Medicine consists of highly specialized subdisciplines but it maintains an undiminished tradition of across-the-field education in general principles. This common ground of knowledge provides the basis for medical action in emergencies and for communication across the specialty fences. Recently, medicine has also started to educate not only its own professionals but the general public with regard to health hazards related to life style, such as smoking or obesity. Geoscience should follow on both counts. We should intensify our teaching of Earth system science as an integrative template for our discipline and get involved in the public debate about climate change, heeding the advice of Frank Press, a geoscientist who served as Science Advisor to a US President (Press, 2008): "The .... challenges that face humankind today mean that it is more essential than ever that Earth scientists apply their understanding of the planet to benefit society and that society invite them to do so."

## 7. Conclusions

- After a century of specialization, Earth system science rapidly emerges as a unifying concept in the geosciences.
- Gravitational pull has differentiated the Earth into layers (or spheres). In each layer masses convect but layer boundaries are leaky such that masses and energy are being transferred across them. In this way, the Earth becomes a complex system of interacting components.
- Prediction in geosciences, such as earthquakes, volcanic eruptions or occurrence of resources in the deep subsurface, is facilitated by tackling the problem in a broad context that includes all relevant components of the Earth system.
- Earth system science is a very advantageous platform for teaching because of the many unifying principles that hold it together, the vivid images and the relatively low level of required mathematics.

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