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Earth and Life -
origins of diversity

Earth sciences for society

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Prospectus for a key theme of the International Year of Planet Earth

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Earth Sciences for Society

What is this brochure for?

This brochure is a prospectus for one of the main scientific themes of the International Year of Planet Earth.

It describes, in accessible terms, why this particular theme has been chosen - why the research that the Year hopes to support under this theme is of such vital importance to our understanding of the Earth System, and to society at large.

The prospectus was written by a panel of world experts assembled by the Science Programme Committee of the Year.

To find out more...

To find out about the other research themes being pursued, please consult www.yearofplanetearth.org (where all our publications can be found).

What to do next...

If you are a scientist wishing to register initial interest in possibly making a research proposal under this theme, please go to www.yearofplanetearth.org download the appropriate Expression of Interest (Science) form, and follow the instructions on submitting this to the International Year.

Protecting the biosphere
is a responsibility of us all

Introduction

The biosphere is the "living sphere" of planet Earth. It is the most remarkable characteristic of our planet, and makes Earth unique within the planetary system. The evolution of life and biosphere began perhaps as early as 4.2 billion years ago, but by 2.7 billion years ago life had started to have a significant effect on the atmosphere, oceans, and lithosphere.

It is the joint aim of research by palaeontologists and biologists worldwide to understand the multiple factors that control the processes of life. This research includes insights into the functioning and stability of palaeo-ecosystems, understanding of biodiversity dynamics over long time scales, and predicting future biosphere vitality. All these topics are inextricably linked. They require palaeontologists, biologists, and Earth scientists to work together at local, regional and global scales. Protecting the present biosphere, both for the advance of human society and as humankind's natural heritage, is a responsibility of us all.

Sustaining a functioning global ecology is one of society's most pressing problems. If the biosphere fails to provide the nutritional and economic necessities of mankind, catastrophic scenarios may well emerge. Earth scientists understand both the abiotic (physico-chemical) and biotic processes that provide the background for the evolution of life. Palaeontologists are uniquely qualified to assess the life processes of the biosphere by looking back in deep time, evaluating the present, and eventually predicting the future. In this respect Earth scientists, palaeontologists and biologists are responsible to society for the four-dimensional (space and time) assessment of biodiversity and ecosystem vitality, a fact that explains the distinctive place held by biosphere research within the framework of the International Year of Planet Earth, and its relevance to the broader Earth-life system, the home of mankind.

The great biodiversity of planet Earth can be explained by its evolution during unimaginably long periods of time. The evidence of its evolution is to be found in the rocks and includes million- and even billion-year old fossils from various kinds of organisms, like bacteria, tiny algae, archaic plants, and ancient animals. At present, 2.7 billion-year-old fossilized algae are the oldest known evidence for life. These organisms were able to produce free oxygen, which did not exist in former ancient atmospheres. As a result, an oxygen-rich atmosphere began to develop some 2 billion years ago, early in the so-called Proterozoic Eon.

Who is behind the International Year?

Initiated by the International Union of Geological Sciences (IUGS) in 2001, the proposed International Year of Planet Earth was immediately endorsed by UNESCO's Earth Science Division, and later by the joint UNESCO-IUGS International Geoscience Programme (IGCP). The Year also boasts a large number of Founding Partner institutions, which are listed on the inside back cover.

The main aim of the International Year - to demonstrate the great potential of the Earth sciences to lay the foundations of a safer, healthier and wealthier society - explains the Year's subtitle: Earth sciences for society.

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Sustaining a functioning global ecology is one of society's most pressing problems

Evolution of life on planet Earth during the phanerozoic

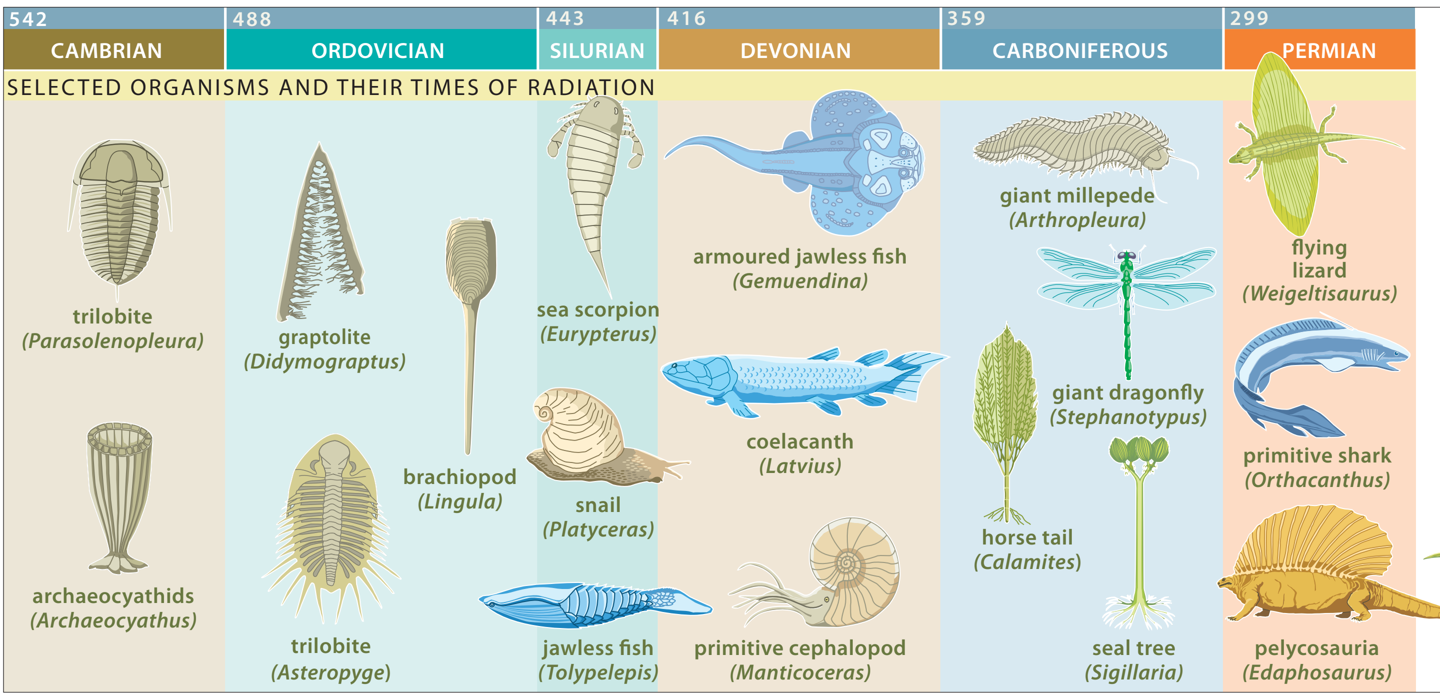
Illustration: Christian Eisenberg in co-operation with Paläontologische Gesellschaft

Paläontologische Gesellschaft

Algal and bacterial mats and mounds dominated life in the Proterozoic for about 2 billion years. It was "only" 600 million years ago that higher organised life of multicellular animals appeared. These animals are the famous Ediacara fauna, named for the Ediacara Hills of South Australia. They were exclusively soft-bodied, which means that they had no shells or any mineralized parts. Some resembled jelly-fish, some sea pens, while others were similar to worms; but many resist all attempts to place them as the rootstock of modern animals, and any attempt to lump them together as one coherent group is probably mistaken. Many Ediacarans probably represented life forms with no known descendants. However that said, they do represent the first experiments of multicellular animal life. The sudden appearance of the Ediacara after the 2 billion-year long era of algae may be related to the continuing accumulation of free oxygen in the atmosphere.

The major breakthrough of modern animal life was associated with the "Cambrian Explosion", starting 542 million years ago. The disappearance of the Ediacarans, the rapid development of complex skeletonised animals and the general acceleration of evolutionary tempo was related to the first appearance of burrowers and – most significant of all - predators. As a consequence of this, many animals started an evolutionary "arms race", and invented hard parts such as calcareous shells to protect themselves. However, once developed, hard parts allowed life to operate more actively with running, swimming, and actively hunting forms. The improved preservation potential of hard parts also gives palaeontologists additional clues to study life's diversification, adaptation and function.

Many spectacular organisms have evolved since then. During the Cambrian period (542-488 million years ago) life was restricted to aquatic environments. The earliest vertebrates lacked bony skeletons, but in the Ordovician thickly armoured fishes began to appear.



During several periods, mass extinctions crushed the diversity of life

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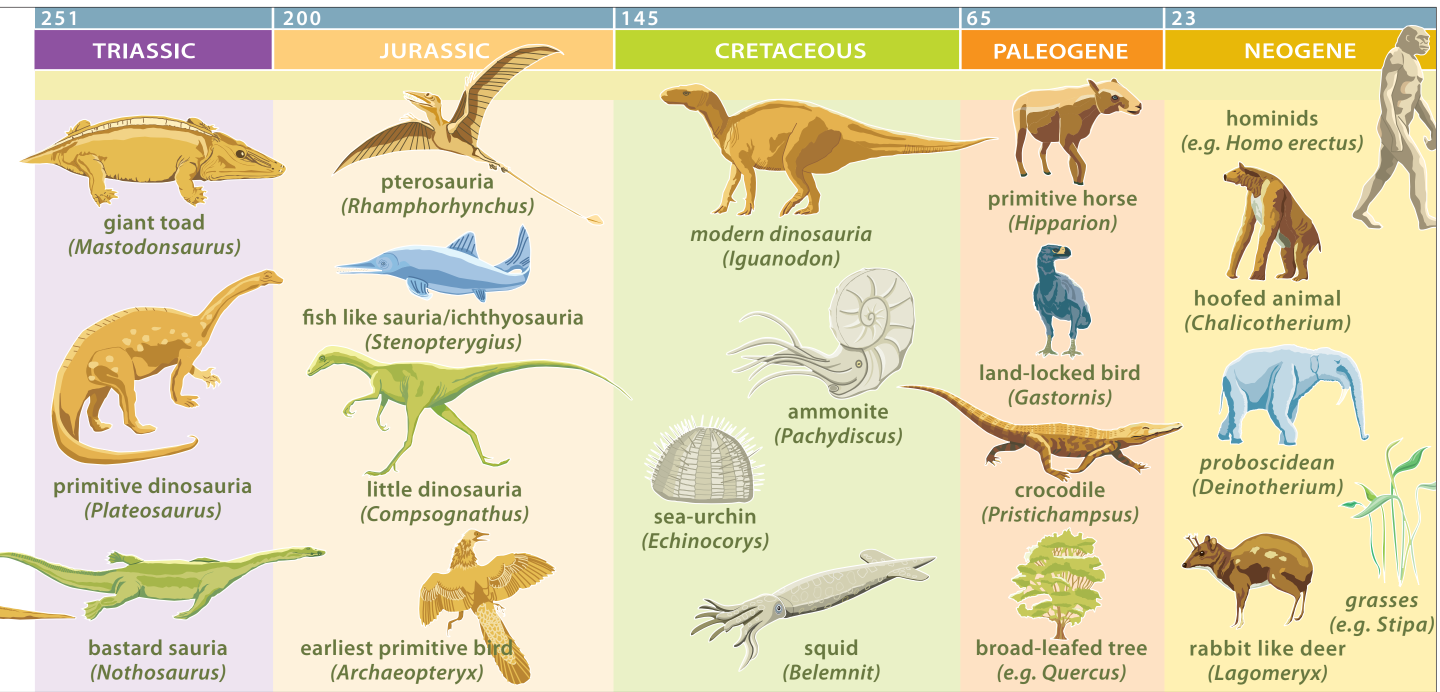
Fossil mammals (including a horse, top) from Messel Pit, Germany; a UNESCO World Heritage Site and the world's richest site for understanding the living environment of the Eocene (57 million to 36 million years ago).

Since then, the invasion of land was the next major evolutionary landmark. Plants first, then scorpions and millipedes, conquered the nearly barren land. Already by the Late Devonian, some 360 million years ago, ancient amphibians took their first steps on land. It is from these amphibians that all the modern tetrapods evolved, incorporating reptiles, birds and mammals. The latter originated in the late Triassic (210 million years ago). At this time they were mainly mouse and rat-sized nocturnal animals that had to avoid predatory dinosaurs and, as a result, evolved highly sensitive ears, eyes and noses, as well as improved intelligence.

All of these unique fossils and ancient organisms formed components of ancient ecosystems and thus were part of the ancient biosphere. Their interactions could accelerate processes of evolution, but could also lead to a breakdown of populations and ecosystems. During times of radiation, evolution occurred relatively rapidly and resulted in numerous new species due to the ability of species to occupy and even create new ecological niches. For example, during the Triassic, Jurassic and Cretaceous periods (251-65 million years ago) amazing events occurred, involving radiation of the dinosaurs, which evolved into the largest terrestrial carnivorous and herbivorous vertebrates that have ever lived on Earth.

Mass extinctions present a striking contrast to radiations. During several periods, mass extinctions crushed the diversity of life; perhaps within just a few thousands of years. Many groups of plants and animals never recovered (e.g. the dinosaurs at the end of the Cretaceous). The most catastrophic event happened at the end of the Permian, 252 million years ago, when about 90% of marine species and about 70% of the land-dwelling species died out.



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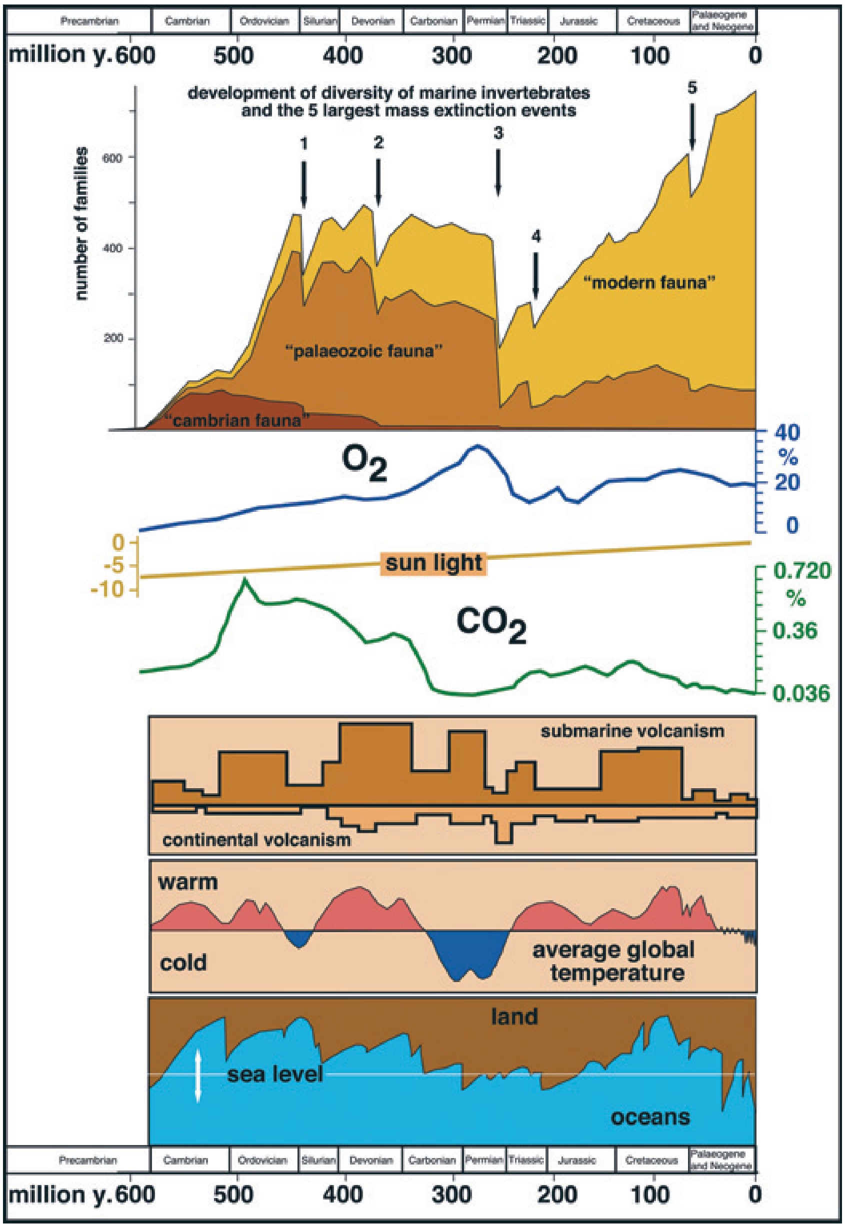
"Sustainable development"

The term 'sustainable development' came from opposition between those who supported policies preserving the 'sustainability' of the Earth's environment and those who advocated economic development. Environmentalists acknowledged that economic development was necessary (in part to avoid imposing the costs of environmental protection on those least able to afford them) but also because economic stagnation often reduces support for environmental protection efforts.

(continued...)

Five major and about ten smaller mass extinctions are known to have punctuated life's history. Roughly, they can be explained as resulting from dramatic environmental changes due to many factors: from delicate interactions of climate change, to plate tectonics, global levels of volcanism, sea-level rise and fall, changing biogeochemical cycles and periodic cataclysmic impacts from large asteroids or comets.

Development of marine invertebrate diversity, the five mass extinction events and possible interactions with volcanism, global climate and sea level fluctuations. Illustration: Wolfgang Oschmann, Frankfurt.



One major goal is to understand how human activities interact with those of the environment

Understanding biosphere dynamics

The *Earth & Life* scientific theme will focus on two key questions:

- How can we better understand the dynamic processes of the biosphere?
- How can our improved understanding help to achieve the sustainable health of the planet's life support systems – an absolute essential if human societies are to survive?

Scientific projects under the title *Past and Future Dynamics of the Biosphere* were recently outlined during the *World Conference on Palaeontology in the 21st Century*, held at the Senckenberg Museum in Frankfurt, Germany.

While some projects arising from that initiative have already begun, others are in urgent need of pursuit in the form of carefully designed projects. The International Year of Planet Earth will provide a new global platform for these research ventures, given that all of them demand a multidisciplinary approach by palaeontologists, biologists, and Earth scientists in co-operation with a broad range of other natural scientists.

One major goal is to understand, among the various factors responsible for biodiversity changes and crises, how human activities interact with those of the environment. Which effects arise from natural long-term variations and which from short-term human activities? This recalls similar problems concerning global warming including, for example, biotic activities as an important cause of CO_2 and NH_4 emissions [see also *Climate Change: the 'stone tape'* in this series].

Scientific projects dedicated to the questions outlined above will focus on six Key issues (see below). These projects can be carried out all over the world. The joint frame of the International Year, and the use of online databases, will ensure that data can be compiled and interpreted as a whole.

Palaeontological online databases are already available, especially for the marine record, such as the Paleobiology Database: http://paleodb.org and PaleoReefs Online: http://193.175.236.205/paleo/ (id = paleo, password = reefs). They enable scientists to collect together the scattered data of scientific research and make it available for everyone - even those without access to modern libraries. All in all, great expertise will be available at the end of the International Year. It will help us to understand and preserve the present-day biosphere, for maintaining a vital planet Earth, and for sustaining modern society.

Modern quantitative methods and analytical tools, but also new theories on the "big picture" of life's evolution are necessary for a better understanding of basic processes that shaped life on Earth. High quality research on the Key issue research projects requires the following multiple approaches:

Likewise, those who advocated economic development recognized a parallel between the protection of environmental endowments and the concept of protecting capital in a sustainable economy. A viable economy must live off its income without a net reduction in capital over time. Similarly, a population must live within the carrying capacity of its ecosystem, which represents a form of natural capital.

Outreach Programme

The Outreach Programme of the International Year is faced with a particular challenge of scale. With a potential $10m to spend, it is inconceivable that it could operate in a prescriptive way. No individual or committee can think of enough wise ways of spending such a sum globally. So the Outreach Programme will, like the Science Programme, operate as a funding body, receiving bids for financial support - for anything from web-based educational resources to commissioning works of art that will help reinforce to the general public the central message of the year. It will enable things to happen locally under the umbrella of an international scheme, lending profile and coherence.

A special Outreach Prospectus in this series (number 11) is available for those who are interested in applying for support.

The sedimentary rock record

reveals a succession of very

different environments

- **A precise temporal framework** through modern stratigraphical methods, with a resolution of about 100,000 years or better. Only by using such a temporal framework will we be able to determine rates and relationships between abiotic environmental and biological processes. Such a framework is now possible through a combination of high-resolution biostratigraphy, radiometric geochronology, magnetostratigraphy, astrochronology, biochronology, and Sr-isotope research. (See also the *EarthTime* Project: http://earth-time.org/.)

- **Quantitative analysis of physical and chemical conditions** through measurement of stable isotopes, such as oxygen, carbon, nitrogen, and others. Such isotopic data are essential for understanding abiotic effects and interactions with biological systems.

- **Monitoring** through fieldwork, laboratory work, drilling projects, expeditions etc. Monitoring requires intensive studies in sedimentology, geochemistry, ecology etc., as well as a wide range of biological investigations of the living descendants of the fossil organisms. Long-term monitoring efforts are crucial for understanding the dynamics of palaeo-ecosystems and for predicting the vitality of present-day and future ecosystems.

- **Documentation** of the morphological characteristics of selected groups of organisms having special biological or ecological importance. A major task is the establishment of robust and precise datasets for different kinds of organisms from different past periods and environments with different evolutionary histories and an exceptional fossil record. An integration of morphological studies, abundance, diversity, abiotic patterns and phylogenetic reconstructions will provide a more powerful description of life processes than could be achieved by any single study.

- **Phylogenetic reconstructions** of selected groups of organisms of special biological or ecological importance. Studies will include new methods, such as mathematical methods as the HIFI (Hierarchical Fit Index) for exploring correlations between stratigraphy and phylogeny, and cladistic or “three-item-analysis” of palaeobiogeography, pointing to relationships between palaeogeography and life.

Key issue 1

Environmental changes and dynamics of biodiversity

The sedimentary rock record reveals a succession of very different environments, ranging from the exclusively microbial and oxygen-poor Archean world to the anoxic and sulphidic oceans of the Proterozoic and on to the heterogeneous modern system with its huge diversity of complex multicellular organisms. Environmental changes have been recorded throughout the Phanerozoic on local, regional, and global scales, affecting the diversity and abundance of a wide range of organisms. Extinction appeared as well as diversification, and retreat of lineages happened in addition to expansion into

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The colonization of the land
is one of the most important
steps in the history of life

Science programme

A panel of 20 eminent geoscientists from all parts of the world decided on a list of ten broad science themes - Groundwater, Hazards, Earth & Health, Climate, Resources, Megacities, Deep Earth, Ocean, Life and Soils.

The next step is to identify substantive science topics with clear deliverables within each broad theme. A 'key-text' team has now been set up for each, tasked with working out an Action Plan. Each team will produce a text that will be published as a theme prospectus like this one.

A series of Implementation Groups will then be created to set the work under the ten programmes in motion. Every effort will be made to involve specialists from countries with particular interest in (and need for) these programmes.

For more information - www.yearofplanetearth.org

new habitats. Environmental changes have multiple effects, which may also concern the environment itself. The evolution of land plants and forests in the Carboniferous, or the mineralization of the shells of marine planktonic organisms, have been instrumental in effecting striking changes in conditions at the Earth's surface. The composition, diversity, and preservation of the fossils, and the abundance and temporal distribution of sediment types and geochemical signatures, delineate environmental changes. Some of these changes, even those as recent as the Early Eocene thermal event, present considerable challenges to climate modellers and to others seeking to understand the modern Earth.

Research efforts will identify time intervals when significant changes took place in biodiversity, the short-term dynamics of these changes, the roles played by biological innovations in generating patterns and rates of biogeochemical cycling (see Key issue 4), and how steady state conditions are maintained. Extinction events and critical intervals have diverse scales and impacts. However, they are key events that make it possible to understand biotic evolution and the development of biodiversity. Hence, this Key issue challenges new understanding of interactions between ecological changes, biotic innovation, and evolutionary success (abundance, diversity, longevity), and processes of biological evolution during times of both stability and rapid change.

Key issue 2

Evolutionary palaeobiology

More than 60 years after G G Simpson's book *Tempo and Mode in Evolution*, most questions of macroevolution (simply defined as evolution above the species level) are still being debated. The origin of such evolutionary novelties as insect wings, chambered shells of ancient cephalopods or tetrapod limbs, as well as the origin of organism "bauplans" (basic morphological patterns of large groups, such as echinoderms, or turtles or bats) is still inadequately known. The tempo of evolution is strikingly variable in different lineages over geological timescales, from those that hardly seem to evolve at all, like "living fossils" *Nautilus* and the horseshoe crab *Limulus*, to evolutionary sprinters like cichlid fishes in ancient lakes. However the underlying mechanisms of these differences remain unclear. With its broad view of time, palaeontology is of crucial importance in this field of research, as the fossil record facilitates the only direct empirical access to the evolutionary history of life.

There are two discrete problems to be studied: the origin of the morphological novelties in a developmental sense, and their success or failure in ecosystems (the latter being linked to Key issue 1). Comparative developmental biologists have produced striking new insights into the origin of some innovations, but only palaeontology provides information on ecological and/or evolutionary success. Macroevolutionary studies require a highly interdisciplinary exchange of palaeontology with geology and biology, including growing research fields like geobiology (see Key issue 4) molecular phylogeny, and evolutionary developmental biology.

The Earth system is controlled

by both biological and

physico-chemical processes

What does the International Year's logo mean? The International Year is intended to bring together all scientists who study the Earth System. Thus, the solid Earth (lithosphere) is shown in red, the hydrosphere in dark blue, the biosphere in green and the atmosphere in light blue. The logo is based on an original designed for a similar initiative called Jahr der Geowissenschaften 2002 (Earth Sciences Year 2002) organised in Germany. The German Ministry of Education and Research presented the logo to the IUGS.

Key issue 3

The development of life on land

The colonization of the land is one of the most important steps in the history of life, and it had a major impact on the further evolution of the geosphere and atmosphere. Living on land required a number of specific adaptations to a basically hostile environment.

Land plants needed special tissues to ensure sufficient stability. They needed protection against desiccation and UV-B radiation, and new reproduction and dispersal strategies. Other major changes concerned respiration and the intake of nutrients. Animals also needed to adapt their life strategies. The evolution of the land flora had a strong impact on weathering processes. Changes in atmospheric O_2 and CO_2 concentrations are directly related to the evolution of the land flora, as is the cycling of organic Carbon (C_{org}). In recent years it has become increasingly clear how complex modern ecosystems are, and how important symbioses between various groups of organisms are for the establishment of ecotopes and ecosystem development. Because soil science and ecology have developed independently, many of the relationships are still imperfectly understood (see *Soil - Earth's living skin*, prospectus 10 in this series).

The major goal is a better understanding of terrestrial ecosystems through time. Main tasks include ecology and life strategies of individual species, based on biological/physiological data on early land-dwelling organisms, to the reconstruction of entire ecosystems, including the mutual relationships and interactions between the various groups of organisms, such as cyanobacteria, fungi, lichens, algae, higher land plants and various groups of animals. Also, relationships between living communities and their abiotic environment are important issues, including the nature of the substrate in terrestrial communities, the availability of nutrients as well as humidity and water in the substrate.

Nautilus: a living fossil.

Key issue 4

Geobiology: the biosphere-geosphere interplay

The Earth system is mutually controlled by biological and physico-chemical processes. This coupled control began with the origin of complex organic molecules about 4 billion years ago, and since then prebiotic and biotic metabolic processes have considerably influenced the Earth system and the development of the geo-biosphere. The concept of geobiology is the interplay between organisms and their combined metabolic processes with various abiotic parameters; thus geobiology is an integrated approach of biological sciences and Earth sciences.

Many geological processes can be understood as geophysiological processes, allowing chemical reactions that would never run under standard thermodynamic conditions. These strongly coupled processes are possibly not restricted to the Earth system and may be realised also on other planets with comparable geological conditions. But the search for life on other planets requires the knowledge of certain biosignatures which could tell us the presence of life metabolic and physiological processes ("Astrobiology").

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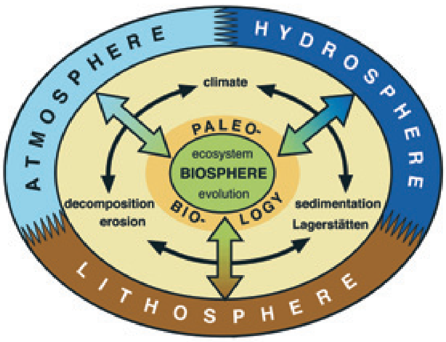
One of the oldest animals from Ediacara Fauna



The role of the biosphere and its interactions.
Illustration: Wolfgang Oschmann, Frankfurt.

Reef ecosystems during the Silurian period (443-416 million years ago)

One major goal is studying the evolution of physiological processes, visible in biosignatures and biomineralization patterns, and its interaction with biogeochemical cycles. Physiological processes are generally controlled by organic molecules, and often pushed by enzymatic pathways. Fundamental physiological changes of biotic processes navigated bioevents and special biochemical cycles known from Earth's history. Also the above Key issues, relating to the evolution of organisms and environmental changes, will require the study of interactions between geosphere and biosphere, and thus the Key issue 4 is also closely linked with them.

Key issue 5

Stability and variability in ancient ecosystems

Natural ecosystems such as reefs and tropical rainforests show profound natural variability over timescales of thousands to millions of years. Although factors governing the stability of ecosystems are well explored, there are great uncertainties concerning the interplay of these factors with the spatial and temporal scales over which they act. The stabilizing effect of biodiversity on ecosystem processes is probably a "scale-invariant" attribute. This already provides some guidance to modern ecosystem management. Additionally, ecosystems tend to collapse during times of major mass extinctions and need longer for recovery than the global species pool. The time of recovery seems to depend on the complexity of metabolic pathways necessary to sustain a functioning ecosystem.

This Key issue links to all other Key issues but refers to integrated systems rather than to individual traits and phylogenies. The main questions to address are:

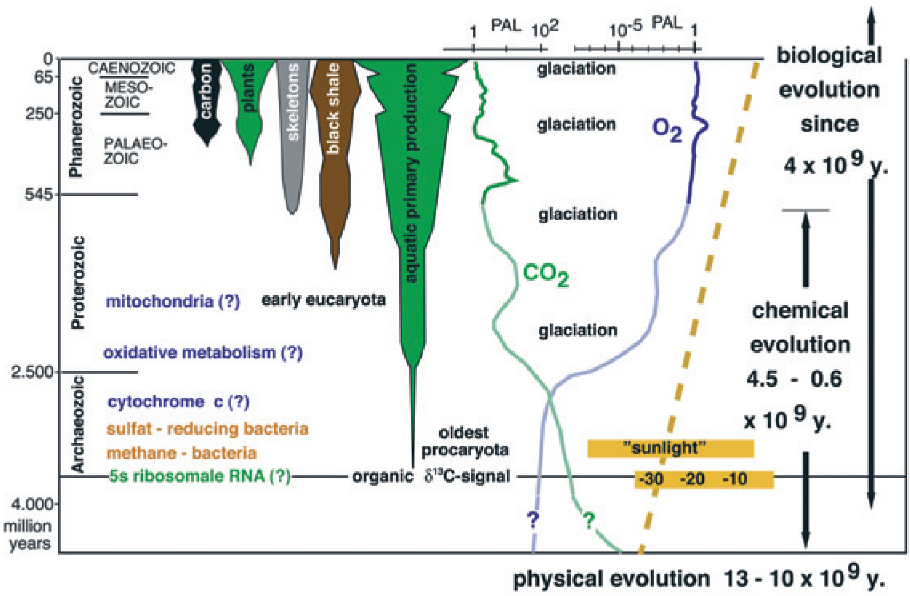
1) the documentation of natural variability and complexity in ancient ecosystems

2) the impact of local versus global changes on ecosystem stability

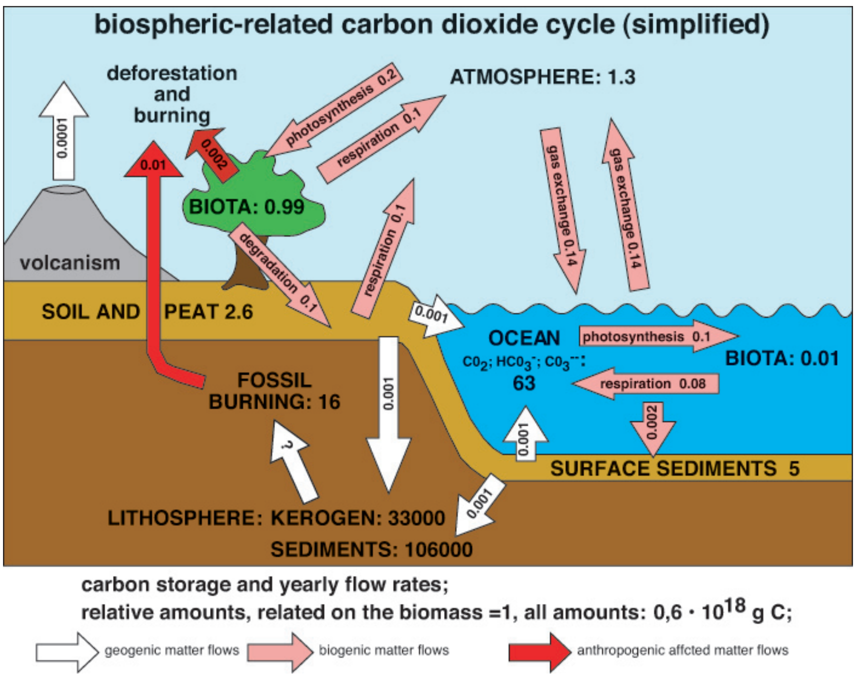
3) the time scales involved in the destruction and recovery of ancient ecosystems

4) the applicability of palaeontological findings to modern conservation biology.

Scientific findings need to be communicated if sustainable megacities are to be a reality



Synopsis of evolution on planet Earth. Illustrations: Wolfgang Oschmann, Frankfurt.



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Key issue 6

Modelling

A model is a physical, mathematical, or logical system which represents the main structures of reality and is able to explain, or dynamically reproduce its functioning. Modelling is used today everywhere in Earth and life sciences. Models are of many of types, but can be usefully categorized as either pattern-based or process-based. Pattern-based models provide descriptions and interpretations of the World. Examples within palaeontology include:

1) descriptions of taxonomic diversity patterns

2) classifications of fossil organisms through, for example, comparative morphology, palaeohistology and biochemistry

3) phylogenetic reconstructions as theoretical schemes of interrelationships between living or fossil organisms based on shared characters, achieved with the aid of computerized techniques (e.g. PAUP or HENNIG86 software).

Pattern-based models also include numerical modelling, such as quantifying the variability of fossil species (biometry and morphometry), phylogenetic studies (cladistics and other methods), classifications (parsimony or phenetic methods), biofacies and assemblage analysis (clustering methods). Process-based models attempt to capture the underlying processes, whether physico-chemical or biological and have an output on the general pattern under study. Such models are common in fields such as ecology or geochemistry, but have yet to be sufficiently widely adopted within palaeontology.

Some fossils

Reconstruction of Cretaceous vegetation and dinosaurs. Illustration: Tom Ungemach

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International Lithosphere Programme (ILP)
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International Union of Soil Sciences (IUSS)
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Supporting institutions

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