Earth Sciences in the 21st century:
A forward look

The broad aims of the Forward Look were:

- **To define where are earth scientists now in the UK science agenda**. *What are our major achievements, funding levels, National capability and infrastructure, etc.*?
- **To discuss how well earth science is currently integrated into the NERC strategy**. *Are our strengths and is our influence being applied to NERC strategy. Should we be redirecting resources? Can we contribute more? What are the next big 3 contributions?*
- **To define the long-term outlook for Earth science.** *The changing planet, requirements for observations and modelling, infrastructure, jobs and skill requirements*
- **To envisage the technology and Infrastructure to Deliver the Science:** *Encompassing: NERC National Capability in Geoscience and European and International Science.*
- **To consider how earth science be better structured**. *Structure and governance within NERC and UK and also within European and international networks.*

As part of the process a two day workshop was hosted by the Geological Society, London at Burlington House, London on the 18th and 19th January 2010. The event involved some 100 members of the UK earth science community selected by application from the academic community, NERC, UK government and industry. Participants were tasked with discussing and making recommendations on a series of themes relevant to Earth Sciences in the 21st century. GSL, NERC and BGS personnel facilitated this event.

The organisers were:

Jon Davidson (Committee of Heads of University Geosciences Departments; CHUGD),
Marjorie Wilson (University of Leeds),
John Ludden (BGS) and
Lynne Frostick (University of Hull and Geological Society, London; GSL)

Outputs

Summary

Many research objectives require us to advance understanding of heterogeneity and scaling issues including the sensitivity of the different components of our environment at the surface and in the subsurface; this will require new measurement and survey techniques, collaboration and integration across Europe and internationally in the use of state-of-the-art infrastructure, including provision of easy web-access to large, more comprehensive, geospatial and temporal monitoring datasets.

All underline the improvements we have made and can make to our understanding of the Earth System, including deep Earth processes, and Earth evolution, and particularly to identify interactions between surface and near surface environments; atmosphere, oceans, continents and the evolution of life.

An important outcome of the process of the forward look has been the **definition of four disciplinary initiatives**. These were defined as areas where significant scientific added value could be achieved through networking scientists, combining infrastructure and facilities and working in international partnerships.

The capacity to train earth sciences and provide top quality graduates for industry, government and academia was recognised, but not within the scope of this forward look. This is to be addressed in a

separate action coordinated by the Geological Society of London (GSL) in the light of the changes in funding of the UK university sector and has been addressed by a series of letters from GSL, the British Geological Survey (BGS) and the Committee of Heads of Geology University Departments (CHUGD) to BIS and HEFCE.

The Initiatives

Initiative 1: Earth and environmental sensitivity: enabling prediction and adaptation for the future

Work over the past few decades has established that conditions at the Earth's surface have developed and are maintained as a result of many feedback mechanisms affecting the geosphere, biosphere and cryosphere across a range of scales, both spatial and temporal. Many of these cause–feedback mechanisms were only discovered or party quantified in recent years and it is thus highly probable that additional mechanisms operating on a variety of spatial scales and timescales have yet to be identified.

A few examples are:

- Climate and landscape evolution are intimately coupled in various ways: vertical crustal motions can affect atmospheric circulation and climate change can effect rates of surface processes such as erosion,
- Changes in nutrient and carbon flows from land to the ocean, in response to precipitation and weathering patterns and the evolution of watersheds, directly impact on marine biogeochemical cycles and ecosystems which, in turn, can alter ocean–atmosphere interactions
- Ice sheet dynamics, particularly in relation to substrate and subglacial hydrology, directly impacts on sea level change.
- Human activities, such as forest clearance, agriculture, settlement affect erosion regimes, landscape resilience, and nutrient or particulate exchange between the land and the oceans.

Landscapes, both terrestrial and marine, are interconnected components of the ecosphere consisting of ecosystems (habitats), including for example tropical rainforests, coral reefs, tundra, estuaries, various Arctic environments and shallow as well as deep sea environments. This patchwork of landscapes hosts the life-support system for the biosphere. On land it is focussed within the Critical Zone described previously. Terrestrial and oceanic landscapes are dynamically transformed by life and its support systems - in particular the water and the carbon cycles - human intervention, and other internal and external processes such as ocean circulation that also respond to climate change.

These systems are particularly complex with a behaviour that is commonly highly non-linear. Understanding non-linearity, sensitivity and cause–effect relationships between these coupled surface environments is essential to advance predictions on environmental impact of climate change.
To inform and enable decisions, there is an urgent need to develop novel and more holistic strategies to enable the society and the natural environment to adapt to the inevitable impacts of climate change. To enable adaptation we need to understand both terrestrial surface processes (including coastal and fluvial geomorphology, land-slipping and soil formation) and oceanic processes (including oxygenation, acidification, nutrient flow and carbon cycling) and their likely response to climate change.

Many systems retain a unique memory of climate change over millions of years, which may result in amplification or dampening of the original forcing signal. Other more reactive systems with shorter response times must be more sensitive to imposed changes.

Understanding the sensitivity or stability of the different components of our environment to future climatic and demographic forcing underpins tailored strategies for adaptation and mitigation.

The geological record of marine and terrestrial sediments is the only source that contains physical, chemical, and biologic responses to climatic and environmental change, across all scales. This exceptional archive covers all climate states and transitions the Earth has faced in the past, from extreme greenhouse to icehouse worlds, providing a exceptional opportunity to inform us about likely trends and trajectories of environmental change, rates and phase relationships connecting Earth surface processes to external forcing, and consequences for the environment. A truly interdisciplinary approach with a focused effort on targeted time intervals would enable quantification of Earth's environmental and climate systems at a global scale. Specific targets would include a higher CO_2 greenhouse world, a lower CO_2 icehouse world, and global carbon cycle perturbations driving rapid changes in Earth's greenhouse gas concentrations.

Current models used to estimate climate sensitivity neglect many feedbacks associated with changes to ice-sheets, vegetation, non-greenhouse gases, various aerosols such as desert dust, interactions between microbial catalysts, and other components of the Earth system. On the other hand, Earth-system models combine and simulate these critical processes and are a step towards estimating the true long-term response of the system to elevated CO_2 – the ‘Earth System Sensitivity’. To make progress it is essential to integrate CO_2 forcing and palaeoenvironmental conditions from selected time periods within Earth system models to directly inform simulation of future scenarios.

The sedimentary record of past climate change has the exclusive potential to enable calibration and tuning of climate sensitivity and non-linearity against natural examples using novel and comprehensive Climate and Earth System models. Such a paired approach will provide improved predictions with less uncertainty. It will address the assessment and quantification of sensitivity of landscapes at global to human scales, calibrated against the geological record of environmental change.

The success of this initiative requires the use of novel coring in critical areas and key time intervals and high-precision analytical techniques to sample sedimentary sequences that record climate perturbations from the more distant past. For the current human time scales long-term observation and monitoring is required in key sensitive environments.

Initiative 2: Resource Security & Waste Management: working with the Earth to develop a sustainable future

In terms of energy, mineral resources and water supply we are facing peak production at a time when global population growth and the emerging super-economies in China, Brazil and India are placing greater demands on resources. Our ability to meet these demands and to postpone peak production depends on a strong economy fed by existing resources to enable transitions to sustainable energy and resource recycling strategies including geological solutions to waste management through “sequestration” and “reverse mining”.

The UK already plays a key role in this not just nationally but on a global basis with super majors in Oil and Minerals: BP/Anglo/RTZ and joint-listed super majors Shell/BHP headquartered in the UK together with many other significant players.

This initiative focuses on supporting the research needed to find new resources and to extend the lifetime or efficiency of known resources through new innovative techniques. Much of the science and technologies needed for the extraction and resource harvesting are required at the end of resource life cycle for waste management. The key challenge areas include:

- Sub-surface storage of resources & wastes (e.g. water, CCS, radioactive waste)
- In-situ energy mining (e.g. geothermal, coal and shale gasification)
- Scenarios & risk modelling
- Minerals for emerging technologies & infrastructures (e.g. rare earths, biominerals, aggregates)
- Enhanced recovery of resources (e.g. oil/gas recovery, mineral recycling, unconventional hydrocarbons)

A substantial proportion of the worlds energy, mineral and water resources are produced from subsurface rock reservoirs. Knowledge of how these resources got where they are, what keeps them there and how they may migrate is very important in the search for new resources and for maximising their extraction potential. Similar understanding is important for predicting how hazardous or radioactive wastes and carbon dioxide will behave if they are stored or disposed of underground and how strategic metals may affect the environment and can be recycled. Research directions need in particular to be focused around an improved understanding of fluid-rock-mineral interactions at all scales from crustal-scale through to nano-scale processes. This research should focus on the fundamental science, crossing existing discipline boundaries in order to extend the range of approaches used for reservoir and basin scale characterisation and modelling so that they are fully applicable across the resource security theme.

The commercial consequences of poor geological modelling can be particularly severe where fluid flow processes are involved as these are governed by the spatial arrangement of extremes in the range of controlling parameters such as permeability, mineralogy and geochemistry. The nature of these processes and their scalability are therefore of paramount importance. Specific scientific directions for further development of our understanding include:

- Multiscale fluid-rock characterisation
- Coupled mass transport processes & multiphase fluid flow
- Uncertainty analysis & predictive models
- Nanotechnology
- Biogeochemistry
- Subsurface imaging technology for resource and waste storage assessment

The development research must be supported by appropriate facilities and the ability to develop enabling technologies. With changing demographics and the shortage of suitably skilled research level geoscientists both in academia and in industry, skills resource will be a significant issue over the next decade.

Networking of the HEI and institutes in these strategic areas along with the provision of shared laboratory resources for rock- mineral characterisation, including synchrotron techniques, is essential. Significant Industry funding of will likely form a key component, but will only continue to be available if the UK Research Councils, especially NERC, continue to fully support the national research culture and infrastructure.

Initiative 3: Forcing, Fluxes & Feedbacks: the Deep Earth-surface interaction: What the Deep Earth does for us?

Volcanic eruptions, earthquakes, and landslides are major natural hazards which are driven by sub-surface processes, but coupled strongly to the hydrosphere and atmosphere. There are two critical linkeages: between volcanic activity and the atmosphere; between the deep Earth and the surface via tectonics.

Magmatism and associated CO2 fluxes is an essential part of the global carbon cycle that links the solid Earth and its surface reservoirs. On shorter time-scales, release of sulphur and other trace species by volcanic eruptions changes atmospheric composition, leading to significant surface cooling and other environmental impacts. The same volcanic processes also provide the vector that brings many essential metals to the upper crust and very exceptionally concentrates them as resources.

A second linkage between deep Earth processes and plate tectonics underpins the global earthquake cycle. On geological timescales, mantle circulation leads to large-scale changes in Earth's surface topography, modifying slope stability (both underwater and on land), and influencing climate by changing atmospheric circulation. Climate can influence the deep Earth via changes in the surface load, for example during the creation and destruction of ice sheets, triggering melting and volcanic activity and changing regional crustal stress fields.

The feedbacks and forcings which couple the deep Earth to Earth's surface can be sub-divided on the basis of the depths at which they occur and to solve the wide-ranging problems posed by these interactions we need to understand process at the three depth levels and integrate the system across the boundaries.

Deep processes – mantle circulation and melting: Understanding how the mantle convects is essential, both to understand the large-scale chemical evolution of Earth's interior (as recorded in erupted magmas), and to understand the dynamical consequences for uplift of the Earth's surface. For the deep Earth carbon cycle we need to quantify how much carbon is cycled from the deep Earth to the atmosphere and back again? How much of the total CO_2 budget in the atmosphere is controlled by the deep Earth, and on what timescales? These problems require input from analogue experimentation from mineral scientists, geophysical tomography as well as numerical models.

Intermediate processes – crustal earthquakes, magma evolution and degassing: This focuses on shallower levels in the mantle and lower crust, where melts form, accumulate and segregate from their source then evolves as they cool, crystallize and interact with the crust. Critical to the timing and style of eruption are the complex processes occurring during solidification; this is a fundamental problem of two- or three-phase flow and requires an understanding of the movement of a reactive multi-phase fluid through a reactive and deformable medium.

Surface processes: Are where interactions between Earth's solid surface and the atmosphere and hydrosphere have consequences and impacts of eruptions, earthquakes and landslides. This is the final stage of the process where there is the direct interaction with the atmosphere, where volcanoes degas with ensuing are the chemical and environmental consequences. An important challenge is to interpret the complex physical and chemical signals of tectonically and volcanically-active systems to develop tools for forecasting the timing and style of hazardous events, and to mitigate the consequences for society?

The processes are all linked, but as one goes deeper into the Earth resolving the process is harder. Nonetheless, recent developments in new technologies (from satellites to submarines, to mobile phones and disposable sensors) have transformed our ability to measure the Earth. They permit imaging and measurement on rates and scales untapped before. The next breakthrough will come from integrating these data streams.

The effect of the deep Earth on topography feeds directly into the first initiative “Earth and environmental sensitivity: enabling prediction and adaption to the future” and this linkage needs to be exploited in order to inform both groups. We require co-ordinated international initiatives with well planned field experiments and the appropriate monitoring, analysis and modelling involving geophysicists, petrologists, atmospheric chemists, seismologists and palaeo-climatologists.

Initiative 4: Origins: How did the atmosphere, oceans, continents, core and life itself originate and how do they influence / have they influenced each other?

How did the deep Earth evolve to produce our surface environment, including the atmosphere, oceans, continents, and the magnetic field, and how did it set the boundary conditions for the origin of life?

A number of processes were operative in the early Earth that are still poorly understood, yet on which substantial progress is now possible. Processes for which evidence exists in the rock record include the moon-forming impact, the formation of the core, cooling of the planet, the formation of the crust, the earliest origins and evolution of life, the rise of oxygen, and the early presence of liquid water despite a faint young Sun.

Recent advances in the dating of early Earth events and isotopic constraints on chemical cycles and interactions, increasingly precise and high resolution chemical analysis of meteorites, ancient rocks, and minerals, a new generation of models of early dynamical processes, and the thermodynamics of earth materials in extreme surficial and deep environments provide a basis for transformational understanding of the origins of our natural environment.

Important questions and research directions

What are the boundary conditions – that is what is the interior of the Earth like today and how does it work?

If we want to understand how the Earth evolved through time we need to benchmark what the Earth is like today as our model target. We have made a good deal of progress towards this, but we still need to understand how mantle dynamics affects Earth’s surface, given that the vast majority of our analytical research is focused within a few km of this interface. A particular focus should be volcanoes (melting transport and eruption) and tectonics, which are key in mediating the interface between the solid Earth and the biosphere/ hydrosphere/ atmosphere:

Quantification of processes and timescales of fluid flow. This general need cross-cuts many themes and will be important in understanding today’s Earth, atmosphere, biosphere and hydrosphere and how they were arrived at.
Integration of geochemical and geophysical research, so that geochemical reservoirs can be reconciled with the geophysical/tomographic constraints on mantle structure
A better understanding of how geochemical reservoirs have evolved such that multi-isotope (Sr, Nd, Pb, Hf, Os, He) constraints can be satisfied

How and when did the core form and when did the magnetic field originate?

Through its interaction with the solar wind, the magnetic field may have had an important influence of the evolution of life. Progress will come from advances in:
Studies of isotopic constraints on timing of early Earth events including the timing of core formation and mantle differentiation.
Experimental and theoretical (*ab initio*) studies of metal-silicate equilibrium at high pressure.
Seismic tomography and a search for deep fossils of Earth evolution, including compositional anomalies that may be remnants of a magma ocean.
The fluxes from the sun affect our planet. They may pose a significant risk to our infrastructure in addition to influencing the upper atmosphere and potentially modifying climate.

How did solid Earth processes set the mass of the surface ocean, and how has the balance between water at the surface and the deep interior changed with time?
The presence of liquid water at the surface makes Earth unique in the solar system. Progress will come from advances in:

Advances in dynamical models of early Earth processes including the moon-forming impact and its aftermath
Thermodynamics of silicate-water-vapour systems
Isotopic and chemical studies of meteorites and comparison to Earth.

What was the nature of the Hadean (>4 Ga) environment? What was the surface environment like at the time that life originated?

The Hadean was a time in which atmosphere, oceans, and solid Earth interacted with each other much more strongly than today. Heat flow from the interior may have exceeded the solar flux by orders of magnitude, the atmosphere may have been in thermodynamic equilibrium with the solid Earth and it may have been sufficiently dense to set the surface temperature.

Progress will come from:

- Concerted efforts to find ancient rocks and minerals, coupled with increasingly powerful tools of micro-analysis,
- A new generation of dynamical-chemical models of the tightly coupled early evolution of the solid-Earth fluid-envelope system
- New constraints on heat transport in the early Earth system, and the formation of the continental crust.

Continued investment in laboratory infrastructure in particular high-pressure experimental facilities and high-precision mass-spectrometers will be vital for extracting geochemical signals. Modelling is likely to play an increasingly important role and continued NERC investment in high performance computing will be vital. Collaboration can be facilitated by programmatic research funding and building international research consortia.

See also:
www.ukgeoscience.org.uk