Earth Sciences in the 21st century:
A forward look
Workshop: 19 January 2010

"Initiatives"
Group Reports

Day 2 discussions identified four overarching "initiatives" from the different themes and commonalities arising from the six breakouts of day 1. The groups were asked to capture a c1-2 pages synopsis of discussions, to include both he challenges and research objectives and a summary of what is needed to achieve them (in terms of both scientific research/advances and training and infrastructure requirements. These are presented below. No proforma was given and the groups have structured their reports as they felt most appropriate to report their individual findings/conclusions. Some duplication of training and infrastructure needs is inevitable, but the groups were asked to include them here for completeness, in the final document, these will be compiled into a separate section.

It is these that will influence the overall structure of at least the draft report to be compiled once people have had chance to comment on these areas.

Initiative 1
Earth and environmental sensitivity: enabling prediction and adaptation for the future
Rapporteurs: Thomas Wagner and Mike Ellis

The grand challenges

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. A few examples are:

(i) Climate and landscape evolution are intimately coupled in various ways: vertical crustal motions can affect atmospheric circulation and thus affect climate; whereas long-time climate change can affect vertical crustal motions by affecting rates of surface processes such as erosion, the uplift in many regions being the isostatic/buoyancy response to erosion.

(ii) 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 via changes in energy transfer, ocean circulation or marine microbial activity.

(iii) Ice sheet dynamics, particularly in relation to substrate and subglacial hydrology, directly impacts on sea level change.

(iv) Particularly important are human activities (e.g. forest clearance, agriculture, settlement) changing erosion regimes, landscape resilience, and nutrient or particulate exchange between the land and the oceans.

Many of these cause–feedback mechanisms were only discovered or party quantified in recent years; it is thus highly probable that additional mechanisms, operating on a variety of spatial scales and timescales, have yet to be identified. A fundamental and unresolved question that couples global scale Earth Surface processes to the human dimension is the extent to which the Earth and Environmental Systems are sensitive to climate change/forcing. Climate is not the only driver of change on the earth surface as few if any landscapes on Earth operate without the direct impact of people and communities. At the human scale, where the impacts of change literally hit the ground, we do not yet know how landscapes and the connected ocean respond

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. The Critical Zone, encompassing the outermost surface of the planet from the vegetation canopy through the soil to groundwater and upper lithosphere systems, sustains the economic and environmental future of modern society and hosts an exceptional high biodiversity. Terrestrial and oceanic landscapes are not static. They 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. Such 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.

Climate change in combination with human land exploitation is commonly considered to pose the most serious long-term threat to the natural environment with far reaching effects on people, places and society as well as on the natural and built environment. In addition to taking action to reduce global greenhouse gas pollution 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. In order to enable adaptation it is essential that we understand both terrestrial surface processes (including coastal and fluvial geomorphology, land-slipping[mass movement] and soil formation) and oceanic processes (including oxygenation, acidification, nutrient flow and carbon cycling) and their likely response to climate change. This is essential to inform and enable decisions to be made on how best to maintain economic resources, human society, and functioning ecosystems against a backdrop of changing climate.

The proposed approach

The Earth's surface forms the dynamic interface that integrates and couples processes in the deep Earth with those operating in the atmosphere and the ocean. These processes respond to both internal and external forcing and define the physical and biological nature of the environment. Climate change affects many components of the Earth and Environmental Systems across a wide range of scales, both through time and in space. 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 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.

Climate sensitivity is defined as the global mean temperature response to a doubling of atmospheric CO_2. It is a fundamental concept used by the IPCC in their assessments of future climate change. However, 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'. Yet many of the processes and feedbacks are not well understood and act on long timescales and are a challenge to model. To make progress it is essential to integrate critical data within Earth system models (in particular CO_2 forcing and palaeoenvironmental conditions from selected time periods) to directly inform simulation of future scenarios.

Computer models provide a global estimate of long-term equilibrium surface temperature for the given CO_2 forcing. It has the advantage over the pure modelling approach in that the palaeoenvironmental data associated with the feedbacks are given to the model rather than calculated, and has the advantage over the pure observational approach in that the model allows a truly global estimate of temperature change.

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.

Studies spanning many different timescales are important. The value of research on documenting anthropogenic changes and predicting changes over coming decades and beyond is self-evident. Studies spanning Late Pleistocene / Holocene timescales are equally important for assessing the response of the Earth system to times of climate instability and for elucidating chains of cause and effect. For example, it has recently been shown that at certain times in the Late Pleistocene the discharge by rivers in northwest Europe has been large enough to affect the thermohaline circulation in the North Atlantic Ocean. Likewise, changes to and feedbacks within the Earth system operating over Quaternary timescales (i.e., the last ~3 million years) are relevant for a number of reasons, including defining the interactions and feedbacks between climate, landscape evolution, and human evolution. It is necessary to look back at the MIS 11 interglacial, ~0.4Ma, for a good analogue, in terms of astronomical forcing, for the present (Holocene). Even further back in time, for example during past greenhouse conditions in the Palaeogene/Cretaceous, there are important lessons to be learned on how the Earth System responds to elevated levels of pCO_2 and short term perturbations of the global carbon cycle and, importantly, how, why, and over what time scales the system recovered from these perturbations. Using novel coring and analytical techniques these climate perturbations from the more distant past can now be resolved at centennial and possible shorter time scale providing exceptional insights to inform the current discussion on how the Earth may operate at high pCO_2. Notwithstanding the importance of research on all timescales, this topic has hitherto been seriously under-researched requiring a coherent, novel and cross-disciplinary approach.

In summary this initiative addressed the assessment and quantification of sensitivity of landscapes at global to human scales, calibrated against the geological record of environmental change.

Initiative 2
Resource Security & Waste Management
Using the earth to develop a sustainable future

Rapporteurs: Alan Gibbs and Bob Holdsworth

Scientific Context & Societal Importance

The geoscience community has a pivotal role in addressing the needs of society both in the UK and globally in the coming decade. 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 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. To ensure resource security the geoscience community needs to be able to continue to provide the fundamental research products and the trained research personnel that are deployed on global projects. These are key underpinnings to UK plc wealth generation, and resource security.

Significant Industry funding of Geoscience Research 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.. Industry investment necessarily follows expertise and research success.

Research Challenges

The research Challenges for the next decade focus on supporting the need 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 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)*

Future Research Directions & Resources

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 as well as 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. Research directions therefore need in particular to be focused around an improved understanding of fluid-rock interactions at all scales from crustal-scale through to nanoscale processes. It is important that the geological framework and evolution is incorporated throughout as a constraint to the fluid and geochemical processes. This research should focus on the fundamental science that unifies these concepts, 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. Industries whose resources lie in the subsurface base most of their planning and investment decisions on models using numerical descriptions of the geology and geological processes. 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*
- *Appropriate research capabilities (people, technologies, facilities)*

It is important that the development of such research directions are 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, people resource will be a significant issue over the next decade. Motivation and recruitment of geoscientists to take up the research and societal challenges as well as the balance between traditional “core” skill and research led training are key issues.

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

Rapporteurs: Marian Holness and David Pyle

Why does it matter?

Volcanic eruptions, earthquakes, and landslides are major natural hazards which are driven by sub-surface processes but coupled strongly to the hydrosphere and atmosphere.

1. The first critical linkage is that between volcanic activity and the atmosphere. Magmatism is an essential part of the global carbon cycle that links the solid Earth and its surface reservoirs. When the mantle melts the magma is enriched in CO_2: movement of molten rock to the Earth's surface thus extracts carbon from the deep Earth and adds it to the surface carbon cycle. Mantle-derived CO_2 is implicated in many of the long time-scale climate variations through Earth history. 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. Evidence for climate-forcing of volcanic activity on the timescales of glacial to interglacial cycles demonstrates the complex two-way feedback between deep Earth and the atmosphere: volcanic eruptions modify climate on timescales from years to millions of years, while changing climates can transform rates of volcanic eruption, and modifying the stability of volcanic edifices and their propensity to collapse. The same volcanic processes also provide the vector that brings many essential metals to the upper crust and very exceptionally concentrates them as resources.
2. The second linkage between the deep Earth and the surface is via tectonics. Deep Earth processes and plate tectonics underpin 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: deep processes – mantle circulation and melting; intermediate processes – crustal earthquakes, magma evolution and degassing; and surface processes – interactions between Earth's solid surface and the atmosphere and hydrosphere; and consequences and impacts of eruptions, earthquakes and landslides.

Objectives

To solve the wide-ranging problems posed by these interactions we need to understand what is going on at these three levels.

1. At the deepest level of interest, we need to understand how the mantle convects. This 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. We need to understand the deep Earth carbon cycle: 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 mineral scientists and seismologists, as well as numerical modelers.
2. Shallower in the mantle we need to understand where melt forms; how it accumulates and segregates from its source; and how, and where, these magmas evolve 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.
3. The final stage of the process is the direct interaction with the atmosphere – how do volcanoes degas and what are the chemical consequences of this? Can we 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?

In order to unravel the complexities of these interactions, we will need to exploit the rich geological record of past events – many of which have no modern parallel. How did major flood basalt eruptions of the past lead to observed changes in paleoclimate? What triggers the formation of large igneous provinces and what is the scale of their impact on the climate?

Research needs

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. We also have new approaches to understanding chemical evolution of magmas and this will allow us to investigate the circumstances in which a range of metals may be concentrated to ore grades.

The effect of the deep Earth on topography feeds directly into the first theme ("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 need a co-ordinated study involving igneous petrologists, atmospheric chemists, seismologists and paleoclimatologists.

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

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, 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

1. 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

2. 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.

3. 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.

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

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.

Research Needs

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. Studying this system requires close cooperation between scientists from disciplines ranging from studies of the deep Earth, to atmospheric chemists. Collaboration among these groups can be facilitated by programmatic research funding. Continued investment in laboratory infrastructure 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.