Earth Sciences in the 21st century:
A forward look
Workshop: 18 January 2010

Breakout Group Reports

Six breakout groups were defined by subject areas varying from wholly applied to wholly academic, which had been drawn up in order to best include all of the [current] main earth science disciplines.

The questions the groups were given to address were:

- ***I. What are the three most important scientific advances in the area in the past 10 years?***
- ***II. What are the three most likely important science advances be in the next 10 years?***
- ***III. What is required to achieve them?***

Participants were assigned to groups by their preference and areas of expertise, with nominated leads and core members to facilitate and guide discussions.

Synopses of the break out groups' discussions and conclusions are reported below.

Breakout Group 1
Applied Geoscience to Serve Society
Katherine Morris (lead)
Helen Reeves and Simon Mathias (core members)

Encompassing Engineering Geology, Hydrology and Hydrogeology, Carbon Capture and Storage, Radioactive Waste Disposal, Contaminated Land, and Environmental Pollution and Health.

The group identified energy, land management and climate change as the key issues to impact on society over the next decades.

I. Most important scientific advances in the past 10 years

1. Demonstration of coupled physical, chemical and biological understanding of key processes in applied geosciences.
2. A development in the fundamental mechanistic and process understanding of transport of key parameters (fluid, gas, contaminant, colloid…) feeding into carbon capture and storage, radioactive waste management, and human health issues

II. Most likely important science advances in the next 10 years

The major contribution that geosciences would make would be in developing a fundamental process understanding across the physical, chemical and biological sciences which would allow management of key issues affecting humans in the zone of human interaction (or in the surface and sub-surface zones impacted on, and required by humans). For example:

1. Development of upscaling (time and space) techniques across the physical, chemical and biological components of the zone of human interaction.
2. Development of biogeochemical models for transport in the zone of human interaction
3. Development of fundamental processes affecting transport at mineral surfaces and of key vectors such as nano-materials
4. Development of methods to both handle and communicate uncertainty in spatial and temporal models
5. More on coupled processes
6. Improved sub-surface visualisation

The impact of these developments would be significant across energy, water, food supply, land use, human health, pollution control. For example, to implement e.g. radioactive waste disposal, and carbon capture and storage and to allow optimisation of our environment for human health, food-, water- and wastes-management.

III. What is needed to achieve them?

1. Underpinning fundamental science support.
2. Integration across disciplines and engagement with industry, politics and the scientific community.
3. Data and knowledge that are interoperable between disciplines (flexible platforms).
4. Appropriate cutting edge analytical techniques (e.g. DIAMOND, 3rd gen. Geophysics).
5. Skills and infrastructure expansion in depleted areas (nuclear) – industrial requirements (CPD).
6. Access to and creation of environmental 'Observatories' in zone of human activity (urban, rural, rock labs). (Centres of Excellence).
7. Access to and investment in cutting edge and appropriate facilities (both in the UK and rest of World). CCS, radwaste require specific and detailed infrastructure.

Breakout Group 2
Natural Resources and Energy

Hugh Sinclair (lead)
Bruce Yardley, John Loughhead, Alan Gibbs and Nick Riley (core members)

> *Encompassing Minerals, Post Peak Oil and Consequences for Resource Development, Dwindling Mineral Resources and Security of Supply.*

Maintaining a secure, sustainable supply of minerals and energy in the face of substantial human population increase and climate change is a major challenge facing the UK and the wider world. Along with materials already in the anthropogenic environment and improvements in eco-efficiency, primary minerals will continue to be vital in maintaining the resource base available to mankind and in delivering the environmental technologies vital to our survival. The UK hosts some of the global majors in both the Oil (Shell and BP) and Mining (Anglo American, BHP and RTZ) industries. All of these are supported by UK trained technical and research staff. This is one of the key underpinnings to UK plc wealth generation, and security, and therefore has to be at the centre of future considerations for the UK Earth Sciences.

I. Most important scientific advances in the past 10 years

1. *Geophysical imaging of subsurface using 3D/4D seismic and Electromagnetic (EM) surveys*. seismic data has enabled the direct imaging of time surfaces in the stratigraphic record, and hence precise analysis of hydrocarbon reservoirs. It has also been widely used in academic research to image a range of phenomenon including meteorite craters, dyke swarms and fault architectures. 4D seismic is now routinely used to image the movement of oil and gas during production of petroleum reservoirs. Electromagnetic (EM) imaging can sometimes enable petroleum to be imaged prior to drilling wells. Traditional exploration usually relies on indirect geological evidence to locate hydrocarbons, with

seismic data used to define rock geometries. However, these techniques are not always sensitive to fluid types; in contrast, EM methods are very sensitive to reservoir fluids.

2. *Petroleum systems modelling*. The petroleum system integrates diverse and extensive information on the geological, geochemical, and migration histories of a province. Whole system modelling allows all these data to be integrated in order to refine understanding of oil and gas generation, migration, and accumulation. Results of modelling are presented visually, numerically, and statistically, thus enhancing predictive capabilities and risk analysis. These techniques have been responsible for the identification of major petroleum reservoirs, particularly in deep water environments.
3. *Metal transport in fluids and magmas.* Determining fluid processes in the Earth's crust impacts on models of ore formation, diagenesis and prograde and retrograde metamorphism, as well as volcanic processes. The search for new mineral deposits to meet demands for metals from a growing and developing population must be informed by improved understanding of ore genesis. In recent years there have been substantive advances in our understanding of deep crustal fluids and how they transport metals. This has come about by the combination of greatly improved analytical technologies, permitting analysis of small individual fluid bubbles in minerals and hence yielding information about quantities of metals being mobilised, and the development of detailed models for fluid flow in specific settings, which permit the sites of reaction and precipitation to be modelled. This has been assisted further by new experimental methods which are providing information about the solubility of rocks in the deep crust and the mantle, and hence show how metals are first concentrated into magma at source.

II. Most likely important science advances in the next 10 years

1. *Prediction of rock-stress-fluid interactions at all scales.*
2. We need to be able to model the interactions between rock, stress and fluid from regional to nano-scales. This is a requirement for detecting undiscovered resources, increasing oil recovery from ageing fields, modelling fracture and microbial stimulation of unconventional oil and gas reservoirs, improved and more efficient mining, and future storage of CO_2 from power plants. As well as investigating interactions on different physical scales, it is also important to understand the effects of time, since patterns of behaviour that dominate over the short timescale of resource exploitation may be superseded by other processes over the longer timescales that must be considered for safe CO_2 storage.
3. Role of microbiota in moderating mineralisation.
4. The role of microbiota in determining the precipitation of key minerals is an area of huge potential to both mineral extraction and remediation of pollution. Academic research on mid-ocean ridge mineral deposits finds that bacteria significantly modify and enhance valuable metal concentrations. Microbiota also generate mineral deposits by concentrating dissolved metals from fluids in the crust and sediments. Elsewhere, microbiota are being found to play a role in the remediation of heavy metal pollution. Hence, mining geologists will need to work in multidisciplinary teams to design more efficient and novel methods of mining and processing, which will include the use of microbiota.
5. Improved understanding of Methane Hydrates.
6. Methane hydrate is a crystalline combination of a natural gas and water that looks remarkably like ice but is inflammable. It was discovered only a few decades ago, and little research has been done on it until recently. By some estimates, the energy locked up in methane hydrate deposits is more than twice the global reserves of all conventional gas, oil, and coal deposits combined. However, we do not know how to determine volumes, or how to extract the gas inexpensively, and no one knows how much is actually recoverable.

III. What is needed to achieve them?

1. Continuing access to strategic research equipment, such as the Synchrotron and ion microprobe.
2. Access to existing and innovative geophysical kit through NERC and private partnerships. Some seismic equipment needs to be available for research independent of industry such as the ability to run Ocean Bottom Seismographs (OBS). Continued academic research into new methods for sub-surface imaging such as 3D EM and seismioelectrical methods, as well as better characterisation of seismic and electrical rock properties.

3. People with the necessary geoscience skills. Industry currently has problems recruiting young research level scientists who are adequately trained in the core skills of understanding geological maps, structural geology, sedimentology and stratigraphy.
4. Efficient public access to public datasets held in NERC, BGS, and DECC archives.

Breakout Group 3
Natural Hazards

David Pyle (lead)
Mathew Foote and Brian Baptie (core members)

> *Encompassing the challenges for Earth Science in Understanding, Prediction and Mitigation of the effects of Earthquakes, Volcanic Activity, Tsunamis and Landslides.*

I. Most important scientific advances in the past 10 years

The group preferred to identify the three most important *drivers*:

1. **Exploitation of new measurement and analytical techniques**. The expansion and application of technology for observing and measuring Earth processes has transformed our understanding of many areas of natural hazards. From satellite-imaging of Earth surface deformation (e.g. post-seismic or volcanic), or of volcanic ash and gases; to submarine imaging of sea-floor processes (e.g. submarine landslides and their link to tsunami), synoptic-scale remote sensing has opened up opportunities in real-time observation, measurement and analysis that have allowed scientists to capture the surface response to solid-earth processes. In parallel, the development of low cost sensors, or sensor arrays, has opened up data streams of high-frequency measurements (e.g. of seismicity; sound; gas composition in volcanic examples) which has transformed our ability to track processes of magma and gas flow in volcanic conduits, for example.
2. **Expansion of modeling capabilities**. Increased access to computing power has allowed for significant advances in our capacity to develop increasingly sophisticated numerical models of the natural processes which are recognized as Natural Hazards. Despite these advances, our ability to understand these processes, and to produce predictive models for future scenarios, are still limited either by our ability to develop full-3D models (e.g. many volcanic conduit models are still 1- or 2D), or by our ability to model at an appropriately fine grid scale.
3. **Advances in probabilistic approaches to hazard assessment** have had a major impact on our ability to understand both what has happened during past geo-hazard events, and what may happen during future events. At the same time, there has been a significant move towards harnessing the potential of 'multiple expert' approaches for real-time hazard assessment, as pioneered in the context of a volcanic eruption on Montserrat.

II. Most likely important science advances in the next 10 years

The *group chose to look from a slightly different perspective, focussing instead on the most significant problems/questions we would hope to have solved in the next 10 years:*

1. Develop tools and processes to integrate data with models, and to exploit the new and continuing opportunities in technology and computing. Examples would include moving from our current ability to *collect* data across large-scale mobile environmental sensor arrays, or to collect multiple high-frequency measurements (e.g. of seismic energy, fluid/gas composition, sound) to turn this into an ability to integrate and interpret these data and thereby advance our understanding of the underlying processes.
2. Extending probabilistic hazard assessment: to quantify and propagate uncertainty throughout our hazard models; to close the circle from an understanding of the physics of the process(es) to the consequence of the event across the range of spatial and temporal scales of interest to society; to build networks with researchers in disciplines outside natural science, in order to properly understand how hazards translate into risks; to engage with the public, particularly in the areas of understanding and communicating uncertainty.

3. To understand the forcings and feedbacks between environmental change and natural hazards, and in particular to understand the links between deep Earth and Earth surface processes.

III. What is needed to achieve them?

Or what factors might influence whether or not these problems are solved:

1. **Long term monitoring and observation**. A commitment to long term monitoring [i.e. continuing to record data on a continuous basis] and long term observation [i.e. using the geological record to extract the history of past events, and their impacts] requires long-term commitments to data archiving and data sharing, and continued investment in the infrastructure needed to process, visualize and model such data (i.e. high performance computing); in the infrastructure to to preserve the paleorecords of geological events (e.g. sediment and peat cores), and the facilities needed to date these events [e.g. cosmogenic and radiogenic isotope laboratories]. For these investments and activities to have their maximum impact requires continued integration with international networks (both in Europe and beyond).
2. **A continued ability to respond rapidly to events of global significance**. Step changes in our understanding of natural processes often accompanies geological events of global significance: in volcanology, examples would include Mt St Helens (1980); Pinatubo (1991); in submarine landslides and tsunamis, a key example would be the great Sumatran earthquake. UK has maintained a leading position in responding to and documenting such events, and in helping to lead the intellectual breakthroughs from these events. The UK needs to maintain and extend its ability to respond rapidly to unexpected geological events, but needs also to have the capacity to respond on a scale beyond that currently supported within the 'urgency' framework. Recent examples of science underpinned by urgency grants include work that followed from Afar (2005), the Wenchuan earthquake (2008) and the eruption of Chaiten (2008).
3. **Trained geoscientists.** There is a continuing need to grow and sustain a highly skilled pool of numerate geosciences graduates. The Bologna process (if adopted) may offer one way of contributing to this pool – by taking in first degree graduates from maths, science, engineering at Masters level, thereby exposing them to the leading problems in geoscience.

Breakout Group 4
Putting the Earth into Earth System Science

Alan Haywood (Lead)
Bob Holdsworth (Second)
Alan Vaughan (Rapporteur)

Encompassing Earth History and Palaeontology, Structural Geology and Tectonics/ Geodynamics.

I. Most important scientific advances in the past 10 years

1. The emergence of Earth System Science itself (research to examine the interactions of different components of the Earth System in time and space)
2. The ability to image the structure and deformation of the earth's surface and the interior in 3-D and 4-D using large datasets has been a significant advance. E.g. the proliferation of space-based systems and the ability to handle this, such as Google Earth. The realisation that processes in the interior influence the Earth's surface and climate
3. The rapid development (complexity and resolution) of numerical climate and environmental models to address future, current and past climate change grand challenges. The advent of Earth System Models which incorporate may more aspects of the Earth climate and environmental systems
4. A greater understanding of the evolution of the early Earth and life.

II. Most likely important science advances in the next 10 years

1. The use of Earth history and Earth System modelling to determine climate and environmental sensitivity to greenhouse gasses.

2. Modelling of the geochemical aspects of fluid flow. Modelling “multiphase fluid flow in reactive deformable media”. Six systems: Hydrocarbons; carbon capture; radioactive waste, mineralisation systems, geothermal, water
3. A greater understanding of the evolution of the early Earth and life.

III. What is needed to achieve them?

1. **Participation in major international research activities**. The UK is excellent at setting the agenda and punches above its weight scientifically yet it cannot hope to maintain its standing with the scientific and technological powerhouses of America and increasingly China unless it participates in major multi-national research initiatives such as IODP, ICDP, IRIS, ESA etc.
2. **Inter/multi-disciplinarily rooted by health discipline –based research**. Earth System Science is multi and interdisciplinary. The strength and quality of this multi and interdisciplinary research is therefore dependent upon the health of the core disciplines which are part of ESS. The Geological skills base in Britain is diminishing. For example, there is a knowledge gap developing in that the industries that need structural geology do not recognise that need. We are losing the pool of skilled people in the universities to teach it. Coal geology is another area where this gap has become apparent. There are virtually no coal geologists left in the UK yet coal is back on the agenda in terms of energy security. *National capability in the core discipline of Geology should be maintained*.
3. Need Earth Observation and further investment in the development and long term maintenance of Earth system models.

Breakout Group 5
Earth Surface – Critical Zone and marine processes

Thomas Wagner (lead)
Mike Ellis, Carrie Lear and Peter Singleton (core members)

I. Most important scientific advances in the past 10 years

1. Evidence-based concept describing the Earth’s surface as a dynamic interface that integrates and couples the deep subsurface with atmospheric and ocean processes and with the biosphere. Examples of this holistic understanding include :
   - The role of climate-driven erosion in driving vertical crustal motions and thus affecting global relief
   - Understanding some of the feedback mechanisms that give rise to climate instability
   - The Critical Zone as a dynamic 3D concept operating and modulating the 2D Earth surface through complex interactions between the atmosphere and carbon stored above and below ground linked through changes in the hydrological cycle.
   - Biota/ecosystems as drivers and modulators of biogeochemical processes in response to climate change.
   - Land-Ocean processes driving large scale exchange and cycling of mater and energy between both main compartments (global biogeochemical cycles)
2. Advanced process understanding of past environmental change through high-resolution climate and environmental records from sediments. Detailed climate records from a wide range of different climate perturbations and depositional environments, both marine and terrestrial, in many cases does now allow to approximate the direction, dimension and timing of change, leading to more quantitative information on rates of change.
3. Instrumental advances in strategic areas, including
   - High resolution chronology
   - Light stable isotope geochemistry
   - Complex modelling
   - In situ, non-invasive experiments and analyses

II. Most likely important science advances in the next 10 years

The group instead chose to express this as the “main challenges”:

Main challenges:

1. The functioning of internal dynamics to external forcing. Advancing the quantitative knowledge of these relationships will improve understanding of processes, feedbacks, thresholds/tipping points, and will reduce or overcome the level of uncertainty. Specific sub-systems to be studied include
   - Feedback mechanisms between climate and forcing mechanisms, the latter including both astronomical effects and internal effects including freshwater inputs to the oceans from melting of ice sheets and from rivers.
   - The dynamics of ice sheets and associated sea level fluctuations
   - The nature of glacial/interglacial transitions, in particular the history of sea level during past interglacials
   - The hydrological cycle and main biogeochemical cycles
   - Ocean acidification and deoxygenation; the thread of spreading dead zones in a future warmer ocean
2. Crossing scales, both temporal and spatial. Any significant advance will require cross-disciplinary concepts that integrate high resolution proxy records from a range of strategic locations and better understanding of nano-scale processes using advanced coupled models. Specific objectives of research include
   - The role of people humans as a geological agent
   - Extending the climate envelope to fully explore climate histories from the deep time sedimentary record.

III. What is needed to achieve (or address) them?

1. Continued engagement with IODP/ICDP to secure access to existing core material and opportunities to propose new UK-led drilling initiatives.
2. Improved infrastructure and larger capacities for key techniques including high resolution chronology and MC-ICP-MS. Maintenance of capacity in techniques relevant to geochronology on Quaternary timescales, including the following: U-series dating, modern high-spec amino acid dating, luminescence dating, thermochronological techniques (e.g., AFT, apatite-helium), magnetostratigraphy, dating using the different variants ofg the K-Ar system (including provision of unspiked [Cassignol] K-Ar dating, currently not available in the UK). Also, maintenance of mammalian and molluscan biology and palynology, due to their importance in Quaternary geochronology.
3. Better financial and structural support for pilot studies especially for interdisciplinary topics
4. Demand to open (industrial or otherwise confidential) databases for academic research; including fostering a new culture to make published data available to the community. Data and derived data products (such as geophysical maps) held by BGS and equivalent organisations should be freely available to academic users, as is the custom in other countries.
5. Improved funding mechanisms (including improved mechanisms for funding pilot studies) cross-disciplinary proposals which are transparent and adequately charged to support this type of research
6. Improved use of new communication media, in particular the internet

----

Breakout Group 6
Deep Earth

Lars Stixrude (lead)
Marian Holness (second)

Encompassing the crust to the core; Igneous and Metamorphic Petrology and Deep Earth Geophysics: Seismology, and Geomagnetism.

I. Most important scientific advances in the past 10 years

Studies of the deep Earth have advanced rapidly over the last few years through increasing quality and coverage of observational data, particularly seismological networks, and satellite-based observations, and improvements in technology, particularly in mass spectrometry, synchrotron radiation, and computational power. Through a variety of initiatives, such as the Cooperative Institute for Deep Earth Studies (CIDER) studies of the deep Earth have seen a dramatic increase in the communication between sub-disciplines ranging from petrology to seismology, and this communication has proved essential as a way of shedding new light on long-standing problems. Among the important advances have been:

1. Structure and dynamics of the mantle. Seismic tomography has revealed the internal structure of our planet in remarkable detail and demonstrated that at least some subducting slabs traverse the entire mantle. This has overturned the long-standing view that the mantle was strictly layered, and presents a continuing challenge to the explanation of the long-term survival of chemical heterogeneity in the mantle. Seismic imaging has revealed fine structure at the core-mantle boundary that is shedding new light on the interaction between core and mantle, the origin of mantle plumes, and the generation of the geodynamo. Some of these features have found an explanation in a newly discovered phase transition: from perovskite, which makes up most of our planet, to a denser post-perovskite phase. The new phase was discovered through a combination of high-pressure experimentation combining diamond anvil cells with synchrotron radiation, and ab initio predictions of crystal structure. Many of these new discoveries are being incorporated into the first generation of fully spherical models of mantle convection, which have already provided new perspectives on the long-term development and survival of geochemical heterogeneities in the mantle and what observed lava compositions can tell us about the dynamics of the deep Earth.
2. Sub-surface magma- and fluid-flow and related reactions. Fluid flow in the deep Earth is remarkably complex because it occurs in a reacting and deforming matrix. Grappling with this complexity is essential for understanding a host of deep Earth processes including ore formation, cycling of volatiles from the surface environment to the deep Earth, and the generation of magma. Major advances have come in U-series dating, which has overturned conventional wisdom about the rates of magmatic transport, deep drilling of the oceanic crust which has revealed a previously unsuspected degree of heterogeneity and uncovered the richness of the processes by which most magma on Earth is emplaced, advances in the theory and modelling of the dynamics of deep fluid flow, including the discovery that fluid flow can become highly organized on many length scales, and advances in fundamental thermodynamics including the development of new tools for the prediction of fluid-present metamorphic reactions that allow us to unravel the history of Earth's crust with much greater confidence.
3. Constraints on earliest-Earth processes. The development of new chronometers and increasing precision of mass spectrometry have transformed studies of the earliest Earth from a realm dominated by speculation to one driven by testable hypotheses. The development of the W-Hf chronometer has demonstrated that the core formed within a few tens of millions of years after the closure of the solar system, much faster than had been thought before. Precise measurements have revealed that the Nd isotopic composition of the observable silicate Earth differs systematically from chondritic meteorites. These has far reaching implications and means either that the long-standing chondritic model of Earth composition is wrong, or that a chondritic complement exists in the form of an ancient, enriched, un-sampled reservoir exists somewhere in the deep Earth, and which may be related to the earliest fractionations of the silicate Earth.

II. Most likely important science advances in the next 10 years

Future contributions are likely to include a renewed effort to understand the influence of deep Earth processes on Earth's surface and how this influence sets fundamental boundary conditions for the evolution of our surface environment and life. Important questions to be addressed will be:

1. How does mantle dynamics control surface topography and sea level? Mantle dynamics has an important influence on sea level even on the time scale of global warming. Models have shown that melting of the sea level rise due to melting of the West Antarctic Ice Sheet will be far from uniform because of the influence of the Earth's gravitational field and elastic deformation of the solid interior.

On glacial-interglacial time scales, the viscous response of the mantle due to ice-sheet unloading has a major influence on sea level. Determining global sea level throughout the quaternary will require advances in dynamical and structural models, particularly a better understanding of the thickness and rheology of continental lithosphere. On longer time scales, mantle convection produces mountain belts and floods entire continents via dynamic topography. Determination of Earth's topography in the deep past will require advances in models of mantle convection, and will serve as boundary conditions to paleo-climate models of epochs such as the Paleocene, which are thought to be the closest ancient analogs to a doubled-CO_2 future world.

2. How are volatiles transported across the solid surface? The solid Earth holds by far the largest reservoir of CO_2, and may contain much more H_2O than the surface ocean. Small changes in the size of the solid Earth volatile reservoirs lead to large changes in the nature of the surface environment and climate on long time scales. For example, there is good evidence that atmospheric CO_2 was four times higher in the Cretaceous, and this additional CO_2 must have come from the solid Earth. If Earth's climate entered snowball states in the geologic past, it likely escaped them by addition of CO_2 to the atmosphere from volcanism. Could H_2O have varied significantly over geologic time? Progress will come from a better understanding of the mechanisms by which CO_2 and H_2O are stored in the crust, mantle, and possibly the core via investigations of material behaviour at elevated pressure and temperature and improved characterization of natural samples; development of a new generation of dynamical models of fluid flow in multi-phase, reactive, deforming media, further advances in isotopic methods for constraining the rates of flow processes.
3. Origins. How were the atmosphere, oceans, and crust extracted from the mantle and when, how did the earliest solid Earth evolve, and how did this impact the evolution of life? The development of giant impact paradigm for the origin of the moon has fundamentally altered our view of the earliest Earth and set a natural initial condition from which to explore its subsequent evolution. How did the resulting silicate atmosphere cool and evolve into a nitrogen rich atmosphere? How and when did water condense on the surface? When did continental crust begin to form and when was it first stabilized? Advances will come from new generations of dynamical models that account for the wide range of fluid dynamical regimes that are relevant, ranging from dense atmospheres, to magma oceans, to the earliest stages of plate tectonics; from continued search and characterization of the earliest materials formed by geological processes, including zircons; and from the development of new geochronometers that will help to date differentiation events.

III. What is needed to achieve them?

1. Programmatic research funding. Our view of where our field is headed fits well with ongoing thematic initiatives at NERC including the proposed theme action plan in "Dynamics of the Earth's Interior and its Surface Manifestation". Programmatic research funding will be essential to sustain a concerted and inter-disciplinary effort in answer the biggest questions
2. Maintain strength in Blue Skies funding opportunities. This will remain an indispensable part of any future progress in studies of the Deep Earth and will allow for the possibility of unanticipated new discoveries that may steer the field in completely new directions.
3. Maintain our presence in satellite observation programs, the International Ocean Drilling Program, and National and local High Performance Computing efforts. There is also a need to enhance deep imaging capabilities including seismographic networks with ocean-bottom seismometers.