Introduction

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The earth sciences are enjoying a renaissance. Global issues in the earth sciences, such as building a tsunami warning system or burning of fossil fuels, are discussed at meetings of world leaders; there is a strong level of popular interest as witnessed by the public response to the acclaimed BBC series, "Walking with Dinosaurs"; while debate about the Permian extinction amongst intellectuals has not been so intense for over a century. Elsewhere the earth sciences are not seen in a positive light, caught in a political storm as "intelligent design" is pitted against Darwinism in the educational boards of the USA and are the target of environmentalists, because of the damage caused by the mining and oil industries. The earth sciences deal with the dynamics and evolution of Earth's crust and the life it supports, its interactions with the ocean-atmosphere system and the Earth's deep interior, and the Earth's near-space environment. It is because the earth sciences deal so directly with our "life support system" they are at the centre of intellectual and political controversy. Of course this is not new. Charles Lyell, one of the founders of geology in the nineteenth century, was not only embroiled in the controversies over the science of the evolution of the Earth and of life, but also the politics. What is new today is the urgency which some of these issues need to be addressed.

The modern earth sciences cover a huge subject range — from earthquakes to global warming. But where are the advances being made and which topics do we need to keep abreast of? A generation ago the principal paradigm driving research in the earth sciences was plate tectonics. The construction of plate tectonic theory was surely one of the great intellectual achievements of the twentieth century. The idea of a dynamic Earth has made as big an intellectual impact as any scientific discovery. Indeed, the triumph of plate tectonic theory seems so complete is there anywhere else for it to go? Some scientists have argued that it is to the terrestrial planets of the Solar System we need to look for breakthroughs of the same significance. However in this book we see that studying the dynamics of the Earth is still a key research area where advances are being made. But perhaps the biggest issues driving research in the earth sciences are about understanding the complexities of environmental change and environmental hazards. This shift is reflected in this book where these issues feature prominently.

One of the key developments in the earth sciences has been a move away from a reductionist approach, where the earth sciences can be reduced in their supposed basic components of the disciplines and sub-disciplines of physics, chemistry and biological. What drove this was a perceived failure of the reductionist approach to deliver on its promises of understanding the complexity at the Earth's surface; examples of which are earthquake prediction and safe disposal of nuclear waste. In the 1990s we saw the collapse of the US and Japanese earthquake prediction programmes and the UK government's refusal to sanction the building of a new underground radioactive waste repository. These can be seen as consequences of the inherent complexity in the mechanical and physical behaviour of the crust, which cannot be solved by classical physics. What has however arisen is an appreciation that the Earth is a complex system, which has to be treated in a holistic way. This is an earth system science approach that is as interested in the interaction between processes as much as in the processes themselves. In the climate system these are called feedbacks — but in these feedbacks, such as cloud formation, that are the principal controls. This change in perception in the earth sciences is seen in this book. Alongside the rise of the treatment of the earth as a complex system, have been the development of the tools that have allowed earth scientists to do this: Improvements in earth observation and particularly satellite remote sensing; improvements in computing power to allow ever more detailed simulations; improvements in the resolution of laboratory analytical techniques. The rise of the internet, ever lower travel costs and improved infrastructure have allowed global inter-comparisons to be made ever more readily. The globalisation of science has also brought us successful large international collaborations such as the ocean-drilling programme (IODP), on a scale which no one country could fund, but can be accessed by scientists worldwide.

The articles in this book have been written by earth scientists from a broad range of backgrounds specialising in a diverse range of research subjects. Our key criterion has been to accept articles only from world-class scientists. But a volume of this nature cannot hope to be comprehensive in capturing all the advances in the earth sciences. The contributing authors are mostly younger scientists, at the forefront of their subjects: They are indeed the future of the subject. The articles address the key areas of advances in the earth sciences in:

- Environmental change
- Dynamics of the Earth
- Applied earth sciences

Editors to a certain extent are at the mercy of the scientists who choose to contribute, or at least to those whom the editors have managed to persuade to break from their research to explain their field to a broader readership. The geographical distribution of the authors does reflect the provenance of this book in the articles originally published in the Philosophical Transactions of the Royal Society, London — the world's longest running scientific journal. There are some obvious gaps: An example is physical volcanology. Volcanic eruptions have been predicted and evacuations carried out following prediction by scientists. There has been a huge increase in the understanding of physical volcanology to facilitate this. The very recent development of landscape evolution and modelling as a subject area is missing. Satellite remote sensing of the cryosphere is not covered — although this might be seen as being more directly linked to meteorology. We do not have an article on Japan's huge computer, the "Earth Simulator". One of the new hot topics of Eocene climate change, 30 millions years ago, is not dealt with. We have no report on how laboratory experiments are transforming our understanding of the Earth's mantle. However we believe the book does give a flavour of the advances currently being made in research on the earth system.

Environmental Change

Environmental change is now one of the key drivers of research in the earth sciences. Geologists have of course always studied environmental change. "The present is the key to the past" was the dictum of James Hutton in the eighteenth century. This dictum was taken up by his successors such as Lyell who could demonstrate that sedimentary rocks were deposited gradually in similar environments to those of today: Old red sandstones originated from deserts; limestones which might cover them were laid down in shallow seas; whilst sandy-clay layers were the run-out of giant submarine flows bringing material from the continental shelves into the oceans, triggered by tectonic activity. The changing environment is recorded in the geological record. What is new is that it is no longer just geologists, but physical geographers, ecologists, meteorologists and oceanographers too who now work on environmental change. The resurrection of a nineteenth century idea that carbon dioxide in the atmosphere is a determinant of our climate, along with evidence of rapid past climate change from ice and ocean sediment and cores, satellite measurements of the global temperature distribution and ice extent and the availability of sophisticated computer programs written to predict the "nuclear winter", created the intellectual environment in which concerted efforts could be made to predict what the future climate holds for us, and its consequences. This research cuts across traditional scientific boundaries, but undeniably forms the most dynamic part of the today's earth science.

The book opens with an article by Dave Reay on the price of climate change. It is probably not possible to start with a more contentious or political scientific issue. He argues that the combined uncertainties in both the science and the economics of climate change are so large that a limitless range of outcomes is possible. However he examines existing cost-benefit analyses and concludes that there are host of abatement strategies that are able to deliver significant carbon dioxide emission reductions at little or no net cost when the full economic impacts of climate change are considered. Yadvinder Malhi examines carbon in the atmosphere and terrestrial biosphere. He argues that the anthropogenic perturbation of the global biogeochemical cycle is so large, that understanding and managing its effects are amongst the most pressing issues of the twenty-first century. One of the key issues is how much carbon dioxide is absorbed by vegetation — the "terrestrial carbon sink". He proposes that controlling deforestation and managing forests has the potential to play a significant role in stabilising atmospheric carbon dioxide concentrations. Andy Ridgwell and Karen Kohfeld, continuing this theme of the need to treat the earth system as a whole, investigate the biogeochemical linking of the land, air and sea. Specifically they examine the role of dust in the earth system. The atmospheric transport of mineral dust is a key pathway for the delivery of nutrients essential to plant growth not only on land, but also more importantly in the oceans. The stimulation of plant productivity by these nutrients controls carbon dioxide take-up from the atmosphere, so the whole system is linked. Finally Richard Twitchett discusses the Late Permian mass extinction. This was a biological catastrophe in a greenhouse world and a salutary reminder of what has happened in earth history.

Dynamics of the Earth

Research into the evolution and dynamics of the Earth is a major research area in the earth sciences, however this is not confined to the solid Earth. Indeed some of the most active research is studying the Earth in its near-space environment. But the widespread acceptance of plate tectonic theory has not meant diminished interest in the solid Earth. Within the broad plate tectonic framework there is the need to understand the details of the rifting of continents and the formation of ocean basins; the ascent of magma in the formation and eventual eruption of volcanoes; the dynamics of the Earth's deep interior and how it is coupled to the Earth's surface evolution. Nowhere has research been more promising than advances in understanding the Earth's iron core. Its enigmatic behaviour is at last giving way to the application of new models of magneto-hydrodynamics coupled with a far better understanding of the core's composition through computation mineral physics. There is also a societal need to understand earth dynamics driven by the need to assess and mitigate earthquake hazard. "Is this even possible?" is a question that drove much theoretical research in crustal dynamics at the end of last century. The problem is not so much that crustal dynamics cannot be modelled, but that the expectation of being able to predict behaviour of the crust during a tiny time interval, of far less than a human lifespan, and in tiny area, covering that of a suburb, is probably unrealistic, when the driving forces operate on geological time and spatial scales. But even here, new techniques are coming to bear on this problem, which may make some resolution possible.

This section starts with a review by Cathryn Mitchell of research on the Earth's dynamics in relation to its environment in space and in particular the Earth's ionosphere. Echoing the need for the Earth to be treated as an integrated system, she says it is becoming clear that to produce "space weather" forecasts new research projects are needed to link together models of the entire solar-terrestrial system, including the Sun, solar wind, magnetosphere, ionosphere and thermosphere. Moving to the solid Earth, Eiichi Fukuyama argues that we are now able to simulate the dynamic rupture process of real earthquakes, once the fault geometry, stress field applied to the fault, and friction law on the fault surface have been provided. Simon Turner looks at the processes of magma formation, ascent and storage in shallow magma chambers prior to eruption beneath island arc volcanoes. The details of these processes can be followed by high resolution dating of between 100 to 10 000 years ago using radioactive isotopes. Tim Minshull examines the new theories on the the break-up of continents and the formation of new ocean basins necessitated by observations of mantle rocks at continental margins. Francis Nimmo and Dario Alfe review recent advances in understanding the properties and evolution of the Earth's core and geodynamo. They focus on the properties of the core-forming materials and how core dynamics generates the Earth's magnetic field (the geodynamo). This article then links back to the first in this section.

Applied Earth Science

The earth sciences have always had a strong applied side. Indeed the world's first geological map was prepared by William Smith who earned his living as a surveyor for constructing canals. Geologists and geophysicists are central to the mining and petroleum industries, which underpin our modern society, but nowadays applied earth scientist are as likely to involved in mitigating natural hazards and controlling pollution. In a complex system, making assessments, which satisfy public and political expectations, is testing. For instance, even if we can understand the dynamics of a major fault, earthquakes unfortunately continue to occur on previously unrecognised faults.

Chris Kilburn describes a new understanding of one of the most devastating natural hazards: Giant landslides. They are caused by the collapse of whole mountainsides, which feed giant landslides that travel kilometres within minutes. Both their size and speed prevent effective hazard mitigation after collapse. Tim Wright reports on one of the most exciting advances in the earth sciences, that of using satellite radar interferometry for remote monitoring of the earthquake cycle. For the first time, detailed maps of the deformation of the Earth's surface during the earthquake cycle can be obtained with a spatial resolution of a few tens of meters and a precision of a few millimetres. In his article, he reviews some of the remarkable observations of the earthquake cycle already made using radar interferometry and speculates on breakthroughs that are tantalisingly close. Dominik Weiss, Malin Kylander and Matthew Reuer address the human influence on the global geochemical cycle of lead. Human activity dominates this cycle as a result of large lead consumption over human history and accounts for an estimated 97% of the global mass balance of lead. The overall burden of anthropogenic lead emissions has decreased but new pollution sources have become important meaning it is still a global problem. Lead is not biodegradable and finds its way into the ecosystem. Hazel Prichard examines other heavy metals, platinum and palladium and their natural and artificial occurrences worldwide. The catalytic converters used to reduce poisonous exhaust emissions from cars use platinum and palladium, which are now accumulating in our cities and approaching concentrations found in natural deposits. In rounding off the volume, David Lary and Anuradha Koratkar look forward to an objectively optimised earth observation system, which will dynamically adapt the what, where, and when of the observations made in real time to maximise information content and minimise uncertainty. They describe a prototype system applied to atmospheric chemistry. An example of its application might be the remote identification of sites of likely malaria outbreaks, the early identification of potential breeding grounds for mosquitoes and sites to apply larvicide and insecticide. Optimising the response would reduce costs, lessen the chance of developing pesticide resistance and minimise the damage to the environment. They describe in effect the practical application of earth system science.