

Deep Earth - *from crust to core*

Earth sciences for society

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



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What is this brochure for?

This brochure is a prospectus for one of the main scientific themes of the International Year of Planet Earth 2005-2007.

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

It was written by a panel of world experts, assembled by the Science Programme Committee for the International Year.

To find out more...

Every science theme will have a prospectus like this one. To find out about the other research themes being pursued under the International Year, please consult www.esfs.org (where all our publications can be found).

What to do next...

If you are a scientist wishing to register initial interest in possibly making a research proposal under this theme, please go to www.esfs.org and download the appropriate Expression of Interest (Science) form, and follow the instructions on submitting this to the International Year. (If you cannot find such a form, it means that it is not ready – please keep visiting the site.)

The deep Earth may sound remote

from everyday concerns, but it has strong

relevance for humanity

Introduction

During the last few decades, Earth sciences have evolved rapidly and are now able to produce scientific models that can help to reconstruct and forecast the past and future processes of the solid Earth.

This includes forecasting the future behaviour of geological systems, and also the prediction of future geological patterns. The structure and processes of the deep Earth may sound remote from everyday concerns, but both have strong relevance for humanity's basic needs, such as supply of water and resources, protection against natural hazards, and control of the environmental degradation of the Earth.

This scientific theme will focus on two key questions:

- how can we better understand mass transfer (see below) at Earth's surface, and its feedback with deep Earth recycling?
- how can our improved understanding of Earth processes lead to better prediction?

Specific projects under these headlines will be on a large scale, and of the highest quality, involving:

- *in situ* and 'real time' monitoring programmes including satellite, surface and borehole monitoring instruments
- geomechanical and geochemical laboratory facilities
- geo-information databases containing historical data on global and regional changes in combination with the vulnerability of natural and human habitats
- building a knowledge base on the modelling and simulation of geo-motions, as well as on risk and impact assessment.

In recent years geologists have come to understand the solid Earth in more measurable ("quantitative") ways. Better seismic techniques have brought us to a better understanding of the 3D structure of the Earth's mantle and lithosphere. We can describe, in numerical terms, how the deep Earth system works; at the same time, quantitative analysis of the basins in which sediments accumulate has allowed us to connect the deep Earth system with the record of those changes written in the sediments that build up over geological time.

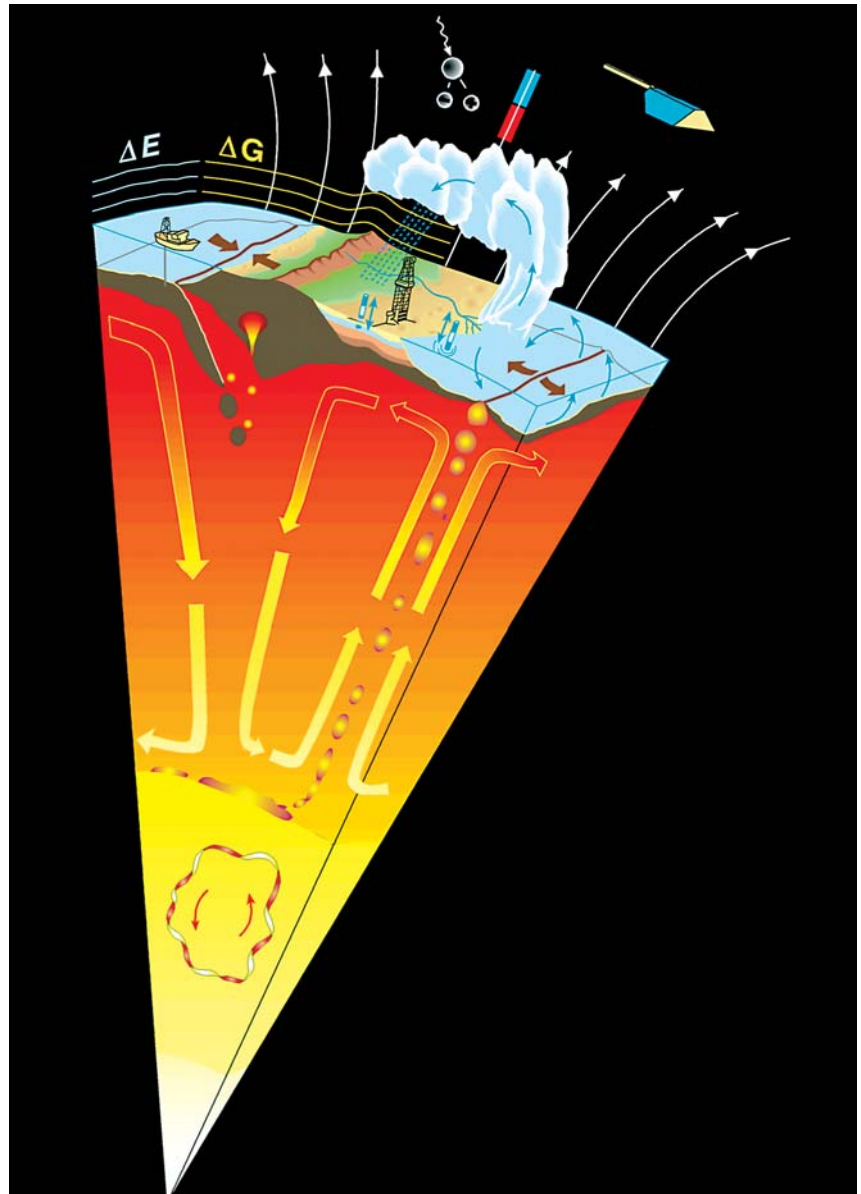
Better ways of "seeing" through solid rock have allowed Earth scientists to understand the fine structure of the Earth's outer shell, or "lithosphere", and how it deforms under pressure from the movement of the Earth's crustal plates, in three dimensions. Recent advances in the ways geologists can give things accurate ages in years have made it possible to find out how fast tectonic and surface processes take place, with the precision necessary to distinguish between the different forces that shape the landscape.





Using space satellites to survey the Earth has allowed us to obtain ever-higher resolution when monitoring the vertical motions of Earth's surface. Modelling the way topography changes with time has now reached the stage where it is possible to couple studies of sediment supply and erosion in time and space. At a much smaller scale, we face problems of sedimentary architecture (the way different sediments are structured), and of imaging this architecture using remote sensing techniques that use seismic or electromagnetic waves to see inside them, like a "body scanner".

Despite enormous progress in the last 15 years, such remote imaging barely keeps pace with the great demands society places upon it, with urgent needs for water supplies, mineral resources, protection against natural hazards and control of the environment.



● **The deep Earth framework**
provides a unifying theme ●

The International Year

Initiated by the International Union of Geological Sciences (IUGS) in 2001, the proposed International Year of Planet Earth was immediately endorsed by UNESCO's Earth Science Division, and later by the joint UNESCO-IUGS International Geoscience Programme (IGCP). The main aim of the International Year - to demonstrate the great potential of the Earth sciences to lay the foundations of a safer, healthier and wealthier society - explains the Year's subtitle: Earth sciences for society.

How will it work?

To achieve maximum political impact, the IUGS-UNESCO team aims to have the International Year proclaimed through the UN system, targeting 2006 as the Year itself. Its ambitious programmes cannot, however, be implemented in twelve months. We expect the Year's activities to begin in 2005 and culminate in 2007.

Mass transfer

"Mass transfer" means the way in which rocks are eroded from certain areas of the Earth's crust and redeposited in others, and the way the Earth's plastic interior responds to those gradual changes in pressure. This presents a new frontier in modern Earth sciences - namely, trying to understand these processes quantitatively.

This research strategy bridges current approaches that separately address high-resolution timescales for a limited near-surface record on the one hand, and the long-term and large-scale approaches that are more typical of studies at the scale of whole sedimentary basins. The essential step towards a four-dimensional (4D) approach (i.e. involving both space and time) requires modelling solid Earth processes in a way that incorporates smaller scale data with high quality modern seismic imaging. We need to probe the deep Earth, to obtain a high-resolution image of both deep Earth structure and processes, if we are to quantify and constrain the forces that drive the Earth's crustal plates.

The deep Earth framework provides a unifying theme capable of addressing, in a process-oriented way, the full dynamics of the Earth system. Recent technical advances (including seismic tomography, Earth-oriented space observations, oceanic and continental drilling, Earth modelling, and analytical techniques) have created fertile ground for a breakthrough by means of a global effort that integrates state-of-the-art methodology and the assembly of global databases.

Key issues

Continental topography: interplay of deep Earth and surface processes

Topography, the landscape's physical shape, is a product of the interaction between processes taking place deep in the Earth, on its surface, and in the atmosphere above it. Topography influences society, not only in terms of the slow process of landscape change, but also through climate. Topographic evolution (changes in land, water and sea levels) can seriously affect human life, as well as plants and animals. When levels of fresh water or of the sea rise, or when land subsides, the risk of flooding increases, directly affecting local ecosystems and human settlements. On the other hand, declining water levels and uplift may lead to a higher risk of erosion and even desertification.

● **The pressure that we are placing
upon the environment
makes us increasingly vulnerable** ●

About the International Year

Although 2006 will be the official “year”, the whole project will begin in 2005 and run through to 2007. The main reason for this is that its ambitious objectives cannot be achieved in twelve months. For this is an international year with a difference. First, it aims to raise a staggering \$20m, making it one of the biggest such enterprises ever attempted. Second, it aims to divide this sum equally between the support of research, and the support of what it terms “outreach” activities – broadly, educational, public relations and other...

These changes are caused both by natural processes and human activities, yet the absolute and relative contributions of each are still little understood. The present state and behaviour of the Shallow Earth System is a consequence of processes on a wide range of time scales. These include:

- long-term tectonic effects on uplift, subsidence and river systems
- residual effects of ice ages on crustal movement (the weight of ice accumulations depresses the Earth’s crust, and takes tens of thousands of years to recover following melting of the ice sheets
- natural climate and environmental changes over the last millennia right up to the present, and
- the powerful anthropogenic impacts of the 20th Century.

If we are to understand the present state of the Earth System, to predict its future and to engineer our sustainable use of it, this spectrum of processes (operating concurrently but on different time scales) needs to be better understood. The challenge to Earth science is to describe the state of the system, to monitor its changes, to forecast its evolution and, in collaboration with others, to evaluate different models for its sustainable use by human beings.

Research will need to focus upon the interplay between active tectonics, topographic evolution, and related sea level changes and drainage pattern (river) development. This includes developing an integrated strategy for observation and analysis, emphasising large scale changes in vulnerable parts of the globe.

Making accurate geological predictions in complexly folded and faulted mountain belts will require collaboration between researchers from several broad fields of expertise. Among other scientific disciplines, geology, geophysics, geodesy, hydrology and climatology, as well as various fields of geotechnology, will need to be integrated.



Geoprediction: observation, reconstruction and process modelling

The increasing pressure that we are placing upon the environment makes us increasingly vulnerable. We have an urgent need for scientifically advanced “geo-prediction systems” that can accurately locate subsurface resources and forecast the timing and magnitude of earthquakes, volcanic eruptions and land subsidence (some of which is caused by human activity). The design of such systems poses a major multidisciplinary scientific challenge. Prediction of solid Earth processes also imposes important constraints on predictions in oceanographic and atmospheric sciences, including climate variability.

Predicting the behaviour of geological systems requires two things: a thorough understanding of the processes, and high quality data. The biggest progress in quantitative prediction is expected to occur at the interface between modelling and observation. This is the place where scientific hypothesis is confronted with observed reality. In its most advanced version, the integrated sequence “observation, modelling, process quantification, optimization and prediction” is repeatedly carried out (in time and space) and the outcome is vital in generating fundamentally new conceptual developments.

Observing the present

Information on the (present-day) structure of the subsurface and the deeper interior of the Earth (at various scales) is a key aspect of solid Earth science. This pertains to the study of both active processes and those that have ceased to be active but which may have contributed to present-day structures. The study of active processes plays an important role in this respect because process-related observations (concerning, for example, earthquake activity, surface deformation and the Earth’s gravity field) can be made (and used) as constraints upon process models. The process-related insight gained from such exercises is very valuable in guiding our reconstruction of past processes.

...avenues of mass communication to bring the main message of the Year - and its research results - home to billions of people world wide. No UN year has ever operated at quite this sort of scale.

Although the research themes provide the Year with a clear focus, the Year will operate entirely responsively, building on demand from the research grassroots. The nine themes have been chosen for their societal impact, their potential for outreach, as well as their multi-disciplinary nature and high scientific potential.





Reconstructing the past

Although the solid Earth has changed continuously through time, it still retains vestiges of its earlier evolution. Revealing the roles played in controlling rates of erosion and sedimentation by internal lithospheric processes and external forcing represents a major challenge.

The sedimentary cover of the lithosphere provides a high-resolution record of the changing environment, as well as of deformation and mass transfer at the surface and at different depths in the crust, lithosphere, and mantle system. In the last few years, pioneering contributions have helped to explain how lithosphere tectonic processes and the sedimentary record are related. These demonstrate, for example, the control exerted by stress fields in the Earth's plates on the sequences of sediments that accumulate above them, and on the record of relative sea-level changes in sedimentary basins. Earth scientists are also becoming increasingly conscious of the way that active tectonic processes affect sedimentary basins, as well as the major implications these processes have for fluid flow and recent vertical motions in the coupled system that links the deep Earth and its surface processes.

The sedimentary cover of the lithosphere provides a record of the changing environment, involving deformation and mass transfer at the Earth's surface and at different depths within the crust, lithosphere, and mantle system. In the past few decades, sedimentary basin analysis has been in the forefront in integrating sedimentary and lithosphere components of the (previously separate) fields of geology and geophysics. Integrating active tectonics, surface processes and lithospheric dynamics in the reconstruction of the ancient topography of these basins and their surrounding areas is a key objective. A fully integrated approach (combining dynamic topography and sedimentary basin dynamics) is also important, considering the key societal role these basins play as resource locations, such as hydrocarbon reservoirs and source rocks. Moreover, given that most people alive today live either within or close to sedimentary basins (in coastal zones and deltas) both populations and their settlements remain vulnerable to geological hazards posed by Earth system activity.

See also Prospectus 3 in this series - *Hazards*.



Science programme

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

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

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

For more information -
www.esf.org





Lithosphere deformation behaviour

The way the rocks of the Earth's mantle flow exerts controls on the thickness and strength of the lithospheric plates, the extent of coupling between plate motions and flow in the Earth's interior, and the pattern and rate of convection in the asthenosphere - as well as more local processes such as the pattern and rate of mantle flow and melt extraction at mid-ocean ridges. In order to understand the dynamic behaviour of the outer parts of the solid Earth, notably the dynamics of lithospheric extension and associated rifting and sedimentary basin development, a detailed knowledge of the way in which the different zones of the mantle flow is essential.

Process modelling and validation

Modelling solid Earth processes is in a transitional stage between kinematic and dynamic modelling. This development cannot take place without the interaction with (sub)disciplines addressing Earth structure and kinematics, or reconstructions of geological processes. In fact, advances in structure-related research, in particular the advent of 3D seismic velocity models, have set the stage for studies of dynamic processes inside the Earth. Structural information is a prerequisite for modelling solid Earth processes. Similarly, information on present-day horizontal and vertical movements, as well as reconstructed past motion, temperatures or other process characteristics, is used in formulating and testing hypotheses concerning dynamic processes. Inversely, the results of process modelling motivate and guide research in observation of the present and reconstruction of the past.

Through the emphasis on process dynamics, it is in process modelling in particular that the full benefits of coupling spatial and temporal scales become apparent. The scale of the processes studied ranges from the planetary dimension to the small scale relevant to sedimentary processes, with the depth scale being reduced accordingly.

● In spite of the great success of

plate tectonic theory,

fundamental questions still remain ●

International Year – themes

Groundwater -
towards sustainable use.

Hazards -
minimising risk,
maximising awareness.

Earth & Health -
building a safer
environment.

Climate -
the 'stone tape'.

Resources -
sustainable power
for sustainable
development.

Megacities -
going deeper,
building safer.

Deep Earth –
from crust to core.

Ocean –
abyss of time.

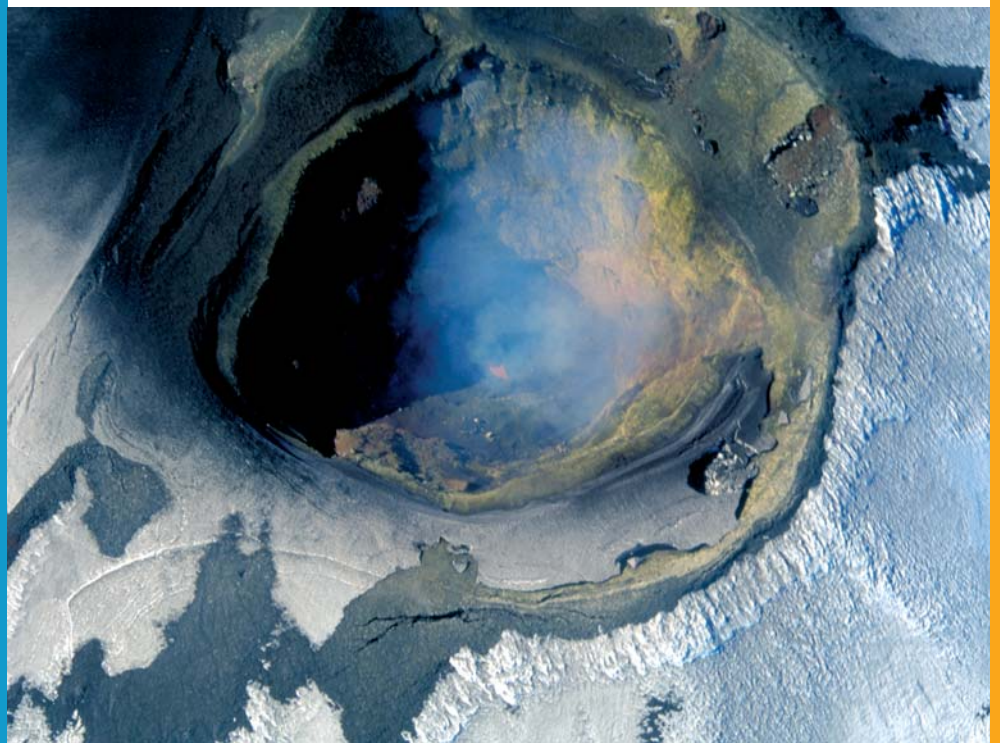
Soils –
thin brown line.

Challenges and new developments

In spite of the great successes of plate tectonic theory in modern Earth science, fundamental questions still remain concerning the evolution of continents and their role in the dynamics of the Earth's lithosphere and mantle. The growth process of continents (on the scale of a differentiating planet), their thickness and the dynamic coupling with the underlying mantle are topics requiring focused attention from a series of sub-disciplines.

Equally important questions remain to be solved concerning mechanisms controlling continental tectonics and their effects on vertical movements, dynamic topography, and sedimentary basin formation. Vital in this respect are the dynamics of splitting continents, how one plate dives beneath another at a subduction zone, how mountains are built and denuded by erosion, and their effects on continental platform evolution and on the boundary processes between oceans and continents. Equally important are the rates and scales at which these processes operate.

In order to quantify the essential processes involved in solid Earth science, it is essential to couple both internal and external forcing. From the extensive scale of (upper) mantle and lithospheric structure and processes, work on crustal structure and processes, the dynamics of topography and sedimentary basins and their sediment fills progresses at increasingly finer scales.



● The modern Earth system approach requires

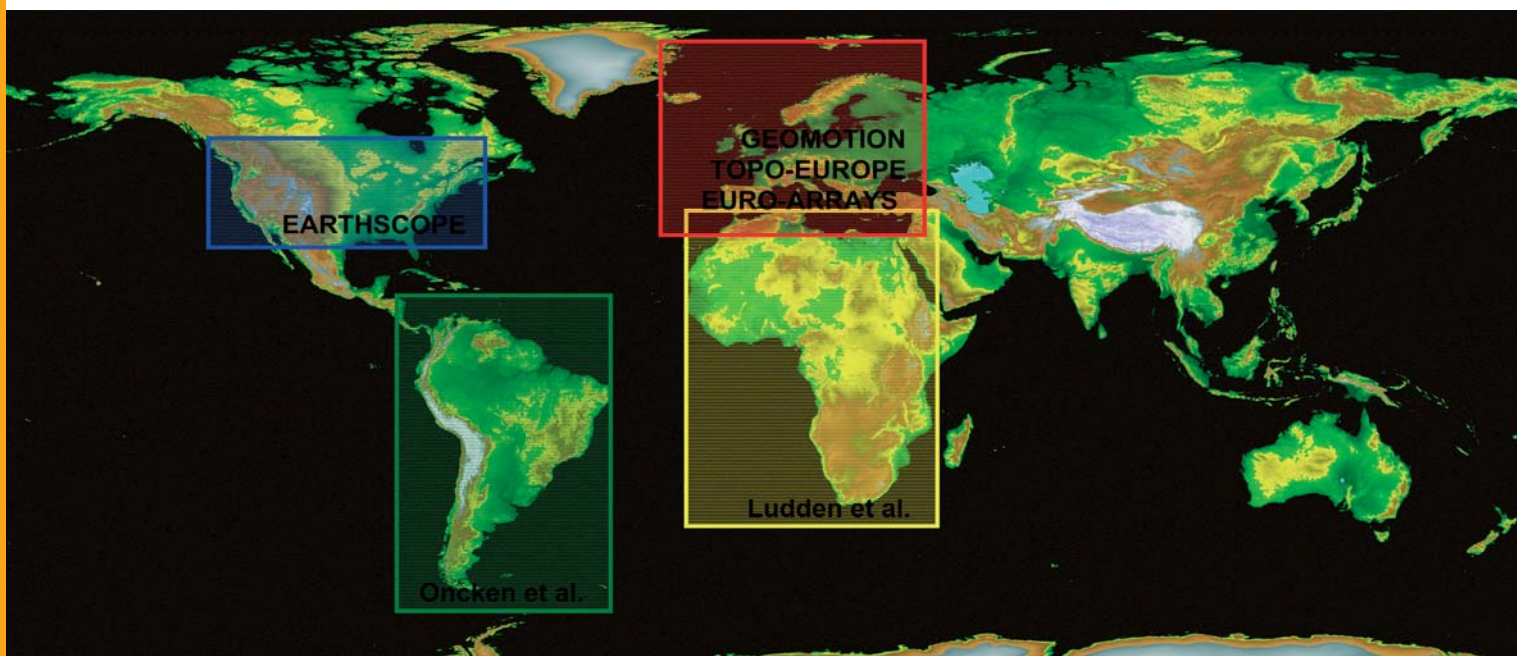
comprehensive integration of existing databases ●

Further information for researchers

Integrated approach to selected natural laboratories and analogues

Analogues are the key to reconstructing the past and predicting the future in the geological sciences. The natural laboratory that is the Earth allows us to observe different time slices at a range of scales, which, on their own, offer only an incomplete record of 4 billion years of Earth history.

Major large-scale integrated deep and surface Earth initiatives are already under development, covering Europe (GEOMOTION, TOPO-EUROPE, EURO-ARRAYS), the USA (EARTHSCOPE), the African Plate, and the South-American Plate. At the same time, major international research initiatives such as the Integrated Ocean Drilling Programme (IODP), the International Continental Drilling Programme (ICDP), and the International Lithosphere Programme (ILP) provide a platform from which to extend these research efforts into other areas of the globe. The complementary strength of research methods focused on selected natural laboratories will lead to a multi-method approach unparalleled so far by any other research programme worldwide.



Outreach Programme

The Outreach Programme is faced with a particular challenge of scale.

With a potential \$10m to spend, it is inconceivable that it could operate in a prescriptive way.

No individual or committee can think of enough wise ways of spending such a sum globally. So the Outreach Programme will, like the Science Programme, operate as a funding body, receiving bids for financial support – for anything from web-based educational resources to commissioning works of art that will help reinforce to the general public the central message of the year. It will enable things to happen locally under the umbrella of an international scheme, lending profile and coherence.

A special Outreach Prospectus in this series (number 11) will be produced to guide those who are interested in applying for support.

Coupled Deep Earth and Surface Processes CODESP

The modern Earth system approach requires a comprehensive integration of existing databases, with the capacity to expand to allow for storage and exchange of new data collected during the growth of the programme. Unification and coupling of existing modelling techniques is needed to achieve full integration of what are currently discipline-oriented approaches and to expand fully 'next generation' 3D applications. Furthermore, flexible exchange for 'feed-back loops' in the quantification of Earth processes is needed at the interface between databases and modelling tools. Consequently, major investments in Information Technology are called for so as to expand existing computer hardware and software facilities. These are subdivided into four major themes. Significant added value will also be realized by developing a Centre for integrated Solid Earth interpretation, validation and modelling as the 'backbone' of Coupled Deep Earth and Surface Processes (CODESP). Such a development will bring together a hitherto non-existent set of integrated hardware and software, dedicated to a 'streamlined' and consistent analysis of large 3D data sets

Coupled process modelling and validation

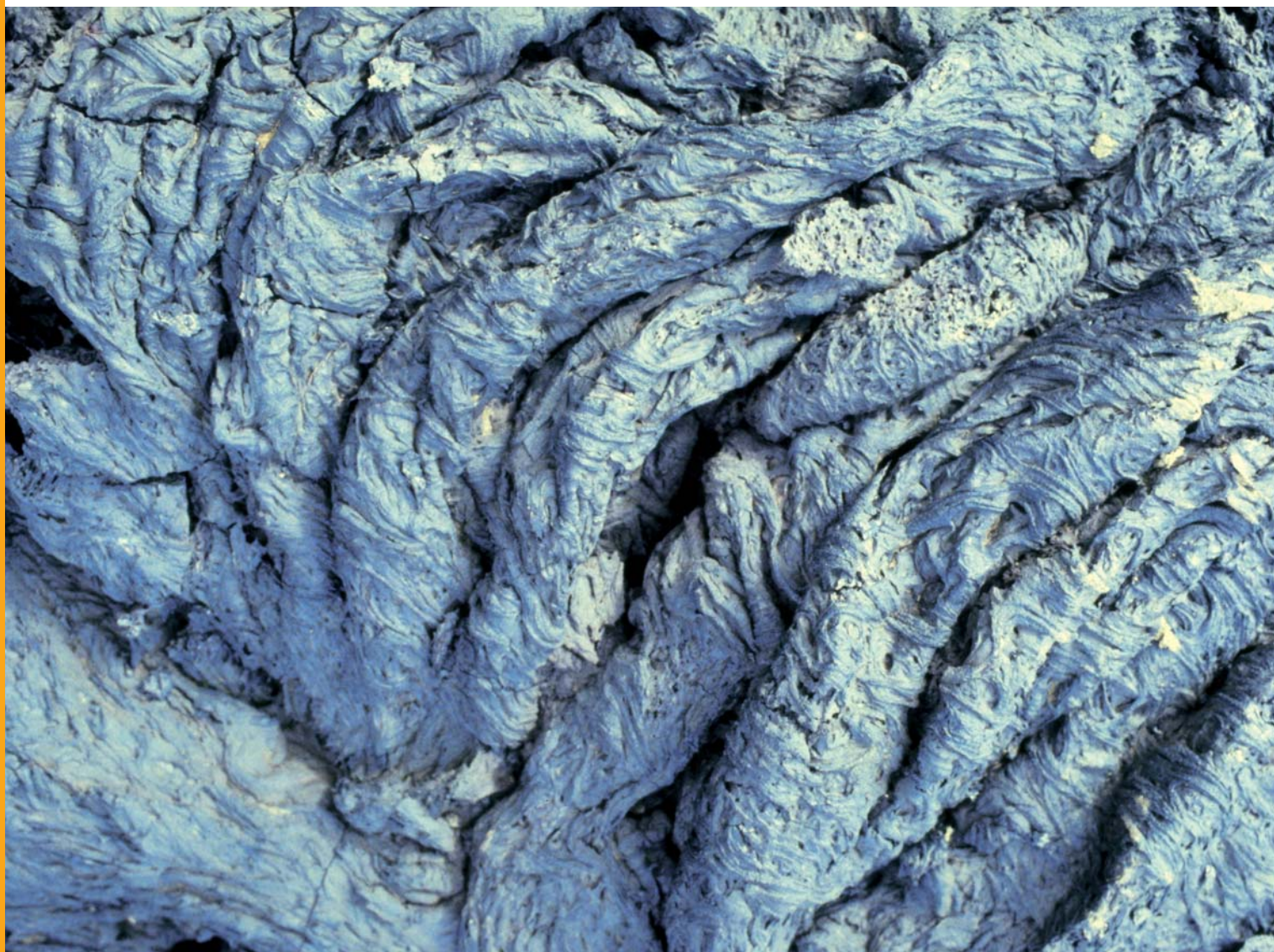
Process modelling and validation allows full implementation and optimization of the quantitative approach pursued in CODESP. In this context, two inter-related aspects should be emphasised. The first is the fundamental capacity of numerical process modelling to link the geometrical/structural, mechanical properties, and kinematic and dynamic aspects (and data) of the processes studied. Second, using this capacity, quantitative modelling and quantitative constraints on fluxes and timing obtained by state-of-the-art analytical tools will play a crucial role in research (and the guiding of research) aimed at deciphering complex interactions between spatial and temporal scales in Earth processes.



● **Training young scientists is an**
investment in the future ●

Added value in capacity building

Training young scientists in the new multidisciplinary research environment created by CODESP is an investment in the future research capacity of the Earth sciences. An international workshop will be held during the International Year of Planet Earth at which invited key researchers will be commissioned to advance this proposed research agenda.



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