THE EARTH'S INTERIOR: A NEW FRONTIER AND A NEW CHALLENGE FOR EARTH SCIENTISTS

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INTRODUCTION

In this era of space exploration, deep expeditions to the ocean bottom and far viewing telescopes, the Earth's interior has emerged as one of the most challenging frontier areas for scientific investigation. Exploration of the crust, by seismic and other means, is well underway but our view of the underlying mantle and core is fuzzy. Plate tectonic theory has revolutionized Earth Science but we still do not understand the driving mechanism or why global processes change with time. The origins of the magnetic field, volcanism, earthquakes, mineral resources and mountain building processes are related to processes in the deep interior. Planetary exploration has opened up the new science of comparative planetology and yet, the most fundamental questions regarding the origin, evolution and composition of the Earth are unresolved because of our ignorance of the characteristics of most of our planet, the interior.

The time is now ripe to make an integrated study of the Earth as a Planet or, in space age jargon, to undertake a mission to Planet Earth. There are several recent developments which make this timely.

DISCUSSION

Space age techniques have made it possible to monitor positions on the Earth's surface with a centimeter level precision. This new capability will revolutionalize geodesy and tectonics. Plate motions and continental drift velocities can now be measured directly. Strain buildup and release across plate boundaries can be monitored. The techniques include use of Global Positioning Satellites, Long Baseline Radio Interferometry and Satellite and Lunar Ranging. A truly global and international program in monitoring plate boundaries is an obvious next step in describing and understanding global tectonic processes, including plate tectonics.

The geoid, or shape of the Earth, contains information about the deep structure of tectonic provinces, including the continental crust, and convection in the mantle. Yet, we do not understand the geoid. There appears to be little correlation of the long wavelength geoid with continents and midocean ridges, two of the most distinctive tectonic elements. This promises to change because of two dramatic accomplishments. The short-lived SEASAT altimeter experiment has provided exquisite relief maps of most of the ocean floor. New seamounts and fracture zones have been discovered and there may even be evidence from these maps of small scale convection in the upper mantle. Similar data over continents requires a new type of mission, such as the proposed NASA GPM. The short wavelength gravity and magnetic fields, mapped on a global basis, are important first order solid Earth data.

The interpretation of potential fields is always ambiguous because the location of the anomalous bodies is uncertain. It has recently been possible to model and explain the long wavelength geoid by using new seismic tomography results for the deep interior. The low order geoid (ℓ = 2-4) appears to be the result of density anomalies in the lower mantle rather than by broad shallow structures. This explains why the connection between surface tectonics and the geoid has been so obscure. A large scale convection pattern in the lower mantle seems to be responsible. A prediction of the new lower mantle model is that there is large relief, about 2 km, on the core-mantle boundary. This has important implications regarding the Earth's magnetic field, the origin of magnetic reversals and the orientation of the Earth's spin axis.

One of the more dramatic breakthroughs in solid Earth physics and chemistry is the application of seismic tomography to the deep interior. Using earthquake generated body and surface waves it is possible to map the three dimensional structure of the interior. Essential to these studies is a global network of broadband digital seismic instruments and international collection and exchanges of data. Such networks can also provide real time information about earthquake locations and mechanisms, and tsunamis. The present results have relatively low resolving power because of the sparseness of the present global digital network. With about 100 global monitoring stations and 1000 portable instruments it will be possible to map the whole interior of the Earth on the scale of surface tectonic provinces. Seismology can also map anisotropy, a parameter related to crystal orientation and the direction of mantle convection. Thus, we have a tool which can map temperature, composition and convection throughout the mantle and, possibly the core. We are already close to answering such questions as the scale and style of mantle convection, the depths of continental roots and hotspots and the depth of origin of magmas.

RESEARCH NEEDS

To address these global questions regarding the origin, structure, evolution, dynamics and composition of our planet requires a global approach. The Earth must be treated as a whole, as a planet; and a holistic approach must be taken. In most areas an approach using both satellite and ground based observations must be used. A global digital seismic network, for example, involves surface instruments telemetering to satellites. The geoid, measured best from space, requires surface measurements for full interpretation. Artificial separation of Earth Sciences into a space part and a surface part can no longer be tolerated. The Viking mission to Mars and the Apollo missions to the Moom showed the advantages of treating the planet as a whole.

The time scales of most geological processes are slow and the strategy of measuring and monitoring the solid Earth is different from a strategy for monitoring changes in the fluid terrestrial envelopes. The composition and structure of the atmosphere and ocean are well known and it is changes that drive those sciences today. For the problems of the interior the baseline is lacking but the techniques are now available.

An integrated Planet Earth Mission would involve:

- Permanent surface observatories monitoring position, ground motion, polar motion, tides, free oscillations, surface waves and body wave travel times
- Transportable arrays to measure position and earthquakes
- Satellites measuring gravity and magnetic fields and serving as communication links with surface observatories
- Satellite mapping of the gravity equipotential surface and the surface composition and tectonics of land areas
- Monitoring of volcanic activity from space
- Isotopic dating of land areas and subocean samples

The study of the solid Earth and its interior is not only a stand-along intellectual endeavor but there are important cross-overs with other disciplines. For example, how important are volcanic eruptions in affecting climate and such phenomena as El Nino? How does surface composition

affect vegetation? What is the relation between polar motion, Chandler Wobble and length of day with circulation of the atmosphere and oceans and earthquakes? What is the past climate of the Earth? What is the contribution of oceanic ridge processes to ocean life and chemistry? What is the interaction between ocean tides and solid Earth tides? What causes changes and reversals in the Earth's magnetic fields and what effects do these have on climate and life?

A network of permanent observatories networks of transportable observatories and integration of these with monitoring and mapping from space are the elements of a Mission to Planet Earth.

An executive summary of a major new proposal follows:

Science Plan for a New Global Seismographic Network

Prepared by the

Incorporated Research Institutions for Seismology
April 1984

Chairman: Professor Adam M. Dziewonski
Harvard University
Cambridge, MA

EXECUTIVE SUMMARY

Presented here is a plan for a major new initiative in the Earth Sciences. The core of this initiative is a ten year, $60M plan to design, deploy, and operate a global network of some 100 seismic stations, telemetered via satellites to data centers around the world. It is the action plan based on detailed scientific studies conducted by the National Research Council over the past five years to provide the principal facility for global seismological observations until at least the year 2015. This plan is submitted by the Incorporated Research Institutions for Seismology (IRIS), a recently formed group of some 50 independent research organizations with the specific objectives of proposing and implementing the new global network and establishing a national facility for seismic studies of the continental lithosphere.

The management of a project of this size is a complex matter. IRIS was formed for this purpose based on previous experience by similar organizations such as the Joint Oceanographic Institutions, Inc., University Space Research Association, and the Universities Corporation for Atmospheric Research.

It is planned that most technical, engineering, and operational aspects will involve subcontracts, with IRIS providing the overall management, direction, contractual support, and scientific advice through its advisory subcommittees. As many aspects of the project will involve close coordination with governmental agencies, IRIS will provide this liaison.

What is a Global Seismic Network?

- An evenly-distributed worldwide deployment of a large number of modern, calibrated modular seismographs.

What Do We Have Now?

- The 140-station, analog-recording World Wide Standardized Seismic Network (WWSSN) installed 23 years ago is an example of a global seismic network that has well served the nation's seismological needs.

- Currently, operational digital seismic instruments are limited in number but, what is most important, they are restricted in functionality and are not adequate to record many earthquakes in their entirety. Current digital instrumentation includes the following networks:

  1. Global Digital Seismic Network (GDSN), which consists of:

     a. Seismic Research Observatories (SRO) - 12 installations;
     b. Abbreviated Seismic Research Observatories (ASRO) - 5 installations;
     c. Digital WWSSN (DWWSSN) - 15 installations.

  2. Regional Seismic Test Network (RSTN) - 5 installations in North America only.

  3. International Deployment of Accelerometers (IDA) - 18 installations

  4. GEOSCOPE, a developing French network - 4 installations

Why a New Global Seismic Network?

- To replace obsolete global analog network with modern, high quality digital instrumentation

- To ensure operation of a broadband, digital network comparable in the number of stations but better distributed than the analog WWSSN

- To improve the resolution of global lithospheric structure, earthquake sources and structural manifestation of mantle convection patterns

- To improve the timeliness and efficiency of data distribution

Why Now?

- Recent results obtained from the analysis of available data demonstrate that significant advances in many problems of fundamental importance to earth sciences could be achieved with the data from a network such as proposed here.

- Technological developments make deployment of such a network operationally and economically feasible.

What are the Scientific Objectives?

- Study of static and dynamic properties of the Earth as a planet

- Global mapping of the lithosphere and deeper lateral heterogeneities

- Resolution of the anisotropy in the lithosphere and deeper parts of the mantle; mapping of mantle flow

- Understanding of the dynamics of earthquakes

- Nearly real-time analysis of large events

What Technological Advances Make this Project Timely?

- Application of electronic control methods and digital data acquisition to seismometry

- Developments in digital mass storage methods

- Advances in satellite communications

- Availability of large computing facilities

What will be the Characteristics of the Network?

- Approximately 100 stations, 3 components each

- Broadband - 5 Hz

- High dynamic range - 140 db

- Real-time telemetry via satellites

How will it be Managed?

- IRIS (Incorporated Research Institutions for Seismology) a nonprofit corporation organized to provide scientists with large scale facilities needed for seismic studies of the earth

- IRIS will provide management direction, contractual support, and scientific advice; technical, engineering, and operational aspects will be subcontracted.

How Much will it Cost?

- $60M over 10 years

What is the Planned Lifetime?

- 30 years, assuming that the network will be gradually upgraded as new technology develops. In this way, the performance of the network should improve with time.

How will the Data be Managed?

- Archived at national facility

- Distributed to data analysis centers and individual research groups

- Some data analysis at major computational facilities

REFERENCES

SCIENCE, The Earth as a Planet: Paradigms and Paradoxes, 27 January 1984, Volume 223, pp. 347-355.

EOS, Transactions, American Geophysical Union, Vol. 65, No. 16, April 17, 1984.

EPILOGUE

Surface Wave Tomography, by Don L. Anderson Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125 (Excerpted with the permission of the American Geophysical Union from EOS, Vol. 65, No. 16, pp. 147-148, April 17, 1984)

Surface waves are now being used by several groups to map lateral heterogeneity [Nakanishi and Anderson, 1982, 1983, 1984a, b; Woodhouse and Dziewonski, 1984] and anisotropy [Tanimoto and Anderson, 1984a, b; Nataf et al. 1984] of the upper mantle on a global basis. The method involves measuring the phase and/or group velocity over hundreds of

small arcs and long arcs connecting earthquakes and seismic stations. These averages are then converted to three-dimensional images of the seismic velocity structure, and, hence, this is a form of tomography. The large amount of data processing required is made feasible by the existance of long-period digital seismic networks including IDA (International Deployment of Accelerometers), SRO (Seismic Research Observatories), and GDSN (Global Digital Seismic Network). These instruments are operated by a variety of university and government groups including University of California, San Diego, U.S. Geological Survey, D.A.R.P.A., and U.S. Department of Energy with the cooperation of many countries. The global coverage is still very sparse compared to the analog W.W.S.S.N. (World Wide Standardized Seismic Network), but preliminary results are very encouraging. The possibility of an expanded global digital network of broadband seismic stations is now being pursued actively by the United States and several other countries. Because of the sparseness of the present network, mantle structure can only be mapped with fairly low resolving power. Only features with half wavelength of the order of 2,000 km can be detected.

The maps in Plate 1 show the results from one recent study [Nataf et al., 1984]. Shown are the parameters VSV and XI at two depths, 250 and 350 km. VSV is the velocity of vertically polarized shear waves, determined primarily from fundamental mode Rayleigh waves, and XI is related to the difference between VSH, the velocity of horizontally polarized shear waves, and VSV. The parameter XI is therefore a measure of anisotropy. Positive XI means VSH > VSV. Aggregates composed of a axis horizontal olivine crystals, for example, are expected to have XI > 0. This situation is probably diagnostic of horizontal flow. Blue areas in the maps represent fast regions or VSH VSV. Orange areas are slower than average or VSH > VSV. The maps are spherical harmonic representations including coefficients up to and including order and degree 6.

In spite of the lack of short wavelength information, there is much important information in these maps. Mid-oceanic ridges and regions of recent volcanic activity are generally slow at 250 km. The regions near the Tasman Sea, New Zealand; Red Sea, African rift; and western North America are slow. The central Pacific, between Hawaii and Tahiti, is also slow at this depth. Fast regions include the Canadian and Fennoscandian shields and the Siberian platform, as expected, but also the North Pacific and the eastern Indian Ocean. Many hot spots are on the edges of low velocity regions rather than centrally located.

The parameter XI is negative over regions of upwelling (East Pacific Rise, Antarctic-Pacific Rise, South Indian Rises, Mid-Atlantic Rise, and the Red Sea region) and

areas of presumed downwelling (Japan, Phillipines, Mariannas, Sumatra). Plate interiors are generally positive XI, suggesting horizontal flow at 250 km.

The maps at 350 km are similar, as they should be since a high degree of correlation between 220 and 400 km was assumed in the inversion. The differences are therefore particularly instructive. The central Pacific, Red Sea, and mid-Atlantic ridge slow anomalies persist, suggesting that these are relatively deep seated. Most shields are no longer evident. The thermal anomaly associated with the East Pacific Rise appears to be displaced. At 450 km depth, not shown, most ridges are fast and most subduction regions are also fast. The velocity and XI parameter at 350 km are consistent with upwelling flow along the East Pacific Rise, the central and southern mid-Atlantic Rise, and the Red Sea area. These parameters are consistent with downwelling in the western Pacific. An upwelling is implied in the south central Pacific.

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