AGU Planet Earth Committee Report: Part II Interior and Crust

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The Earth's mantle, core, and crust comprise 99.98% of its mass. The mantle, making up the bulk of the mass at 70% and composed of higher density rocks (rich in magnesium silicates, plus some iron silicates), extends an average of 15–2900 km deep. The core is the center of the Earth, 2900–6370 km deep, composed mainly of molten iron. The crust is the outermost layer of the solid Earth, composed of lower density rocks (rich in silica and aluminum and calcium silicates) 6–40 km thick.

The Earth's ocean and atmosphere outgassed from the interior very long ago, and economic mineral deposits also formed far back in the past. Today, however, important processes still shape the Earth, such as the continuous recycling of volatiles—water and carbon dioxide—through the interior, as well as the chemical and mechanical breakdown of rocky material essential to soil on the land and to sediments in the ocean. Without these processes, the biosphere could not exist. Most of this base of the solid Earth, essential to life, has been furnished on time scales of millions of years, much longer than those of circulation and renewal in the ocean, atmosphere, and biosphere. But, by the same token, those parts of the environment that depend on solid Earth processes, such as soil and petroleum, cannot be replenished in human time if exploited or destroyed. And the solid Earth can also have drastic impacts on human beings in a very short time, such as through earthquakes and volcanic eruptions. Understanding this complex system requires going very deep into the Earth and very far back in time.

We are in a period of remarkable discoveries about the solid Earth. With recent advances in knowledge of mantle dynamics and core-mantle relationships, we may be on the threshold of developing a working model for the whole of the Earth's interior. One approach, seismic tomography, constructs three-dimensional images of the Earth's interior by analyzing seismic (earthquake) waves. Another approach is geochemical mapping—plotting the distribution of the many chemical compounds, elements, and isotopes of the Earth. Other knowledge is gained through high pressure experiments on Earth materials, and through fluid dynamical computa-

tions using the gravity field and other surface data. Seismic information about the core-mantle boundary has accelerated study of the geodynamo, which is the generation of the Earth's magnetic field by flow in the electrically conductive, fluid iron core. And it is mantle dynamics that controls evolution of the lithosphere, the outermost layer (0–150 km thick) of the mantle plus the crust, which is colder and hence stiffer and stronger than the material it encloses. This layer provides the basis for the crust and the great variety of regional structures important to human beings.

Upper Mantle, Convection, Mantle Structure

The mineral structures of rocks from the mantle, such as lherzolite (a dense rock high in magnesium, with some iron, believed to characterize the mantle more than 30 km deep), determined up to pressures corresponding to a marked seismic discontinuity—or marked change with depth—670 km deep, show phase transitions that correlate well with recent data on seismic discontinuities, although there are ambiguities in some depth intervals. (These phase transitions are changes in atomic arrangement normally requiring changes in pressure or temperature.) Melting as observed in experiments places an important constraint on conditions for melting in a convecting mantle. It is now agreed that the lower mantle is mainly perovskite, a rock similar in composition to lherzolite, but denser because the pressure forces atoms of magnesium and iron silicates into closer arrangements.

Basalts are the most common of igneous rocks, a class of rocks that form by partial or complete melting of a parent material. Basalts are composed of a mixture of calcium-aluminum silicates and iron-magnesium silicates that would be expected to form from a partial melt of rock such as lherzolite. Basalts comprise most of the ocean floor below a thin sediment layer. Analysis of radioactive isotopes in basalts and other rocks confirm that at least two reservoirs of sources for crustal rocks exist in the mantle. These reservoirs have remained physically separate for a couple of billion years. Recent research results, in fact, suggest at least five distinct reservoirs. These results must be reconciled with mantle convection—a steady motion in the solid Earth of a few centimeters per year, powered by radioactive and primordial heat—which is strongly shaped by subduction—the sinking or shoving of lithosphere back into the interior of the Earth. Subduction is probably the characteristic of the Earth that distinguishes it most from other planets.

One model of mantle convection postulates two layers, the lower composed of “primitive” material, not yet differentiated into crustal

rocks, and the upper, less than 670 km deep, composed of depleted material, from which crustal components have been extracted. Another model proposes that the mantle has one layer extending 2900 km down, so that subduction occurs all the way to the core-mantle boundary. Other models combine the simple one- and two-layer conceptualizations.

Fluid dynamical calculations can reconcile convection with tomographic and gravity data, provided that the deep mantle is 10–100 times as viscous as the upper mantle, but more constraints are needed to reach definitive conclusions. One recent interpretation combines one- and two-layer models in a mantle in which the 670-km boundary can be breached by lithosphere slabs of sufficient density contrast.

Seismic tomography results are revealing the density structure of the mantle in three dimensions. As resolution improves, this structure may be interpreted in terms of temperature and compositional variations, for variations in seismic velocities with direction indicate flow directions. But a more extensive and precise global seismic network is needed to infer the major patterns of mantle convections.

Mantle dynamics are controlled by density differences, which arise from melting and other phase transitions, and from thermal and compositional variations. Laboratory measurements of the density of silicate melts at very high pressures in shock wave apparatus suggest that melt produced below 200–300 km depth may be denser than the solid matrix. This strongly implies that the evolution of a planetary body depends on its size, which greatly affects pressures at depth. These effects should be reflected in the relative abundances of the many chemical elements: some that are rather rare act as tracers for histories of differentiation. It used to be thought that those trace elements that do not fit easily into the crystal structure of the abundant elements—“incompatibles”—were progressively flushed to the outer layers through partial melting; instead, it appears that melts below 200–300 km may have concentrated these elements downwards.

Dense magmas, or accumulations of molten rock, are consistent with the idea of a magma ocean: a layer of molten rock, perhaps 100 km deep or more, existing at the surface soon after the Earth's formation. Another model of the mantle posits a layer of denser rock which crystallized from a magma ocean, perched in balance between the perovskite of the lower mantle and the enriched lherzolite above it. A still different hypothesis is that megaliths—large masses of colder rock—form where subducted lithosphere piles up above the dense perovskite at the 670-km seismic discontinuity, and then spread out to form a layer between the separately convecting upper and lower mantle. All of these mantle models, invoked to account for some aspects of trace element and isotope geochemistry, generate intense debate among researchers.

Whole Earth Solidus, Geotherm, and Differentiation

Recent advances in high-pressure experimental techniques using static (large press, diamond-anvil) and dynamic shock-wave appa-

ratures are refining our ideas about melting temperatures and geotherms, or changes of temperature with depth, within the Earth. The fusion curve (which plots how the melting temperature varies with pressure) for iron provides an estimate of the temperature at the inner-outer core boundary, which leads to estimates for the Earth's center and core-mantle boundary. Another great advance is the determination of the solidus curves for lherzolite and perovskite. (These plot the temperature, as a function of pressure, of change from a completely solid state to a mixture of solid and liquid.) These curves, calculated to pressures corresponding to 2000-km depth, and geotherms calculated through the mantle, indicate a significant temperature difference between mantle and core, which generates ideas about how core-mantle interactions affect both the density variations in the mantle above and the geodynamo mechanisms in the core below.

The internal structure of the Earth is associated with chemical differentiation, which has been studied in recent years from several different perspectives, such as mantle dynamics; isotope, trace element, and inert gas geochemistry; mantle-crust evolution; physics of rock-fluid systems; and magmatic processes.

The chemistry of magmas is controlled by the physics of rock-fluid systems, and we need more data on their physical properties. The densities and viscosities of magmas through the uppermost mantle and lithosphere are now fairly well determined. Laboratory experiments have also provided insights about the percolation of melts through a solid matrix, as necessarily occurs in the mantle. These experiments are complemented by theoretical studies of fluid flows in deformable matrices, thus defining conditions for fluid migration.

Subduction and Continental Collision

Subduction, already mentioned above, is undoubtedly very important to both tectonic processes, which effect deformation by stress, and to petrological processes, which cause change of composition by melting or other mechanisms. These effects of subduction are major problems in understanding mantle heterogeneities and the evolution of the continents. We now have a good picture of the dehydration reactions and curves for inferred materials in the reservoirs of oceanic lithosphere, the overlying mantle wedge, and the deep continent. We also have a general idea of thermal structures, but without enough detail to make definitive choices among alternative processes. Inferences of seismic velocities in subduction zones constrain these temperatures, since waves travel faster in cold rock than in hot. But there is still debate over how much volcanism in ocean island arcs originates from subducted oceanic crust, and how much from the overlying mantle wedge.

Different petrological patterns characterize continent-continent collisions, such as the one that caused the uplift of the Himalayas and the Tibetan Plateau. Recently discovered combinations of metamorphic rocks—structurally changed by heat, pressure, and volatiles, short of melting—evidence histories of high pressure in their mineral structures, indicating their origin at least 100 km deep.

These inferences also depend on laboratory experiments in high pressure apparatuses. It is especially remarkable that these rocks returned to the surface rapidly enough to preserve these mineralogical messages, which is a challenge for structural geologists to explain. Isotope studies of mineral inclusions in metamorphosed rocks also provide new information on time factors in the depth-temperature-time evolution of mountain ranges.

Improved detailed insight into the thermomechanics and chemistry of these subduction zone processes will contribute greatly to understanding volcanic outbursts, and hence to alleviating this hazard.

Continental Kinematics

Plate tectonics describes the horizontal motions of rigid slabs of the Earth's surface, with deformation confined to relatively narrow zones between the slabs. Plate tectonics has provided a kinematic framework—described purely by motions, without reference to cause—for study of many aspects of continental geology, including exploration for energy and mineral resources. The theory provides a whole new way of looking at geology, employing paleogeography, paleobiology, paleoclimatology, and paleoceanography. These studies enable reconstruction of potential sites for mineral concentrations of petroleum, phosphates, and other economic resources. The continents are kept drifting by oceanic rifts, and discovery of submarine vents and associated mineral deposits have revolutionized interpretations of the origins of many ore deposits.

Kinematic patterns on a much shorter time scale are important to advances in understanding hazards generated by the solid Earth. At the margins of the global-scale tectonic plates, such as between the African and Eurasian plates in the Mediterranean and between the Pacific and North American plates in California, the patterns of motion indicate a number of microplates, some only a few kilometers in extent. The study of these marginal zones is currently a hot topic, and one with great practical implications, since such zones often attract the building of large urban complexes. Alleviating earthquake hazards in these areas requires detailed measurement of the microplates' motions, as well as improved theoretical insight. Newly developed compact radiointerferometric systems, which employ phase differences of radio signals received at different locations, now offer the capability of achieving the requisite mobility and speed of observation to achieve this required detail. One such effort, the Global Positioning System (GPS), is a configuration of 18 satellites at 14,000-km altitude, which the Department of Defense is placing in orbit for navigation purposes, but which will also be valuable to measure differences in geodetic position.

Research Needs

To realize the societal as well as scientific potential of these exciting developments in solid Earth geophysics, measurement programs must be expanded in several respects. Since 70% of the Earth is covered by water, and much of the significant structure and processes of the Earth exist at depth, these programs require closer examination than

feasible from space, using aircraft, ships, ground observatories, and drilling to depth.

Maps are of great importance as fundamental data sets, but the traditional topographic and geologic maps are still sketchy and non-uniform over much of the world. The new multispectral space systems, however, enable qualitatively different maps with great detail to be produced. A vigorous program of scientific continental drilling is required to provide the third dimension, the underground truth to interpret geophysical measurements.

A new measurement system will generate enormous amounts of data, necessitating complementary systems to organize, disseminate, and archive the data. Modeling is also necessary to understand the processes behind this data. Overall, research requires not only the best data sets and the fastest computers, but also the best minds with imaginative ideas. Computers, for example, have provided some heuristic representations of mantle convection, and current ideas about "chaos" apply well to this highly non-linear phenomenon, even though it may not be turbulent in the traditional sense, as applicable to a stream of water.

Measurement Needs

The Earth-oriented part of the National Research Council (NRC) study "Mission to Planet Earth" comprised essentially two programs: EOS, the spaceborne "Earth Observing System" planned for the mid-1990s, and PLATO, a "Permanent Large Array of Terrestrial Observatories," proposed to complement EOS. The systems will collect integrated sets of global, synoptic, and simultaneous observations from both satellites and the Earth's surface. EOS, as described in the NRC study, includes tethered satellite systems, a magnetic field explorer, a geopotential research mission, spectrometers, a laser ranging system, synthetic aperture radar, and other measuring systems. PLATO includes ocean-bottom geophysical observatories, a land-based global seismic network, GPS receivers, laser corner reflectors, borehole stations for drilling operations, and many other aspects.

To complement these space and ground-fixed observatories, systematic one-time mappings are necessary from air or ship, with repeated detailed surveys in areas of contemporary tectonic change.

Summary

It is clearly time to develop "Earth System Science" for the Earth's crust and interior, following the example of those mainly concerned with atmospheres and oceans. The solid Earth is a system comparable in complexity to these, but operating on a much longer time scale. This system embodies links between the core-mantle interactions, mantle dynamics, and the generation and evolution of lithosphere, and so to the biosphere that forms a thin layer between the solid Earth and its fluid envelopes. The stages of origin, migration, and subduction of the lithosphere are all associated with lithosphere/hydrosphere interaction, and continent formation is tied to interactions between the mobile mantle and the lithosphere. The continents evolved between mantle and fluid envelopes,

and the biosphere and human beings depend on all of these.

We have probably gained more fundamental knowledge about the Earth's interior during the 1980s than in all of previous scientific history. During the same period, however, the cumulative and damaging effect of human society has become dramatically obvious. We do not know if we have the time to complete our understanding of the Earth before our aggressive attack on the planet irreversibly depletes the resources, such as soil and petroleum, that are not economically replaceable by future generations.

Implementation

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The problem-oriented discussions in this series mention many observations, experiments, and modelings that are needed to carry out the goals of the Planet Earth Initiative. The next logical step would be to compile from these mentions an enumeration of measurable (for example, cloud coverage and ocean surface temperature), with a view to specifying the instruments, platforms, spacings, frequencies, etc., at which these measurements should be made. This step has already been taken for significant fractions of the problems discussed. Tables 1 and 2 are outlines of such a compilation, the most comprehensive but not the most detailed, drawn from the 1988 National Research Council/Space Science Board report, *Space Science in the Twenty-First Century: Mission to Planet Earth*. Its emphasis is on the global approach, and some might argue that 10,000 "simple

Table 1. Elements of a Mission to Planet Earth

Quantity	Element
1	Space Station
1-2	special-purpose satellite missions
5	geosynchronous orbiters
2-6	polar orbiters
18-24	GPS constellation
2-3	tracking and data relay satellites
1000	floating buoys, "pop-ups"
100	moored buoys
100	ocean bottom stations
100-1000	smart ground stations
1000-10,000	simple ground installations
	aircraft
	balloons
	rockets
	ships, research
	ships, opportunity

Table 2. Summary of Instruments and Measurements for the Mission to Planet Earth: An Integrated Infrastructure Matrix

Measurement	Measurement Systems					
	Polar Orbiter	Geosynchronous	Other Satellites	Aircraft Balloons	Ocean Stations	Ground Stations
Magnetic field	G		G	G	G	G
Gravity field (geoid)	G	G, A	G	G	G, A	G, A
Stratospheric chemistry	C, P			C	P	P
Aerosols	M, P	M		T	T	T
Winds	A, P		A	T	T	T
Severe storms	R, M	R, M	D	T	T	T
Clouds	M, P			T	T	T
Precipitation	R, M, P	R, M	M, D		T, S	T
Particulate matter	M, P	M		T	T	T
Tropospheric chemistry	C, P			C	C	C
Ocean currents	M, A	M, A	A, D		A	
Ocean chlorophyll	M	M		O	O	
Ocean salinity	M	M			O	
Lake levels			A			O
Sediments	M	M	D		O	
Sea state	R	R	D		O	
Sea ice	R, A, M	R, A, M	A		O	
Glaciers	R, M, A		A			A
Snow	R, M	R, M				A
Topography	A		A			A
Surface temperature	M	M		O	O	T
Albedo	M	M				T
Surface geochemistry	M	M				
Geological features	R, M	R, M				
Cultural features	R, M	R, M				
Vegetation	M	M				T, C
Soil moisture	M	M				
Soil erosion	M	M				
Surface strain	A		A, D			A
Seismic wave velocities		D		S	S	
Tectonic deformation			D, L		S	S

Instrument categories are M, multispectral imaging; R, radar imaging; A, altimetry ranging; P, vertical profile remote sensing; D, data links; T, meteorological instruments; O, oceanography instruments; S, seismographs-acoustic detectors; G, gravimeter-magnetometer; C, chemical composition instruments; and L, locations, precise geodetic.

ground installations" are too few for such efforts as studies of crustal motion.

In addition to the measurements outlined in Tables 1 and 2, drilled holes; laboratory measurements; data management—processing, analysis, and archiving; and modeling are needed. All of these are activities that require significant investment in equipment and facilities to accomplish a balanced understanding. Also, focus on the end scientific information required to make headway on the problems—both the content and the form thereof, is needed.

AGU is most concerned about getting underway a complete "Mission to Planet Earth," that is, an overall international effort that is balanced by including the many necessary complements to the polar and geostationary platforms planned in the 1995–2010 time frame.

With some exceptions, mostly solid Earth, spaceborne systems in Table 1 appear to be well underway. In particular, the National Aeronautics and Space Administration's Earth Observing System (EOS) is being well implemented, with principal investigators selected for 19 instruments. The first polar-orbiting platform is scheduled for launch in 1997, a second in 1998, and possibly a geostationary platform in 1999. We hope that this schedule is assured by launch from the expendable vehicle Titan IV, rather than from the Space Shuttle.

In addition, smaller missions are scheduled for the period 1991–1995. Meanwhile, already launched systems, such as LANDSAT and GOES, limp along. The decision to commercialize LANDSAT made its products too expensive for scientific research. We hope that the budgets for the implementation of EOS will provide sufficient support for the entire process of data analysis and interpretation. Only through federal funding can research on this scale be carried out, and it will be several years before even partial commercialization is feasible—perhaps never, unless there is a great change in how environmental protection and control is organized. GOES demonstrates that systems built for conventional weather prediction may not provide data that is accurate enough, or in forms suitable to archive for long-term research.

However, there is no implementation to the same extent of surface-observing systems. As pointed out in the discussions of the interior, oceans, and atmosphere, there are plans proposed by international scientific societies, such as the Federation of Digital Seismographic Networks, the International Geosphere Biosphere Programme, and the World Climate Research Programme, but their implementation depends on national agencies. Within the United States, an enhanced effort is planned in climate research, with \$191.5 million funding for Fiscal Year 1990 [Office of Science and Technology Policy/Committee