SECTION III.

REPORT OF THE PANEL ON LITHOSPHERIC STRUCTURE AND EVOLUTION

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SECTION III.

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SUMMARY

As the twenty-first century approaches, better knowledge of the physical and chemical structure of the solid Earth's upper few hundred kilometers and how it has evolved over the past several billion years becomes increasing important for solving the basic problems which face human society, such as dwindling natural resources, deterioration of the environment, and loss of life and property through natural disasters. For example, the Earth's lithosphere contains the coal, petroleum, and uranium we rely upon for fuel, as well as the metals used in construction, communications, and industry. Through an improved understanding of the Earth's geologic history, we can more efficiently discover the untapped resources we need until alternatives to the limited natural resources can be found. In addition, the scientific community has become increasingly aware that the problem of global change can not be addressed solely through studies of the Earth's atmosphere, hydrosphere, and biosphere. The lithosphere contains the only record of global change before the influence of industrial society, which allows us to distinguish the anthropogenic signals from natural cycles. Finally, monitoring of volcanic eruptions and lithospheric plate motions by seismic and strain networks must be accompanied by broad-based geologic and geophysical studies of the lithosphere's physical properties and how it has been deformed in order to obtain the fundamental knowledge needed to predict exactly where and when lithospheric plate motions will lead to earthquakes and volcanic eruptions.

Many of the most basic questions concerning the lithosphere's structure and evolution can be addressed through space-based observations that NASA is capable of providing. These include:

1. What is the deep thermal and chemical structure of continental versus oceanic lithosphere? Can we explain why the oceanic lithosphere appears to reach an equilibrium thickness of 125 km in only 200 Ma while continental lithosphere continues to thicken to values 2 to 4 times greater?
2. How has the lithosphere formed and aged over the history of the Earth? Is the paradigm of plate tectonics, so clearly demonstrated to be correct for the modern Earth, appropriate for the young Earth? Alternatively, did the lithosphere evolve in a different fashion in the past dictated by its higher temperature and lower degree of differentiation? If so, can we recognize and reconstruct pre-plate teconic styles of lithospheric evolution?
3. What are the processes of rifting and extension in continental versus oceanic lithosphere? Uniform stretching models have proven extremely useful in describing rifting in the oceans, whereas recent studies of continental rifting have emphasized the role of subhorizontal detachment systems in accommodating extension. Are these differences real, and if so, what controls them? Progress in understanding the difference relies on deeper knowledge of the structure and dynamics of both kinds of rifts and the rheology of both types of lithosphere.
4. What areas of the continents are currently undergoing epeirogenic uplift and subsidence? Can we link these vertical movements to thermal and dynamic processes inferred from seismology and gravity to understand the formation of intracontinental basins and arches? How does eustatic sea level change relate to continental tectonics and sedimentation throughout the Phanerozoic? What is the present-day rate of eustatic sea level rise, and can it be distinguished from post-glacial rebound? Can we use geologic information to distinguish sedimentary, thermal, flexural, eustatic, and tectonic components of subsidence in order to address problems ranging from petroleum exploration to rheology of the lithosphere?

5. What is the thermal and chemical structure of midplate plateaus, swells, and super-swells? How do they relate to mantle plumes and continental rifting and convergence? How rapidly do midplate swells rise and fall? Are the rates consistent with conductive transfer of heat in the oceanic lithosphere, or is dynamic flow required? How much heat is liberated from the mantle by midplate volcanism and swell formation?

6. What is the rheology of the lithosphere and how does it interact with the asthenosphere at oceanic trenches and continental collision zones? What stresses act on the downgoing plate from its own negative buoyancy, surface and subsurface loads, and resistance to penetration through a viscous mantle?

Progress in solving these problems is dependent upon availability of several key data sets which NASA could effectively acquire using space technology, such as altimetry, potential field data, remote sensing imagery, and absolute vertical positioning. The following prioritization assumes that the remote sensing instruments now in operation, TM and SPOT satellite systems and the ASAS, TIMS, AVIRIS, NS-001, SAR, SIR-C, and photographic aircraft systems, will continue to provide data throughout the program life. We also assume that planned EOS systems or equivalent including SAR, TIMS-class ITIR, and HIRIS be in operation as scheduled, and that better altimetric coverage over the oceans is best achieved through the efforts of foreign space agencies due to classification issues. With these assumptions we prioritize our needs as follows:

1. **Digital topography over the continents (30 m horizontal, 4 m vertical).** These data are essential to all scientific objectives.
2. **Gravity measurements (<100 km horizontal, 2 mGal).** One approach to acquire these data is for NASA to contribute the GPS receiver and a drag-free system to ensure the success of the ESA Aristoteles mission, which would be an important first step in obtaining high resolution, global gravity data and for the purpose of demonstrating the feasibility of gravity gradiometry from space. However, it is unlikely that this mission will provide the accuracy and resolution we require. Therefore, NASA should pursue plans for a follow-on low-altitude gravity mission, such as the Superconducting Gravity Gradiometer Mission.
3. **Magnetic measurements.** Given the expense of flying missions in low-Earth orbit, we recommend that magnetic field measurements be included with both (Aristoteles and SGGM) gravity missions. A higher orbit, MFE-type mission is also important for isolating the core field from the lithospheric field.
4. **High spatial (approximately 5 m) resolution stereo panchromatic data.** One approach would be to use the Large Format Camera. This high spatial resolution stereo system fills an important void in planned remote sensing missions. The instrument or equivalent should routinely be flown on the Shuttle and/or on some other platform until global stereo coverage of the continents is obtained.
5. **Vertical Positioning.** The exciting prospect of directly measuring the vertical motions associated with the evolution of the lithosphere is still a decade or more away, but it will continue to be an elusive goal unless we begin now to improve the accuracy of absolute vertical positioning and start acquiring baseline measurements of signals that can be resolved a decade or more later.

In addition to providing the basic global data sets described above, NASA is in a key position to

- **foster cooperation among the space agencies of the world to address major scientific and environmental problems, with a philosophy of maximizing data exchange and the development of complementary missions; and**
- **realize the scientific potential of this data by funding data analysis as well as acquisition.** Selection of specific investigations and geographic sites for study should be based on the results from peer review process.

INTRODUCTION

The importance of the lithosphere can hardly be overemphasized from either a scientific or a societal perspective. From a purely scientific standpoint, the lithosphere preserves the only record of the Earth's geologic, biologic, and climatic history. From a societal standpoint, the lithosphere is the dynamic layer responsible for both natural hazards and resources, as well as the surface upon which we live.

Because of its importance, many U.S. and foreign agencies are devoted to the study of the lithosphere, but their efforts are fragmented by shorelines, political boundaries, and specific agency missions. From a space-based perspective, NASA can bridge these gaps by providing uniquely global data to constrain models of lithospheric structure and evolution via remote sensing, geopotential fields, altimetric measurements, and precise positioning.

Our present understanding of lithospheric processes is based on the concept of plate tectonics developed from observations in the ocean basins. We know that continental lithosphere is not mechanically equivalent to oceanic lithosphere because continental nuclei are more than 3 Ga old, whereas the ocean floor does not exceed 200 Ma in age. One of the major unsolved problems in Earth sciences is the question of whether this difference in the plate-tectonic recycling history of continental versus oceanic lithosphere can be explained solely by the difference in composition and thickness of continental *crust,* or whether it requires fundamental differences in the thermal and chemical structure of the subcrustal upper mantle.

To address this question, it is crucial that we develop a refined understanding of the compositional, structural, and thermal differences between oceanic and continental lithosphere. These three basic properties provide the keys to determining the magmatic, metamorphic, and sedimentary processes that have led to the differentiation and modification of the lithospheric chemical and thermal boundary layer, as well as the rheological laws which govern its deformation in response to applied stress. NASA can contribute to this understanding via a vigorous program in solid Earth science with the following objectives:

1. **Determine the most fundamental geophysical property of the planet: the detailed shape of the surface of the lithosphere (i.e., the topography) to a vertical accuracy of a few meters with a horizontal resolution of a few tens of meters;**
2. **Determine the global gravity field to an accuracy of a few milliGals at wavelengths of 100 km or less;**
3. **Determine the global lithospheric magnetic field to a few nanoTeslas at a wavelength of 100 km;**
4. **Determine how the lithosphere has evolved to its present state via acquiring geologic remote sensing data over all the continents.**

The topographic, potential field, and remote sensing signals of interest for studies of the long-term evolution of the lithosphere change extremely slowly on human time scales. Even if they can be accurately measured only once in the next decade, we can make substantial progress in inferring their time dependence by studying similar features in different stages of development. However, a exciting prospect for the next century is the possibility of directly detecting vertical motions at the Earth's surface predicted by isostatic adjustment to changes in surface loads (e.g., ice sheets), the temperature or composition of the lithosphere, and dynamic forces at its base. Therefore, we list as a longer-term objective of NASA's program for studying the evolution of the lithosphere:

5. **Improve the accuracies of vertical positioning to the sub-millimeter level and gravimetry to the sub-microGal level to test and directly calibrate models for the temperature, density structure, and rheology of continental and oceanic lithosphere.**

TOPOGRAPHY

Topography is one of the most basic geophysical characteristics of the planet Earth. Topographic data are vital for lithospheric research, with application to geological and geophysical studies. Geologists devote the entire field of *geomorphology* to the study of land forms for the purpose of understanding the dynamic, volcanic, and tectonic processes which build relief, as well as surficial processes such as weathering and erosion which wear it down. From a geophysical perspective, variations in elevation balance buried density anomalies arising from thermal and chemical inhomogeneities to bring about isostatic equilibrium. In addition, surface relief causes major perturbations to the gravity field, magnetic field, and seismic travel times for which we must correct before geophysical data can be used to probe structures within the Earth's interior. High priority goals of the SES should be:

- **aquiring a global digital continental topographic data set with at least 30-m horizontal resolution and 4-m vertical resolution;**
- **encouraging altimetric missions (e.g., ESA's ERS-1) to map the marine gravity field to an accuracy of 1 mGal with a resolution of 10 km for the purpose of predicting bathymetry in the 10 to 100-km wavelength band.**

The present status of our knowledge of the Earth topography and the scientific requirements which we discuss below are summarized in Figure 1.

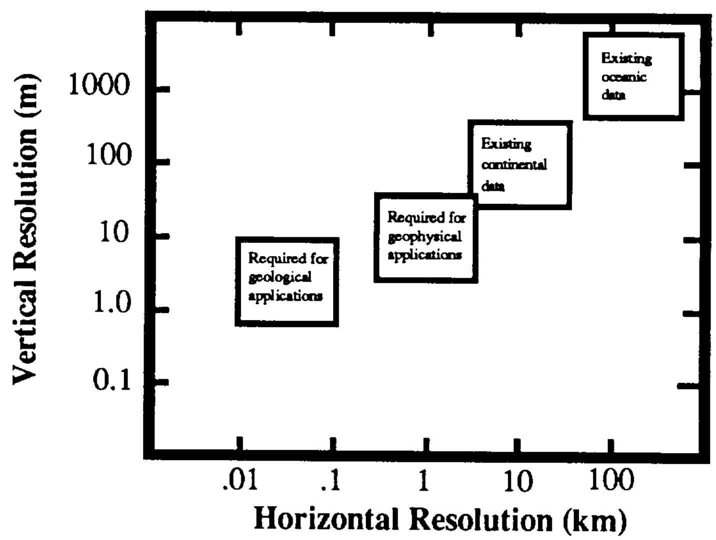


Figure 1. Scales (extent) of desirable global topographic coverage and appropriate resolution required for studies of lithospheric structure and evolution. For comparison, the best presently available global continental and marine data are shown.

Continental Topography

The continental surface has developed over millions to billions of years in reponse to volcanism, earthquakes, glaciation, and the effects of wind and surface water. The relief of a province alone can provide a good estimate of its age and the processes to which it has been subjected. In addition to the geologic and geophysical applications, topographic data over the continents are essential for atmospheric and slope corrections of image data acquired at wavelengths ranging from visible to microwave.

Present Status. Today, topographic data mostly consist of contours drawn around unevenly distributed spot height measurements [*Topographic Science Working Group*, 1988]. Available digital data are limited areally and for the most part derived from the same information used to create the contour maps. The best available global digital coverage for the continents has only about 5-km horizontal resolution, of little value for geological or gravity modeling of the continents. These data additionally suffer from the fact that 18 separate reference datums (horizontal control surfaces) are in use by different countries to measure local elevation. **A long term commitment by SES to utilize NASA satellite technology to create a digital topographic data set with a common global datum would contribute substantially to research related to lithospheric evolution.** Resolution requirements for the proposed data set are defined based on geological and gravity modeling requirements.

Geological Requirements. Topographic information is not only used as a base for geological mapping but also enables geologists to use surface mapping results to constrain the three-dimensional geometry of rock units and geological structures. This information in turn, constrains sedimentological and tectonic models describing the environmental and deformational history of continental crust.

The resolution of topographic data required for stratigraphic and structural studies is defined by mapping scale, local relief, and the attitude and thickness of mapping units. A standard maximum mapping scale used in such studies is 1:24,000. Based on National Mapping Accuracy Standards and geological mapping experience as described by *Lang et al.* [1987] and in the Remote Sensing section of this document, this mapping scale requires at least 30-m horizontal resolution and 4-m vertical resolution topographic data. This horizontal resolution is also appropriate because it is compatible with Thematic Mapper data, a standard remote sensing data set for lithologic and structural mapping of the continents.

Gravity Modeling Requirements. Accurate topographic data are required to correct gravity measurements used to model density distribution and infer structure of both continental crust and oceanic lithosphere. The requirements for topographic data in support of gravity studies as described by the *Topographic Science Working Group* [1988] and in the Gravity section of this report is 1-km horizontal and 10-m vertical resolution.

Suggested Approach. Minimal acceptable resolution requirements are most tightly constrained by geological research needs. Present space technology limitations indicate that acquisition of the 30-m horizontal and 4-m vertical resolution data set requires a phased/iterative approach. An initial digital topographic data base could be obtained with a radar altimeter, creating the first global digital topographic data set with a single datum. Horizontal resolution of such a data set would probably not exceed 100 m [*Topographic Science Working Group*, 1988]. Already available 30-m resolution digital data would then be incorporated. Finally, new data, acquired from aircraft or satellite using photogrammetric analysis of optical stereo images as well as laser altimetry would be iteratively incorporated. Appropriate GPS measurements could be used to adjust these elevations to the same datum as that used for the radar altimeter base. The process would continue until a global digital topographic data set with 30-m horizontal and 4-m vertical resolution was obtained.

Sea Floor Topography (Bathymetry)

Bathymetry is primarily an expression of volcanic and tectonic processes because seafloor erosion rates are low compared to the continents. Large-scale variations in seafloor topography (from shallow ridge crests, 2-5 km, to deep ocean basins, 5-6 km) are due to cooling and contraction of oceanic lithosphere as it moves away from a spreading axis. Departures from the normal depth-age relationship reveal areas where lithosphere has been reheated and/or crustal thickness varies. While these basin-scale variations are well described, the fine-scale bathymetry is not. Global knowledge of bathymetry at 10-km scale would allow us to:

- Refine models of the generation of oceanic lithosphere by mapping ridge morphology;
- Constrain the volume of intraplate volcanism by taking inventory of the number and size of undersea volcanoes;
- Improve models of relative plate motion by identifying and tracing oceanic fracture zones;
- Update resource assessments by mapping uncharted sedimentary basins on remote continental margins;
- Delineate regions of intraplate deformation and incipient subduction to understand plate/mantle dynamics;
- Improve our understanding of convergent plate boundaries by surveying subduction zones and back-arc basins.

Present Status. It is startling that the topography of Mars [*Carr et al.*, 1977] and Venus [*Masursky et al.*, 1980] has been mapped at a higher resolution than the topography of the Southern Ocean. There are still many 5 degree by 5 degree areas in the South Pacific, South Atlantic and Southern Indian Oceans that have not been explored by ships. Shipboard surveys to date have measured the large-scale (1000-10,000 km) variations in bathymetry, but fine scale bathymetry (10-100 km) is known only in isolated regions. Even with advanced swath mapping tools such as Seabeam, it would take many decades to survey significant portions of the sea floor in these remote areas.

Suggested Approach. Bathymetry cannot be directly measured from a satellite. However there are at least two ways that the space program can contribute to charting bathymetry. The first involves satellite-based navigation and communication. GPS navigation of research vessels is now required for taking full advantage of the high-accuracy swath mapping techniques such as Seabeam and SeaMarc. We perceive that during the next 20 years, unmanned ocean surface or subsurface vehicles may need to communicate with a central facility using a satellite link.

The second contribution from space techniques is to use satellite altimetry, which maps the topography of the equipotential sea surface (marine geoid), for locating features in uncharted areas [*Haxby*, 1985; *Sandwell*, 1984]. Details in the marine geoid reflect seafloor topography, especially at wavelengths shorter than 100 km. In addition to locating features, a complete two-dimensional mapping of the marine geoid could be used along with available shipboard bathymetric profiles to predict bathymetry in uncharted areas at 10 km resolution.

The basic approach is to take advantage of the correlation between the geoid or gravity field and bathymetry at short to medium wavelength [e.g. *Dixon et al.*, 1983; *Freedman and Parsons*, 1986]. High-accuracy and resolution geoid and gravity field data, derived from pulse-limited radar altimetry, may be used to interpolate between existing shipboard bathymetry profiles. This technique relies on the assumption that the relationship between gravity and bathymetry is uniform over small areas (~200 km by 200 km). Because of upward continuation of the gravity field from the sea floor to the sea surface, the best achievable horizontal resolution of predicted topography will be approximately twice the average water depth. Over the resolution band 10 km to 100 km, the estimated vertical accuracy of this technique is ~100 m (Figure 2).

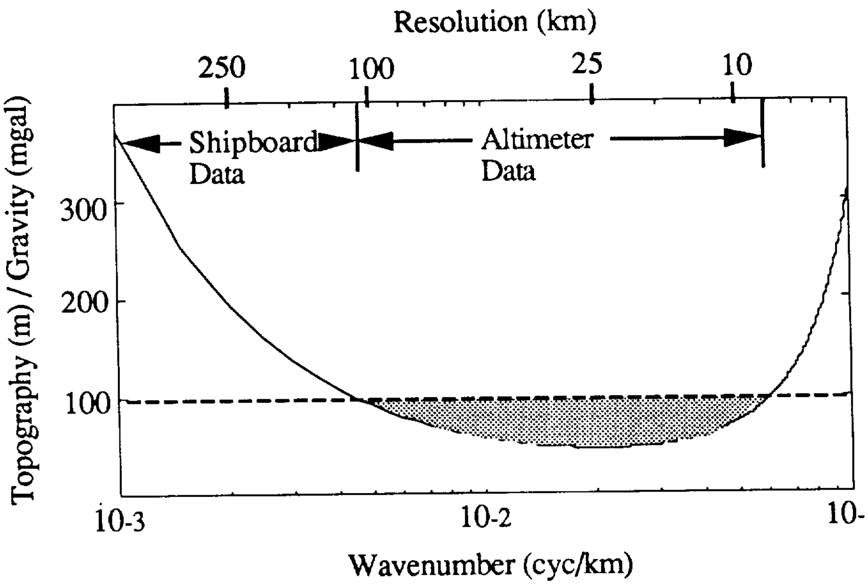


Figure 2. Ratio of sea floor topography to sea surface gravity for an Airy compensation model. Assuming a five-year altimeter mapping mission could recover the marine gravity field to an accuracy of 1 mgal at resolutions of 10 km, then this simple model predicts that marine gravity can be used to estimate sea floor topography on horizontal scales of ~10 km to ~100 km to an accuracy of 100 m. At longer wavelengths (resolution > 100 km) sea floor topography must be constrained by sparse shipboard profiles since the effect of isostatic compensation reduces the gravity effect.

GRAVITY FIELD

Gravity anomalies arise from lateral variations in density beneath the Earth's surface. These density variations may be caused by changes in either temperature or mineralogy, and thus an understanding of the Earth's gravity field at wavelengths less than the thickness of the lithosphere is *essential* to understanding the thermal and chemical differences between continental and oceanic lithosphere. We recommend that NASA work towards major improvements in the global gravity data base via

- **measuring the gravity field from space with an accuracy of a few mGals and a resolution of 100 km or less;**
- **encourage altimetric missions (e.g., ESA's ERS-1) to map the marine gravity field to an accuracy of 1 mGal with a resolution of 10 km.**

Note that for the purposes of measuring with radar altimeters the sea surface slopes arising from dynamic ocean effects such as currents, tides, and eddies, the oceanographic community requires a *gravimetric* marine geoid accurate to 20 cm at wavelengths of a few 100 km. Thus the gravity field requirements needed for solid Earth studies also satisfy the needs for oceanography.

Continental Gravity

Solving a number of problems central to the study of the structure and evolution of continental lithosphere requires accurate and detailed global gravity data. These problems include:

- the deep thermal and chemical structure of continental lithosphere. Continental lithosphere appears to be 2 to 4 times thicker than oceanic lithosphere. Is this deeper continental root solely a thermal effect, or does it require a chemicallyinduced density reduction to stabilize it against convective overturn? This deep structure provides the context within which all the other problems must be examined.

- the process of rifting and extension. Uniform stretching models have proven extremely useful in describing rifting in the oceans, whereas recent studies of continental rifting have emphasized the role of subhorizontal detachment systems in accommodating extension. Are these differences real, and if so, what controls them? Progress in understanding the difference relies on deeper knowledge of the structure and dynamics of both kinds of rifts and the rheology of both types of lithosphere.
- the deep, and in many places the shallow, structure of mountain belts. Serious questions remain as to the mode and depth of isostatic compensation, the relative role of topographic and subsurface loads, the origin of the subsurface loads, and the long-term rheology of continental lithosphere involved in their evolution.
- subsidence and reactivation of sedimentary basins and passive margins. It is important to develop the ability to distinguish sedimentary, thermal, flexural, eustatic, and tectonic components of subsidence in order to address problems ranging from petroleum exploration to rheology of the lithosphere.
- the nature of major heterogeneities in thickness and density of the continental crust, which apparently persist for billions of years due to the strength of continental lithosphere, and may control tectonic evolution upon reactivation of the continental basement.

We list briefly below the present state of gravity information over the continents and the improvement needed to address these problems. For a more detailed discussion of the scientific problems, see reports by *Gravity Workshop* [1987], *Topographic Science Working Group* [1988], and *Mueller and Zerbini* [1989].

Present Status. Existing data in the public domain at 4-mGal accuracy and 100-km resolution cover only 22% of the area of the exposed continents. Political and geographical barriers prevent further acquisition by means of traditional ground surveys. Since many countries consider gravity data strategic information for missile guidance, there is little prospect of gaining access to classified data in the near future. As in the case of the topographic data base, individual surveys are referenced with respect to different base levels which complicates the compilation of data sets across national (and even state) boundaries.

Requirements. Figure 3 summarizes the gravity field requirements needed to address the above problems. For example, the density anomalies arising from differences in continental versus oceanic thermal and chemical structure between 100 and 400 km should give a surface gravity anomaly of 1 to 5 mGal. The deep continental gravity anomaly must be resolved across continental margins (i.e., by a satellite technique valid over both land and water), and requires no worse than 100 km horizontal resolution.

Gravity anomalies can distinguish among various models for lithospheric extension by constraining the thermal structure and flexural rigidity in rifts. Broad constraints would be obtained with gravity data accurate to 1 or 2 mGal at horizontal resolution of 100 km, attainable by spacecraft. Specific information on spatial variation of flexural rigidity, given low expected elastic thicknesses, requires 1 mGal accuracy at 20 km or better resolution, potentially attainable by aircraft survey. The requirements for gravity data over orogens needed to test models of continental rheology, mechanisms of plate loading, and the structure resulting from continental suturing are similar, although the accuracies need not be as great since the expected signal is higher over mountain belts than over rifts.

Global gravity data with 1 mGal precision and 50 km spatial resolution, combined with topography, bathymetry, and radar ice-thickness data, are required to determine the forces driving subsidence of sedimentary basins and the mechanics of the lithosphere. Data at lower resolution would allow delineation or detection of sedimentary basins with petroleum potential hidden offshore, under ice-sheets, and under allochthonous crystalline thrust sheets.

High quality (5 mGal, 50 km resolution) gravity data, in conjunction with crustal seismic studies, can constrain the existence and mode of compensation of heterogeneities within continental lithosphere. This will allow assessment of their role in vertical motion of the continental lithosphere.

For all of these problems, sound interpretation of the gravity field in terms of the Earth's interior properties will require global topography known with great statistical accuracy at 25 km wavelengths. To achieve this, continental topography should be measured to better than 10-m accuracy at 1km horizontal resolution.

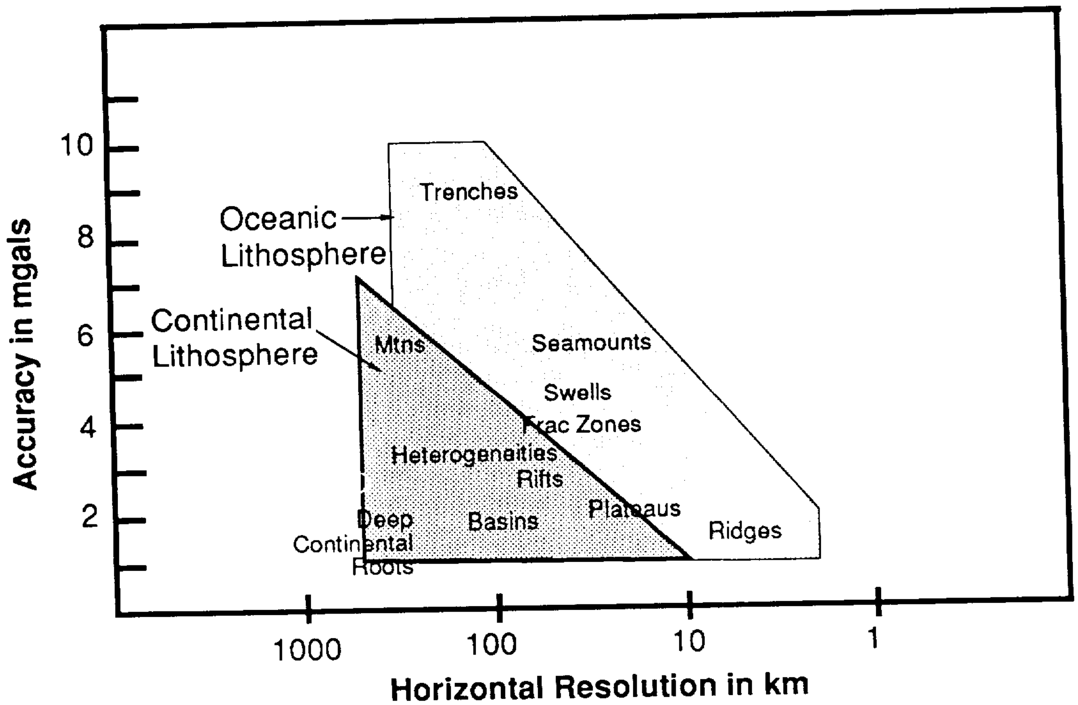


Figure 3. Summary of the requirements for gravity measurement accuracy as a function of spatial resolution needed to solve basic problems in lithospheric sturcture and evolution.

Marine Gravity

Altimeter data from Seasat and GEOS-3 amply demonstrated that satellite observations can yield major advances in our understanding of the thermo-mechanical structure and evolution of oceanic lithosphere. In the past decade, altimetry data over the oceans has been applied with much success to models of lithospheric structure in all major oceanic provinces, from the mid-ocean ridges where the lithosphere is formed to trenches where it is consumed. However, a number a outstanding problems concerning the oceanic lithosphere remain to be solved because available altimetric geoids lack sufficient resolution, accuracy, and/or continuity at shorelines. These problems include:

- lithospheric rheology and mantle dynamics at midocean ridges, and how they relate to topographic segmentation of ridges, axial horsts, and medial valleys. What is the relative importance of active versus passive rifting?
- the thermal structure of the upper mantle beneath fracture zones and how it evolves with time. Why does the simple thermal plate model, which so successfully

predicts the depth/age relationship for oceanic lithosphere, fail to describe the geoid anomaly measured across oceanic fracture zones? What are the relative roles of lithospheric flexure, thermal stress, variations in crustal structure, and small scale convection in explaining the discrepancy?

- lithosphere/asthenosphere interaction at subduction zones. What stresses act on the downgoing plate from its own negative buoyancy and resistance to penetration through a viscous mantle?
- the thermal structure of midplate swells, superswells, and their relationship to mantle plumes. Do these depth anomalies arise primarily from reheated lithosphere or thermal anomalies maintained in the convecting asthenosphere?
- the origin of oceanic plateaus and their mechanism of compensation. Which ones are simply thickened oceanic crust and which are continental fragments?

We list briefly below the present state of gravity information over the oceans and the improvement needed to address these problems. For a more detailed discussion of the scientific problems, see reports by *Gravity Workshop* [1987], *Topographic Science Working Group* [1988], and *Mueller and Zerbini* [1989].

Present Status. Because sea surface height is a fairly close approximation to the marine geoid (within a few 10's of cm), satellite altimeter missions such as Geos-3, Seasat, and Geosat, have provided a view of the marine gravity field far superior to what we have over the continents. In the Southern Oceans, the marine gravity field is better mapped than the bathymetry. Nevertheless, because the gaps in Geos-3 and Seasat coverage exceed 100 km at the Equator and because most of the Geosat data remains classified, we still do not know the marine gravity field to better than a few mGals at a resolution less than 100 km. Furthermore, better altimetry data alone will not satisfy many of the requirments for marine gravity, such as needing a *gravimetric* geoid for isolating dynamic sea surface slopes and a gravity field continuous at shorelines for modeling features at continental margins (e.g., subduction zones).

Requirements. Figure 3 summarizes the requirements in terms of accuracy and resolution of marine gravity data needed to address the problems listed above. The study of midocean ridges places the greatest demands in terms of accuracy and resolution, because the lithospheric plates are so weak on very young lithosphere that the gravity signal of interest is small and of short wavelength.

To address the question of the problem of the plate structure across fracture zones, we need a gravity field accurate to 1 mGal at a resolution of 50 km or less. To realize the full potential of such data, gravity field modeling must be also constrained by better topographic data from the oceans and seismic information on crustal structrure.

The largest gravity anomalies on Earth occur at trenches where the subduction of oceanic lithosphere into the mantle creates the greatest thermal, seismic, and geochemical anomalies. The large amplitude of the anomalies leads to accuracy requirements of only 5 to 10 mgals at 100- to 200-km resolution for studying plate interactions, but the gravity or geoid map must be continuous from the undeformed seafloor, across the outer rise, trench, forarc, and island arc to the overriding plate.

The large amplitude (10 m) and long wavelength (~500-1000 km) of the geoid signature from the thermal anomaly responsible for uplifting midplate swells is adequately mapped for the large northern hemisphere swells such as Hawaii, Bermuda, and Cape Verde, but those in the south-central Pacific, such as Society, Cook, and Austral, are barely resolved in both amplitude and planform [*McNutt and Judge,* 1990] against the background of the South Pacific superswell [*McNutt and Fischer*, 1987]. Thus more dense altimeter data with higher resolution would contribute to the study of swells in the South Pacific. In addition, such data would allow much better calibration of the flexural rigidity of oceanic lithosphere supporting the individual hot spot volcanoes capping these swells [*Watts,* 1978]. Because the base of the elastic plate corresponds to an isotherm near

500°C to 600°C [*McNutt and Menard*, 1982], by measuring the elastic plate thickness as a function of distance along the subsiding thermal swell as it moves past the hot spot, we can chart the depth to this isotherm as a function of time [*McNutt*, 1984]. This view of the evolution of one isotherm provides a strong constraint on the details of the thermal structure imposed by the hot spot that connot be resolved by the more general integral constraints on low density provided by the longer-wavelength geoid anomaly over the swell. A thorough understanding of the mechanism by which the hot spot reheats the lithosphere requires such knowledge of the vertical and lateral structure of reheating.

Satellite altimeter data have been used to estimate depths of compensation for a number of marine plateaus from the slope of geoid height versus topography [*MacKenzie and Sandwell*, 1986]. For smaller plateaus, the accuracy of this procedure is limited by the accuracy and coverage of existing satellite alimeter data. A complete gravity/topography study requires a field accurate to 1 mgal at a resolution of 50 km.

Suggested Approach. For many of these features the resolution requirements are so stringent (~10 km spatial resolution) that they can only be supplied from space via altimeters. In the case of subduction zones in particular, the necessity of having a field that spans the shoreline leads to the requirement that data be obtained using non-altimetric techniques, such as a gravity gradiometer in low orbit. Even if gravity data at the required resolution and accuracy is obtained, the ability to address many of these problems will be hindered by our extremely poor knowledge of seafloor bathymetry. Therefore, in support of potential field modeling, we also require a **non-altimetric** measure of the topography at comparable resolution to the gravity and geoid data. Although this can only be supplied by acoustic signals from surface ships, NASA can contribute to this effort by providing easy access to GPS technology for navigation.

MAGNETIC FIELD

The lithospheric magnetic field arises from minerals in the TiO_2-FeO-Fe_2O_3 ternary system behaving as permanent or induced magnets between the Earth's surface and the Curie isotherm, which is approximately 600°C for most geologically significant minerals. This signal is commonly termed the "crustal" magnetic field because the continental Moho appears to be a sharp magnetic boundary, but here we adopt the more general term "lithospheric" magnetic field to include the possibility of sources in the oceanic upper mantle beneath the crust but shallower than the Curie isotherm. Thus maps of the lithospheric magnetic field can be sensitive indicators of lithospheric mineralogy, temperature, and age (via the dependence of remanent magnetization on the strength and direction of the paleomagnetic field when the rocks last cooled through the Curie isotherm).

In a broad sense, the use of short and intermediate wavelength magnetic anomalies to trace surface structures into the subsurface and to infer the depth to an isotherm which controls the acquisition of magnetic properties is analogous and quite complementary to the interpretation of gravity anomalies. Both types of measurements suffer from the upward attenuation of field strength with altitude, which limits the resolution with which anomalies can be recovered from space. However, unlike the gravity field, the crustal magnetic field is contaminated by unmodeled secular variation of the core field whenever data from magnetic surveys acquired at different epochs are combined. Thus the case for acquiring a globally uniform field within a short period of time from space is even more compelling for magnetics than gravity.

The Magsat mission, which returned vector magnetic field data from elevations of 325 to 550 km between November, 1979 and June, 1980, is the best demonstration to date of the potential for satellite magnetic field measurements to contribute to studies of lithospheric composition, mineralogy, structure, and temperature. Many of the important scientific results for that mission are collected in the April, 1982 issue of *Geophysical Research*

Letters and the February, 1985 issue of the *Journal of Geophysical Research*. We recommend:

- **a follow-on, lower altitude, vector magnetic field mission to measure the lithospheric field to an accuracy of 1 nT at a resolution of 100 km, combined with**
- **a higher altitude, longer duration mission to effectively model and remove secular variation from the lithospheric signal**

for the purpose of addressing questions such as:

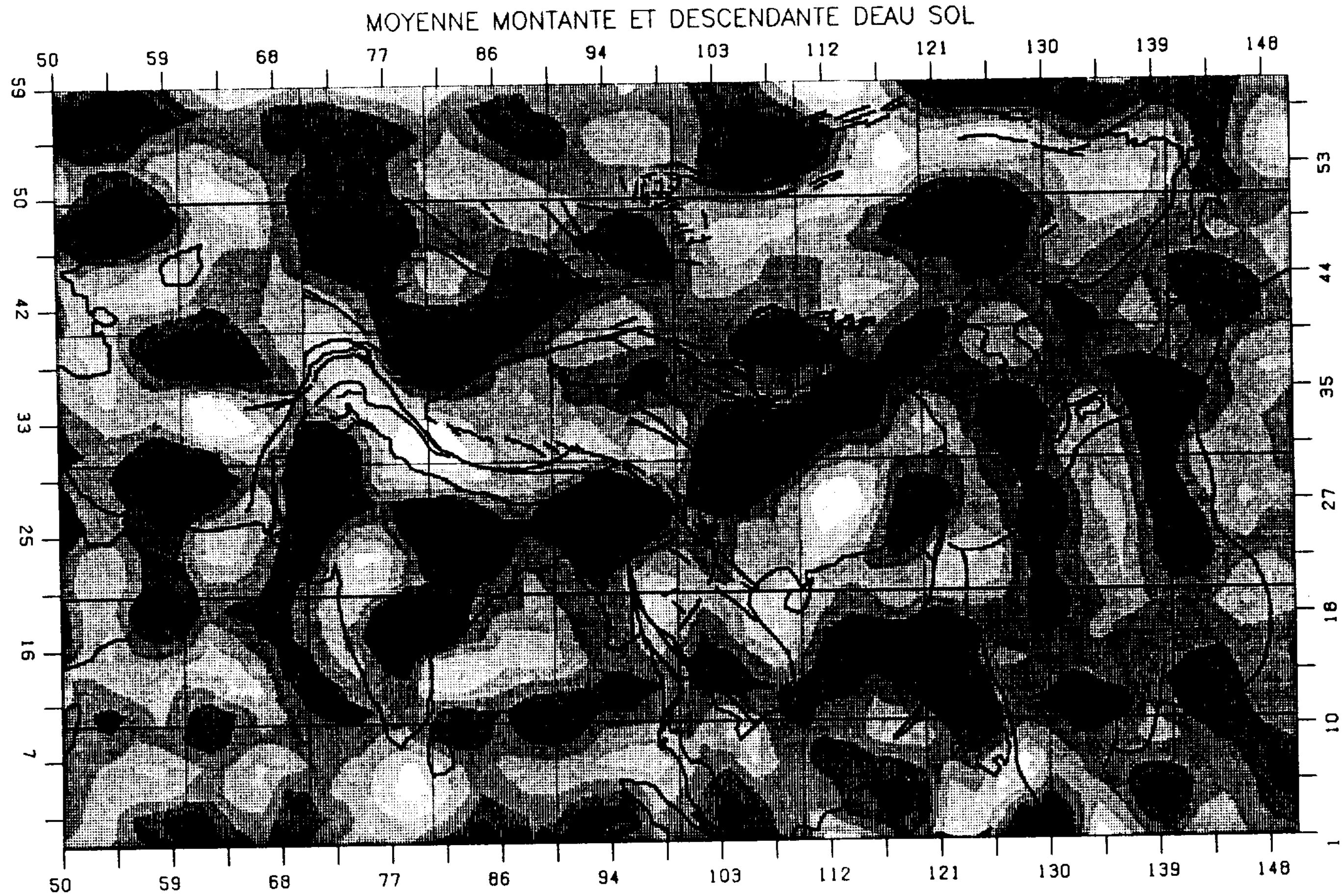
- the origin of intermediate-wavelength magnetic anomalies over oceanic lithosphere. Do these anomalies reflect lateral variations in thickness of the oceanic crust, depth to the Curie isotherm, or Fe-content in the shallow lithosphere?
- the magnetic effects associated with subduction zones and hot spot traces. How much is the Curie isotherm depressed or elevated? What are the Fe-Ti anomalies in the associated volcanics?
- lower crustal mineralogy and temperature beneath the continents. How does it contrast with that of oceanic lithosphere? Does it produce a large magnetic signal at continental margins? Can this contrast be used to distinguish oceanic from continental submarine plateaus?
- the depth to the Curie isotherm in continental areas. Can it be used to distinguish between thermal expansion versus crustal thickening as the explanation for plateau uplift?
- the relationship of large-amplitude magnetic lineations in the continental basement to ancient and modern tectonic motions, including continental rifting and suturing.

Present Status. As pointed out by *Langel* [1985], the Magsat data has not had the expected impact on quantitative studies of the Earth's crust because of its limited resolution for crustal studies (400-500 km wavelengths), problems with contamination from core and external fields, and north-south filtering of the data which leads to poor east-west resolution in the lithospheric anomalies.

Requirements. Based on the Magsat experience, we are now in a position to design a lower altitude magnetic mission, preferably flown during a solar minimum and in conjunction with a higher altitude, long-duration mission for core field studies. The availability of reliable data from such a mission is likely to lead to rapid advances in both theoretical as well as observational aspects of lithospheric field modeling. A higher resolution (~100 km), more accurate (~1 nT) global magnetic survey would allow us to address the questions listed above by better resolving the correlation of magnetic anomalies with tectonic features, lithospheric age, and mapped variations in crustal mineralogy (e.g., high Fe-Ti basalts from the Galapagos spreading center). For example, Figure 4 shows an intriguing correlation between Magsat anomalies in Asia with Cenozoic faults. However, the Magsat data does not have sufficient resolution for tectonic studies. A lower altitude mission would surely improve our understanding of the sources of the lithospheric magnetic field and how they relate to thermal and compositional heterogeneity of continental versus oceanic lithosphere.

Note that in addition to obtaining these high resolution lithospheric data, it is critical that we have better models of the core and external fields in order to convincingly separate the three magnetic signals. This can only be done by long-term monitoring of the secular variation as well as external field variations, since any contribution to the intermediate-wavelength signal arising from lithospheric sources should be "static".

Figure 4. The vertical component of the long-wavelength magnetic anomaly field derived from Magsat and downward continued to a uniform altitude near the Earth's surface, is compared to the distribution of major Cenozoic faults in southeast Asia. Strike-slip faults tend to be more localized above negative anomalies, whereas positive anomalies correspond to stable blocks and old cratons. From *Cohen and Achache* [1990].



Studying the continents is critical to understanding the lithosphere because the rocks they contain are the only record of Earth evolution before 200 Ma. Historically, the basic reference for such study has been geologic maps. The spatial distribution of rock units and structure, along with paleontological, chronological, compositional, and geometrical information summarized in geologic maps, are the basic data that allow detailed reconstruction of the evolution of continents. Specifically, geologic maps critically constrain global, regional and local determination of plate kinematics, intracontinental strain, and potential field-based models of the lithosphere and upper mantle. They summarize the sedimentological and paleontological record used to determine Phanerozoic climate change, sea level fluxuations, and biological events. They provide basic observations used for resource exploration, assessment, and development, including water, construction materials, minerals, and energy resources.

As a result primarily of NASA space technology, the concept of the geologic map has been expanded beyond that of a simple paper product. NASA-developed remote sensing methods have made it feasible to acquire gridded, digital, uniform-resolution geologic "maps" of continents. When these "maps" are combined with field and laboratory measurements, and other geologic, geophysical, and topographic data, they permit the 3-dimensional study of the geometry and kinematic development of continental crust. Such observations, coupled with theoretical models of mechanical properties of the lithosphere, will permit study of the dynamic processes responsible for the evolution of continental lithosphere. NASA's chief contribution to these efforts should be in

- **maintaining present remote sensing capabilities from satellites and aircraft, including instruments such as SAR, ITIR, and HIRIS planned for Eos;**
- **developing new hardware to provide higher spectral and spatial resolution in remote sensing data;**
- **making global data sets available to the research community at a *reasonable* cost; and**
- **supporting research that utilizes these data to address science objectives.**

Examples of potential research questions addressable by these methods include:

- Did plate tectonic processes operate in the early history of Earth? The composition and structure of rocks that were generated, preserved, and currently exposed at the surface, particularly in cratonic cores of continents, provide clues to the rate of crustal production and suspected higher heat flow during early Earth history that may have resulted in a tectonic style distinctly different from modern plate tectonics.
- What is the 3-dimensional kinematic history of continental crust? Three-dimensional, restorable kinematic models that portray the structural, sedimentological, and thermal history of continents are fundamental to interpreting deformational stresses and understanding the dynamic processes associated with continental evolution.
- What are the directly-observable, 3-dimensional characteristics of oceanic lithosphere? Numerous problems dealing with oceanic lithosphere formation, alteration by magmatic and hydrothermal fluids, transport, emplacement, etc., can be studied with remote sensing of ophiolites, fragments of oceanic lithosphere obducted onto the continents during plate collision or subduction events.
- What is the relationship between eustatic sea level change and continental tectonics during the Phanerozoic? Attempts to apply the concept that cyclical sedimentation in continental interiors is directly controlled by eustatic sea level changes to the detailed stratigraphic record in continental interiors have resulted in considerable controversy related to the relative contribution of tectonics and eustatics to these cycles [*Sloss*, 1984]. Resolution of this controversy requires an interdisciplinary approach which

includes image-based approaches to identifying the lithologic record of these events and determining the global geometry of the record in relation to the local, regional, and global tectonic and climatic record.

Results obtained from NASA SES scientific activities will also yield technology that can be transferred to the private sector for resource assessment, exploration and development.

Present Status

Remote measurements obtained from aircraft or satellite sensors provide gridded sampling and digital measurements of geophysical and geochemical properties of weathered rock surfaces exposed on the continents. Gridded data cannot be practically obtained using conventional geological methods. This characteristic of NASA-developed remote sensing technology provides a powerful tool for "mapping" the continents as well as identifying field sites for other studies.

Two approaches exist for extracting geologic information from remotely sensed data: 1) the photogeologic approach, and 2) the spectral approach. Both are aimed primarily at improved geological mapping that can be used to constrain stratigraphic, structural and geophysical models of crustal evolution in the same ways that conventional geologic maps are used.

The photogeologic approach uses knowledge about the weathering and erosional characteristics of strata and their tonal and topographic expression to map lithology and structure. This approach has evolved over a 50 year period using aerial photographs, and can be applied to pictures obtained from any image data acquired at wavelengths ranging from the visible through the microwave. With stereographic pictures, or combined topographic data and monoscopic pictures at the same scale, attitudes of geological surfaces can be measured directly.

The spectral approach uses knowledge about the physical interaction of electromagnetic radiation and rock/soil surfaces to extract compositional information from remotely sensed data. This approach is used principally in analysis of visible through thermal infrared (0.4-12.0 micrometers) multispectral remote sensing data, and is based upon theoretical, laboratory and field determinations of spectral properties of minerals, soils, rocks, and vegetation. This knowledge is the basis for aircraft and satellite sensor designs and image processing technique developments that make remote multispectral surveys of the continents a viable tool for lithologic mapping.

During the period 1982 through 1985, NASA developed new remote sensing systems including operational satellite systems such as TM, and experimental aircraft systems such as AIS/AVIRIS and TIMS. These systems, largely unknown to geologists, significantly enhance research capabilities and productivity.

Taken together, these NASA-developed technologies show that it is now feasible to measure remotely variations in attitude, thickness, and lithology of rocks exposed on the continents, thereby aiding development of quantitative models of the stratigraphic and structural evolution of continental crust. Below we describe specific remote sensing measurement capabilities that SES should maintain and new capabilities that SES should develop in order to implement these efforts.

Requirements

NASA remote sensing observations can contribute to resolving the scientific questions listed above by providing accurate compositional and structural information of continental lithosphere, in a synoptic format that facilitates intercontinental comparisons. Specifications for different instruments which sample the electromagnetic spectrum are given below.

Visible and Short Wavelength Infrared (0.4 to 2.5 micrometers). Global and relatively broad-band data acquired over these wavelengths is provided by the TM. Spectral and photogeologic analyses of TM data have successfully been used to address a broad range of problems related to the composition, structure, and evolution of continental crust [e.g., *Abrams et al.*, 1983; *Abrams et al.*, 1985; *Lang et al.*, 1987; *Paylor et al.*, 1989]. TM multispectral data will serve as a basic data set for SES research. Cost of TM data will be the primary limitation for their use; SES should address this problem which will be exacerbated because global science objectives will result in larger geographic targets for continental research.

Recent trends in instrument development, spectral analysis, and photogeologic interpretation show a need for both higher spectral and spatial resolution than that provided by the TM. AVIRIS aircraft and HIRIS satellite high spectral resolution data will be required to obtain detailed compositional information over critical sites. SES should continue development of both systems and provide data over critical research targets.

SPOT, Large Format Camera and Soyozkarta data have shown the value of high spatial resolution data. A high priority goal for SES will be to provide one time, global, high spatial resolution (approximately 5 m) stereo panchromatic data to the research community.

Thermal Infrared (2.5 to 14 micrometers). Multispectral thermal infrared data have been used to address problems of compositonal mapping, especially those involving the silicate minerals, that cannot be addressed using data acquired at other wavelengths [*Kahle and Goetz*, 1983; *Kahle*, 1980; *Lang et al.*, 1987]. Diurnal thermal data additionally can be used to measure thermal inertia. The only operational multispectral thermal system available today is the TIMS aircraft system that samples the 8 to 12 micrometer interval in 6 channels. Continued operation and deployment of this system over critical research sites should be a high SES priority. A long term SES goal should be acquisition of one time, global, multispectral thermal data with at least the same spectral resolution as that provided by TIMS. The proposed ITIR system should logically have this primary objective. Additionally, SES should investigate the geological utility of multispectral data acquired over the 3 to 5 micrometer interval.

Synthetic Aperture Radar (active microwave). Synthetic aperture radar (SAR) is uniquely suited to photogeological studies in areas where rocks are hidden beneath clouds or vegetation, or in hyper-arid regions where thin sand layers obscure outcrops [e.g., *Blom et al.*, 1984; *Sabins*, 1983]. Presently, no global SAR coverage exists, although NASA has acquired Seasat, SIR-A and SIR-B orbital data over many regions. SES should provide SAR data over critical sites using the available aircraft system. A long term SES goal should be acquisition of a one time, global SAR data set. The proposed Eos SAR (or a free flyer equivalent) is a mission that would accomplish this goal.

Field Studies. A wide range of field studies is required in conjunction with remote sensing data acquisition and analysis. These include in situ validation studies (ground truth), especially for checking lithologies and structures. Field measurements, including VIS-IR and TIR reflectances and radar backscatter over known lithologies, quantitative determination of vegetation and soil cover, and soil moisture measurements are also necessary.

Ancillary field studies, not needed to interpret the remote sensing data but required to project remotely acquired surface information into the crust and lithosphere, are also required. These studies may include, but are not limited to, magnetic and gravity studies, borehole and core data, and seismic reflection data, as well as conventional geological field measurements and paleontological studies.

Laboratory Studies. Laboratory studies needed include spectral measurements of rocks, mineral, and soils as needed to interpret remote sensing measurements. X ray diffraction, chemical analyses, and radiometric age determinations are also required.

VERTICAL POSITIONING

There exist numerous measurements of *relative* vertical motions on the Earth's surface. The techniques for measuring relative motions are diverse and span all time scales. For example, we can infer the subsidence of carbonate reefs with respect to sea level over tens of millions of years from drilling atolls. The offset of Holocene sediments across fault scarps yields constraints on the relative vertical motion of adjacent crustal blocks over 10's of thousands of years. Coastal tide gauge measurements provide very precise contemporary estimates of the relative change in sea level, but such measurements only have relevance for geodynamics at coastal sites, and even then are limited by our understanding of the absolute rise in sea level as a function of position on the Earth's surface caused by global warming. Unfortunately, there are very few direct measurements of *absolute* vertical motions, which means that a number of key geophysical models remain untested and many fundamental geodynamic parameters remain uncalibrated. We recommend that NASA undertake an effort in the next decade to

- **improve the accuracies of absolute vertical positioning to the sub-millimeter level and gravimetry to the sub-microGal level to measure signals associated with the long-term mechanical deformation and thermal evolution of the lithosphere.**

Space technology has already advanced to the point where we can directly measure the horizontal motions of plates. If we also had sufficient accuracy and precision to resolve vertical motions, we could address problems such as:

- What is the present-day pattern and rate of post-glacial rebound? Better constraints on rebound from space observations (absolute vertical positioning, time-dependent gravity) will lead to improved models of the rheology of continental lithosphere and the viscosity of the sub-continental mantle.
- What is the present-day rate of eustatic sea level rise? Although most melting of the Pleistocene glaciers was accomplished 5000 years ago, eustatic sea level may still be rising at the rate of 0.5 mm/yr as the result of slow secular melting of glaciers caused by increases in atmospheric carbon dioxide [*NASA Advisory Council, Earth Systems Science Committee*, 1987]. Instruments such as coastal tide gauges only measure the sum of eustatic sea level rise plus post-glacial rebound plus any tectonic effects. By tying directly tide gauges to an absolute vertical reference frame, we can separate the sea-level changes from the post-glacial rebound and tectonic signals. **Priority in the next decade should be placed on understanding post-glacial rebound and its relationship to truly eustatic changes in sea level, otherwise we will be unable to resolve the signals from any of the other effects discussed below.**
- Why does the depth/age curve for oceanic lithosphere flatten with age? Has it reached thermal equilibrium so that it is no longer subsiding, or does an overprint from midplate volcanism make it shallower than expected, even though it still is subsiding?
- How rapidly do midplate swells rise and fall? Are the rates consistent with conductive transfer of heat in the oceanic lithosphere, or is dynamic flow required?
- Where are the areas of the continents current undergoing epeirogenic uplift and subsidence? Can we link these vertical movements to thermal and dynamic processes inferred from seismology and gravity to understand the formation of intracontinental basins and arches?

The demonstration that space geodetic techniques can be used to measure instantaneous plate velocities has without doubt been one of the stellar successes of the Crustal Dynamics Project. However, without good models for horizontal plate motions based on careful geologic and geophysical mapping of offsets that took many millions of years to form, we would have had no way to verify the geodetic results. Therefore it is critical that any attempts to observe instantaneous vertical motions be integrated with a careful examination of the geologic record to estimate uplift and subsidence rates on million year time scales.

Requirements

Extremely stringent requirements in terms of accuracy in absolute positioning come from the rates of the vertical motions we seek to observe directly. Figure 5 illustrates the signal amplitudes relevant to the motions discussed above. Of the types of motions shown on this figure and discussed below, only the post glacial rebound is directly measurable with today's technology. We discuss the requirements for the others in the hope that this will drive technological improvements in vertical positioning systems during the next decade.

Although the following requirements are expressed in terms of the absolute change in elevation with time, the measurement of changes in gravity by an instrument fixed to the Earth's surface is an alternative to point positioning for detecting vertical motions. The signal expected depends upon how the vertical motion is compensated. For example, if the change in elevation dh is modeled as simply the free-air effect due to a change in the distance between the gravimeter and the center of the Earth with no net change in mass, then the gravity change dg is given by

$$dg/dh = -0.307\ \mu\text{gal/mm on land}$$

$$dg/dh = -0.265\ \mu\text{gal/mm under water}$$

with the effect being less under water due to the decrease in thickness of the water layer above the gravimeter. If an uplift is accompanied by an increase in mass of mantle density below the gravimeter, then the relevant gravity change is

$$dg/dh = -0.169\ \mu\text{gal/mm on land}$$

$$dg/dh = -0.127\ \mu\text{gal/mm under water}$$

Various models of isostatic compensation would predict gravity signals lying between these two extremes.

Since the current generation of absolute gravimeters is accurate to 3-10 μgal, it would take 10 to 20 years to resolve with a gravimeter vertical motions at the rate of 1 mm/yr. Sub-millimeter/yr rates of vertical motion are therefore not directly observable with the present gravimeter technology. For rates of motion at the mm/yr level, gravimeters can provide an independent check for precise vertical positioning if the change in mass accompanying the vertical motion is unknown (e.g., thermal contraction of the oceanic lithosphere), or an important complement to positioning if the mechanism is unknown. Note also that deployment of absolute gravimeters on the sea floor is an attractive alternative to determining submarine vertical motions through point positioning since the accuracy of the measurement is not limited by our knowledge of the speed of sound in sea water.

Post-glacial Rebound and Eustatic Sea-Level Rise. Although the maximum rates of post-glacial rebound (14 mm/yr) are centered on the formerly glacier-covered regions of Hudson Bay and Fennoscandia, simple models for the Earth's viscoelastic structure predict significant vertical (and horizontal!) motions at the mm/yr level over much of the globe. Certainly the first task in any program to understand vertical motions is to improve models of post-glacial rebound, since that signal is so much larger than any arising from thermal anomalies in the lithosphere or convection in the subcontinental asthenosphere.

We can exploit the large number of coastal tide gauge stations measuring vertical motion relative to sea level to improve the global coverage of instantaneous measurements of rebound in the following way. Suppose the eustatic rise in sea level (i.e., that change in sea level due to the addition of water to the ocean basins, assuming a stationary coast) could be modeled as the addition of a water layer of uniform thickness w everywhere in the oceans. Then by measuring the change in relative sea level and absolute vertical position at the same coastal site, one could uniquely determine the value for w and remove that from tide gauge measurements everywhere in order to obtain absolute vertical motions (i.e., the vertical motion of the coast with respect to the center-of-mass of the Earth) from the relative ones. Of course, the effect of a eustatic rise in sea level is not to add a water layer of uniform thickness everywhere. Rather, the new sea level surface must conform to an equipotential which is not merely parallel to the former equipotential because water, ice, and mantle rocks have been redistributed in the process of deglaciation. Thus we need to *simultaneously* solve the coupled problems of both rebound and sea level rise by comparing absolute and relative sea level changes at several locations. In addition, to solve the sea level problem we require a long-wavelength gravimetric (as opposed to altimetric) geoid accurate to 10 mm or less [R. Sabadini, personal communication, 1989].

The importance of solving the sea level problem goes far beyond the immediate goal for geodynamic purposes of separating tectonic from eustatic motions. Knowledge of eustatic sea level changes is critical for studies of global change, currently a high national priority. In addition, improved models of eustatic sea level changes at present will improve our understanding of how sea level rose throughout the Holocene, which can solve a number of difficulties in interpreting the Recent sea level record.

Thermal plate models. Suppose we wish to calibrate κ, the thermal diffusivity for oceanic lithosphere, by measuring directly the subsidence of young lithosphere. Predicted motions involving conductive cooling of the lithosphere can be calculated from the thermal plate model. The largest rates of subsidence occur on young oceanic lithosphere near the midocean ridges, but are still less than 2 mm every 10 years. The subsidence rate of old oceanic lithosphere, if indeed it continues to subside, is an order of magnitude smaller yet. Clearly we need even better accuracy than we have at present from space geodetic techniques, or we need long observing programs, if we want to directly observe the subsidence of the lithosphere. Even with measurements an order of magnitude better, we would have to devote much effort into understanding the noise spectrum for vertical motions at the level of 10's of micrometers. The prospect of measuring subsidence of the oceanic lithosphere using space-borne altimeters or gradiometers is even more gloomy. The predicted change in geoid as the plate contracts and subsides is only -0.15 μm/yr [*Parsons and Richter*, 1980] because the elevation change is locally compensated.

The rates of vertical motions associated with midplate swells can be very much larger. The only swell for which we have an estimate of the rise time is the Hawaiian swell, which is elevated 2.5 km in just 8 my assuming that the bathymetric profile southeast of Hawaii is steady state [*McNutt and Shure*, 1986], which yields an uplift rate of 0.31 mm/yr. Note that this rate of uplift is nearly twice the rate of subsidence for young oceanic lithosphere, and is therefore the principal observation evidence against any sort of conductive mechanism for transporting heat into midplate swells. If this relatively rapid uplift rate can be directly confirmed for Hawaii, and also measured for other hot spots on lithosphere of different ages in order to calibrate how the initial thermal structure of the lithosphere affects swell rise time, we would gain critical new constraints on the interaction of the lithosphere with hot spots. It would also be advantageous to monitor the subsequent subsidence of a midplate swell, but the characteristic rates are nearly an order of magnitude less.

It is more difficult to test thermal boundary layer models for the continents. For example, the predicted difference in subsidence rates for a 125-km thick plate and a 400-km thick plate, both of Early Paleozoic age, is only 0.007 mm/yr. If the thermal subsidence is offset by a chemical buoyancy effect [*Jordan*, 1975, 1978, 1988], the difference in subsidence rates for the two plate models may be even less. The rate of epeirogenic movements in continental interiors caused by poorly known thermal and dynamic factors is larger, 0.03 mm/yr, based on the thickness of sedimentary units in intracratonic basins, but is still beyond reach with present technology.

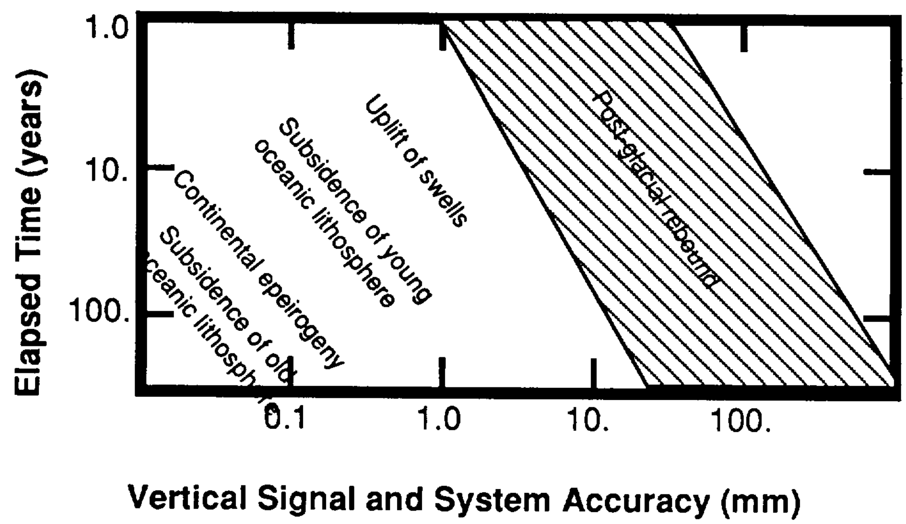


Figure 5. Trade-off between system accuracy and duration of observation campaign needed to resolve vertical geodetic signals. Even if a very long term program is initiated to measure directly these signals, the interpretation of the data will require first that the post-glacial rebound contribution be thoroughly understood and modeled before other, much smaller contributions can be interpreted reliably.

PRIORITIES AND RECOMMENDATIONS

Progress in understanding lithospheric structure and evolution is dependent upon availability of the global data sets described above which are more effectively acquired from space. Our prioritization assumes that the remote sensing instruments now in operation will continue to provide data throughout the program life. These include TM and SPOT satellite systems, the shuttle-borne SIR-C radar, and the ASAS, TIMS, AVIRIS, NS-001, SAR, and photographic aircraft systems. We also assume that planned EOS systems or equivalent including SAR, TIMS-class ITIR, and HIRIS be in operation as scheduled. We also assume that better altimetric coverage over the oceans is best achieved through the efforts of foreign space agencies due to classification issues. With these assumptions we prioritize our needs as follows:

1. Digital topography over the continents (30 m horizontal, 4 m vertical). These data are essential to all scientific objectives.
2. Gravity measurements (<100 km horizontal, 2 mGal). One approach is for NASA to contribute the GPS receiver and a drag-free system to ensure the success of the ESA Aristoteles mission, which would be an important first step in obtaining high resolution, global gravity data and for the purpose of demonstrating the feasibility of gravity gradiometry from space. However, it is unlikely that this mission will provide the accuracy and resolution we require. Therefore, NASA should pursue plans for a follow-on low-altitude gravity mission, such as the Superconducting Gravity Gradiometer Mission.

3. Magnetic measurements. Given the expense of flying missions in low-Earth orbit, we recommend that magnetic field measurements be included with both Aristoteles and SGGM gravity missions). A higher orbit, MFE-type mission is also important for isolating the core field from the lithospheric field.
4. High spatial (approximately 5 m) resolution stereo panchromatic data. One approach would be to use the Large Format Camera. This high spatial resolution stereo system fills an important void in planned remote sensing missions. The instrument should routinely be flown on the Shuttle and/or on some other platform until global stereo coverage is obtained.
5. Vertical Positioning. The exciting prospect of directly measuring the vertical motions associated with the evolution of the lithosphere is still a decade or more away, but it will continue to be an elusive goal unless we begin now to improve the accuracy of absolute vertical positioning and start acquiring baseline measurements of signals that can be resolved a decade or more later.

In addition to providing the basic global data sets described above, NASA is in a key position to

- **foster cooperation among the space agencies of the world to address major scientific and environmental problems, with a philosophy of maximizing data exchange and the development of complementary missions; and**
- **realize the scientific potential of this data by funding data analysis as well as acquisition.** Selection of specific investigations and geographic sites for study should be based on the results from peer review process.

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