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FINAL REPORT

TO THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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"Inversion of Gravity and Bathymetry in Oceanic Regions for Long-Wavelength Variations in Upper Mantle Temperature and Composition"

1 January 1992 - 30 June 1993

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(NASA-CR-192272) INVERSION OF GRAVITY AND EATHYMETRY IN OCEANIC REGIONS FOR LONG-WAVELENGTH VARIATIONS IN UPPER MANTLE TEMPERATURE AND COMPOSITION Final Report, 1 Jan. 1992 - 30 Jun. 1993 (MIT) 5 p
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PROJECT SUMMARY

Introduction

Long-wavelength variations in geoid height, bathymetry, and SS-S travel times are all relatable to lateral variations in the characteristic temperature and bulk composition of the upper mantle. The temperature and composition are in turn relatable to mantle convection and the degree of melt extraction from the upper mantle residuum. Thus the combined inversion of the geoid or gravity field, residual bathymetry, and seismic velocity information offers the promise of resolving fundamental aspects of the pattern of mantle dynamics. The use of differential body wave travel times as a measure of seismic velocity information, in particular, permits resolution of lateral variations at scales (hundreds of kilometers to a few thousand kilometers) not resolvable by conventional global or regional-scale seismic tomography with long-period surface waves. These intermediate scale lengths, well resolved in global gravity field models, are crucial for understanding the details of any chemical or physical layering in the mantle and of the characteristics of so-called "small-scale" convection beneath oceanic lithosphere.

In 1991 we proposed a three-year project to the NASA Geophysics Program to carry out a systematic inversion of long-wavelength geoid anomalies, residual bathymetric anomalies, and differential SS-S travel time delays for the lateral variation in characteristic temperature and bulk composition of the oceanic upper mantle. The project was funded as a three-year award, beginning on 1 January 1992, under grant NAGW-3036 to the Massachusetts Institute of Technology (MIT), where the Principal Investigator (PI) was a Professor of Geophysics.

On 1 September 1992 the PI assumed a new position as Director of the Department of Terrestrial Magnetism (DTM) at the Carnegie Institution of Washington. On 17 November 1992 we submitted a continuation proposal to support the second and third years of this project through DTM. The continuation proposal was approved, and funding for the second and third years of effort began on 1 March 1993 under NASA grant NAGW-3564. In January of 1993, the grant to MIT was given a no-cost extension to 30 June 1993, and Professor Thomas H. Jordan was named as the Principal Investigator given that Professor Solomon was then on extended leave from the MIT faculty.

Thus the grant to MIT was only 18 months in duration, even though the research tasks which that grant supported will be carried out over three years, and for two of those years much of the research will be carried out at another institution. This report constitutes the final technical report for grant NAGW-3036 to MIT.

Research Objectives

The objectives of this multi-year project, as stated in the original proposal to NASA, have been as follows:

(i) For each of several oceanic regions - including the North and South Atlantic, eastern and southern Pacific, and Indian and Arctic Oceans - to collect all available SS-S differential travel time data from records of suitable earthquakes at digital seismic stations operating as part of one of the global networks.

(ii) Where appropriate, to add PP-P differential travel times as an independent data set for each of these regions.

(iii) For each region, to carry out joint inversions of geoid, bathymetric, and travel time residual data to recover intermediate- and long-wavelength variations in upper mantle temperature and composition.

(iv) To interpret the results of the inversions in terms of convection and melt extraction in the oceanic upper mantle.

Research Progress

By means of a large data base of digital seismograms and waveform cross-correlation and spectral ratio techniques, we measured SS-S differential travel time residuals and differential attenuation in order to determine lateral variations in upper mantle structure beneath the Mid-Atlantic Ridge and East Pacific Rise. Differential travel times of such phases as SS and S with identical source and receiver have the advantage that residuals are likely to be dominated by contributions from the upper mantle near the surface bounce point of the reflected phase (SS). Under this assumption, differential SS-S travel time residuals have been mapped at the SS bounce points as a means of delineating lateral variations in mantle structure. After removing the signature of lithosphere age, we found evidence for long-wavelength variations in SS-S residuals along the Mid-Atlantic Ridge. The dominant wavelength of these variations is 1000 to 7000 km. These travel time anomalies correlate qualitatively with along-axis variations in bathymetry and geoid height.

We formulated a joint inversion of travel time residual, geoid height, and bathymetry under the assumption that all arise from variations in upper mantle temperature or bulk composition (parameterized in terms of Mg#). The inversion employs geoid and topography kernels which depend on the mantle viscosity structure. Inversion for temperature perturbations alone provides good fits to travel time and geoid data. The fit to topography, which is likely dominated by unmodeled crustal thickness variations, is not as good. The inversions for temperature favor the presence of a thin low viscosity layer in the upper mantle and temperature perturbations concentrated at depths less than 300 km. Compositional variations alone are unable to match the travel time and geoid or bathymetry data simultaneously. A joint inversion for temperature and composition provides good fits to both geoid and travel time anomalies. Temperature variations are ± 50 K and compositional variations are ± 0.5-3 % Mg# for models with the temperature variations uniformly distributed over the uppermost 300 km and the compositional variations either distributed uniformly over the same interval or concentrated at shallower depths. The magnitudes of these variations are consistent with the chemistry and geothermometry of dredged peridotites along the Mid-Atlantic Ridge.

Differential travel times of SS-S pairs in the east central Pacific show several differences from the North Atlantic. The most obvious difference is that the travel time residuals are significantly larger than in the Atlantic, even at a fixed age. The travel time - age relation is weaker in the Pacific, although this may be partially attributable to the fact that we have not sampled a large range of plate ages in the eastern Pacific. In the Atlantic our results are not consistent with the presence of a simple pattern of azimuthal anisotropy, while in the Pacific the data are consistent with the presence of weak anisotropy in the upper mantle. It has been suggested that anisotropy may be more pronounced at fast spreading rates than at slow spreading rates both in the lithosphere (due to a rate dependence of the mechanism for orienting olivine crystals in the lithosphere) and the asthenosphere (because the asthenospheric flow beneath fast moving plates is likely to take the form of a progressive simple shear which can produce a lattice preferred orientation of olivine crystals), and our results are consistent with this suggestion. There is substantial ambiguity in our anisotropy measurements for the Pacific, however, due to a poor sampling of azimuths, so that it is also possible that lateral heterogeneity rather than azimuthal anisotropy is producing the observed azimuthal pattern. Sampling at a more uniform distribution of azimuths should make this result less ambiguous, and as more seismic stations are deployed at new geographic locations our chances of resolving this issue will improve.

Inversion of travel time residuals, geoid, and bathymetry data for the eastern Pacific indicates that compositional variations alone are inadequate to match all of the data simultaneously, similar to our results for the north Atlantic. Temperature variations alone, however, produce significant variance reduction. The inversion solutions indicate excess temperature in the vicinity of the Galapagos hotspot in the range 50 - 150 K. Further analysis is needed to determine the effects of subduction zone structure and possible crustal thickening in the eastern Cocos plate region.

As a complement to the study of travel times, we have measured SS-S differential attenuation in the north Atlantic region. Mapping seismic Q in the upper mantle is an important tool for assessing mechanisms of lateral heterogeneity because the attenuation of seismic waves is sensitive to variations in temperature and to partial melting. Differential attenuation is positively correlated with SS-S travel time residual. Both differential attenuation and travel time residual decrease with increasing seafloor age. The age dependence of SS-S travel time residual can be explained entirely by the cooling of the oceanic lithosphere, i.e., contributions from the asthenosphere or from a mantle melt fraction are not required. The assumption that plate cooling also dominates the variation of differential attenuation with age permits the derivation of an empirical Q^{-1}-temperature relation for the oceanic lithosphere, i.e., the depth interval 0-125 km. However, both the absolute values and the depth distribution of Q we obtain under this assumption are at variance with the results of surface wave attenuation studies, and the variation of Q^{-1} with temperature that we derive is not as strongly dependent on temperature as that observed in laboratory studies. We have therefore developed models for Q in which lateral variations include contributions from the asthenospheric low-Q zone as well as from lithospheric cooling. The Q models obtained under this alternative assumption are in good agreement with those obtained from surface wave studies and are therefore preferred over those models with lateral variations confined to the upper 125 km. Systematic long-wavelength (1000-7000 km) variations in upper mantle differential attenuation, corrected for seafloor age, are evident along the axis of the Mid-Atlantic Ridge. These variations correlate approximately with long-wavelength variations in shear wave travel time residuals and are attributed to along-axis differences in upper mantle temperature.

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