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GEOPHYSICAL GEODESY: THE STUDY OF THE SLOW DEFORMATIONS OF THE EARTH

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Geophysical observations provide the principal source of information on the interior structure of the Earth. They include the travel times, amplitudes and frequencies of seismic waves, the flux of heat through the surface, and magnetic-field parameters. Geodetic observations of the external gravity field and of the shape of the planet provide further constraints. Together with physical and chemical arguments, these observations form the basis for estimating the properties of the Earth's interior and for constructing models that describe the evolution of this and, largely by extrapolation, of other terrestrial planets. Geological observations, including geomorphology and geochemistry, are the key to understanding the history of the Earth's crust; of deformation events, of times of metamorphism and igneous activity and of horizontal and vertical movements. Palaeomagnetism provides the principal quantitative evidence for the large scale horizontal displacements and deformations, at rates of a few centimeters per year averaged over about 10^6 years. The examination of seismicity provides information on local and regional deformation of the crust on much shorter time scales. The central problem is the determination of the physical processes that led to these upheavals. What is the nature of the forces acting on the crust that have shaped it into its present state? What process is responsible for the large scale horizontal movements? What is the origin of the heat sources that produced the metamorphic and igneous events? The geodetic contributions to understanding these geological processes fall into two categories. The first is where observations provide a measure of the response of the Earth to known forces. In surface loading problems, where the applied force is known, observations of the deformation provide constraints on the rheological properties of the crust and mantle. In the second class of problems, the geodetic observations are used to provide constraints on the forces themselves. Many geophysical observations can be reconciled with radially symmetric Earth models, but the satellite results for the gravity field indicate that lateral structure is also important and these data point to a non-hydrostatic state within the Earth. These global gravity results reflect dynamical processes within the Earth and provide one further constraint on the Earth's present structure and, less directly, on its evolution.

The spectrum of the Earth's deformation is illustrated in Figure 1. At low frequencies and long wavelengths, the dominant deformations of the Earth are associated with mantle convection and its surface expression, plate tectonics. At the high frequency part of the spectrum, in both the dimensions of space and time, the dominant deformations are the earthquake displacement fields, the "instantaneous" expression of plate tectonics and mantle convection. The two extremes of the space-time spectrum are therefore closely related to each other, as well as to many of the intermediate wavelength-timescale deformations. The evidence for global tectonic motion is overwhelming, but models describing this motion are essentially kinematic ones and only rarely do they specify the dynamic mechanisms responsible for the surface motion and seldom do they specify the deformation beneath the crust or lithosphere. A central aim of modern geophysics and geology is to reach a quantitative understanding of the mechanisms involved and while considerable progress towards this goal has been made over recent years, it can hardly be said that the problem is fully understood. This inadequate state can be attributed to several factors of which two are particularly relevant: the limitations of our knowledge of the crustal and mantle rheology, and the limited understanding of the nature of the tectonic forces acting within the planet. Considerable geophysical research is directed, therefore, not only towards these global problems but also towards solving rather specific problems, including the refinement of seismic models of the Earth, the determination of the rheology of the crust and mantle, and the examination of tectonic processes at plate boundaries and within plate interiors.

With the broad definition of geodesy to include the study of crustal motion, the spatial and temporal variations in the gravity field and the tidal and rotational deformations of the Earth, the geodetic observations play an important role in the study of the structure and evolution of the Earth. Figure 2 summarizes specific geodetic techniques that may be applied to examine the deformations summarized in Figure 1. At the very long

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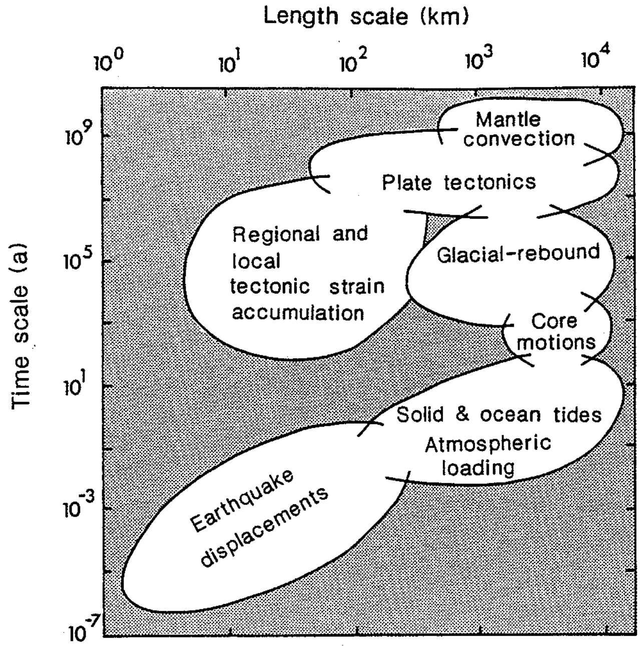

Fig. 1. The space-time spectrum of geodynamic processes leading to deformation of the Earth.

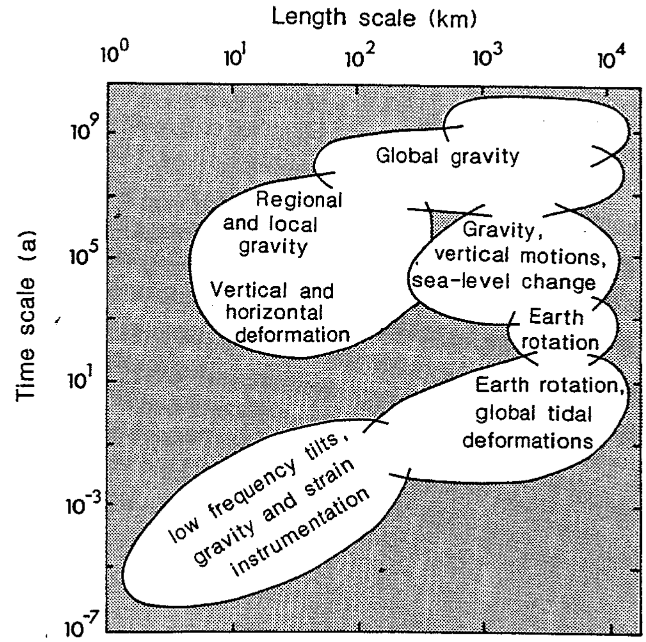

Fig. 2. The geodetic techniques relevant to measuring the deformations illustrated in Figure 1.

time scales, the observations of gravity and geoid anomalies provides information on the non-hydrostatic stress in the Earth and on the response of the Earth to this stress. For example, observations of gravity over seamounts or sedimentary basins provide a measure of the response of the lithosphere to loading on time scales of 10^6-10^7 years. On time scales of 10^3-10^4 years, observations of apparent changes in sea-level provide estimates of the response of the mantle to the extensive deglaciation that occurred between about 18000 and 6000 years ago. On shorter time scales, of days to decades, observations of the Earth's tides and rotation provide estimates of the global elastic and inelastic response of the planet. Locally, the geodetic observations provide estimates of crustal deformation that may otherwise go undetected because the seismic instrumentation response is insufficiently broad. Measurements of tilt and strain also elucidate the deformation process before and after the time of earthquakes. Even if there is not a geodetic remedy for every geophysical problem, there are many instances in which the observations play a supporting role. It must be recognised, however, that these observations provide information for only a very short segment of the Earth's history, of at most 100 years. This interval can sometimes be extended by using historical and palaeontological observations, as in the case of the Earth's rotation, or by examining geomorphological evidence, as in the case of variations in sea-level relative to present shorelines. This extrapolation is indeed necessary to bridge the time gap between the "instantaneous" geodetic measurements of deformation on the one hand and those geological and geophysical measurements of motion and deformation that represent average rates over geological time scales of 10^6 years or longer.

The new geodetic measurement techniques include the precise tracking of satellites, both artificial and the Moon, the long-baseline interferometric observations of radio sources, and the measurement of the Earth's gravity field using various sensors mounted on satellites. These new measurement procedures have not yet made a major impact on the geophysical discussion of the Earth's dynamic character, in part because these technologies have themselves been evolving rapidly and homogeneous data sets do not yet exist for even a few years. Yet the geodetic developments of the past two decades have now reached the point where one can see geophysical signatures arising out of the noise from only relatively short series of observations and one example of this is the VLBI observation of the Earth's short-period nutations. The promises that proponents of the new measurement methods have been making for many years, as discussed, for example, in the still highly relevant "Williamstown document" (Kaula 1970), are now being delivered.

As the accuracy of the space-geodetic measurements has increased, so has the complexity and cost of the equipment and it may well be asked whether all techniques that have been developed are necessary. Is it required to track artificial satellites with both lasers and electronic systems such as GPS? Is it necessary to develop and apply both laser ranging to the Moon and VLBI? The answer to these questions is yes. The GPS system does not, at present, preserve its inherently high precision when the station baselines exceed 100 km or so, and laser tracking is very complementary to GPS in crustal deformation studies on regional and continental scales. High precision laser tracking of close Earth satellites also provides the principal information for measuring the long wavelength part of the gravity field and on the time dependence of this field caused by tidal, meteorological and glacial rebound deformations. These observations are, however, less suitable for measuring the long-period components in the Earth's rotation because of the difficulty of modelling with high accuracy the secular and slow periodic perturbations in the satellite motion. Here VLBI methods are more appropriate in that the astrometric reference frame is well defined and in that these measurements have the potential for very high resolution observations. For the measurement of the global plate motions the VLBI methods appear to be at least as satisfactory as the satellite tracking methods, insofar as any conclusions can be drawn from only the short series of data that are now available. The lunar laser ranging methods would be the least satisfactory of the new methods for measuring the kinematics of the Earth, but it is the only method presently available for observing the orbital and spin motions of the Moon.

It would be hazardous to predict where our understanding of the deformations of the Earth will be when several decades of precise observations are available. New responses to known driving forces are likely to be discovered and as yet unknown mechanisms will be postulated. One reason why this prediction is hazardous is that the level of observations are now such that they are much contaminated by environmental factors, ranging from the meteorological excitation of the Earth's rotation to the role of rainfall and groundwater variations in crustal tilt measurements. What will be required in order to exploit fully the new geodetic measurements is a parallel observation program of the appropriate regional and global atmospheric-oceanic-hydrologic parameters. Another reason why the prediction is hazardous is that progress will undoubtedly occur in complementary areas of geophysics that require revision of today's concepts. Advances in seismic tomography will be very substantial once global and regional digital broad-band seismic networks are in full operation, and this will undoubtedly change today's dogmas on mantle convection and the interpretations of the gravity field will have to be adjusted accordingly. In some areas, the geodetic data has outstripped complementary geophysical data. For example, measurements of the flux of heat out of the Earth's interior are poorly distributed and improved gravity data will not contribute greatly to understanding the relations between these two geophysical quantities unless there is significant progress in the collection and interpretation of heat flow data. Even the surface topography is now less well known over many parts of the world's oceans than is gravity or geoid height, and future high resolution gravity field studies, using satellite-to-satellite or gradiometry techniques, could produce a similar state of affairs over large continental areas. Significant progress in understanding the Earth's gravity field will, therefore, come about only if knowledge of these other geophysical fields is also improved. One prediction that can be safely made is that the interpretation of future geodetic measurements of the Earth's deformation will require an increasingly deep understanding of geological and geophysical processes and that the measurements will become an increasingly integrated part of the Earth Sciences.

A few suggestions about anticipated developments over the next decade can be made with some assurance if only because the lead time of new satellite missions is almost this long. One area for ongoing geodetic research will be the Earth's gravity field. The solutions of the spatial variation in gravity, as derived from the analysis of perturbations in satellite orbits and from the analysis of satellite altimetry data, represent one of the major geophysical successes of the space program and these observations have played a very significant role in studies of mantle convection and lithospheric dynamics. Modest improvements in the knowledge of this field can still be expected, even if no new spacecraft are launched, through improved analysis techniques and through further precise laser tracking of some of the existing reflector-carrying satellites. A launch of additional satellites of the STARLETTE type, as has been mooted by the French space agency Centre National d'Etudes Spatiales, would also lead to useful improvements in the accuracy of the long and intermediate wavelengths in the gravity field. These developments would not, however, give significantly higher resolution of the gravity field over the continents than is now available and to achieve this a very major program will be required that is centred on technologies such as satellite-to-satellite tracking or satellite-gradiometry, as has been proposed by both the European Space Agency (ESA) and the U.S. National Aeronautic and Space Administration (NASA). A major value of such a mission is to provide much improved gravity information over active tectonic provinces at plate boundaries such as Tibet and the Himalayas or the Andean Cordillera. Altimetry data collected by the satellite GEOSAT and by the proposed joint ESA-NASA TOPEX mission will lead to an improved knowledge of the gravity field over the oceans but their major scientific contribution will be to the oceanographic studies of the time-dependence of the ocean surface and the associated forces and motions.

The study of the Earth's tides will remain an area of study where major progress can be made, both in the modelling of the ocean tides and in the estimation of the effective tide parameters from the analysis of perturbations in satellite motion. Altimetry data from the GEOSAT and TOPEX satellites will make major contributions to the former problem and additional STARLETTE-type satellites would contribute greatly to the latter problem. The principal contribution of such studies would be improved estimates of the rate of energy dissipation in the oceans and solid Earth and the estimation of the frequency dependence of the Love numbers due to both mantle anelasticity and fluid core effects.

Another important development will be the establishment of geodetic networks on the scale of tectonic plates for the measurement of crustal motions, probably with laser ranging and VLBI methods to establish regional frames and with GPS-type observations for the densification of the net that is required for understanding the strain cycles of the crust. The studies initiated in the eastern Mediterranean, centred on mainland Greece and the Aegean Islands, provides one example of such a combination of techniques that appears to be appropriate for the study of crustal deformation at complex plate boundaries. Measurement of time-dependent variations in height will be important in these programs and there will be a need for precise and long-term monitoring of sea-level as well as for geomorphological and geological studies of past motions. The continuous monitoring of motions of the major tectonic plates, with the methods of VLBI and satellite laser ranging to satellites, will provide an invaluable data base for analysing the plate motions to complement the geological estimates that are representative of average conditions over the intervals of 10^6 years. The importance of these "instantaneous" deformation measurements increases with the duration of the observation series and a minimum observation period would be the characteristic time interval between very large interplate earthquakes.

The Earth's variable rotation is another area of study where much progress can be anticipated as the records of the highly accurate observations increase in duration. This includes the nature of the excitation of the Chandler wobble but supplementary geophysical and meteorological information, such as atmospheric winds and surface pressure and the displacement fields of large earthquakes, will also have to be measured with improved accuracy and temporal resolution. Here the study of the Earth's rotation and crustal deformation is very complementary. Meteorological noise in the variations in length-of-day is now at least as great as the measurement noise and it represents a major limitation to the interpretation of the high frequency oscillations. Only with meteorological corrections will it be possible to examine questions such as the frequency dependence of Love numbers with any degree of confidence that the results are meaningful. Improved knowledge of the long period zonal ocean tides is also essential. New insight into the decade scale variations in both polar motion and length-of-day will be slower in coming, for the supportive information required for evaluating possible excitation mechanisms includes the time dependence of internal geomagnetic field parameters and the mapping of the topography of the core-mantle boundary by seismic methods. Here gravity field studies are complementary to the rotation studies.

These are only a few examples of matters that require further study if the newly emerging highly accurate observations of the Earth's deformation are to be understood. Many other examples could be given (Lambeck 1988). The really exciting work is only beginning.

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