SOME GEODETIC ASPECTS OF THE PLATE TECTONICS HYPOTHESIS

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Geodetic observations of gravity, body tides, the Earth's rotation and crustal motion and deformation potentially provide important constraints in the general inversion of geophysical data for determining the structure and evolution of the Earth. More specifically, the geodetic data provide constraints on the rheology of the planet in the frequency range intermediate between geological and seismic frequencies, on the geologically instantaneous kinematics of the Earth and on the mechanisms responsible for the motions within the Earth, results that are intimately related to the plate tectonics hypothesis. The discussion is limited here to only a few aspects of these "geodetic" aspects of this hypothesis, including deformation along plate boundaries, intraplate tectonics and vertical motions.

Introduction

A general objective of the solid Earth sciences is to understand the structure - both physical and chemical - of the Earth as it is at present and to deduce from this the planet's evolution since its formation. The geophysical contribution to this broad problem is the measurement on or near the Earth's surface, of a number of quantities: Travel times, amplitudes and frequencies of seismic waves, the magnitude and direction of gravity, the flux of heat through the Earth's surface, magnetic and electrical field properties or strain and deformation. It is the inversion of these data, together with physical and chemical arguments, that provides the basis for the earth models and for the speculations on how these models may have evolved with time.

If the term geodesy is rather broadly defined its contributions to geophysics fall into the rather traditional categories of the Earth's gravity field, its solid tides and rotation, and its crustal motions and deformations. Such a subdivision is more a consequence of the manner in which the geodetic measurement techniques have evolved than of the underlying geophysical phenomena which themselves are closely related. In the above context, of these observations contributing one more piece of

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information to a complex geophysical inverse problem, it is more appropriate to consider the geodetic quantities as providing two main inputs: (i) a measure of low frequency motions and deformations of points fixed to the Earth's crust, and (ii) the gravitational potential - and its low frequency temporal variations - on and outside the Earth's surface.

Following Kaula[1] it is convenient to describe the low frequency motions and deformations in terms of their spatial and temporal spectra (Figure 1). In the frequency domain the geodetic measurements lie roughly between the seismic observations at high frequencies and the palaeomagnetic and geological observations at the low frequency end of the spectrum. Spatially, the geodetic observations span the entire spectrum, from global observations based mainly on satellite and other extra-terrestrial techniques, to local observations based mainly on conventional geodetic measurement techniques. At low frequencies and long wavelengths the dominant geophysical phenomenon is mantle convection and its surface reflection, plate tectonics. The geological record provides evidence for extensive horizontal offsets of geological features along

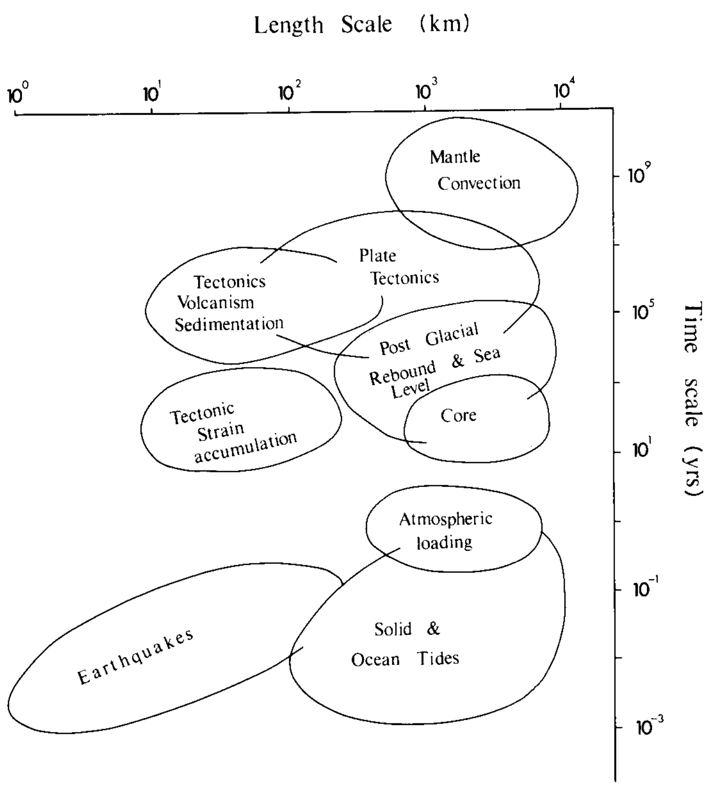

Figure 1. Space-time spectrum of geodynamic processes (adapted from Kaula[1])

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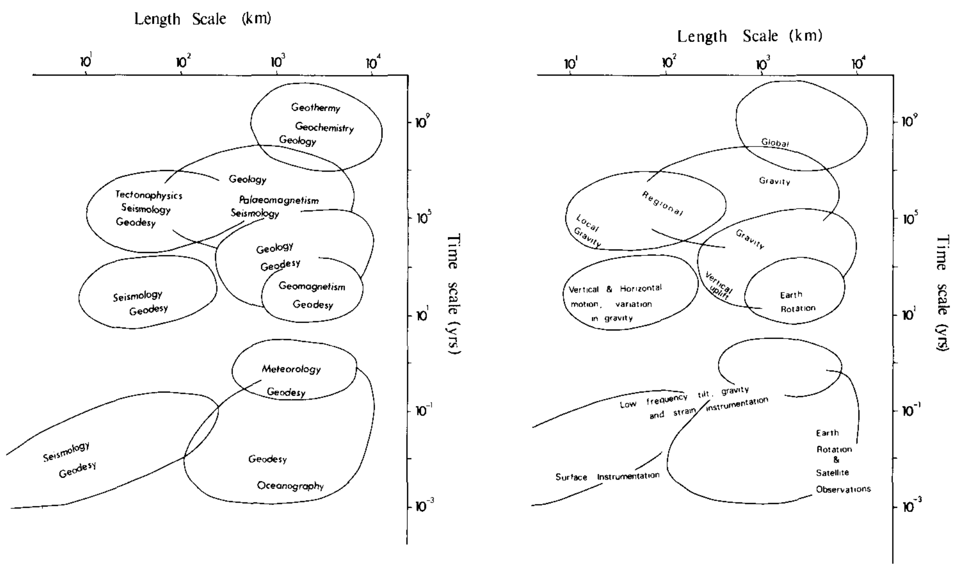
fault systems and for vertical uplifts as seen in raised beaches and terraces. While the palaeomagnetic record provides the principal evidence for a large scale orderly and global displacement of the continents and ocean floor on a typical time scale of 10^6 years and at rates of a few centimeters per year. At the other end of the time-space spectrum, the dominant phenomena are the local displacement fields associated with earthquakes, the "instantaneous" expression of plate tectonics and mantle convection. Obviously the two extremes of the bi-spectra are intimately related.

Figure 2 illustrates some specific areas to which the geodetic observations may contribute. Broadly, these contributions fall into two categories. The first is where the measurements provide a measure of the response of the Earth to either known or unknown forces. In some



a. b.

Figure 2. a. Disciplines of the Earth Sciences that contribute to the dynamic processes sketched in Figure 1.

b. Geodetic techniques or observations that contain potential information on the dynamic processes of Figure 1.

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instances, such as surface loading problems where the load history is partially known or in tide problems where the applied force is known, the deformation observations provide constraints on the rheological properties of the crust and mantle. Vertical uplift observations over areas previously subjected to extensive glaciation, provide estimates of mantle viscosity, while the tide and rotation observations provide estimates of the global elastic and inelastic response at frequencies that are high in geological terms but low by seismologists' standards.

In the second class of problems the observations provide constraints on the forces themselves. Examples of this include motions and deformations associated with a variety of tectonic problems. Another example is given by the global gravity field where the implied lateral density anomalies provide evidence for the non-hydrostatic state of the mantle and for some form of mantle convection. Shorter wavelength gravity anomalies will reflect mainly crustal structure and will provide constraints on local and regional tectonic processes and on crustal rheology. Both classes of problems, often of considerable intrinsic interest, provide key inputs into the mantle-convection and plate tectonics problems. And while poets[2] and geologists[3] have been aware of the upheavals within the Earth for some 150 years geodesists too will find that these problems are inescapable.

A requirement for investigating the above-cited problems is the establishment of geodetic frameworks with respect to which the strain rates and deformations can be measured and via which the geodetic measurements can be related to other geophysical observations. In this paper an attempt will be made to lay down some geophysical requirements for testing aspects of, and contributing to the understanding of, the global plate tectonics hypothesis, since it is probably in this area where the geodetic observations will make the most important contributions to geophysics. I will not address myself here to the problems of the Earth's rotation and tides. The geophysical imports of these subjects has been discussed elsewhere[4,5] and the discerning geodesist can draw from these books his own conclusions about appropriate geodetic reference system requirements for these matters.

A not entirely unrelated problem, both in terms of the geodetic measurements and in terms of physical consequences, is the input that these measurements have in physical oceanography. The problem here is to deduce the circulation in the oceans from a variety of observations (e.g., acoustic travel times, currents, temperatures, density) and the geodetic measurements provide a boundary condition at the free surface[6]. Intellectually the problem, is not very different from the geophysical one except that the ocean can be sampled down to all depths, and that the time scale involved is relatively short, leaving much less room for speculation than is permitted of the geophysicist.

"Geodetic" aspects of the plate tectonics model

The plate tectonics hypothesis has been clearly defined by LePichon

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et al.[7] and needs little elaboration here. The proposed model is essentially a kinematic one in that it does not specify the dynamic mechanism responsible for the motions and neither does it define the nature of the motions below the crust. Built mainly on geological and palaeomagnetic observations, the hypothesis only represents average motions at the Earth's surface, averages over time spans of the order of 10^6 years. Studies of seismicity along plate boundaries confirm the overall global tectonic motions provided that the results are averaged over a time interval of 50-100 years or longer[8] but only geodetic observations will give an "instantaneous" picture of the motions as well as provide further and possibly more dramatic observational support for the hypothesis, should such still be required to convince its recalcitrant objectors. The National Aeronautical and Space Administration's geodynamics program considers as one of its principal objective the "testing" of this plate tectonics hypothesis by direct measurements[9]. Convinced "drifters" may not share this concern and may instead see these measurements as fulfilling a scientifically more important role, namely in contributing to understanding several closely related problems; the rheology of the crust and upper mantle, the mechanism responsible for the motions and deformations of the plate, and ultimately the prediction of earthquake activity.

Figure 3[10] illustrates schematically the average relative motions of the major plates for the last 5-10 million years, with the motions being determined mainly from the marine magnetic anomalies, seismic slip vectors and transform fault directions. Typically the plates move at

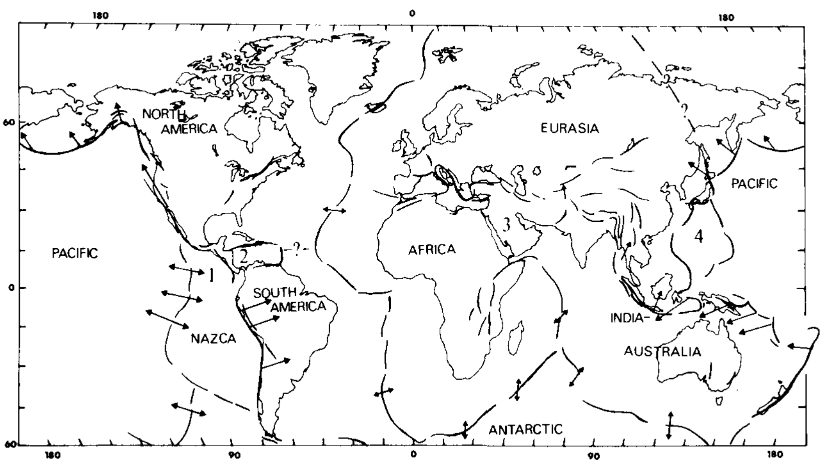

Figure 3. Motions at the boundaries of the tectonic plates[10]. Arrows indicate direction and rate of motion (see scale in bottom right hand corner). Spreading margins are indicated by the double arrows and motion at converging boundaries by single arrows.

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rates of a few cm per year with the oceanic plates such as the Pacific and Nazca moving faster than the predominantly continental plates of Eurasia and North America. This presumably implies that viscous drag forces are operating on the base of the plate and that they play a regionally variable role[11]. Maximum relative velocities of nearly 20 cm yr^{-1} occur along the Pacific-Nazca boundary while the lowest velocities of 1-2 cm yr^{-1}, occur between the mainly continental plates of Africa and Europe. By providing an instantaneous picture of the global tectonics regime and by comparing these results with the seismic and magnetic evidence for motion, insight may be gained into certain aspects of the rheology of the lithosphere and anthenosphere and into the mechanism driving the plates. Matters upon which these measurements may throw some light include the following.

(i) Discrepancies are often seen at plate boundaries between slip-rates based on seismic data and on the magnetic-anomaly data. Are these evidence for present motions being different than those over the past few million years? Is it due to aseismic deformation? Or is the distortion occuring over a broad zone along the plate boundary?

(ii) What is the response of the interiors of the plates during their relative motions? Do the plates behave as rigid units during their motion or are they subject to deformation?

(iii) What is the nature of the deformations along the plate boundaries? Over what distances do these deformations occur? Is the motion uniform or jerky? Is there evidence for slowly propagating stress waves?

(iv) What is the relation between horizontal and vertical motions, particularly along plate boundaries?

An area where the geodetic measurements will not contribute is in resolving the geophysically vexing problem of absolute motion, a concept that has a different meaning here than in geodetic usage. One day it may be possible for geodesists to detect motions of their tracking stations with centimeter accuracy within an absolute celestial reference frame but in geophysics it is the motions of these stations relative to the inaccessible interior of the Earth that is of importance[7]. An overall westward motion of the lithospheric plates over the underlying mantle, for example, would not be detected by the geodetic measurements. One would erroneously interpret such a coherent drift as a change in the speed of rotation of the Earth although it is only the crust that is involved. It is the same as the older problem of the separation of continental drift from polar wander[4,12]. Geophysicists have resolved the problem in a seemingly ad-hoc way with the introduction of Wilson's hot spot model and with the associated axiom that the hotspots are fixed relative to each other and to the deep mantle[13]. The result is apparently self-consistent[10,14] and the model is useful but it cannot be tested by external, geodetic measurements. Other attempts at establishing a fixed reference frame have been based on calculations in which the plate motions have been constrained to plausible physical properties[15].

The above comments are, in many respects, mere platitudes, drawing attention once again to aspects of the plate tectonics models that are more talked about than quantitatively analysed and geodetically observed.

One reason for this state of affairs is the lack of observational evidence in between the frequency bands provided by seismology and geology, a sufficiently large and reliable geodetic data base not yet being available to permit an unambiquous evaluation of some of the above aspects.

Deformation along plate boundaries

Very large earthquakes account for most of the energy release and fault slip within a seismic zone. Events smaller than "very large" are not significant contributors and are usually considered to be local phenomena, either aftershocks or local reactions to the stress redistributions accompanying the larger quakes[16]. One may expect that the large earthquakes should follow a systematic pattern if the plates are moving regularly but seismicity records suggest instead that motion at the plate boundaries is not continuous but occurs mainly in jerks separated in time by a few decades to a few centuries[18]. The recurrence interval between large earthquakes along a particular section of a plate boundary is variable, about 60 years along the Alaska-Aleutian region, about 100 years for Chile[17] and longer at the India-Eurasian boundary. Seismicity studies have also revealed that large earthquakes occur in sequence around a sector of a plate and several migration patterns have been observed[19]. For example, Mogi[19] noted a progressive migration of seismicity from Japan to Alaska in about 35 years and also from Central America to Southern Chile in about the same time interval. The migration rates are of the order 150-300 km $year^{-1}$. These migrations of seismic activity have been attributed to the presence of long-period stress waves or stress diffusion[18].

The stresses and strain history at a zone of continental-oceanic convergence can be qualitatively described in the following terms (Figure 4). During intervals between great earthquakes along a particular segment of a subduction zone the lithospheric plate, overlying a viscous asthenosphere, is relatively stationary at the trench boundary. The plate is under stress due to the more-or-less steady plate tectonics driving force - either gravitational forces or viscous drag forces at the base of the plate[21] - and the state of compression may extend well into the interior of the plate. At the trench, the lithosphere is held fixed by frictional forces along the interface of the continental and oceanic plates but to the sea-ward side of the trench there is an upward bulging of the oceanic lithosphere[22]. With time the stresses and deformation increase until a critical stage is reached and one or both of two things can occur. Underthrusting of the oceanic plate may occur if the frictional force is exceeded at the trench and the boundary between the underthrusting plate and the adjacent restraining plate is broken and a temporary decoupling of the converging plates occurs. Secondly, the bending moment of the oceanic plate may become excessive, resulting in a tensile fracture in the upper boundary of the lithosphere where the bulge and bending moment are a maximum. This gives rise to two types of major earthquakes at the zones of convergence[23]; decoupling earthquakes resulting in the underthrusting, and tensile lithospheric earthquakes that break the lithosphere seaward of the trench. Simple plate models

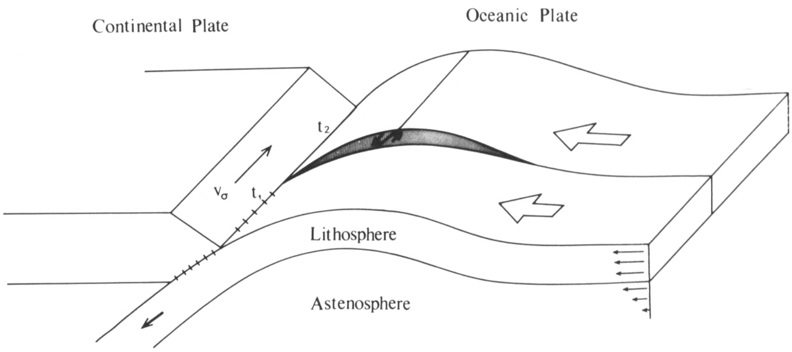

Figure 4. A simple model of stress accumulation at a subduction zone[18]. The oceanic plate is under compression but its motion is locked at the trench. When the stress concentration is sufficiently high a decoupling earthquake occurs at time t, decreasing the stresses in the segment of the subduction zone closest to the viewer, but increasing it elsewhere (in the section away from the viewer). This leads to a subsequent earthquake at time t_2. v_σ denotes the velocity of the propagation of the stress wave along the subduction zone.

suggest that the latter may occur at distances of about 100 km from the trench[18].

The deformation phenomena associated with these earthquakes, other than the obvious co-seismic deformations, are several and include an accelerated plate motion in the vicinity of the boundary before the decoupled lithospheric boundary heals. During this time interval the rate of underthrusting of the down-going slab and the rate of approach of the oceanic plate to the trench will increase while the stress previously built up in the plate as a whole is relieved. On the continental side of the trench a sinking of the lithosphere may occur while on the oceanic side there will be a reduction in the elevation of the lithospheric bulge. This cycle of crustal movements has long been recognized although variations from this general model do occur[24].

At the time of the earthquake the stress will diffuse partly at elastic wave velocities and adjacent segments of the arc will feel immediately the consequences, triggering further seismic activity along other parts of the arc. But, because of the viscous coupling of the

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lithosphere to the underlying asthenosphere, kinematic stress waves are also generated[18,20] which serve to decrease the stress in the interior of the plates but increase it elsewhere along the plate boundary. The post seismic deformations may be of the order of 1 - 5 m/year within about 100 km of the boundary - the rate decreasing with time - and for these waves to travel the length of the plate may take several decades.

The comparison of seismic slip-rates with the rates inferred from the instantaneous plate motion models indicates that agreement along many boundaries is satisfactory only when the seismic data is averaged over a long time period[8]. Elsewhere substantial discrepancies have been found between the computed seismic slips and the inferred rates and either much of the motion is aseismic or the current plate motion is significantly different from that of the past[24]. Along the Marianas trench, for example, the motions are predicted by the plate models to be of the order of 10 cm year^{-1} but no large-moment earthquakes appear to have occurred there during the last few centuries. Elsewhere, near Japan the disparity between the two estimates is a factor of about 5 [17] and between Eurasia and India it is a factor of about 3 [25] while along the San Andreas fault system it is perhaps a factor of 2 [26]. The discrepancies along the subduction zones may be a consequence of insignificant coupling between the continental and oceanic lithospheres so that the subducted plate is not locked by frictional forces and is permitted to subduct more easily resulting perhaps in "slow" earthquakes[27] or perhaps in no seismic activity at all. At the continent-continent interaction between India and Eurasia the discrepancy may well be a consequence of the deformation being taken up over a major part of the two plates since the large scale tectonics of Asia as a whole appears to be a result of this collision[28] while in California, where a major part of the deformation occurs along well defined faults, substantial deformation may occur well into the Basin and Range province of the western U.S.[10,29].

This brief summary of seismic events along plate boundaries clearly indicates that the deformation associated with an earthquake is more complex than suggested by the elastic dislocation theory which describes only the instantaneous deformation at a time of faulting. What the above comments indicate is that pre-seismic deformation occurs and it is important to understand this, not only because it is a premonitory phenomena but also because it is informative on the rheology of the crust and on the mechanism driving the plate. Geodetic evidence of these pre-seismic movements abound and go back at least as far as the 1920s[30]. But the interpetation of these data has not always been clear partly because adequate systematic surveys are generally not available[31]. Following the actual earthquake, accelerated crustal deformation may persist for several years and total post-seismic deformations may reach several meters[32]. These deformations are a maximum near the plate boundaries but may still be significant at the 10 cm level hundreds of km away from the boundaries. The geophysical interest of these observations is that they provide insight into the nature of coupling between the crustal layer and the underlying material. Some simple models have been proposed to explain these post-seismic deformations and stress diffusion[18,20,33], models whose central aspects may be tested by a few well-planned measurements taken over a 5 - 10 year period immediately preceding and following a large earthquake.

Intraplate tectonics

An important axiom of the plate tectonics hypothesis is that the plates behave as essentially rigid entities. It would be truly remarkable if the large, irregularly shaped tectonic plates can be moved without deformation over large distances along the surface of the ellipsoidally-shaped earth[34]. But what permits geologists and geophysicists to make this assumption and make the hypothesis reasonable is that the time scale of their model is quite different from that of the average geodesist's lifetime. It works because the motions are averages over long time periods but in the "snap-shot" picture provided by the seismic and geodetic evidence some deformation of the plates undoubtedly occurs, as is indicated by the stress-waves travelling away from the plate boundaries and by intraplate seismicity. The magnitudes and time constants of internal deformations of the plates are clearly important in understanding intraplate tectonics and intraplate seismicity as well as in interpreting the geodetic measurements; for how can one be sure that plate motion is occurring when any internal deformations of the plate are not monitored?

In recent years there has been a substantial increase in the information available on the state of stress within the continental areas of the plate, information provided by in-situ stress measurements and by earthquake fault-plane solutions[35]. The resulting stress patterns are considerably more complicated than those predicted by the simple plate tectonics models due to a super positioning of local and regional stress fields on the global field where the former may be associated with loading of the crust by sediments, by igneous activity or by non-hydrostatic mass distributions associated with past geologic events.

Evidence that continents as a whole are subject to differential stresses is readily seen in the distribution of seismic activity within the continents of North America,[36] or of Australia[37]. Sykes[38] summarized the distribution of the intraplate earthquakes and of igneous activity and one of the principal conclusions he reached was that in continental areas seismic activity tends to be concentrated along pre-existing zones of weakness - along unhealed faults - within areas affected by the youngest orogenesis that predated the opening of the present oceans and led to the present cycle of plate tectonic activity. This seismicity is presumably activated in response to the present-day stress regime in the plate but which is not necessarily the same as that which created the zone of weakness in the first place. Examples abound; the Rhine graben in Europe[38], the New England - Ottawa zone of weakness (postulated to be a continental continuation of the Kelvin seamount chain[36,38]) or the Adelaide Geosyncline in South Australia[39]. Where the lithosphere is thick, cold and strong - as for the cratons and the older ocean basins -

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seismic activity is generally much reduced and there is usually little evidence for geologically recent break-up or rifting.

Vertical motions

The plate tectonics hypothesis as it is commonly accepted is concerned predominantly with horizontal motions and largely ignores vertical deformations; an omission that has sometimes been seized upon as a demonstration of failure of the model in part or as a whole[40]. But vertical motions obviously accompany the plate motions, particularly along the boundaries and height and gravity data provide an important quantity for constraining stress and deformation models. For example, at the subduction zones the accumulation of stress will result in an elevation of the lithosphere on the continental side of the trench and in a growing bulge ocean-ward of the trench. When decoupling of the lithosphere occurs such that the stress at the boundary is released, there may be a sinking of both features. A well documented case history of the vertical motions during the pre-seismic, coseismic and post-seismic deformation cycle is provided by the Nankaido earthquake of 1946 in southern Japan where extensive first-order leveling and triangulation networks have been resurveyed on several occasions over the last 100 years. Differential uplifts of 1 m over distances of about 100 km occurred during the co-seismic phase. The pre-seismic vertical motions over some 30 years prior to the earthquake were of the order of 10 - 20 cm over the same distance, while the post-seismic deformations over two decades following the event were of similar magnitude. Equally well documented case histories are provided for other regions in Japan[41]. Apart from these measurements evidence for secular uplift is also seen in uplifted marine terraces, both in southern Japan and along most of the compressive margins of the Pacific plate.

Elevation changes have also been noted along transform faults and a widely discussed example is provided by the still enigmatic Palmdale bulge[42] where repeated levelling from 1961 to 1971 revealed height changes of 25 cm over distances of about 150 km. These vertical motions, by pointing to anomalous areas of the crust, may be important premonitory indicators of seismicity.

Within the plate interiors vertical motions in response to variable surface loading conditions are common, although these are not usually associated with Earthquake activity. Well known examples include the post-Pleistocene rebound of Fennoscandia and the Laurentide region[43] where the presently observed uplift rates are of the order of a few mm per year. These rates, taken together with geological observations of vertical motion, have provided useful information on the viscosity of the mantle below the lithosphere[45]. Viscosity estimates of the mantle below the oceans are more difficult to come by. One possible example is for Iceland where extensive glaciation and subsequent rebound has also occurred[46] but here the problem is complicated by the presence of an active spreading center which may also be associated with vertical motions.

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Elsewhere in the oceans subsidence of some islands has also been noted, a few mm/year in the case of the Hawaiian islands[47] for example, and this has been interpeted in terms of a viscous relaxation of the stress in the oceanic lithosphere due to the volcanic load[48]. Island uplift and subsidence may also occur in association with the stress cycle near the subduction zones as discussed previously. I am unaware of observations that support this aspect of the model but simple order-of-magnitude calculations demonstrate that it may not be insignificant - of the order of centimeters.

Geodetic Requirements

In one sense the geodetic requirements for monitoring the motions and deformations associated with the plate tectonics hypothesis are readily stated. A highly accurate dense network of stations, along plate boundaries and within the plate interiors, whose positions in three dimensions are determined at regular and frequent time intervals. If the realities of resources and geography are considered the specifications become considerably more difficult to detail and the requirements for each problem will probably need to be investigated separately. At this stage I am not prepared to lay down specific requirements as it is the function of this meeting to do so. All I can do is offer some general points that may be considered in subsequent discussions.

As indicated earlier, I do not consider that the measurement of present-day plate tectonics is the most important goal. The reason for this is related to the complex behaviour of the plates at and near their boundaries and the possible presence of long period strain waves that travel deep into the interiors of the plates. In order to glean a coherent picture from the observations of motion and deformation it will be necessary to integrate motions over at least several decades if some of the finer aspects of the plate response to stress is not fully understood. Instead, I consider that the important contributions are to be made in areas relatively close to and across plate boundaries, particularly at the continent-ocean lithosphere collision zones, at transform faults and at spreading centers. Such contributions would lead to a better understanding of earthquake mechanisms and stress propagation as well as of the lithosphere and mantle rheology.

At the subduction zones the geodetic points should extend well into the plate interiors (up to 1000 km?) to monitor the pre- and post-seismic deformations associated with the large decoupling earthquake and the network should extend along large segments of the plate boundary to provide the basis for studying the nature of stress propagation along the boundary. Geographical considerations will probably limit the nature of the network that can be established since the physically more tractable solutions involve ocean plates and few stable island sites will be available. The required density of stations will be high - with a separation of less than 100 km - since deformations may vary rapidly over short distances and a lesser density could readily lead to

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misleading interpretations of the results. Already established geodetic networks should be fully integrated into the new networks for while these measurements may not meet the accuracy standards quoted for the new measuring techniques, they are all we have at the moment and it will be a long time before we have anything that is better. A complete geological record and complementary geophysical surveys and instrumentation should also be available.

For the question of understanding the plate boundary deformations "absolute" scale and orientation of the network is not essential and the essential criterion is one of repeatability so that strains can be determined. To fit the regional observations into the framework of the global plate tectonics hypothesis some link to the centers of plates, to stations on the stable regions, must also be considered so that while a single global reference frame is not entirely necessary it is a desirable feature. What is a stable region remains problematical for while old cratons are generally not subject to active seismicity they are often subject to vertical motions.

Several areas are appropriate for geodetic studies of the kind outlined. Examples of accessible transform faults include the New Zealand Alpine fault and the Californian fault system, two areas where the geological and geophysical records are relatively complete. Of a spreading center we have Iceland or the Gulf of Aden where considerable work has been done in recent years[49]. For a subduction zone, southern Japan provides a well documented record of both past geodetic and seismic results although here it will be difficult to monitor the deformations on the seaward side. Possibly the New Hebrides - Tonga - Fiji region merits a close investigation.

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