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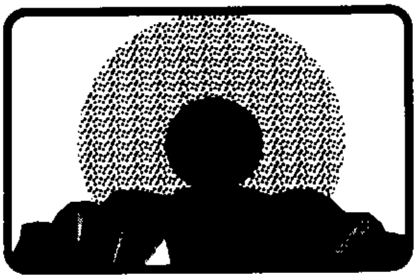

The Earth's Core

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ABSTRACT

The current status of knowledge of the Earth's inner and outer cores is reviewed from the standpoints of seismology, gravity, Earth rotation, and the geomagnetic field. Because of the remoteness of the deep interior, geophysicists have used great ingenuity in processing and interpreting surface data that is contaminated by many local (surficial and crustal) sources. Despite the lack of direct data from the deep Earth, there has been a rapid growth in knowledge in the last decade due to advances in instrumentation and the blossoming of interdisciplinary studies.

Of major interest at the present time is the interaction between the mantle and core, each of which contains a major convective regime, powering, in one case, plate tectonics and, in the other, the geodynamo. These regimes meet at the core-mantle boundary (CMB), which has provided a tempting target for seismology, magnetism, geodesy and high-pressure physics; much has been learned from the interchange between geophysicists in these disciplines. In this review, it is suggested that the predominant themes for the next decade, growing naturally out of existing trends, are 1) improvements in the quality and coverage of global data sets, particularly those in geomagnetism, geodesy and seismology, 2) increased international co-operation through participation in interdisciplinary studies such as SEDI (Study of the Earth's Deep Interior), and 3) exploration of the non-

linear aspects of dynamics within the Earth.

Core studies are clearly not undertaken primarily for their social relevance, nor for any quick economic spinoff. The primary goal is to understand the structure, dynamics and evolution of the deep interior, as a prelude, it is to be hoped, to the exploration of other planets. Each component of our national science effort is involved in this exciting and challenging goal. We need government institutions to provide the long-term economic stability with which to carry through essential observational campaigns at the surface, particularly as part of interdisciplinary, global initiatives. We need educational institutions to provide the leadership and vision with which to stimulate the science and train students. The university community benefits from the financial support of large companies to assist in the support of students and to sponsor specialized research projects, wherever the goals of industry and basic science connect. Last, and by no means least, we need the moral support of our population to allow the pursuit of these fundamental questions.

RÉSUMÉ

Le présent article passe en revue l'état actuel des connaissances sur le noyau externe et le noyau interne de la Terre, sous l'angle de considérations séismologiques, gravimétriques, géomagnétiques, et de la mécanique rotatoire de la planète. Étant donné l'inaccessibilité de l'intérieur de la planète, les géophysiciens ont dû faire preuve de beaucoup d'ingéniosité dans le traitement et l'interprétation des données de surface, lesquelles sont contaminées par plusieurs sources d'origine crustale ou superficielle. Malgré le manque de donnés provenant directement des couches profondes de la Terre, il y a eu au cours de la dernière décennie un accroissement rapide des connaissances découlant de percées dans le domaine de l'instrumentation et d'un foisonnement d'études interdisciplinaires. Un sujet d'intérêt important à l'heure actuelle est les interactions entre le manteau et le noyau, ces derniers comportant chacun un système de convection de grande envergure, l'un étant le moteur de la tectonique de plaques et l'autre celui de la géodynamo. Ces systèmes de convection viennent en contact à la frontière noyau-manteau (FNM) et cet interface a constitué un pôle d'attraction de l'intérêt pour les disciplines de la séismologie, de l'étude du magnétisme, de la géodésie, et de la physique des hautes pressions. On a beaucoup appris des échanges qui ont eu lieu entre les géophysiciens de ces diverses disciplines. Dans le présent article rétrospectif, nous soumettons à l'attention que les thèmes d'intérêt de la prochaine décennie seront dans la suite naturelle des tendances actuelles, soit 1) l'amélioration de la qualité et de la couverture des jeux de données à l'échelle du globe, particulièrement ceux touchant le géomagnétisme, la géodésie, et la séismologie, 2) l'accroissement de la coopération international grâce à des participations à des études interdisciplinaires telles la SEDI (Étude de l'intérieur profond de la Terre), ainsi qu'à des recherches préliminaires portant sur les aspects non-linéaires de la dynamique de l'intérieur de la Terre. Les études du noyau ne sont pas entreprises surtout pour des motivations d'ordre social ou dans l'espoir de retombées économiques à court temre. L'objectif premier est la compréhension de la structure, des mécanismes, et de l'évolution de l'intérieur profond de la planète en vue de préparer l'exploration d'autres planètes. Chaque composante de notre effort national est engagé dans une démarche excitante visant à relever ce défi. Nous avons besoin d'institutions gouvernementales et de leur stabilité économique afin de mener à bien les campagnes d'observations de surface, particulièrement dans le cas de projets interdisciplinaires, et/ou à l'échelle du globe. Nous avons besoin d'institutions d'enseignement visionnaires pour former des étudiants et qui auront un effet stimulant pour la science. La communauté universitaire jouit du support financier de grandes sociétés lorsqu'il s'agit de soutenir financièrement les étudiants et de patronner des projets de recherche spécialisés, à chaque fois que les objectifs du secteur privé coïncident avec ceux de la recherche fondamentale. Finalement, mais non le moindre de nos besoins, nous avons besoin du support de notre population afin que la recherche sur ces questions fondamentales puisse se poursuivre.

INTRODUCTION

All methods of studying the Earth's interior, below the mid-crustal depth of the deepest drill holes, are indirect. We sample a physical parameter at the Earth's surface, distributed very inhomogeneously in space and time, and attempt to infer all aspects of the interior from these measurements. Despite the very uneven data coverage and the many ambiguities in interpretation, all geophysical methods agree with the basic average structure of the Earth as defined by the radial dependence of seismological parameters, though there is much disagreement on many of the subtle details.

At the outset, we are forced to acknowledge that even with the best data imaginable, many of the problems are inherently ambiguous (*i.e.*, the data can be satisfied by many equivalent, but distinctly different, sets of parameters). This is why in geophysics there has been much mathematical discussion of what can be deduced uniquely about a many-parameter system like the Earth from a relatively sparse set of surface measurements. The subject of generalized inverse theory was developed in the 1960s and, as applied to measurements of the frequencies of the seismic-free oscillations (or normal modes) and body wave travel times, is largely responsible for the high-quality seismic models we now possess. Subsequently, many other subject areas have tackled the questions of ambiguity that are implied by sparse data sets; for example, what can we say about velocity fields near the top of the fluid core from measurements of the surface magnetic field of the Earth? Or what can be said about lateral heterogeneity in the structure of the *D* " layer (at the base of the mantle), using observations from seismology and geodesy?

A fundamentally non-unique problem is that of the thermal history of the Earth, and its present temperature distribution. Since the thermodynamic equations are effectively unidirectional in time (they cannot be integrated accurately backward without infinitely abundant and precise current conditions), there exists an infinite number of possible starting conditions with which to derive the current thermal flux in the Earth. In particular, one is free to speculate on the heat crossing the CMB by trading this off against the heat production in the mantle, although in the future other data (particularly geochemical) will shed light on this important question. Even more problematical from the point of view of dynamo theory is the fact that the important toroidal component of the Earth's magnetic field is totally screened from surface magnetic field measurements by the electrically insulating mantle. Consequently, in studying the dynamics of the core associated with magnetic field production, one must rely solely on extrapolation of the Earth's surface (poloidal) field to infer the fluid velocities at, and just below, the CMB.

Another fundamental problem is connected to the theory of non-linear dynamical systems where the solutions, although derived from perfectly deterministic equations, may exhibit stochastic features in certain parameter regimes, a situation now accepted for the equations governing three-dimensional mantle convection. In chaotic systems, the evolution of the system is dependent on infinite detail in the initial conditions, and infinitesimal changes in those conditions can result in major changes in the evolution of any particular solution in time. This implies that it is quite hopeless to search for solutions of the governing equations that can correctly predict details of the dynamics, such as the current velocities of the tectonic plates. Consequently, attention is turning to the search for parameters that describe the general topology of the mantle flow and its space- and time-averaged properties.

This point is also relevant to various aspects of the geodynamo. If, for example, the equations governing the dynamo process are in a chaotic regime, one may be able to say very little concerning the phenomena of reversals (*e.g.*, Crossley *et al.*, 1986), except that they are an integral part of the system and not derived from any readily identifiable physical cause. There is a strong connection between these ideas and synoptic meteorology that we are reminded of daily.

Two excellent textbooks cover the recent state of knowledge of the core: Melchior (1986) and Jacobs (1987). In addition, a selection of further articles might include Brush (1980, 1982) on the scientific discovery of the core, Smylie *et al.* (1984) on the dynamics of the inner and outer cores, Rochester (1984) on core effects on Earth rotation, Crossley (1984) and Rochester and Crossley (1987) on short-period core dynamics, Masters and Shearer (1990) for a seismological overview, and Bloxham and Jackson (1991) on the problem of determining the core flow from magnetic field observations.

Space does not permit the coverage of all problems dealing with the core. Reluctantly, I have chosen to pass over the problem of the main field generation — although it is clearly one of the major problems in geophysics and the dominant theme of core research — because this is a highly complex subject (which occupies a relatively small number of workers), both in the difficulty of programming the full equations in a three-dimensional spherical Earth with parameters that mimic those predicted for the core, and in the mathematical analysis of the magnetohydrodynamic field equations. One can only note that a self-consistent dynamo model has so far proven elusive and that work is in progress.

The topic of paleomagnetism has also been omitted from this review, although for quite different reasons than for the dynamo problem. In this case, there is a vast literature from a large community dealing with all aspects of magnetic field observations, including many detailed analyses of the reversal process itself. However, dynamo theory and core dynamics have not developed sufficiently to be tested by the paleomagnetic data, and the discussion, at present, instead centres on fascinating questions such as whether reversals are connected to lower mantle heterogeneity and processes at the CMB (*e.g.*, Hoffman, 1992).

Similarly, I have touched only briefly on the work concerning high-pressure chemical reactions that have been observed in diamond anvil cells, one aim of which is to elucidate the extent of mixing at the CMB between the mantle silicates and oxides with the outer core (OC) iron alloy. This research field is dependent on: 1) the results obtained from only a few high-pressure laboratories, and 2) the sharp differences of opinion concerning the thermodynamic reactions at high temperatures and pressures.

On the other hand, I have given perhaps undue emphasis to the field of core dynamics, not only because it is the field I know best, but also because it is energetically pursued by many Canadian geophysicists and is appropriate for this Canadian view of the core.

TECHNIQUES

Naturally enough, seismology has provided most of the data for the elastic structure of the Earth. At seismic periods, the interior is treated as a static snapshot, and there has been no attempt thus far to interpret seismic data in an evolutionary sense, *i.e.*, to ascribe a time evolution to seismically determined variables that may be related to internal dynamics. Since the era of modern seismology is so short (for example, it is barely 30 years since the discovery of the Earth's free oscillations and ten years since mantle tomography was developed), the study of the time variation of seismic parameters remains a subject for the future.

In order of increasing period, the time spans for looking at the deep interior are: for seismology (10^{2} seconds to 1 hour), gravity (1 second to 1 year), Earth rotation (1 hour to 10^9 years), and the magnetic field (1 year to 10^9 years). Of more limited use are sea-level (surface topographic) data, useful for dynamics of the mantle (in particular its viscosity), and heat flow data, appropriate for long-term evolution of the Earth's heat budget, and surface plate motion vectors that can be used indirectly in constraining mantle dynamics at long time periods. These latter methods provide indirect information concerning the deep interior in the period range 10^3-10^8 years. Until recently, there was virtually no overlap at all between the above techniques. Seismology stopped at 54 m, the period of the gravest free mode ${}_0S_2$, gravity variations were dominated by the tides, principally in the 12-24 hour period range, and Earth rotation studies were concerned with periods longer than the 5-day means traditionally used for the instantaneous pole position. Magnetic field studies of the deep interior are limited to periods longer than 1 year by the insulating properties of the mantle.

In the last decade, there has been some interest in the gravitational response of the liquid core at tidal periods (1 hour and longer) through the phenomena of internal gravity waves, although we are severely hampered by the apparent lack of any direct evidence that internal wave motion can be excited or detected. Similarly, rotation measurements are now routinely performed at periods as short as 1 hour by techniques such as very long baseline interferometry (VLBI) and global positioning system (GPS), although, at short periods, these studies are used to study the interactions of the atmosphere and oceans with the solid Earth, rather than deal with dynamics of the deep interior.

Nevertheless, our models of the interior have improved substantially as a result of co-operative studies using a combination of all the different techniques, and co-ordinated through international programs such as SEDI (an International Union for Geodesy and Geophysics Committee, Lay *et al.*, 1990). It is certain that interdisciplinary programs hold the key to solving the mysteries of the deep structure and dynamics of the Earth and other planetary bodies.

Seismology

The two principal branches of seismology for the deep interior are body wave studies and normal mode (equivalently free oscillation) studies. The former measures both the travel times of *P* and *S* waves from the earthquake (or more rarely, large nuclear explosion) epicentres to surface stations, and also the waveforms of the arriving phases and their respective attenuation. The travel times are primarily indicators of the *P* and *S* velocities with depth, the waveform details give information on the structure of the boundaries along the travel path, and the attenuation reflects a combination of the anelastic *Q* (bulk and shear attenuation) structure and scattering due to inhomogeneities.

Pedantically speaking, the title of this article should be "The Earth's Cores", since seismology has clearly identified two quite separate identities, a liquid outer core (OC) and a solid inner core (IC). Such a model was, in fact, considered by Halley (1691) on evidence that the geomagnetic field showed evidence of the now-familiar "westward drift". The "discovery" of the OC is, however, usually attributed to Oldham (1906), who first examined anomalies in the travel-time curves of the newly discovered *P* and *S* seismic waves with epicentral distance. Considerable debate (Brush, 1980, 1982) ensued about the nature of the core, which was shown by Gutenberg (1914) to begin at a depth of approximately 2900 km. Although seismologists argued over the reason for the apparent failure of *S* waves to be transmitted through the core, it was the work of Jeffreys (1926) that confirmed its fluidity on evidence from tidal theory that the globally averaged rigidity was consistent with no *S* waves and reduced *P* wave velocities at depth. Some years later, Lehmann (1936) discovered the inner core boundary (ICB), and soon Birch (1940) assumed, and Bullen (1946) demonstrated, that the central IC is predominantly a high-pressure phase of iron.

In the intervening years, seismology has developed enormously through the deployment of a worldwide network of seismometers and the use of computer processing and, although no new major developments can rival the discovery of the core, the story of seismology in the second half of this century is dominated by the study of the major boundaries. Recent improvements to core models are incremental adjustments to the seismic velocities and attenuation of models derived 10-20 years ago, and these refinements are won only by paying a great deal of attention to the seismic structure at shallower depths in the mantle and crust.

Geodesy

Geodetic measurements are concerned with observations of the Earth's rotation. Of the three components of the rotation vector, as defined in a body reference frame, the (ω_1, ω_2) components (Greenwich and 90° E of Greenwich) define the polar motion, and ω_3 defines the change in the rotation rate (about the spin axis) or changes in the length of day (LOD) Rochester (1984). Both types of measurement have undergone dramatic improvement in the last 20-30 years, firstly with the improved accuracy gained by atomic clocks (in use since 1955) and later by hydrogen maser clocks, and secondly with the use of artificial satellites using ranging techniques such as Doppler measurements and laser ranging. Impressive as these developments are, they are overshadowed both by the predominance of very long baseline interferometry (VLBI) as the most precise method of determining the Earth rotation parameters and also by the emergence of new techniques, such as Global Positioning System(GPS), which is very much easier to implement than VLBI and can be mounted on mobile units.

These geodetic techniques are used for the deep interior to provide data on the coupling between the various components of the Earth system. In particular, both the OC and the IC have their own modes of wobble which, in principle, are excited by torque imbalances in the core/mantle/atmosphere rotating system. These wobbles, called the nearly diurnal free wobble (NDFW) and the nearly diurnal free inner core wobble (NDFICW) for the OC and IC, respectively, appear as nutations in the space frame, respectively, the free core nutation (FCN) and the free inner core nutation (FICN). Additionally, of course, the presence of the inner and outer cores influences the rotation of the mantle and, thus, the body frame to which the geodetic instrumentation is attached. Thus, precise geodetic data can shed light on the various coupling coefficients between the OC/mantle and IC/OC, and on some of the physical parameters involved, such as ellipticity (flattening) of the CMB. In this way, geodesy is a valuable independent constraint which must be satisfied by models constructed from other data sets.

Geomagnetic Field Studies

The geomagnetic field acts over rather longer time scales than most of the other methods. This is due to two factors. The first is the sluggish flow velocity in the outer fluid core (estimated at 3×10^{-4} m•s^{-1}) to which the magnetic field is strongly constrained to move by the so-called "frozen flux" hypothesis. The high electrical conductivity of the OC (5×10^5 siemens•m^{-1}) prevents rapid field diffusion (on time scales less than several decades) and the magnetic lines of force necessarily follow faithfully the fluid motion. The second factor is the extremely low electrical conductivity of (most of) the mantle, which severely attenuates any toroidal field that can leak from the core. The surface field is thus obtained predominantly by diffusion of the much weaker poloidal component of the magnetic field at the CMB.

Magnetic changes at the CMB therefore appear at the surface with periods longer than 1-4 years. An interesting example of this occurred in late 1969, when a pronounced change in the length of the day was found some years before a magnetic "jerk" was detected in some European observatories (*e.g.*, Whaler, 1987). There is a strong possibility that this was an event with a common origin that involved a significant exchange of angular momentum between the core and mantle, and appeared in the rotation rate.

In the last decade, a vigorous debate has been engaged over the extrapolation of surface magnetic observatory field data to the CMB to assess the flow regime at the top of the core. The problem is poorly constrained and the results depend significantly on what additional constraints are introduced. Although there is a broad consensus on some of the major features of the flow, there is disagreement on the important question of whether core material upwells just below the CMB.

Significant early contributions to this subject were made by Benton and his colleagues (*e.g.*, Benton *et al.*, 1979) in which they identified null-flux contours, regions of zero vertical magnetic field, at the CMB. Subsequently, Gubbins and his colleagues initiated a campaign to significantly improve the historical magnetic data set which can be used for the downward continuation studies (Bloxham *et al.*, 1989). Such maps have been used to infer the core velocity field just below the CMB, although this cannot be done without additional strong assumptions. For example, one can assume the flow is either steady (time independent), geostrophic (rotation balances pressure and gravity, so the magnetic field is ignored), or toroidal (zero radial component at the CMB).

The implications of these assumptions are well reviewed by Bloxham and Jackson (1991) and Hulot *et al.* (1992), who demonstrate that the main features of the flow are unaffected to a first approximation by the assumption made. In particular, there is a dominantly symmetric flow (about the equator), which is much stronger at Atlantic longitudes than in the Pacific, with two circulations at ±45° latitude. These flows are, of course, the modern analogue of the classic "westward drift" (Halley, 1916; Bullard *et al.*, 1950; Olson, 1989). On the important question of whether the flows show upwelling or downwelling below the CMB, which pertains to the existence of a stably stratified layer at the top of the core, the interpretations are, as yet, inconclusive.

High-Pressure Physics and Chemistry

Knowledge of the physical state of the Earth's core, as a high-pressure phase of iron, has changed remarkably little since Weichert (1896) first presented a convincing model of the interior, combining what was then known of chemical abundances with data on Earth's mass and moment of inertia from astronomical and geodetic observations (Brush, 1980). Even the details on the particular phase of iron and the location of the triple point have remained pretty much as Birch (1952) proposed, according to Anderson (1990). However, there has now developed a vigorous debate over the melting curves of Fe and FeO with volume (or pressure). On the one hand, Boehler (1992) confirms the high-pressure data of Ringwood and Hibberson (1990), which implies much lower core temperatures than obtained from the melting experiments of Jeanloz and his colleagues (*e.g.*, Jeanloz, 1990; Knittle and Jeanloz, 1990). The two groups (both using diamond anvil cells, although different detection methods) suggest CMB temperature ranges of 2600-3400°C and 3800-4800°C, respectively, and corresponding values of 3500-4200°C and 6600-7600°C at the ICB. As Duba (1992) remarks, these differences are truly astounding and represent the large experimental uncertainties in reproducing core conditions in the laboratory. Needless to say, the discrepancy leads to substantially different inferences concerning the core's energy budget.

Other major questions at the present time concern the conductivity of *D″* and the nature of the light element(s) in the OC.

THE SOLID INNER CORE

Physical State

Remarkably, the solidity of the IC core has been seismologically confirmed by only a few tentative observations of the body phase PKIKP, a *P* wave in the outer core bouncing off the inner core boundary (ICB), and only one reported detection of PKJKP (a *P* wave in the OC travelling through the IC as an *S* phase) by Julian *et al.* (1972). Unfortunately, the very small predicted amplitude of this phase (Doornbos, 1974) casts doubt on this detection and, thus, on direct body wave evidence for the solidity of the IC.

The strongest seismic evidence for the solidity of the IC comes from fitting various Earth models to free oscillation data. The claimed observation of the spheroidal mode $_{11}S_2$ (Dziewonski and Gilbert, 1973) seemed conclusively to demonstrate the IC is solid, since this mode should not appear at all in models with a fully fluid core. This mode was later shown to be explained by coupling to neighbouring modes (Masters *et al.*, 1983). Reports of the detection of other modes sensitive to the inner core, *e.g.*, $_2S_2$, $_6S_2$ and $_7S_3$, have recently been made by Suda and Fukao (1990) and Imanishi *et al.* (1992), using the sompi method, although again, it remains to be seen whether these are confirmed by other workers. Nevertheless, the assumption of a solid IC considerably improves the fit of Earth models to free oscillation data, which is compelling indirect evidence for a solid IC.

The anelastic attenuation *(Q)* of the IC has been reported as both greater than (Suda and Fukao, 1990) and lower than (Widmer *et al.*, 1991) that of the mantle, in both cases with greater attenuation near the surface of the IC. A more recent study by Niazi and Johnson (1992) favours the lower Q value (175) with no depth dependency within the IC; the situation is obviously unresolved.

Seismic studies now suggest there may be either aspherical velocity structure in the IC (Poupinet *et al.*, 1983; Ritzwoller *et al.*, 1986) or anisotropy, with the crystals aligned along the rotation axis (Morelli *et al.*, 1986; Shearer *et al.*, 1988; Creager 1992). The latter possibility could be explained either by some form of solid-state convection in the IC, or a preferred orientation of crystallization at the ICB as the IC grows by freezing out from the core fluid. This clearly is a subject that will be addressed by better recordings of core phases by international seismological observing period (ISOP), a program sponsored jointly by SEDI, the International Association of Seismology and Physics of the Earth (IASPEI) and the Inter-Union Commission on the Lithosphere (ICL), in the decade to come.

The ICB Density Contrast and the Slichter Modes

An important parameter from a number of points of view is the density contrast across the ICB. The most reliable seismic tool for understanding this quantity is the ratio of reflected amplitudes of the phases (PKIKP/PcP); the two travel paths are identical in the mantle, but PcP is reflected from the CMB, whereas PKIKP is reflected from the ICB. Bolt (1991) suggests that the density contrast could be as high as 1.5 g•cm^{-3}, consistent with the estimates of Souriau and Souriau (1989). This is in clear disagreement with an interpretation of the same data by Shearer and Masters (1990), who argue for a value <1.0 g•cm^{-3}.

Normal mode studies (Masters and Shearer, 1990) favour a density contrast of approximately 0.5 $g \cdot cm^{-3}$ on the basis of a fit to modes with substantial kinetic energy at the ICB. This value can be reconciled with the value obtained from body wave data by assuming the latter data is biased, and should be regarded as giving an upper limit to the density contrast.

For this particular problem, it is fortunate that another observation could be made that would give a definitive answer. This is measurement of the pendulum motion of the IC about the Earth centre of mass. The motion is dynamically allowed because the OC and mantle move in the opposite direction to the IC to conserve overall linear momentum. This inner core translation, popularly called the Slichter mode (Slichter, 1961) for a non-rotating Earth model, is split by the Earth's rotation into three modes of different periods (Smith, 1976). The eigenfrequencies of the "Slichter triplet" have been usually computed using first-order perturbation theory, a technique that works well for the seismic-free oscillations due to their short periods (<<1 hour) compared to 12 hours. For an inviscid fluid outer core, the periods of the Slichter triplet for Earth model PREM (Dziewonski and Anderson, 1981) are 4.77 hours, 5.31 hours, and 5.98 hours using this technique. Complete allowance for rotation refines these values only marginally (Crossley, 1992; Rochester *et al.*, 1992; Rochester and Peng, 1993).

Despite determined efforts to observe this motion (Rydelek and Knopoff, 1984), to date it was thought to be too weakly excited to be observable (Crossley *et al.*, 1991). Recently however, Smylie (1992) claimed to have detected the Slichter triplet in a stack of four superconducting gravimeter records from Europe. The importance of this observation is that the periods of the Slichter triplet are primarily determined by the density contrast at the ICB. Smylie (1992) not only estimated the ICB contrast as close to the model CORE11 (Widmer *et al.*, 1988), but also inferred a fluid core viscosity much higher than the laboratory estimates traditionally accepted.

This claim has been contested on several theoretical grounds by Crossley *et al.* (1992). Smylie (1992) based his theoretical eigenperiods on a Love number approach that assumes the IC and mantle can be treated statically (Smylie *et al.*, 1990) and this leads to Slichter periods some 40% shorter than the seismic periods. Further, Smylie uses the subseismic approximation in the core equations, which causes a further slight shift in eigenperiods (Crossley and Rochester, 1992). As some readers will already be aware, this debate is still being pursued in the literature.

However, other studies have failed to confirm the very weak peaks using different superconducting gravimeter data sets (Hinderer *et al.*, 1992; Jensen *et al.*, 1992), which argues against the claimed detection. The technique of stacking global superconducting gravimeter records remains, however, a valuable pointer to future studies of this type, which are part of the global geodynamics project (GGP), another SEDI-sponsored project.

The IC and the Geodynamo

Traditionally, the IC has been assumed to be growing by freezing material from the OC, thus liberating the light fraction of the OC fluid at the ICB and yielding not only the latent heat, but also chemical buoyancy to power the geodynamo (*e.g.*, Braginsky, 1963; Gubbins *et al.*, 1979). This process is elegantly described in a much-neglected book by Verhoogen (1980). The time during which the inner core has grown to its present size has been recently estimated by Buffet *et al.*, (1992) to lie between 1 gy and 3.6 gy, depending on the heat flux assumed through the CMB.

The dynamical (precessional) motion of the IC and its possible influence on magnetic field generation has been investigated by Szeto and Smylie (1984) and Szeto (1988). Using different assumptions, Hollerbach and Jones (1993) find that a highly conductive, but dynamically passive, IC expells an initial toroidal field, thus leaving a diffusive poloidal field similar to that of the mantle.

THE FLUID OUTER CORE

From a seismic point of view, the OC has been a relatively easy region to treat. Assumed to be a low-viscosity fluid (*e.g.*, Gans 1972), there are apparently good reasons to expect there to be no lateral density in homogeneities (Stevenson, 1987) and a near adiabatic temperature gradient. The lack of lateral structure has been challenged by Wahr and de Vries (1989) and is apparently incompatible with free oscillation studies, which favour a degree 2 type aspherical structure in the OC (*e.g.*, Widmer *et al.*, 1992), and several models of the core include some region of stable stratification, *i.e.*, no convection (*e.g.*, Crossley, 1984), particularly near the top of the core. Inversion of body wave data (*e.g.*, Kohler and Tanimoto, 1992) fails to clearly resolve the ambiguities between lateral velocity variations in the OC and CMB-related inhomogeneities.

Rigidity Estimates

Various lines of evidence suggest the outer core is a fluid, although only in the case of a Newtonian linear fluid does this mean that its rigidity is identically zero. Indeed, the assumption of zero rigidity has never been conclusively proved in geophysics and the door is left open to a small, but finite rigidity perhaps associated with a slurry in the outer core (Busse, 1972). The upper limit set by seismology is about 10^9 $N \cdot m^{-2}$ or 0.01 of the mantle value (Lapwood and Usami, 1981, p. 68), while, from success in modelling the liquid core to account for the 18.6 year forced nutation, Jeffreys (1970, p. 295) argues for a much lower (upper) limit of 6×10^7 $N \cdot m^{-2}$.

Although occasional references to this subject continue to appear (Mochizuki, 1990), they are not persuasive enough to convince the majority of geophysicists that the core has non-zero rigidity. It is likely that the presence of the FCN, strongly inferred from geodetic and gravity measurements, demands completely zero shear modulus, although this has not been demonstrated numerically.

Viscosity Estimates

On the question of the kinematic viscosity for the core fluid, the current estimates are either "high" geophysical upper limits (between 10^{-1} and 10^5), or "low" laboratory experimental extrapolations (between 10^{-7} and 10^{-3}), in units of $m^2 \cdot s^{-1}$. Lumb and Aldridge (1991) suggest that this large discrepancy may be due to the difference between linear viscosity, measured in the laboratory, and effective or eddy viscosity, which may be appropriate for dynamics of the core. If so, it suggests that the core fluid is in a turbulent regime for a wide frequency range of physical phenomena (associated primarily with rotation studies).

Thus, researchers are free to assume any viscosity within these bounds, depending on their purpose, although the uncertainties are conveniently used by many authors to assume that the core fluid is essentially inviscid to a first approximation. This is a convenient, but sometimes dangerous assumption because viscosity changes the order of the governing equations, so a fluid with a vanishingly small viscosity is different from that having zero viscosity; mathematically, non-zero viscosity is a singular perturbation of the inviscid equations. In some of the more recent dynamo modelling (*e.g.*, Glatzmeier, 1992), finite viscosity (as well as compressibility) has been re-introduced into the Navier Stokes flow equations, although most magnetohydrodynamic studies still assume zero viscosity.

In another context, that of short-period dynamics of the liquid core and the search for internal gravity waves, zero viscosity has also been assumed, although once again it is recognized that Eckman layers are present even in a low viscosity fluid. These layers play a significant role in dynamics of the core during changes in rotation rate (in the limit this becomes the spin up problem, (Greenspan, 1964)) and in the introduction of separate boundary layer solutions for the internal gravity wave/inertial wave problem (Rieutord, 1991). A very recent attempt was made by Smylie and Qin (1992) to introduce finite viscosity into the boundary layer problem for the Slichter modes. Contrary to most authors, they chose the high regime for viscosity; this results in significant shifts from the inviscid Slichter periods.

Gravitational Stability, N^2

From a seismic point of view, the outer core has always been treated as though it were chemically homogeneous and in a virtually adiabatic state ($N^2 = 0$, where N is known as the Brünt-Väisälä buoyancy frequency). Such a condition is one of neutral gravitational stability, also known seismically as the Adams-Williamson condition (Bolt, 1957). There are persuasive, simple arguments, that indicate (*e.g.*, Higgins and Kennedy, 1971; Stacey *et al.*, 1981) that a convecting core, where the temperature gradient is super-adiabatic ($N^2<0$), will tend toward a condition of nearly neutral equilibrium.

On the other hand, Higgins and Kennedy (1971) first proposed that the core, or more likely a portion of the core, may be stably stratified ($N^2>0$), thus inhibiting convection and implying chemical inhomogeneity. Stable layering in the core raises the possibility of internal gravity wave motion, which is strongly affected by the Coriolis force associated with the rotation of the Earth. More recently, the issue of whether a stably stratified layer can exist at the top of the core has concerned a number of geophysicists studying the magnetic field exptrapolation problem, discussed in more detail later (*e.g.*, Whaler, 1982).

On this particular issue, seismology is uncharacteristically ambiguous (Masters, 1979) as the density profile in the core is not known to sufficient precision to yield a definitive answer (Crossley and Rochester, 1980). Most radial seismic models give stability profiles that vary around the neutral condition, but cannot definitively rule out non-neutral stratification. As indicated above, the issue of stability is crucial for the role of convection associated with magnetic field generation and, as will be discussed later, implicated in the attempt to map the fluid flow at the top of the core from surface magnetic field measurements.

There exists the possibility that the fluid core may be laterally homogeneous, such that some regions may be gravitationally unstable (convecting), while the rest may be stable, in much the same way as envisaged for the lower mantle (Jeanloz and Morris, 1987). Such a model would be consistent with plume or blob type (probably turbulent) convection, rather than the smooth (linear flow) core-wide circulation traditionally assumed. Despite the arguments concerning lateral homogeneity in the core, it seems likely that chemically driven buoyancy would result in localized convection and, thus, a chemically heterogeneous (non-neutral) core stratification.

The question of the core's formation has been re-examined, with a novel suggestion (Stevenson, 1993) that the OC may be chemically layered with a stable boundary at mid-fluid depths. Stevenson stresses the probable complexity of core processes and the difficulty of resolving the issues with present information. This leads us to review the subject of core undertones as an alternative possibility for direct observation of the stability parameter in the core.

Short Period Core Dynamics

The role of core stability has stimulated a very active branch of the science, combining seismology with the physics of rotating fluids, and leads to the possible detection of internal gravity waves in the core of the Earth (core undertones) using superconducting gravimeters. From one point of view, this subject began with the paper by Pekeris and Accad (1972) on the calculation of the internal gravity wave periods for a stably stratified core in the absence of rotation. From another point of view, it has long been known that a neutrally stratified rotating fluid can support inertial waves with periods longer than half the rotation period, *i.e.*, 12 hours for the Earth, as presented, for example, by Greenspan (1969). On the experimental side, there is abundant evidence for the existence of inertial waves in a homogeneous incompressible fluid shell (*e.g.*, Aldridge and Toomre, 1969; Aldridge, 1975) and an interesting development connecting inertial waves and magnetohydrodynamic waves, which may be equatorially trapped in the core (Zhang, 1992).

This subject has since developed into a major effort, dominated by Canadian geophysicists (*e.g.*, Crossley and Rochester, 1980; Smylie *et al.*, 1984). A comprehensive, but now obviously dated, review of Canadian contributions to global geodynamics is contained in Rochester (1979).

The theoretical problem is to compute the spectrum of internal gravity waves for a rotating radially stratified fluid in a thick shell. This problem has been solved satisfactorily for thin fluids, such as the atmosphere where a "traditional approximation" (neglect of the horizontal component of the Coriolis acceleration) can be used to simplify the equations considerably. The Earth's core has considerable thickness (compared to its diameter) and the full Coriolis acceleration vector must be used. It quickly became obvious that keeping the Coriolis force in the full equations of motion for the Earth was computationally a difficult problem (*e.g.*, Johnson and Smylie, 1977; Crossley and Rochester, 1980). An attempt was made by Smylie and Rochester (1981) to circumvent these difficulties by introducing the subseismic approximation (SSA) into the flow theory, and both this and the Boussinesq approximation (Crossley and Rochester, 1980) have been successful as a first approximation to the eigenmodes of a shell with rigid boundaries.

Three major avenues of solution for the rotating Earth have now developed, the first two of which concern a variational principle for the subseismic wave equation. The initial attempt (Smylie and Rochester, 1986) was limited to inertial waves in a core with rigid boundaries, and a more general functional for elastic boundaries, formulated by Rochester (1989), was used in a series of papers by Smylie (Smylie, 1988; Smylie *et al.*, 1992). Further realizing that this approach required Earth models to have a neutrally stratified outer core, Rochester and his co-workers developed a two-potential variational principle that avoids the necessity for the SSA (Wu and Rochester, 1990) and leads to successful solutions for a rotating shell of fluid (Wu and Rochester, 1993). Recently, Wu (1993) re-introduced a modified form of the SSA, although Crossley and Rochester (1992) and Rochester and Peng (1993) have presented arguments against the SSA.

The third approach continues the original truncated spherical harmonic expansion of Crossley (1975), but, with the growing computational power at our disposal, the ability to obtain convergent solutions with long coupling chains has become quite feasible (Crossley, 1993). All three approaches use the computational elegance of internal load Love numbers to allow for the elastic boundaries of the core and to obtain solutions in the inner core and mantle.

At the present time, the question of the excitation of the core modes has only been solved for an earthquake excitation, although other mechanisms, for example, tidal (Lumb *et al.*, 1992), have been raised. The best estimates of the strength of the surface gravity associated with the core oscillations puts them just below the detectability level of modern gravimeters, *i.e.*, 1 ngal [$=10^{-12}$ of surface gravity] (Crossley *et al.*, 1991).

There have been several observations claiming to have detected core oscillations (Melchior and Ducarme, 1986; Aldridge and Lumb, 1987; Melchior *et al.*, 1988), but none has withstood the test of time. Although some studies have been negative (Zürn *et al.*, 1987; Mansinha *et al.*, 1990; Cummins *et al.*, 1991), the possibility of observing the core modes is sufficiently enticing to warrant the maintenance of the theoretical and observational effort now underway. A major Canadian effort in this regard is the Canadian Superconducting Gravimeter Installation (CSGI) project, which has been running a superconducting gravimeter at Cantley, Quebec since 1989. This represents a highly successful co-operation between university geodynamicists and the Geological Survey of Canada (GSC) Geophysics Division, which has done a superb job of running and maintaining the facility for a variety of gravity projects in Canada.

At the present time, the CSGI data processing has yielded studies on tidal development (Merriam, 1992b), air pressure corrections (Merriam, 1992c), and residual non-tidal gravity variations (Hinderer *et al.*, 1993) that make a significant contribution to Canadian core studies. As an extension of this work, the Canadian-based GGP initiative (Aldridge *et al.*, 1991), has been launched to form a network of superconducting gravimeters to study the core oscillations and other global gravity signals. This project was adopted by SEDI at the Vienna meeting of the IUGG in 1991, and represents one of the new thrusts in global geodynamics applied to the deep interior.

The Nearly Diurnal Free Wobble

Gravity meters, measuring anomalous tidal gravimetric factors at periods close to one sidereal day, have for some years provided indirect evidence for the existence of the Nearly Diurnal Free Wobble (NDFW), a nutation of the axis of the Earth's fluid core with respect to that of the mantle (*e.g.*, Rochester *et al.*, 1974; Neuberg *et al.*, 1987; Merriam, 1992a). Further indirect evidence for the space motion associated with this wobble, the FCN, has been convincingly demonstrated using VLBI data (Gwinn *et al.*, 1986).

The observations have been directly interpreted in terms of the flattening of the CMB, in which the non-hydrostatic shape of the boundary is a second degree zonal harmonic of approximately 0.5 km maintained by either fluid circulation in the core or convection at the bottom of the mantle. However, there are other possibilities, such as density anomalies in the mantle, that may be involved (Dehant and Wahr, 1991).

THE CORE-MANTLE BOUNDARY REGION

Unquestionably, the portion of the Earth's interior that has received the most attention in recent years is the core-mantle boundary (CMB). By all measures, this is the most important discontinuity in the Earth, across which there are major changes in composition, rigidity, viscosity, and electrical and thermal conductivity. Such discontinuities in physical properties naturally lead to the formation of boundary layers when considering the dynamics (including thermal and magnetic effects) of the adjacent material.

Despite the wealth of seismic evidence (too voluminous to review here, but see Young and Lay (1987) for a review) that *D* " is anomalous, both radially and laterally, Bolt (1991) reminds us there is compelling seismic evidence supporting a very sharp seismic boundary (maximum 2-3 km wide) from observations of the high frequencies of certain core-reflected phases (PKP). A recent study (Vidale and Benz, 1992) supports the idea that the CMB may be very sharp and *D* " weak or non-existent in some locations. Nevertheless, seismic data seems to demand a globally averaged low-velocity zone at the base of the mantle (*e.g.*, Lay and Helmberger, 1983), with perhaps lateral variations being consistent with some of the data (*e.g.*, Wysession and Okal, 1988). It is also possible to interpret the travel time anomalies in terms of scattering by three dimensional inhomogeneities at the CMB, as first argued by Haddon and Buchbinder (1988). Despite disagreement on the detailed seismic structure of *D* ", this layer is assumed to incorporate the other boundary layers (thermal, viscous, chemical, magnetic) that have been proposed for the base of the mantle.

Additionally, this layer has been invoked as both the source of mantle plumes (*e.g.*, Duncan and Richards, 1991) and the graveyard of subducted slabs (*e.g.*, Creager and Jordan, 1984). It is difficult to adequately model a laterally heterogeneous layer for the accurate computation of seismic travel times and amplitudes, and some studies (*e.g.*, Rekdal and Doornbos, 1992) have come to the conclusion that part of the claimed CMB topography may be due to poor modelling.

As a chemical boundary layer, the possibility of the transport of metallic Fe from the core into *D* " has important consequences for electrodynamic CMB coupling (*e.g.*, Buffet, 1992) as it furnishes a mechanism for providing the enhanced electrical conductivity long assumed to be present at the base of the mantle. There is, however, evidence that the overall conductivity of *D*" may be little changed by any reasonable amount of Fe transport (Poirier and Le Mouël, 1992), the consequences of which would reduce EM coupling and at the same time strengthen one element of the magnetic field continuation problem, *i.e.*, the assumption that the mantle contains no magnetic sources.

Hide (1969) originally suggested there may be "bumps" on the CMB that would have important consequences for the rotational coupling of the core to the mantle. The first tangible evidence for such structures came from mantle tomography (*e.g.*, Morelli and Dziewonski, 1987), although the amplitudes of the topography they obtained (1-5 km; also implied in the travel-time residuals of Creager and Jordan, 1986) alarmed workers in other fields. In particular, geodetic considerations (*e.g.*, Wahr, 1987, 1990) seem to suggest a much smaller overall ellipticity of the CMB.

Nevertheless, the possibility of undulations on the CMB has stimulated workers in all fields to examine the consequences of lateral variations in thermal, pressure, chemical and magnetic coupling between the mantle and the core. Understanding and reconciling the various data sets pertinent to CMB topography problem has become a truly multidisciplinary effort that is epitomized in projects such as SEDI.

FUTURE PROSPECTS

A few remarks concerning the future health of the discipline are clearly appropriate in the context of this symposium. I have already covered many of the latest developments and it is unnecessary to labour the point that the future is simply a continuation of the present. We should look for the most promising trends in our crystal ball.

Global and International Projects

Much of the work on the Earth's core is now reported in the context of the SEDI project, an IUGG Union Committee that was initiated at the Vancouver General Assembly in 1987. The initial thrust of SEDI was to tackle the geodynamo problem, but the scope of the project rapidly broadened to include any and all geophysics and geochemistry that deal with the deep interior. The success of SEDI can be measured by the three highly successful symposia that have been held (1988 Blanes, Spain; 1990 Santa Fe, United States; and 1992 Mizusawa, Japan) and the many well-attended SEDI sessions at regular international conferences. Without a doubt, the success of SEDI lies in its emphasis on interdisciplinary research and the opportunity it provides for the exchange of ideas on diverse data sets. SEDI supports many activities such as INTERMAGNET, ISOP and GGP, in geomagnetism, seismology and gravity variations, respectively; the first is underway and the other two are both well along in the planning of their respective observing periods. The next SEDI symposium will be at Whistler Mountain in Canada in 1994, sponsored by the Canadian Geophysical Union.

Because global scientific programs often originate in the United States and Europe, both of which invest heavily in gathering data in areas such as seismology, geomagnetism and geodesy, it might be tempting to imagine that scientists in Canada can simply wait until the data becomes available through computer networks. Such thinking is both politically myopic and scientifically dangerous. Canada has a huge land mass that should be put to good use in the Earth sciences. For core studies, the most useful contribution would be the creation of a domestic network of geodetic reference stations (similar to the existing stations at Penticton and Algonquin), including the latest technology (VLBI, GPS and superconducting gravimeters). Such stations would fully participate in the global networks, *e.g.*, international radioastronometric interference service (IRIS) and therefore claim for their participants first rights to the data. More than this, only when local scientists have the knowledge of, and expertise with, the modern technology and data acquisition systems can they appreciate the complexities of, and fully exploit, the data.

Non-Linear Dynamics

I have said little about the advance of non-linear dynamics into core studies, such as the convection problem. However, this subject is quite new and many of the implications have not been fully developed. Many studies suggest that the core probably has a complex velocity field at many time and distance scales, and we surely will not ever be able to model the flow in detail. What we can do is to model averaged properties of the flow and deduced statistical measures that are appropriate to our observations. In this respect, we share the problem with those studying mantle convection.

RESOURCES AND FUNDING

The Role of Educational Institutions

Since this article originates in a university, it is natural to comment on the trends that have been evident now for several years. Declining student enrollments in the earth sciences have followed the decline of the exploration industries. This situation has been aggravated by the overall contraction of academic and government jobs during the last ten years, so scientific and financial rewards can no longer be seen as attainable for our brightest young minds. While this situation has demoralized domestic science students, the vacuum has been filled, with variable success, by increasing numbers of foreign students, especially those from far eastern countries.

Without casting any doubt on the excellence of our geophysics students, they face stiff competition for the few industrial and academic jobs that are available in geophysics each year. Many students, particularly foreign students, are quickly lost to the system after their degrees are completed. We are certainly in a crisis with respect to continued survival of our scientific heritage in geophysics. It is difficult to imagine a return to the heady days of the 1960s when geophysics participated in the growth enjoyed by all sectors of the economy.

The best that can be done is to continue the work that is currently underway and provide the necessary environment for the new challenges ahead. As far as core studies are concerned, one of the most important factors is for Canadian geophysicists to participate in the new international programs that are bringing the disciplines much closer together. This requires government support and commitment. Core studies can rarely be tied to industrially motivated research, so the prevailing trend in many of our universities to inject research with a strong dose of corporate, goal-oriented missions would not serve our needs at all.

My own impression is that the Natural Sciences and Engineering Research Council (NSERC), being effectively the only supporter of fundamental research in Canada, does possess the necessary awareness of its responsibilities through the committee members that are recruited directly from the universities. Whenever a strong university/government group has materialized with a good project, NSERC has generally responded in reasonable time and with appropriate funding. It is clearly up to NSERC to maintain its peer review system and to continue to support the freedom to use the funds wherever the scientific returns may be greatest.

The funding crisis is emphasized by the relatively small weight given to the earth sciences community compared to physics and/or chemistry (for example). There is an unfortunate misconception that planetary science is not fundamental in the same way as is astrophysics or high-energy physics. Additionally, Canadian geophysics has been traditionally *resource driven*, rather than *science or curiosity driven*. After all, what remains of a culture but the ideas it produced? Do we remember the Greeks for their lifestyles or passing pleasures or for the success of their business community? Important though such aspects are to the general population, they are ultimately only the supporting structure on which great ideas and their realizations in science and art flourishes. For example, once one understands how planets sustain their magnetic fields in detail, *this information remains forever part of mankind's heritage*. The same is true for all fundamental truths. In short, geophysics (as it pertains to planetary cores) is predominantly a *cultural*, rather than an *economic*, activity.

We, in the university community, have an enormous responsibility to help young people learn and to give them appropriate leadership in science. We are clearly having a tough time doing this with the small numbers of students who are coming into our earth science programs. It is clear that the character of universities is moving away from scholarship, and students frequently treat university as vocational training. To counter this, modern earth science programs need to be introduced into high school and pre-university training. The restricted funding for students from individual research grants should be replaced by direct grants from the government to students (both undergraduate and graduate), who would be free to study wherever they wished in Canada.

Geophysics in the Government

It is obvious that government institutions are uniquely positioned to provide the long-term stability that the geophysical monitoring of our planet requires. While university groups may come and go, depending on the demographics of individuals and chance assemblages of talent in particular subject areas at particular times, it is the government research institutions that have the resources both to establish fundamental observing stations and to keep them running for decades at a time.

Clearly though, much more is required beyond the straightforward task of data collection. Government institutions, like universities, constantly have to be on the lookout for the brightest, most talented scientists in order to take a leading role in the scientific and technological life of the country. And such talented people need the time, space and resources to develop their own ideas on the analysis and interpretation of the data. It seems to me both pointless and wasteful to enlist the services of a first-rate scientist and then to restrict him or her either solely to collecting data for the public sector or to rote processing and interpretation using methods developed by others, years earlier. Scientists employed by government need active participation in the development of models and in the testing of data against their own hypotheses, in other words similar opportunities as accorded university researchers. How do we convince our politicians and governmental bureaucrats of this?

A great problem in Canada is that our best scientists almost never make it into the political arena, unlike some European countries. In France, for example, V. Courtillot, a highly respected geophysicist of great ability, has occupied the position of advisor to the Minister of Education. Although he still writes regularly on scientific issues concerning fundamental geophysics, he has been active in promoting the intellectual challenge of earth science in the political arena. On the other hand, most senior government geophysicists are many levels away from a policy-making position in Ottawa. Usually the administrators have little direct knowledge of the scientific fields under their command and little appreciation of the methods by which science advances.

The Private Sector

I was reminded of the important role major corporations can play in basic science by a recent trip to Japan to attend the biannual SEDI conference in Mizusawa, a small city about three hours by train north of Tokyo. This conference, on the core mantle boundary, was on as esoteric a subject as one might expect to find anywhere in earth science, and yet it was treated with great respect by both the local citizens and many major Japanese industries. The latter, including several well-known electronic and electrical companies, certainly would have no direct interest in the subject matter. Nevertheless, the financial backing given to SEDI was significant and sets an example that could well be emulated (but probably won't be) in Canada.

Planning

The advantages of long-term planning and investment by government and industry should not even merit debate. Naturally, the university community is critical when NSERC launches grand strategies (*e.g.*, Centres of Excellence) that leave little room to support the creativity of individuals at universities and reduce the flexibility offered by a more even funding of research activity. If large projects dissipate valuable funds by creating too much bureaucracy, underfunding will prevent researchers from being able to participate in the continuing global initiatives. We need projects of an intermediate funding level that both bring researchers together and also can respond quickly to new and developing areas, while making the best use of existing resources.

To continue the excellent work that Canadians have contributed to global geodynamics, it seems obvious that the further loss of university and government positions must be avoided and the student population revitalized. The only way I can see to do this is to promote geophysics, as much for the rewards it brings as general culture and basic science, as for its use in the exploration and environmental industries, vital though these are to our economy and public life.

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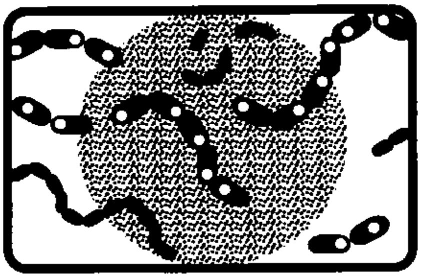

The Ancient Biosphere

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ABSTRACT

The origin and development of life on Earth is intimately linked to the physical evolution of the planet's surface and upper lithosphere. The future of research on the ancient biosphere is filled with as much excitement and uncertainty as the future of the Earth itself. The trend will be to build on traditional strengths, such as biochronology, paleoecology and paleobiogeography, and to seek completely new research directions driven by new technology, new concepts, and new requirements for information.

The traditional strength of paleontology in providing the time scale necessary for evaluating the duration and rates of physical processes will remain important. Biostratigraphy will be more closely integrated with new concepts in physical stratigraphy, such as event and sequence stratigraphy. Paleoecological and paleobiogeographical data, which only fossils can provide, will be more fully interpreted to produce refined models of basin processes. Studies of extinction and radiation of the Earth's biota through time will lead to a fuller understanding of biological evolution and its relationship to the physical evolution of the Earth. The desire to test the Gaia Hypothesis will spur much of this research.

The application of new technologies will greatly enhance our ability to study fossil organisms without damaging specimens. Computer technology will permit better data management, and manipulation and display of both data and images, thus enhancing our interpretive skills.

The integration of paleontology with geochemisty will result in a profound improvement in our understanding of paleo-oceanography and paleobiogeography. The chemistry of fossils, reflecting the chemistry of the oceans in which they lived, will allow interpretation of large-scale trends, and greater understanding of events such as extinctions and radiations. In terms of organic geochemistry, paleontology will be taken to the molecular level, moving beyond the economically driven study of biomarkers to elaboration of the temporal distribution of biomolecules and their implications for evolution.

Understanding the evolution of the biosphere is of crucial importance to interpreting global change, an issue that will grow in public importance during the coming decade. In order to appreciate the impact and rate of global changes in the ancient and present biosphere, there is a requirement for a clearer understanding of biodiversity. Recent trends indicating a decline of systematic paleontology and biology will have to be reversed if we are to gain a comprehensive view of global change. Research on the ancient biosphere is of increasing importance to the future of the planet — particularly to its human population — as it becomes more evident that the continuing survival of the species is in doubt.

A prime component of future scientific work must be the explanation and interpretation of results to the general public. Development of scientific literacy is perhaps the most pressing challenge facing the scientific community.

RÉSUMÉ

L'origine et le développement de la vie sur la Terre sont intimement liés à l'évolution de la surface de la planète ainsi que de la partie supérieure de sa lithosphère. Tout comme l'avenir de la planète, les recherches dans le domaine des biosphères du passé comportent beaucoup d'exaltation et d'incertitudes. Les nouvelles avenues de recherche devront s'établir à partir de domaines de recherches déjà bien établis tels ceux de la biochronologie, de la paléoécologie et de la paléobiogéographie. Elles devront également s'élaborer selon des avenues de recherche vierges,