# GEOPHYSICS 2001

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**Abstract.** An attempt is made to try and predict those fields of research in geophysics which are most likely to prove rewarding in the next one or two decades. Topics covered are the early history of the Earth, satellite geodesy, mantle convection, geomagnetism, aeronomy and space research.

## 1. Introduction

It is not easy to look ahead and decide where we should put most of our effort in the years to come. It is easy to make a list of questions for which we do not know the answer – such as what is the origin of the solar system, what is the origin of the Earth's magnetic field, is it possible to predict earthquakes? We will probably never know for certain the answers to such fundamental issues, although we shall undoubtedly learn much more about them. A list of such problems would not be very helpful – it is far better to try and pinpoint those areas which hold out some hope of real progress being made by a more concerted effort and those in which little work has been done for some time but in which even a small increase in knowledge would be of value.

This meeting is concerned only with magnetism, rotation and convection in the solar system and I will confine my remarks to them. However, it should not be forgotten that seismology has the highest resolving power of all geophysical methods that are used to study the structure of the Earth and is the main tool for determining many parameters that are critically important to our understanding of the dynamic behaviour of the Earth. It is particularly difficult to determine variations of some parameters such as conductivity or viscosity and we may be forced to study related phenomena such as anelasticity or attenuation. Mechanisms of attenuation are very sensitive to thermal conditions and it is difficult to determine their radial and lateral variations in as much detail as the elastic properties. However they can offer basic information on thermodynamic conditions in the mantle. To understand attenuation in the core and solid inner core, it would be interesting to consider new physical mechanisms e.g. the effects of a magnetic field.

## 2. Early history of the Earth

I look forward to increased knowledge of the early history of the Earth – particularly on the question of differentiation during accretion and partial or complete melting. The greatest breakthrough in this area may come through isotopic comparative studies. Isotope geochemistry and cosmo-chemistry provide essential data for constraining speculations on the way in which planets are put together, differentiate, and evolve. Extinct radioactivities constrain the time scale of the formation of the solar system, lead

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isotope studies constrain the rapidity of core formation, and studies of the samarium-neodymium system provide tantalizing glimpses of the way in which the Earth's mantle may be layered. We should also be able to settle once and for all the question of whether the anomalous iridium-rich layer at the Cretaceous-Tertiary boundary is the result of a collision of a large asteroid with the Earth as proposed by Alvarez et al. (1980). In this connection, recent analyses by Rampino and Reynolds (1983) of the clay mineralogy of samples from the Cretaceous Tertiary boundary layer at 4 localities have shown that the boundary clay is neither mineralogically exotic nor distinct from locally derived clays above and below the boundary.

We can also hope to learn much more about the Earth from the next generation of space missions. The U.S. Committee on Planetary and Lunar Exploration gave the study of comets one of the highest priorities of future planetary research. Comets are the only obtainable source of the primitive material from which the solar system evolved, and are believed to contain a record of the physical and chemical conditions of the interstellar medium and the primordial solar nebula. Furthermore, comets may have contributed appreciable amounts of volatile material to the present atmospheres of the terrestrial planets. It has also been suggested that cometary material was important to the evolution of life on Earth.

My first interests in geophysics were concerned with the thermodynamics of the Earth's interior, and I look forward one day to a more confident history of the thermal evolution of the Earth. I am not too hopeful, however, of seeing any major developments – this would necessitate a significant breakthrough in the theory of melting which would be important in many other branches of physics and metallurgy. Improvements in our understanding of the behaviour of materials at high pressure can however be anticipated. Static and shock wave experiments provide the capability for a variety of property measurements over a range of temperatures and pressures including conditions in the Earth's core. Phase diagrams can be delineated and the partitioning of constituents determined (either directly in a diamond cell or indirectly by application of thermochemical arguments). Transport properties such as electrical conductivity are also measurable. The diamond cell anvil technique in particular, is still largely untapped and in the next decade could provide a wealth of thermodynamic data at high pressures.

## 3. Satellite Geodesy

The last 10–20 yr have seen tremendous developments in spatial geodesy – VLB1 and the use of lunar and satellite laser – ranging techniques. However the geophysical potential of such technological advances has not yet been fully exploited. The deployment of a network of permanent VLB1 type instruments and laser-ranging stations could lead to greatly increased improvement in the precision of measurements of polar motion. Most people believe that the Chandler wobble is a single damped free oscillation of the Earth maintained by some irregular excitation process – the recent work by Okubo (1982) confirms this conclusion. However, I don't think that we shall learn what excites the Chandler wobble, or what causes the damping of its motion although it should prove possible to settle once and for all the question of a possible relationship between earthquakes and the Chandler wobble. Here, as in the decade variations in the l.o.d., the mechanism of core mantle coupling has still not been satisfactorily resolved and deserves further attention. Again, using recent developments in spatial geodesy with stations strategically placed on different plates, it should become possible to determine whether present day plate motions agree with the average motion inferred from magnetic anomalies. It should also be possible to establish whether the motion is smooth (on a time scale of a few years) or more erratic. About 50 % of the Doppler observations made on a Navy Navigation Satellite over a 9-yr period have been analyzed to determine the motion of 8 sites on the North American plate and 12 sites on 7 other plates (Anderle and Malyevac, 1983). The computed plate motions were not statistically significant compared with the standard errors of measurement of 1 to 5 cm $yr^{-1}$ except for the Australian, European, and Pacific plates. The measured motions of these plates were about twice those inferred from geologic records, but were in the proper direction.

An area that has been pursued at Newcastle in the past and in which I would like to see more work done is the use of palaeontological data for direct evidence of the length of the day, month and year in the geologic past. Growth increments on the shells of marine organisms are clearly observed, but can we always be sure that they really indicate diurnal, monthly and annual periods with all time increments faithfully recorded? More work on control specimens is needed and I believe would repay the effort involved.

Finally, have we yet settled the question of whether the gravitational constant $G$ decreases with time as postulated by Dirac leading to an expansion of the Earth? Recent work by Canuto (1981) has suggested that in some theories of gravity the presently available data actually favour an increase in $G$ with time.

## 4. Convection

A question which I anticipate will be resolved is whether there is whole or two-stage convection in the mantle. If the mantle is convecting throughout its volume (at the high Rayleigh number necessary to account for the observed mean surface plate speed), there should be a substantial heat flow across the core-mantle boundary. There should then be a well-developed thermal boundary layer at the base of the mantle. Seismic evidence for this is quite convincing, but further investigations are highly desirable. The existence of a thermal boundary layer at the base of the mantle could help in understanding another important characteristic of the convective circulation. Because of the combination of a sharp temperature gradient with low viscosity, this boundary layer would be convectively unstable and serve as an efficient source of small-scale thermal inhomogeneities which would rise plumelike to the Earth's surface at rates sufficiently rapid that their ascent would be quasi-adiabatic. Such thermal events, perhaps accompanied by partial melting at the base of the lithosphere, provide an attractive explanation of intraplate volcanism. The cold thermal boundary layer at the Earth's surface (the lithosphere) is affected in precisely the opposite fashion by the temperature dependence of viscosity. Here the effective viscosity is so high, due to the low surface temperature, that the lithosphere is able to withstand the large temperature contrasts across it without suffering disruption through buoyant instability.

Although the model of whole mantle convection is appealing, it does not necessarily correspond to reality. If the Earth initially accreted with a stable density stratification or if irreversible processes such as melting and partial differentiation led to subsequent stratification, the large-scale flow associated with plate motions could not penetrate throughout the mantle. The cessation of seismicity at 700 km, the compressive state of stress in some subducted slabs and the apparent segregation of the mantle into at least two geochemical reservoirs are readily explained by a stratified model. The question of whether the mantle is stratified, with each layer forming a closed convecting system, is one of the most interesting, and as yet, unresolved problems.

## 5. Geomagnetism

The theory of geomagnetism has developed comparatively recently. Twenty five years ago, it was shown rigorously that the dynamo mechanism can provide a feasible means for the generation of magnetic fields in electrically conducting liquid bodies, such as in the outer core of the Earth. So far there has been little comparison with laboratory data – experimental work is highly desirable for the understanding of non-linear phenomena. Work is proceeding on trying to determine the details of core motions – I believe, however, that more progress will come from a consideration of the possible driving mechanism for the geodynamo. Different mechanisms have in the past been proposed – precession, thermal convection and the one that at the moment enjoys the greatest support, gravitational differentiation of material in the core to form the solid inner core. I would hope that more definitive conclusions can be reached in the future. Experimental and theoretical work on compositionally layered, convecting systems should prove valuable in this respect.

I think that another fruitful area would be a detailed analysis of archaeomagnetic data to study intensity variations of the Earth's magnetic field. Can the intensity change by up to 50% or more in a hundred years as some recent work has indicated? Apart from such comparatively rapid changes, it is rather surprising that the intensity of the geomagnetic field has apparently remained remarkably constant (within a factor of 2 or 3) over geologic time.

There are some very special features of the geomagnetic field that need an explanation and which deserve special study e.g.

(1) Reversals of the field – and particularly the so-called excursions or aborted reversals. Can we dismiss this problem just by saying that it is a common feature of non-linear systems?

(2) The persistent tilt of the dipole axis.

The exploration of planetary magnetic fields by space probes has given a great impetus to developing a theory of planetary magnetism – although I cannot see any hope of establishing a general scaling law. Let me list just 3 problems that have, and still need more attention paid to them:

(1) Lunar magnetism – I need say no more on this, since Professor Runcorn has long championed the idea of a small lunar core which acted as a dynamo in the moon's early history.

(2) The absence of a magnetic field on Venus. One would expect that a body similar in many respects to the Earth would have a magnetic field. It's absence cannot be put down to its much slower rotation – the Coriolis force would still be dominant.

(3) The small tilt ($< 1°$) of the dipole axis of Saturn's magnetic field.

## 6. Aeronomy and Space Research

It is remarkable what progress has been made in geomagnetism and aeronomy during the last 2 decades in a field where a controlled experiment is rare. Progress has come about in a variety of ways, some of which are not to be found in conventional 'laboratory' physics. The sheer vastness of the phenomena to be observed has demanded, and continues to demand, numerous observations and often the accumulation of lengthy time series of data. Whilst Gauss was able, with relatively few observations, to determine some of the harmonics of the geomagnetic field, we need, for some purposes, (e.g. the investigation of the interaction of the solar wind with the magnetic field), many orders of magnitude more information than was available to Gauss. Outside of geophysics, the exploration of the natural plasma in the environment of the Earth in space has provided, and will continue to provide, tests of physical theories and the finding of new phenomena in plasmas unattainable so far in Earth-bound laboraties. There are, of course , still many unresolved problems of geophysical interest such as: What are the conditions for creating an aurora and what is the true nature of the mechanism of the interaction of the solar wind with the geomagnetic field? We also need to know far more about the chemistry of the upper atmosphere. There is still much argument and conflicting reports of the effect of the release of chlorofluorocarbons into the atmosphere – whether it presents a hazard to the Earth's ozone layer and entails the threat of drastic climatic changes. The same can be said for the effect of increased carbon dioxide in the atmosphere.

## 7. Data analysis

Geophysics is essentially an observational science. Data acquisition, analysis and storage have increased in complexity and related demands exceed the capacity of existing information-handling systems, and demand new models of collective, multi-group or even international data analysis and interpretation. The complexity and nonlinearity of many of the physical processes involved require massive studies with computer simulation and numerical modelling techniques. The demands on rapid information exchange on who is doing what, where and when are beginning to exceed the capability of present-day scientific information services, especially in their currently reduced operational state. These more general problems will affect all branches of science in the future.

## Appendix

Following the discovery (Jacobs, 1973, 1981) that Lewis Carroll had made significant contributions in the field of Geophysics, further research has brought to light his early interest in plate tectonics. The following is a preliminary draft of one of his verses in Through the Looking-Glass,

The ocean floor was moving fast
Moving with all its might
It did its very best to reach
The subduction zone that night
And this was odd, because you know
No zone was yet in sight

Ray Lyttleton and Keith Runcorn
Were walking close at hand
They wept like anything to see
Such quantities of sand
Said Ray "Where did it all come from?
I cannot understand"

"The time has come", Keith Runcorn said,
"To talk of plate tectonics
It's simple if you will expand
In spherical harmonics
The motions of the continents
At speeds that are subsonic."

"Expand, expand," Lyttleton cried
"You really are exacting
You cannot build your mountains
Unless the Earth's contracting
You need no sea-floor spreading
The oceans are compacting."

"As Ramsey showed us long ago
But few Earth scientists heeded
The mantle and the core are one
No iron at all is needed
A phase change will just come about
When some pressure's exceeded."

"I weep for you," Keith Runcorn said
"I deeply sympathize
That the power of plate tectonics
You cannot realize
That you cannot see whence comes this sand
Is really no surprize."

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