# EARTH
# *and*
# PLANETARY DYNAMICS

# Crafoord days

## 16 - 18 Sept 2002

Programme – The Crafoord lecture – Abstracts

# Crafoord Symposium

## Earth and Planetary Dynamics

Monday 16 September in Lund, Tuesday 17 September in Stockholm

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| Chairperson: | *David G. Gee, Dept. of Earth Sciences, Uppsala University, Sweden* |
| 09.00 | Opening of the Symposium:<br>*David G. Gee* |
| 09.05-09.45 | Comparing Earth, Mars and Venus<br>*Dan McKenzie, Crafoord Laureate 2002* |
| 10.15-11.00 | Plate Tectonics<br>*Richard Gordon, Dept. of Earth Science, Rice University, USA* |
| 11.15-12.00 | Constraints on Global Mantle Circulation from Seismic Tomography<br>*Stephen Grand, Dept. of Geological Sciences, University of Texas, USA* |
| 12.00-13.00 | Lunch |
| Chairperson:<br>*Sweden* | *Roland Gorbatchev, Dept. of Geology, Lund University, (in Lund), Stefan Claesson, Museum of Natural History, Stockholm, Sweden (in Stockholm).* |
| 13.00-13.45 | The Strength of the Continental Lithosphere<br>*James Jackson, Dept. of Earth Sciences, University of Cambridge, UK* |
| 14.00-14.45 | Glacial Rebound of Scandinavia – Rheological and Glaciological Inferences<br>*Kurt Lambeck, Research School of Earth Sciences, the Australian National University, Australia* |
| 15.00-15.45 | Internal Structure and Thermal Evolution of Mars<br>*Maria T. Zuber, Dept. of Earth, Atmospheric and Planetary Sciences, Massachusets Institute of Technology, USA* |
| 16.00-16.45 | Early Earth, Moon and Mars, and Isotopes<br>*Alex N. Halliday, Dept. of Earth Sciences, ETH Zentrum, Zurich, Switzerland* |

# CRAFOORD LAUREATE 2002

## *Dan McKenzie*

**DAN MCKENZIE** was born in 1942 in Cheltenham, England. He obtained his undergraduate and graduate education in Cambridge, UK. He was elected Fellow of Kings College Cambridge in 1965 and obtained his Ph.D. a year later. He was elected Fellow of the Royal Society (UK) in 1976 and Professor of Earth Sciences in Cambridge in 1985. In 1996, he was promoted to Royal Society Professor of Earth Sciences in Cambridge. McKenzie has worked extensively outside the UK for short periods, mainly in the USA. He has been awarded several of the world's most prestigious prizes and is acclaimed by many as the most influential geoscientist of the last half-century.

# THE CRAFOORD LECTURE 2002

# The Dynamic Earth

Dan McKenzie

**Your Majesties, President of the Academy, Dr Margareta Nilsson and other members of the Crafoord family, members of the Academy, ladies and gentlemen, it is a great honour to have been given the Crafoord Prize this year by the Royal Swedish Academy of Sciences. I will try to explain how I ended up doing the research that I have done.**

When I was an undergraduate most geological lecturers believed that the continents were not moving, though many would mention that some people speculated that they drift. The situation has now changed completely, and no Earth Scientist is taken seriously if they insist that the continents are not moving. My research career started in 1963, when most Earth Scientists still belived that they were stationary. I was one of a number of people whose research changed peoples' minds about continental drift. Jason Morgan and I discovered the modern version of the theory, Plate Tectonics, in 1967. My research since then has been concerned with understanding many other geological and geochemical phenomena that are directly affected by such motions. Yet, despite our best efforts since the 1960s, I am sure that there are more major discoveries to be made, because a dynamic Earth is much more complicated and interesting than the static Earth of my undergraduate days.

## My early education

My story really starts in my last year at school, in 1960. I had been given a place at Kings College, Cambridge to take a degree in Natural Sciences. This title goes back a long way, and includes subjects like Physics, Chemistry, Geology, Metallurgy, as well as the Biological Sciences. Kings College gave me this place after I was interviewed by a well-known classicist, with whom I found I shared an interest in wild orchids and in Dostoevsky's novels. Largely I suspect for these reasons he gave me a place to do Physics! At the time I had not taken any of the National Exams, and so had essentially no qualifications. In the summer before I started at Cambridge I discovered that I had to take three science subjects. So I had to learn a new subject, and could not simply continue to learn Mathematics, Physics and Chemistry, as I had in my last two years at school. Because of the timetable, I could choose between Geology and Physiology. I knew nothing about either, so I borrowed all the books I could find on both from the school library. I found the standard Physiology textbooks terribly dull: they were written for medical students and were crammed with facts. I was much more fortunate with Geology books, largely I suspect because no-one taught Geology at my school. There were only two: Lyell's Principles of Geology and Geikie's Ancient Volcanoes of Great Britain, both written in the Nineteenth Century. Lyell's book especially is marvellous. It is full of careful interpretations of simple observations, made without any complicated equipment. He is particularly concerned with how the large scale features of the landscape form. Much later I discovered that Lyell's book had had the same impact on Charles Darwin when he read it during the voyage of the Beagle. So my mind was made up. Lyell's marvellous book made me into a geologist, as it had done to so many people before me.

I started as an undergraduate in October 1960, and was very disappointed by the Geology course, which required me to remember a great many facts, like the names of the type fossils by which zones were identified and the names of the zones themselves. I found I could do this easily, but found it boring. So I gave up Geology after a year to become a physicist, but fortunately not before I had seen a completely different side of the subject which I found quite different and much more interesting, which was geological fieldwork. I went to Arran Island in Scotland with a large party of first year undergraduates, and so enjoyed my experience that I volunteered to be a field assistant of a graduate student who was working in Spitsbergen. This student is now Professor Gee, who I am delighted is here today.

In 1960 many of the great Cambridge physicists were still giving lectures. I went to listen to Dirac lecture on his relativistic equation, and Hoyle on stellar structure and elemental synthesis. But I found the more recent work much less interesting. I came to know Drummond Matthews, who was always known as Drum, and Maurice Hill, both of whom were marine geophysicists at Kings, and slowly realised that Geophysics combined what I most liked about both Physics and Geology. So I applied to be a graduate student in Geophysics. Drum and Maurice were both clear that Sir Edward Bullard, who everyone called Teddy, should be my supervisor. I have ended up where I am now because of the interest these three people took in my education, and I will always be grateful to them for doing so (Fig. 1).

**Fig. 1** *On board Discovery II in 1956. Maurice Hill is in the middle of the back row, and Teddy Bullard is at the right in the front row. On this cruise Teddy discovered the high heat flow associated with the Mid-Atlantic Ridge, which ten years later I showed was due to plate creation.*

The next three years I spent learning what we did and did not understand about the interior of the Earth. In the USA there are graduate lecture courses, which transmit the prejudices of the professor to his or her students. There have never been any graduate courses in Geophysics at Cambridge: instead you learn the subject by reading the books and journals and talking to people who know more than you do. This approach has the important advantage that you have to think things out for yourself, and of giving you the confidence to do the same again in a different field if necessary. But inevitably you end up knowing nothing about some areas of the subject, which can sometimes be acutely embarrassing. The first problem I worked on at Teddy's suggestion was the equation of state of the lower mantle. I made some progress: enough to get a Research Fellowship at Kings College, for which I had applied at Maurice's suggestion, and to persuade Don Anderson at the Seismological Laboratory of the California Institute of Technology (Caltech), who was one of my referees, to offer me a post-doc fellowship there also. But I could not understand how to model the atomic interactions in minerals like olivine properly. Unless one could do so, the whole enterprise seemed to me no better than empirical curve fitting. So I gave up this field and instead tried to understand the origin of the Earth's long wavelength gravity anomalies. Such features cannot be supported elastically, and must be the result of some other process. I thought then (and still do) that they can only be maintained by convective circulation, and wrote a Ph.D. thesis on the fluid dynamical processes involved and on the creep behaviour of materials at temperatures close to their melting points. I made enough progress to earn a Ph.D., but now realise that this problem was too hard for a graduate student. I have continued to work on different aspects of this problem throughout my career, but expect it to remain an active area of research long after I am gone.

One aspect of Geophysics in the early 1960s that is hard for modern graduate students to believe is that it was possible to read most of the important papers that had been published in the entire subject during the three years it took to obtain a Ph.D. Another consequence of the limited number of people working in the field was that most of the well-known geophysicists came to Cambridge to visit Teddy, Maurice and Drum. Some came for long periods on sabbatical, others passed through and gave seminars. So I came to know most of the American geophysicists in this way while I was still a graduate student. Freeman Gilbert invited me to Scripps Institution of Oceanography for six months, where Teddy spent his summers. I met Walter Munk there for the first time, whose work on tides and on the propagation of gravity waves influenced me greatly. His work showed how simple physical models could be used to understand complicated geophysical problems. By the time I wrote my Ph.D. in September 1966, on the shape of the Earth, I had an extensive knowledge of Geophysics, and a reasonable background in Fluid Mechanics and Geology, but had not done anything new that was of any importance. Everything changed in the following year.

## Plate Tectonics

Whether or not continents drifted had been the major controversy in Geology since Wegener's time, and slowly came to dominate research in Geophysics, and especially in Marine Geophysics, during the 1950s and 1960s. This story has now been told many times. Of the scientists at Cambridge, Maurice Hill was the least sympathetic to the idea that continents drift. At the time the continents were believed to plough their way across the ocean floor, like ships at sea. But Maurice argued that there was no evidence of massive deformation in front of or behind them. We now know that continents move as part of larger plates that contain both continents and their surrounding oceans, and that new plate is produced on oceanic ridges and destroyed in trenches. So Maurice's concerns were entirely correct. Drum Matthews and Fred Vine published an explanation of the oceanic magnetic anomalies in 1963, but they themselves were not convinced that their proposal was correct. But everything changed in the summer of 1966, when Fred Vine, who was by then at Princeton, and Lynn Sykes at Lamont Geological Observatory of Columbia University, used magnetic anomalies and earthquake mechanisms to show that new sea floor was created along mid-ocean ridges. I attended one of the earliest meetings at which these results were presented, in New York in early November, and was completely overwhelmed. I immediately started to work on sea floor spreading, as a post-doc at Caltech, where I went in January 1967 with Don Anderson's support. The first problem I tried was a thermal model for plate creation on oceanic ridges, which allowed both the shape of the ridges themselves and the variation of heat flow through the sea floor to be calculated analytically. This model has formed the basis of most later studies of this problem. The second paper I wrote with Bob Parker on sea floor spreading is probably still the best known of all my papers. Teddy had used a theorem of Euler's to fit together the continents round the Atlantic. Euler proved that any motion of a spherical cap on a sphere could be described by a rotation about an axis through the centre of the sphere. Teddy used this theorem as a convenient method of fitting the edges of continents together (Fig 2), but Bob and I realised that we could also use it to describe plate motions, and hence continental drift and sea floor spreading. Though we did not know it at the time, Jason Morgan had had exactly the same idea some months before us.

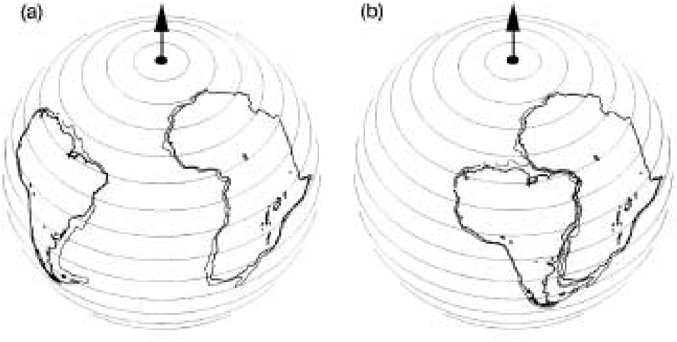

**Fig. 2** *The fit between Africa and South America obtained by Teddy Bullard and his colleagues using Euler's Theorem. The theorem states that any motion of a rigid plate on the surface of a rigid sphere corresponds to a rotation of the plate about some axis that passes through the center of the sphere. The problem on the Earth is that every point on its surface is on a moving plate, and no rigid sphere exists. So one plate must be chosen and taken to be fixed. Then the motion of any other plate with respect to this fixed plate corresponds to a rotation about an axis. In this figure Africa has been taken to be fixed, so South America moves. (a) shows the location of this axis, marked with an arrow, that Teddy and his colleagues found for the motion between Africa and South America. The circles are lines of latitude about this axis, just like the usual lines of latitude about the Earth's rotational axis. (b) shows the original position of the two continents before the South Atlantic opened, obtained by fitting the edges of the continents together. These edges are under the sea, and are not the present coast lines. As the continents move, every point on the South American plate moves in a direction that is parallel to the latitude lines. This behaviour is easily seen by comparing the positions of the latitude lines in the two pictures before and after opening. Their position on South America does not change.*

These two papers made me well known, even though I was only 25. In the same way as the physicists who discovered Quantum Mechanics in the 1920s must have known, I knew that the new ideas were correct and that they would allow many phenomena to be understood that had been well known to geologists for many years. I had no permanent job and was not married, and so could work very hard and quickly. In the next three years I published 15 papers on Plate Tectonics, one of which was 91 pages long and described most of the geological history of the Indian Ocean. During this time I lived for six months of each year in Cambridge and six months in California, either at Caltech or Scripps. Much of the work I did during this period has become part of our general understanding of how the Earth works, and is now included in undergraduate courses in Geology. Few people now know or care who made what discovery. In its final form, which Jason Morgan and I proposed in 1967, Plate

Tectonics is one of the easiest parts of Geology to understand, and in the U.K. is taught to school children. Few recent discoveries in the physical sciences have become so widely understood so quickly. There are a number of reasons why this happened. One is that Plate Tectonics is a kinematic theory: it simply describes the observed motions of the plates at the Earth's surface and is not concerned with the forces that maintain them. Kinematic models are much easier to understand than dynamical ones. Another is that the final form of the theory has not required any changes in the thirty years. Satellite techniques now allow the relative velocities between plates to be measured directly, and have shown that the geological estimates of the velocities are generally accurate to 5%.

The work I did in this period was immediately recognised, and I was quickly elected to the Royal Society and given international prizes. It is extremely gratifying to be acknowledged by one's colleagues, especially so early in one's career. But I became increasingly concerned about the research I was doing. I realised that the very success of Plate Tectonics meant that it would soon cease to be an interesting area in which to do research. This process happened even faster than I expected. Two obvious areas of research that Plate Tectonics had opened up were the origin of the forces that maintained the motions and the question of whether Plate Tectonics could also describe continental deformation, and, if not, what new ideas were required? I worked very hard on both problems, but at first had little success. One difficulty was that I was spoilt. I had come into the subject at exactly the right time, and had discovered something important and simple four years after I started as a graduate student. I now know enough about the history of the Earth Sciences to realize that such events are rare, but at the time I expected my rapid progress would continue. Another problem was that I had to learn what were, for me, new areas of Physics and Geophysics. As always is the case in new applications, it was not at first obvious what the relevant areas were that I needed to learn.

## Continental deformation and basin formation

The problem of continental deformation is illustrated in Fig. 3, which shows the earthquake locations from the Mid Atlantic Ridge to Afghanistan. In the Atlantic the earthquake deformation occurs on a narrow plate boundary between the Eurasian and North American plates, but in the Mediterranean and Middle East the deforming belt

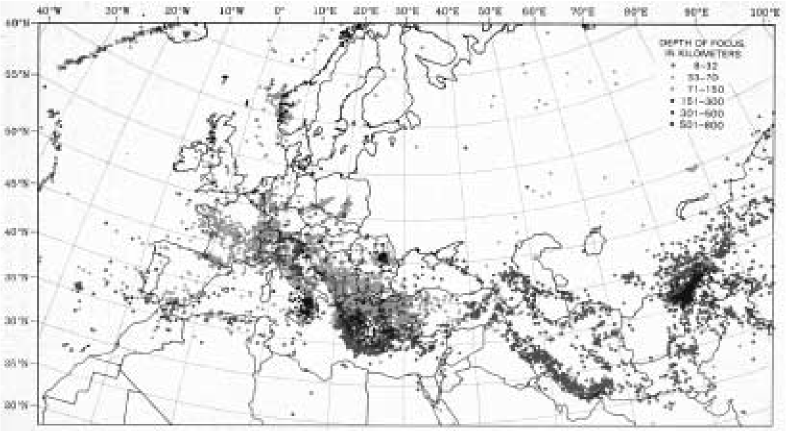

**Fig. 3** *The locations of earthquakes from the eastern Atlantic to Afghanistan. In oceanic regions the earthquakes are confined to narrow belts which form the plate boundaries, but they are spread over bands as wide as 1000 km where the deforming zones cross continents.*

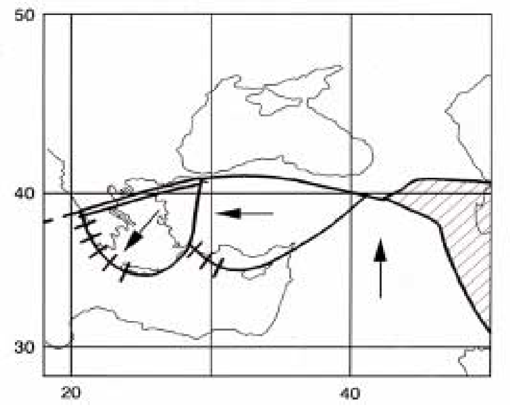

**Fig. 4** *The locations and mechanisms of the earthquakes in the eastern part of the Mediterranean require the presence of two small rapidly moving plates, one consisting of much of Turkey and the other of the Aegean Sea and Greece.*

is in places more than 1,000 km wide. The most obvious and easiest way to study deformation is to determine the mechanisms of earthquakes, and I asked Peter Molnar at Lamont to show me how to do this. It took about a day to do each one, and I studied every earthquake I could use in the eastern Atlantic, Mediterranean and Middle East. I started in 1967, and spent a week or two on this project every year for the next ten years. At first I could make no sense of the data. The problem was that the plate motions in the Atlantic required Africa to be moving northward towards Europe, but the largest and most active fault in the whole area was in Turkey. It had broken in many earthquakes, which had slid Anatolia westwards relative to the Black Sea and Europe. This direction was at right angles to the motion of Africa. The only explanation I could think of was that there were two small plates, (Fig. 4) one containing most of Turkey and the other most of the Aegean and Greece, that were moving rapidly westward relative to Eurasia.

Satellite measurements (Fig. 5) have now beautifully confirmed my suggestion. Such small rapidly moving plates are common in regions where continents are colliding. Their presence is one reason why geologists who studied continental deformation did

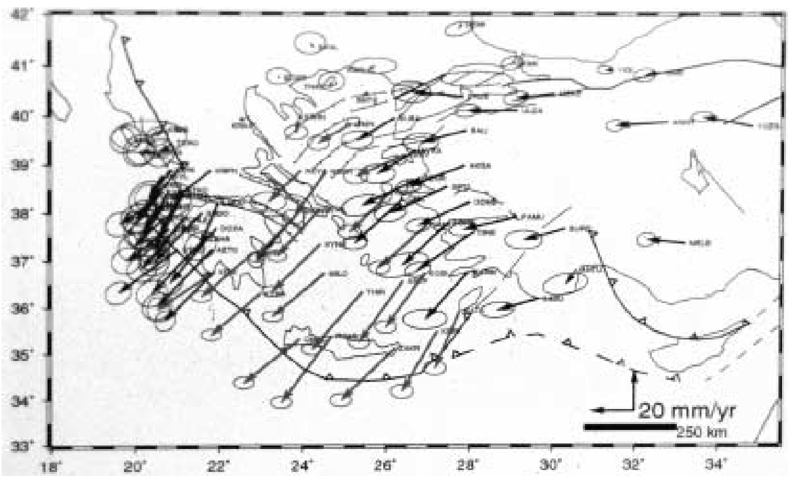

**Fig. 5** *Velocities with respect to Eurasia, measured using satellite geodesy, which confirm the presence of the plates shown in Fig 4.*

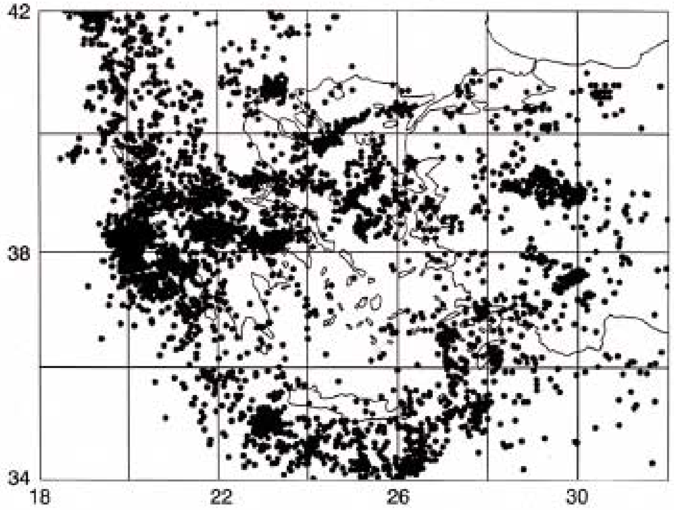

**Fig. 6** *Earthquake locations in the Aegean and surrounding regions, showing how widespread is the present deformation of this region.*

not discover plate tectonics. But there were clearly further complications. The earthquakes in Fig. 6 in western Turkey, the Aegean and Greece do not lie on narrow boundaries defining the edges of the Turkish and Aegean Plates. The interiors of the plates show up because they lack earthquakes, but their fuzzy edges are often a hundred kilometres wide. This fuzziness is real, and is not due to errors in the earthquake locations. Clearly such regions cannot be described by the motions of rigid plate with sharp boundaries. It took me nearly ten years to understand how to model such deformation, even though the answer was (in retrospect!) obvious. In regions like the Aegean, plate boundaries cannot be modelled using a single fault with the plates on either side moving with different velocities. The next simplest model is to allow the change in velocity to be uniformly distributed over a zone. Where plates are moving away from each other, such a zone will be stretched. What then happens is shown in Fig. 7. The cold part of the Earth near the surface, which is called the lithosphere, is stretched and thinned, as is the crust. This stretching is taken up by large faults (Fig. 8) and causes the surface of the Earth to subside. This is how the Aegean Sea has been produced. By the time the stretching stops, the lithosphere has been thinned, and slowly returns to its original thickness as the hot mantle below cools. Because of thermal contraction, this cooling produces further subsidence, but without any deformation. This sequence of events had already been seen in many sedimentary basins, but what had so puzzled everyone was how such basins were able to accumulate thicknesses of sediment as great as five kilometres, all of which had been deposited in shallow water. The stretching model in Fig. 7 provides an obvious explanation for this observation, provided enough sediment is being deposited to fill the basin as it subsides. Fig. 9 shows a profile across part of the North Sea, a typical sedimentary basin. The tilted blocks were formed during the extensional phase and are bounded by faults like that in Fig. 8. They are overlain by flat sediments deposited as the lithosphere cooled and contracted.

Once we understood the process it was easy to test whether the model was correct, simply by comparing the thickness of the crust beneath a sedimentary basin with the amount of subsidence. Drum Matthews carried out this test in the North Sea, using

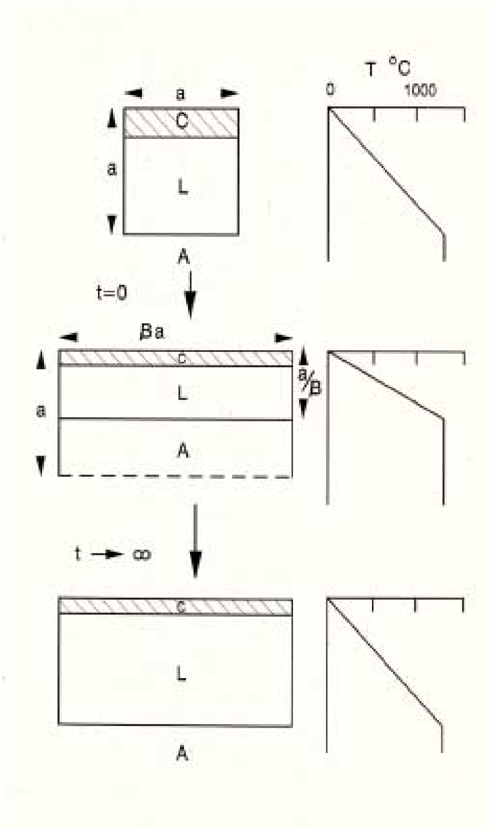

**Fig. 7** *A sketch to show how sedimentary basins are produced by stretching the lithosphere. The lithosphere in the top panel is stretched by a factor* β, *to produce the thinned lithosphere in the second panel. Such stretching thins the crust, marked C, and increases the temperature gradient. The upper surface of the crust subsides as the stretching occurs. When the stretching ceases, the lithosphere thickens by cooling the region below, marked A (bottom panel). Further subsidence then occurs due to thermal contraction.*

**Fig. 8** *One of the large faults in eastern Greece produced by extension. I am the figure showing the scale.*

sound echoes from the base of the crust to measure its thickness. Clear echoes require a large explosions, and Fig. 10 shows a picture of Drum and his graduate student Phil Christie waiting to explode one ton of dynamite in the North Sea. This experiment beautifully confirmed the theory. It was immediately accepted and exploited by oil companies, who were interested in these ideas because much of the oil in basins like the North Sea is trapped in the shallowest parts of the tilted blocks. Their involvement

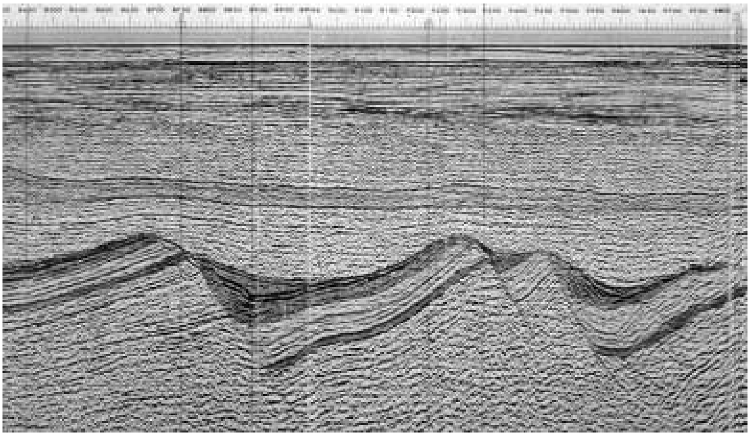

**Fig. 9** *Tilted fault blocks covered by flat lying sediment in the North Sea, produced by the two phases of subsidence shown in Fig. 7.*

brought me into close contact with their geologists, for whom I have developed a profound respect. I was greatly encouraged by the success of this idea, and the resulting paper is the most cited of all those I have written. Its success convinced me that I was not going to be one of those scientists who only had one good idea. I was also encouraged that I myself had collected the basic data, by determining the mechanics of earthquakes. The other obvious continental problem was distributed shortening, and I attempted to work on this problem in the field in Iran. But Iran was a difficult place to work, and became impossible after the Iranian Revolution, so I and my students did not make much progress. It is clear that we now have the technology to attack this problem, using satellite photographs and earthquake mechanisms, and that Iran is an ideal place to study continental shortening. But we still know little about this process, and about the metamorphism that accompanies such contraction.

## Mantle convection

The other project I started in the early 1970s was a study of the mechanisms that maintain the plate motions. Some of the suggestions that were being proposed involved changes to basic physical theories. Scientifically I am very conservative, and it

**Fig. 10** *Phil Christie (left) and Drum Matthews on board a ship in the North Sea, waiting to explode a ton of dynamite. Their experiment was designed to test the model in Fig. 7 by measuring the crustal thickness.*

seemed to me likely that geophysical observations of low energy processes could be explained by our existing knowledge of physics. The obvious method of maintaining the plate motions was some form of thermal convection, because the plate motions themselves transport heat from the deep interior of the Earth to its surface. But I knew little about thermal convection and nothing about the numerical methods required to solve the relevant equations, which required access to the largest available computers. I did, however, have a friend in Applied Mathematics, Nigel Weiss, who is an astrophysicist. One of Nigel's principal interests has been the solution of the equations governing convection, and we decided to work together on mantle convection. From him I learnt how to carry out such calculations, and together we made some progress. It quickly became clear that the convective forces were sufficiently large to maintain the observed motions, and that no novel physics was required. But we were not able to generate convective velocity fields that looked anything like the plate motions.

## Planetary tectonics and convection

As our understanding of the dynamics of the Earth improved during the 1970s and 1980s, I started to wonder whether other planets behaved in the same way. Venus was the most likely to do so, because it is so similar in mass and size to the Earth. But Venus is always covered by clouds, and so the solid surface cannot be photographed. For this reason it remained the most poorly known of the rocky planets. In about 1980 NASA put forward a proposal to map Venus using radar, and I applied to be one of the investigators. My proposal was accepted, and over the next ten years I discovered how frustrating planetary exploration can be compared with terrestrial fieldwork. The spacecraft, called Magellan, finally went into orbit round Venus in 1990. It produced beautiful images of the surface, which showed almost no structures that could have been produced by Plate Tectonics. Their absence was a major surprise, and showed how little we really understand about why the tectonics of the Earth, and especially that of the oceans, could be described so well by the relative motion of a few rigid spherical caps. An important difference between the two planets is that the Earth contains large amounts of water whereas Venus is dry. The presence of small quantities of water in mantle minerals weakens them, and we suspect that such weakening allows faults to slip and generate earthquakes. But we still don't understand this process properly.

Most of what we know about the Earth's interior comes from studies of seismic wave propagation. At present we have some very limited seismic data from the Moon, but not from any of the other rocky planets. We can expect that major advances in our understanding of these bodies will occur when we can obtain good seismic data from these planets and satellites.

## Geochemistry and melting

Before the implications of Plate Tectonics had been properly explored, features like mid-oceanic ridges were believed to be the surface expression of upwelling convection currents in the mantle below the plates. As the consequences of the simple kinematic theory were understood, it became clear that almost all surface features resulted from plate motions, and contained no information about the deeper convective circulation. So as time went on we had fewer and fewer observations with which to constrain the geometry and velocity of mantle circulation, and the few observations that could be used for this purpose became more important. One of the hardest of these to exploit was a discovery by Paul Gast at Lamont, that the isotopic ratios of $^{87}$Sr/$^{86}$Sr and of the lead isotopes in basalts from oceanic islands such as Iceland and Hawaii are different

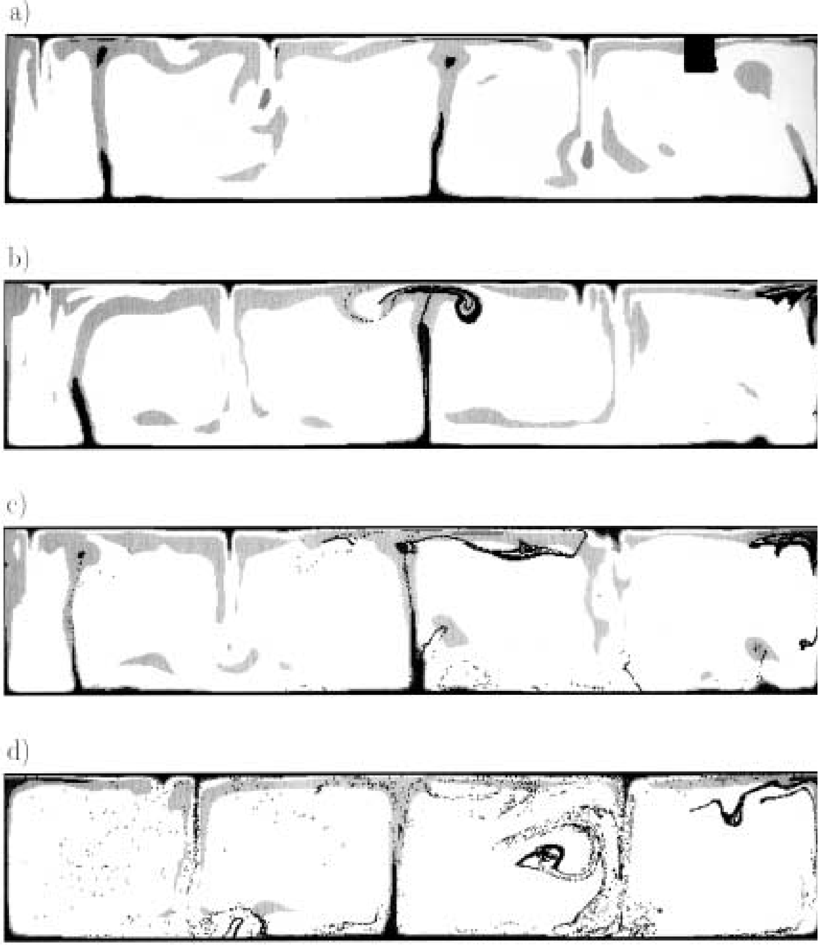

**Fig. 11** *(a) shows vigorous time-dependent convection in which a square region has been marked by inserting particles. (b), (c) and (d) show the locations of particles at times of 261 Ma, 545 Ma and 1573 Ma respectively after the particles were inserted.*

from those of mid-oceanic ridges. $^{87}$Sr is produced by the slow decay $^{87}$Rb, and the lead isotopes by the decay of uranium and thorium. These differences were unexpected, because basalts are produced by melting the convecting upper mantle below the plates. They require the sources of the basalts to have remained separate for about 1,000 million years, or about 1/4 of the age of the Earth. It is not easy to understand how this can occur in a vigourously convecting mantle. Fig. 11 shows what happens when a large number of particles are introduced into a small part of a convecting layer. The circulation spreads them out into thin sheets which occupy the whole layer, and we believe that such spreading occurs too quickly to allow the observed isotopic anomalies to be produced. The isotopic anomalies therefore provide an important constraint on the nature of mantle circulation. But it is not easy to discover what this constraint is, partly because the measurements are made on basalt, and not on the mantle material from which the basalt is generated by melting, and partly because the fluid dynamics of convective stirring is not yet well understood.

When I first became interested in this problem, I expected to find an extensive discussion of mantle melting in the standard petrological textbooks. I was surprised and disappointed to find that almost nothing had been written about this problem. From a fluid dynamical point of view the problem is difficult, because a partially molten rock behaves as two fluids, the residue and the melt, whose viscosities are very different. I was pleased to find that I could derive the general equations that described the behaviour of this material, and even more so when various mathematicians obtained analytical solutions to the governing equations. From a petrological point of view two results were of particular importance. The first was that mantle upwelling beneath most spreading ridges is sufficiently fast that heat loss by thermal conduction can be ignored. The amount of melt generated is then easily calculated (Fig. 12). The second was that melt fractions as small as 0.03% could separate from their solid residues. The first result is especially important, because it has allowed the volume and composition of melt from spreading ridges and from plumes to be estimated. Such calculations now allow petrological and geochemical observations to be used to constrain mantle temperatures and flow rates. We are also finally starting to understand the significance of the isotopic anomalies in oceanic islands that Paul Gast discovered.

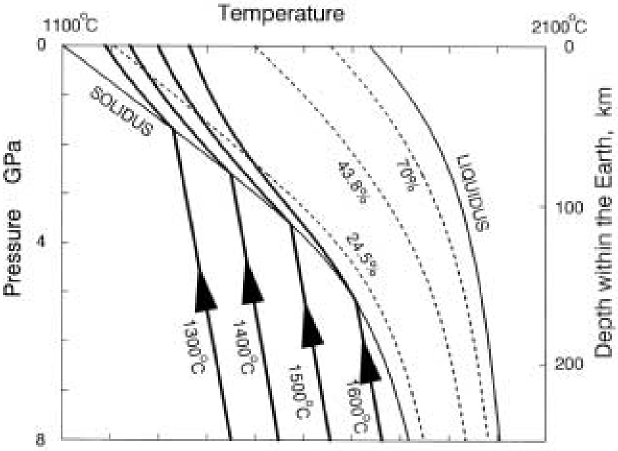

**Fig. 12** *Sketch to show how melt is generated beneath spreading ridges. When the upwelling solid material meets the solidus it starts to melt, and its temperature decreases because of the heat required to do so. The dashed lines show different melt fractions. The higher the initial temperature, the greater the amount of melt generated.*

I have now been an active research scientist for more than 35 years, and my interests have taken me into most parts of the Earth Sciences. I have published papers with more than 120 co-authors, and I have greatly enjoyed working with so many excellent scientists in different fields. I have found that the best people are the easiest to work with and to understand. They may be prickly, but they are enthusiastic about what they do, and want to transfer this enthusiasm to me. What I have brought to these collaborations is an understanding of Mathematics and Physics, and an ability to construct simple physical models of the processes involved. I am sad that this approach is becoming less popular, because I believe it has been and remains the key to understanding the world in which we live.

# INTRODUCTION TO CRAFOORD SYMPOSIUM

## Plate Tectonics – the fundamental Earth Science paradigm

David G. Gee, Department of Earth Sciences, Uppsala University, Sweden

The Geosciences contribute in three important ways to our understanding of Man's place in Nature. The first is the concept of the VASTNESS of TIME – the great age of the Earth, as originally conceived by James Hutton, two hundred years ago. The second is EVOLUTION – the origin and ancestory of Man, as presented by Charles Darwin, half a century later. The third is PLATE TECTONICS – the fundamental unifying paradigm for understanding the history of Earth.

Plate Tectonics concerns the cold uppermost layer of the Earth, composed of both crust and upper mantle. This layer is called the lithosphere; it contains our mineral resources and provides the surface environment on which the biosphere can thrive. Plate tectonics explains the distribution and movement of continents and oceans, the growth and destruction of mountain belts; it controls the Human environment, from the rocks beneath our feet, to the clouds above our heads. The name of Dan McKenzie is intimately tied to the development of this paradigm.

Two important kinds of evidence were essential for the birth of Plate Tectonics. The first concerned an appreciation that continental and oceanic crust have fundamentally different compositions; the second – that continents drift.

Evidence for continental drift was presented by Taylor and Wegener early in the last century (1910–1915) and was for a long time met with general scepticism. It was not until the 1950's that studies of palaeomagnetism provided independent evidence for the movement of the continents. Thereafter, with the mapping of the bathymetry of the oceans and studies of the composition and magnetic properties of oceanic crust, the scene was set for Plate Tectonics to take over.

At a very early stage in his career, in the mid-1960's, McKenzie wrote key papers about the shape of plates and the kinematics of their movement, providing a robust framework for understanding Plate Tectonics. He was not alone in this part of the Earth Science revolution, but his papers were seminal for the establishment of the paradigm. He described what every school-child now knows, that the Earth's surface is composed of half a dozen vast regions (and several smaller ones) – the lithospheric plates. Within these plates there is little deformation; by contrast, the extensional and compressional boundary zones between the plates are the scenes of the real action, with major earthquakes, volcanic eruptions, large displacements and mountain building.

Plate motion is maintained by convection created by the Earth's heat engine. McKenzie's early numerical modelling contributed to the modern foundation for interpretations of the dynamics of this mantle convection. Hot, new oceanic lithosphere is generated at extensional plate boundaries, which are generally manifest as mid-ocean ridges. This young crust stands high in the oceans; as it moves laterally and cools, it subsides to several kilometres depth and eventually collapses, subducting back into the deep mantle.

During the 1970's, McKenzie focused much of his attention on plate boundary deformation, particularly the mountain zones created by the collision of continental crust. His work on earthquake source mechanisms permitted analysis of processes going on deep in the crust in zones of active faulting. His tectonic interpretations of such areas as the Eastern Mediterranean have been of importance for hazard risk assessment in these regions of high population density.

Another aspect of McKenzie's research that has had a great influence on our society resulted in an apparently simple paper written in 1978 "Some remarks on the development of sedimentary basins". It grew out of his interest for extensional deformation within plates and provided a model that has been applied world-wide, with profound economic consequences for the hydrocarbon industry. As basins subside and fill with sediments, hydrocarbons are generated and fluids flow, laterally and vertically.

McKenzie's versatility as a geoscientist allowed him to make a remarkable change in focus in the early 1980's. He recognised that the geochemistry of mantle-derived volcanic rocks provides basic information about Earth's convection system. He focused on the quantitative geochemistry of magma melt generation and delved into the fluid dynamics of two-phase flow. His work resulted in papers which have revolutionised our concepts of how melts form, segregate and flow in the mantle and break through to the Earth's surface. This work led to an integration of geophysics and igneous petrology.

Interest in global tectonics, mantle convection and mantle melting on Earth led McKenzie to a closer analysis of the neighbouring planets Mars and Venus. From NASA's Magellan Mission to Venus, he obtained geological and geophysical data that stimulated comparisons with Earth and have led to important inferences about mantle viscosities and compositions.

Interdisciplinary innovation, integrating classical geological observations with geophysics and geochemistry, has characterised McKenzie's career. By bridging the gap between surface tectonics, with its societal impact, and the deeper driving mechanisms, he has established a brilliant, unique position within the world's Earth Science community.

# Comparing Earth, Mars and Venus

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Almost all that we know about the interior of the Earth has come from studies of the propagation of seismic waves, generated by earthquakes and by various types of explosions.As yet we have no useful records of seismic waves from Mars or Venus, so we cannot use seismology to explore their interiors. Such frustrations are common in planetary geology. But the gravity fields and shapes of all three planets are now well known. The shape of Venus was measured with a radar altimeter on the Magellan spacecraft, and that of Mars by a laser altimeter on Mars Global Surveyor. The gravity fields of both planets have been accurately determined from the orbit of these two spacecraft.

It is surprising how much information can be extracted about the interior state of a planet from its shape and its gravity field. The shortest wavelengths that can be used for such studies is governed by the height of the spacecraft above the planetary surface, and is 200–300 km. At shorter wavelengths the gravity variations at the height of the spacecraft are too small to have a detectable effect on its orbit. The relationship between the gravity field and topography at short wavelengths is controlled by the thickness of the elastic layer that supports the topography. In the Earth's ocean basins the thickness of this layer is controlled by the temperature gradient, and varies from less than 5 km on spreading ridges to more than 30 km in old ocean basins. The base of the elastic layer has a temperature of 400–600 ºC. Similar variations occur on continents, though the temperature gradient is less well known. On Venus, however, an elastic thickness of 25–30 km agrees with all the observations, and there is no evidence for regional variations like those found on Earth. The surface temperature of Venus is about 430 ºC, so venusian rocks must be able to support elastic stresses at higher temperatures than can those on Earth. We believe that this difference is caused by the lack of water on Venus. The thickness of the elastic layer on Mars has changed with time. It was about 15 km when the craters of the southern hemisphere formed about 3 Ga ago, and is now about 70 km. This increase occurred as the radioactive heating decayed and the planet cooled.

The gravity and topography at wavelengths that are too long to be supported by the elastic layer are maintained by variations in crustal thickness and by convection in the solid mantle. The two effects are easily separated because the crustal thickness variations are compensated, and so produce topography that is not associated with gravity anomalies. In contrast, only convection can maintain long wavelength gravity anomalies, which can therefore be used to map the planform of the convection. The convective anomalies on Venus are much larger than those on Earth, probably because the mantle viscosity is higher due to the absence of water. Because the elastic layer on Mars is now 70 km thick and the planet is small, even the longest wavelength anomalies are affected by the elastic layer, and it is difficult to isolate the convective signal.

On both Venus and Earth there is evidence that the long wavelength topography has changed with time. Changes in convective planform with time are to be expected on both planets because the convection is so vigorous.

# Plate Tectonics

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One way in which the plate tectonic approximation has been modified from its original assumptions has been the recognition and incorporation of diffuse (or wide) plate boundaries (hundreds to thousands of km wide) in addition to the traditional narrow plate boundaries (0.5 km to a few km wide). Diffuse plate boundaries cover ≈15% of Earth's surface. Some traditionally defined plates contain 2 or 3 plates that are in measurable relative motion and are separated from one another by diffuse plate boundaries. We refer to these plates-within-a-plate as "component plates" and we refer to the plate that contains them as a "composite plate", which also contains one or more diffuse plate boundaries and is delimited by traditional narrow plate boundaries. For example, the Indian, Capricorn, and Australian plates, each of which is rigid or nearly rigid, are component plates. In contrast, the Indo-Australian plate is a composite plate comprising these three component plates and multiple diffuse plate boundaries.

The displacement rates across diffuse oceanic plate boundaries (up to ≈15 mm $yr^{-1}$ ) tend to be lower than across narrow plate boundaries (≈12 to ≈160 mm $yr^{-1}$). Strain rates are distinctively different in (i) plate interiors ($10^{-20}$ $s^{-1}$ to $10^{-17}s^{-1}$), (ii) diffuse plate boundaries (up to ≈$10^{-16}$ $s^{-1}$ in the oceans and ≈$10^{-15}$ $s^{-1}$ in the continents), and (iii) narrow plate boundaries (≈$10^{-13}$ $s^{-1}$ to ≈$10^{-11}$ $s^{-1}$). The effective viscosity of the lithosphere in each of these 3 states is also distinctively different: (i) stable plate interiors (≈$10^{25}$ to $10^{27}$ Pa s), (ii) diffuse plate boundaries ($10^{23}$ to $10^{24}$ Pa s in the oceans and ≈$10^{22}$ Pa s in the continents), and (iii) narrow plate boundaries (≈$10^{17}$ to $10^{19}$ Pa s, about the same as that of the asthenosphere). The vertically averaged rheology over geologic time of diffuse plate boundaries can be approximated as a power-law fluid. Deforming oceanic lithosphere typically has a higher power-law exponent (≈6 to ≈20 ) than does deforming continental lithosphere (≈3).

The pole of relative rotation between the two component plates on either side of a diffuse oceanic plate boundary tends to lie in the middle of the plate boundary, unlike the pole of rotation between adjacent plates separated by a narrow plate boundary, which tends to lie a considerable distance from the plate boundary. This difference in behavior is a consequence of the strong mechanical coupling across a diffuse plate boundary in comparison with the (presumably much weaker) coupling across a narrow plate boundary. Simple physical arguments show that any nonzero component of torque about an axis through the middle of a diffuse oceanic plate boundary cannot be balanced unless the pole of rotation lies in the boundary.

# Constraints on Global Mantle Circulation from Seismic Tomography

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The kinematics of the mobile surface of the Earth is well explained by the theory of plate tectonics. Although it is accepted that convection in the Earth's mantle is the dynamic process that results in plate tectonics, it is still unclear what form convection takes in the mantle. Related to this, there is still uncertainty as to whether there are distinct layers within the mantle (chemical and otherwise) and how the mantle has evolved over time. Seismic tomography, the mapping of the three dimensional variations in compressional (P) and shear (S) wave speeds through the mantle, provides the only high resolution information available on the structure of the interior of the Earth. Recent three dimensional images of variations in P and S wave speeds have provided our first views of convection within the mantle.

Earthquakes produce both P and S waves as well as surface waves that are commonly recorded by a global network of seismographs. With first order knowledge of the seismic wavespeeds in the interior of Earth, one is able to determine the path through the Earth that the waves take from their source to receiver. Measurements of the arrival times of the waves allows one to set up an inversion for the three dimensional variation in wavespeeds throughout the interior of the planet. Due to the uneven distribution of earthquakes and seismographs, however, the sampling of the interior of the Earth by direct P and S waves is incomplete. Using computer simulations of elastic wavepropagation through the Earth we are able to identify many waves on seismograms that are reverberations within the mantle. The travel times of these waves allow a more complete coverage of the mantle.

Recent tomographic models of the mantle by different groups have begun to converge in terms of large scale structures within the mantle. A common interpretation of the seismic results is in terms of temperature where faster than average wavespeeds imply colder temperatures and therefore downwelling mantle and slower wavespeeds imply hotter than average mantle. Our present seismic images show a very complicated pattern of cold and hot regions within the mantle that indicate that mantle flow is likely to be quite complicated within the Earth. Distinct changes in the pattern of downwellings are seen near depths of 670 km (the depth of the deepest earthquakes), 1200 km, and 1800 km. Similarly, slow regions show changes in pattern with depth as well. It is likely that the mantle is layered in terms of viscosity, thermal expansion coefficient, or chemical composition resulting in different flow regimes in different depth ranges. Comparing the history of past plate convergence with the seismically imaged cold regions in the deep mantle indicates that deep mantle flow may differ from one region to the next and may be time dependent as well.

# The Strength of the Continental Lithosphere

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We have known for a long time that the continental interiors do not behave like rigid plates when they deform. Earthquakes, faulting and mountains spread out over broad belts, rather than concentrate in the narrow zones that define plate boundaries in the oceans. With information from earthquakes, satellite imagery and space-based geodesy (principally GPS), we now know a lot about the present-day configuration and distribution of active deformation on the continents. But our understanding of continental tectonics is confused by not knowing what really controls these patterns of deformation we see at the surface. For the last two decades, the popular view has been that the continental lithosphere is like a “jelly sandwich”, with a weak lower crust lying between a strong upper crust and a strong uppermost mantle. This view originated from the observation that earthquakes (and, by implication, frictional slip on faults) are generally restricted to the upper part of the continental crust, below which deformation is assumed to happen by creep. Creep strength is known to be very sensitive to homologous temperature (the ratio of actual temperature to melting temperature). We therefore expected that the transition from relatively high-silica, low-melting-temperature rocks in the crust, to relatively low-silica, high-melting-temperature rocks in the mantle would be reflected in a strength contrast at the crust-mantle boundary (the Moho). Indeed, because of its great vertical extent, the creep strength of the mantle lithosphere was often thought to be the greatest contributor to the integrated strength of the continental lithosphere as a whole. A recent re-assessment of earthquake depth distributions and gravity anomalies on the continents makes it difficult to maintain this simple jelly-sandwich view. It now seems that the layer in which earthquakes occur may be the only significant source of strength in the continental lithosphere, and that the upper mantle beneath the continents is relatively weak. This is a major change in our view of the continental lithosphere, with many implications for continental tectonics and mechanics. The reason we were previously misled is likely to be because we failed to appreciate the influence of very small amounts of water on creep strength.

# Glacial Rebound of Scandinavia – Rheological and Glaciological Inferences

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An important physical property that controls the Earth's dynamical and thermal evolution is the viscosity of the planet's mantle. Measurements on terrestrial materials in the laboratory provide insight into the mechanisms controlling viscous deformation but extrapolation of these results to the time and length scales that characterize the Earth is uncertain. Nature provides one of the best examples for examining the viscous structure of the planet as a whole. The past ice sheets loaded the crust and deformed the mantle and the relaxation after the removal of the ice is still seen today. Sea levels change because of the surface displacement under the ice loads and this is seen in the geological record as well as in precise geodetic measurements. The planet's gravity field changes and is reflected in the motions of satellites around the earth and in its rotation. From such observations it is possible to infer the viscosity structure of the planet. Key questions are: (i) what is its depth dependence, (ii) is the viscosity profile spatially variable, (iii) is the viscous response linear or non-linear. The glacial rebound is a global phenomenon because of the changing ocean loads as ice sheets wax and wane. Thus observations from sites far from the former ice margins also contain relevant information and by combining the various observations it becomes possible to answer some of these questions.

Of the last ice sheets, the best know are those over Scandinavia and the British Isles, where the ice margins during the last ice retreat have been mapped with some confidence. Also there exists a large body of field evidence for the rebound history of the crust around and beneath the former ice load. The inversion of the field data for mantle viscosity is limited by uncertainties in ice thickness and the inversion schemes must include parameters that describe unknown aspects of the ice sheets. Much of the current research is directed at improving understanding of the mass distributions within the ice sheets since the last glacial maximum about 20,000 years ago. The results from the inversions establish that depth dependence of the viscosity is significant. Evidence is also accumulating for lateral variability in the upper mantle viscosity. The glaciological results of the inversions provide robust constraints on ice thickness over Scandinavia at the time of the last deglaciation. These models for the rebound and the sea-level change are now sufficiently well-developed to provide high resolution reconstructions of the shoreline evolution for Scandinavia.

# Internal Structure and Thermal Evolution of Mars

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Clues to the evolution of Mars are preserved in the geology and geochemistry of the planet's surface and in the structure of the interior. Today Mars is mostly geologically inactive, characterized by an outer rigid shell that implies a low heat flow from the interior. However, the geology of ancient terrains and recent geophysical observations provide intriguing evidence for an early dynamic interior when heat loss was more intense and the planet may have displayed a weak and easily deformable surface shell. The period of early, intense heat loss correlates to the period of time when Mars displayed a thicker atmosphere than at present, and when liquid water flowed on the surface. Observations from recent orbiters and landers enable the linkage between the internal structure and surface evolution of Mars to be explored.

The bulk density of Mars indicates the presence of an iron core. Tracking of the Viking and Pathfinder landers to measure the slow precession of the planet's spin axis constrain the radius of the core to be about half the radius of the planet. The core state (solid or liquid) is presently unknown and determining it will require either a seismic network on the surface or more precise measurements of the planetary wobble than are currently possible. Observations of intense remnant magnetization of the crust point to the presence of an early, intense magnetic field produced by a dynamo motions inside a cooling liquid iron core. Unlike Earth, the Martian dynamo "shut off" early in the planet's evolution, at about the time the largest ancient impact basins formed. The early demise of the Martian dynamo indicates rapid cooling of the planet's interior.

The massive Tharsis volcanic province represents the surface expression of a large mantle plume. While Tharsis was long believed to have formed over the entirety of Martian geological history, observations now indicate that the bulk of the volcanic material was emplaced during the time that water flowed on the surface. The release of water and carbon dioxide associated with eruption and emplacement of Tharsis lavas are likely linked to the thick atmosphere and significant surface water that characterized the earliest Martian epoch.

Observations of gravity and topography have enabled the first reliable models for the structure of the crust, and the thickness of the lithosphere, or rigid outer shell. Models indicate a mean crustal thickness of 50 kilometers, corresponding to about 5% of the planet's volume. Regional estimates of the thickness of the lithosphere show a correlation with the age of surface or subsurface loading that is consistent with a declining heat flow over time.

# Early Earth, Moon and Mars, and Isotopes

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The terrestrial (inner) planets Mercury, Venus, Earth and Mars are dramatically different from the larger outer planets in being dominantly composed of oxygen, silicon and magnesium (largely combined in the planet's outer silicate portion) and iron (mainly in the metallic iron core). The most widely accepted approach to determining the origins of the terrestrial planets has been dynamic modelling using Monte Carlo simulations to find a distribution of planets similar in size to that observed. These provide evidence that each of the terrestrial planets grew over tens of millions of years, as a result of collisions between many smaller objects. However, these same models do not explain the outer gaseous rich planets nor do they explain planet formation around other stars. Nearly 100 such extra solar planets have been detected. In many systems the terrestrial planet forming region hosts gas-giant planets and these must have formed rapidly because they orbit young stars and are dominated by nebular gas and, or ice. We have no current models that relate the formation of our own solar system to those being discovered elsewhere.

Therefore, other approaches and tests are necessary. The most powerful new methods harness isotopic variations produced by radioactive decay of early solar system nuclides now long extinct. The most effective method has been hafnium-tungsten chronometry. Hafnium and tungsten are both present in small amounts in the Earth, with concentrations of less that one part per million. Yet these apparently insignificant trace elements hold important clues as to how quickly the terrestrial planets formed. There are 6 isotopes of hafnium today but at the start of the solar system there was a tiny amount (<0.01%) of another isotope, $^{182}$Hf. This decays with a half-life of 9 million years to a common isotope of tungsten, $^{182}$W. Because the Earth is over 4.5 billion ($10^9$) years old all of the $^{182}$Hf is now extinct - converted to $^{182}$W in the first 50 million years of solar system history. By comparing W isotopic compositions of inner solar system metals and rocks that had different proportions of hafnium to tungsten (Hf/W) during accretion and core formation we can determine the age of the object being studied. We find that asteroid-sized objects formed in the first few million years of the solar system. Mars formed in the first 15 million years. The Earth took longer – at least 30 million years. The Moon formed in the final stages of Earth formation. These data provide strong support for the protracted time-scales implied by some dynamic simulations but leave us wondering – is our solar system unusual?