From Plate Tectonics to Geodynamics

William Jason Morgan

Plate tectonics quantified the ideas of continental drift. It gave predictions of the rates of closure at trenches and motion along transcurrent faults based on the opening rates at mid-ocean ridges as measured with sea-floor spreading anomalies. The key assumption of plate tectonics is that the plates are **perfectly** rigid with no internal deformation. The theory thus assumes that **all** tectonic activity occurs at plate boundaries. The deformation across the entire 10,000 km of the North American or the Pacific plates is perhaps 1 cm/yr; the deformation across a roughly 100 km zone at a plate boundary is 5 – 10 cm/yr. Therefore most activity is at the boundaries, "all" with an 80% or 90% accuracy. There are intra-plate earthquakes and internal rift-like features (the Basin and Range in the U.S., the East African Rift, back-arc centers, ...), but these are secondary (≈ 10% ?) compared to the number and size of the earthquakes at plate boundaries or to the magnitude of the rifting or mountain building at plate boundaries.

Because plate tectonics could be used to make specific predictions, it was "testable". Do different circuits across different mid-ocean ridge loops give the same result, do predicted plate motion differences between two plates agree closely with earthquake first motion studies at plate boundaries, do hotspot island chains align in directions as predicted by the theory – at the 80% – 90% level the model passed all these tests. Also, the concept of a tough, uniformly moving 100 – 200 km outer shell led to many quantitative models which described different aspects of tectonics. Examples are the model of heatflow in ocean basins and the resulting age-depth relation and models of downgoing slabs with predictions of thickness and thermal structure. Boundary conditions for models of the mid-ocean rifting processes were taken from this concept. Many quantitative "rules" were discovered; the dip of a subduction zone versus the velocities of the converging plates, the "age" of subducting sea-floor (>40 m.y.) that has the negative buoyancy to sink at a trench, the earthquake pattern at subducting slabs. Plate theory was used to make reconstructions of past times, and the sizes and shapes of ocean basins have been used in calculations of ancient ocean currents and their effects on past climates. And as the main features of rifts and trenches were understood, more subtle features such as hotspots could be found.

We are now poised to move beyond "rigid plates". New techniques can measure cross-plate distances to roughly 1 cm accuracy, and in a decade distortions of ≈ 1 mm/yr will be known. The "space geodesy" techniques of VLBI (Very Long Baseline Interferometry, using radiotelescopes and radio stars), SLR (Satellite Laser Ranging, using laser pulses bounced from satellites) and GPS (Global Positioning System, using suitcase-sized radio receivers to record the signals broadcast by navigation satellites) all have this ≈ 1 cm accuracy. What can we expect to learn in the next few years? How much do the plates deform? Is there a pattern? Does this correlate with the intraplate earthquakes? For example, 15 years ago Sykes and Sbar showed that stress in northeastern United States has a remarkably uniform pattern – the maximum horizontal compressive stresses as evidenced by micro-earthquakes, borehole instruments, and other *in situ* measurements all gave the same NE-SW orientation. They proposed this is due to plate wide stresses; can shortening in the NE-SW direction be measured? There are two zones in the generally aseismic eastern North America where earthquakes are more concentrated than elsewhere, in the Boston-Ottawa and Carolina-Ozarks zones. These two zones are where the North American plate moved over hotspots in the Mesozoic. Did the hotspots weaken the plates in these bands? Can measurements show there is enhanced deformation across these zones leading to the enhanced earthquake activity? Is present plate deformation affected by horizontal motions due to glacial rebound? Our models say present-day mm/yr horizontal motions are to be expected, but what do measurements say? Is the mid-Atlantic ridge between Norway and Greenland now opening faster than the long term average because of plate contractions due to the recent melting of ice in Fennoscandia and Hudson Bay? Is the Pacific plate stretching north-south in response to the pull toward the Aleutian and New Guinea subduction zones? From the stretching of plates, can we infer the stresses acting on the bases of the plates and thus add dynamics to our kinematic description of motion? Also we should be able to learn about the many little pieces now left out of the present plate tectonic descriptions. When the motions of the apparently many independent blocks in China are measured, is there a pattern and can a unifying model be constructed? Why are there so many curved trenches in Indonesia — will learning how Indonesia deforms make sense out of this?

With these techniques, we should also learn many of the details of how deformation occurs at plate boundaries. Of particular interest is the uplift rates of mountains; does this closely correlate with erosion rates? We think we know the total rate of closure across different mountain belts, but how is the uplift and compression distributed across collision zones such as Taiwan or Tibet? From studies of the deformation at active rifts, what can be learned about the rifting process. With these new tools, a new era should be dawning for the study of the earth, just as the development of the sea-floor anomaly technique gave the measurements that led to the plate tectonic era.

Melting Beneath Plate Boundaries

Dan Peter McKenzie

People like you who live near plate boundaries know that earthquakes and volcanoes occur in the same regions. Here in Japan the earthquakes are produced by the movement of the Pacific plate beneath our feet, and everyone believes that the same process causes melting, though exactly how is not yet clear. Though it is less obvious, melting also occurs where plates are separating, on mid-ocean ridges, and all the oceans are in fact underlain by a layer about 7 km thick of solidified melt that was generated on ridge axes. The magnetic anomalies that have allowed the sea-floor to be dated are caused by this volcanic layer, which became magnetised in the direction of the main magnetic field of the Earth at the time that it was formed. The ridges round the world are presently producing about 20 km^3 of melt every year, compared with about 1 km^3 that is produced where plates are being destroyed beneath island arcs like Japan. It is fortunate that the ridges are under water, so that the molten rock does little damage. In the few places where it is not, like Iceland, the production of large volumes of very hot low viscosity lava causes severe problems to the inhabitants.

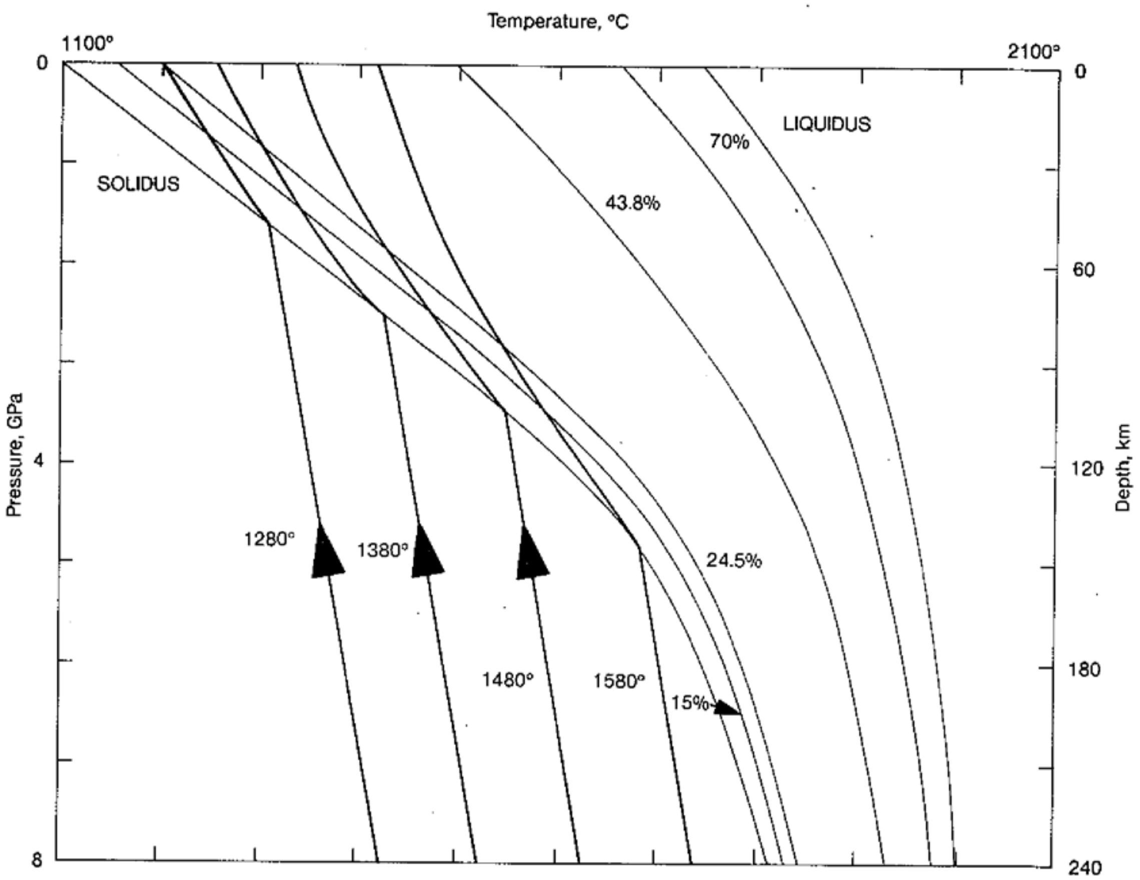
Before plate tectonics was understood, geologists thought that the reason why so much melt is being produced by ridges is because they are the surface expression of the rising limbs of convection cells in the deeper part of the mantle. The high heat flow through the sea floor near ridges and their elevation above the surrounding ocean floor was also thought to be the result of convection. It is still common to find illustrations in geological text books showing hot rising limbs of convection cells beneath ridges. I remember that such pictures puzzled me greatly when I was a graduate student, because I could not understand how the convection cells could remain beneath the ridges as the ridges move. Africa, for instance, is surrounded by spreading ridges which must therefore be moving away from each other. But how could the convection cell beneath the Mid Atlantic Ridge move away from that beneath the Indian Ridge 5,000 km away at exactly the right speed so that they both stayed beneath their respective ridges? I remember talking to Tuzo Wilson about this problem when I was a graduate student at Cambridge in 1965 when he was working on the idea of transform faults, which was later central to the whole idea of plate tectonics. At that time neither of us could really understand how to get round this problem. We now believe that the solution is that the ridges are not in fact the surface expression of the rising limbs of convection cells in the mantle, but are simply places where two plates are separating. The mantle below the plates upwells passively into the space between. There is then no difficulty in understanding how Africa can be surrounded by ridges, all of which are moving away from each other.

Though Tuzo talked about this idea, and compared the plates to ice flows, he did not work out the details of this suggestion. This was done by myself and by Xavier Le Pichon, and by John Sclater and Barry Parsons, who carefully compared the calculations with the shape of the ridges and with the variation of heat flow with plate age. They found that the predictions of the theory agreed very well indeed with the observations. This agreement implies that the ridges are indeed formed by passive upwelling. I think this explanation of the shape of the ocean basins is one of the great successes of plate tectonics. It also explained something that had puzzled me every since reading Darwin's Voyage of the Beagle as a schoolboy. I think anyone who is interested in the Earth should read this book; it is a wonderful view of the natural world through the eyes of one of the best scientists that has ever studied geology. But what puzzled me so much was his explanation of coral atolls. He argued that they were produced by the upward growth of coral as volcanic islands sank. His explanation accounted for all the observations beautifully, but what I could not understand was how **all** oceanic volcanoes could be sinking. Where did the water come from that allowed this to happen, and, even if there was some hidden source of water that we did not know about, how could the depth of the oceans increase without flooding the continents? Darwin suggests that some regions of the sea-floor are sinking and others rising, but his map shows that huge areas of the Pacific and Indian oceans are sinking, and that only the edges are going up. Plate tectonics has now made the solution to this puzzle obvious. All sea-floor is produced on ridge axes, and, as the plates age they cool and sink. Therefore all volcanic islands will sink with time with the surrounding sea-floor, until the plates are returned to the mantle beneath island arcs like Japan. This process does not require the average depth of the ocean to increase. The subsidence is a universal feature of the sea-floor, and Darwin's coral atolls are the expression of a process that occurs everywhere on the sea-floor.

All these ideas have been accepted by geologists, and now form part of all modern undergraduate lecture courses; it is not now possible to do much new in plate tectonics. So my own research interests changed, from plate tectonics to worrying about mantle convection. But I was always unhappy that we had never really understood the melting processes that occur beneath ridges properly, and had no simple physical theory of how the melt that makes up the oceanic crust is produced. Because of my interest in mantle convection, I wanted to use the compositions of the melt erupted from oceanic islands to understand the evolution of the convection cells in the mantle. But I was worried that I did not understand how melt was made and how it separated from its residue of crystals. So about seven years ago I thought I had better try to understand melting and melt production on oceanic ridges. I thought that the melting processes beneath volcanic islands would be more complicated that those beneath spreading ridges, and suspected that the melting beneath island arcs would also not be very easy to understand. Being a physicist by training, I thought I had to begin by obtaining the equations that control the movement of the melt and the residual crystals. These are rather complicated but very useful. When I solved them I found to my surprise that it was rather easy to separate the melt from its residue. Molten regions as thick as 50 km separate from their melt in a few million years if the melt fraction is 5%. Some rare types of volcanic melts can even separate when the melt fraction is only 0.1%. These results surprised many people besides me, but they should not have done. Two geochemists, Paul Gast and Robert Kay, had used the composition of the melts to argue that melts could separate even when the melt fraction present in the source was as small as 0.5%. I then wondered if I could use the equations to explain how melt is produced beneath spreading ridges. But I was somewhat nervous about starting to work on this problem. Many of the best known igneous petrologists had worked on it, and I knew that they disagreed with each other, sometimes very violently and in public. When I first became interested in melting I knew little igneous petrology, so I persuaded Mike Bickle, a proper petrologist at Cambridge, to work with me. I am very glad I did: many times he has stopped me from going astray. We thought we should start by finding out the volume and composition of the melt that should be produced by the passive ridge model that so successfully explained the subsidence of the sea-floor and the heat flow distribution. Melting occurs because the melting temperature increases with pressure, so, if the solid mantle beneath the plates is sufficiently hot, it will start to melt as it upwells to fill the gap between the two separating plates (Figure 1). To our surprise we could find no-one who had done this calculation. When we started work we discovered why: it was somewhat more difficult to do than we had expected. But we invented some ingenious ways out of our difficulties. We were also surprised to find that the experimental results from almost everyone who had carried out melting experiments were in extremely good agreement, even though the same people vigourously disagreed about the interpretation. We quickly found that our simple calculations produced the right amount of melt of the right composition (Table 1), but we then had to understand all the arguments people had given as to why ours, the simplest possible melting scheme, was wrong, and then why their arguments in turn were wrong. Though I started with little knowledge of igneous petrology, I ended with a great deal! I am pleased that no-one has pointed out to me an argument that I did not know about. Perhaps this will not be about to change!

In the last three months Keith O'Nions and I have been using trace elements, especially the rare earth elements, to study melting processes using some rather complicated mathematical methods called inverse theory. We found that we could use the rare earth elements to find the melt fraction as a function of depth beneath ridges, and then calculate the volume and composition of the melt produced. Table 1 shows the results, which agree very well with the observed composition and with the earlier calculations that Mike and I carried out. The great advantage of the rare earths is that their behaviour is very predictable: they could have been designed by physicists to study geological processes. They can be used to study melting in situations where the behaviour of the major elements is poorly understood. We have used them to show that rare magnesium-rich melts called komatiites, that were produced in the first half of the Earth's history, resulted from almost total melting of the mantle, and that alkali- and carbonate-rich melts are formed by the separation of melt fractions as small as 0.1% from a garnet-rich mantle. The

Figure 1



As solid mantle material upwells along paths marked by arrows it meets the solidus and melts. The lines between the solidus and the liquidus are marked with the melt fraction in %. The total amount of melt produced depends on the initial temperature.

Table 1

	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O
Oceanic crust, average	51.1	0.60	16.6	7.2	9.2	12.8	2.3	0.12
Calculated from melting model	50.93	1.03	15.33	7.90	10.61	11.36	2.16	0.27
Calculated from rare earths	50.48	1.23	15.40	8.27	10.76	11.29	2.30	0.27

melts being produced beneath our feet show a clear signature of melting in the presence of amphibole, as do all continental shales. Keith and I are now starting to look at melts from the Moon, Mars and asteroids, it now seems that another whole area of the Earth Sciences can be understood using simple models from plate tectonics.

Towards the end of his life I remember talking to Harry Hess about the success of plate tectonics. He was sad because he thought that the major problem in the Earth Sciences had been solved, and that the subject would become dull and specialist. For some years after he died I think he was right: we had to find out what could and what could not be understood using the new theory. Because it was so strikingly successful, much of the work in this period led to few new ideas. But it did give us confidence that we could describe the behaviour of the Earth using simple ideas with unexpected accuracy. Now that we know the problems that require new ideas, we have much greater confidence in our ability to model the processes accurately and to understand very precisely what is going on. I do not expect another change as profound as that which occurred after the discovery of plate tectonics, partly because I think the able young geologists and physicists now coming into the Earth Sciences are less dogmatic and are better scientists than those who took such extreme positions for and against continental drift in the first half of this century. Unlike Harry, I think the Earth Sciences are now more attractive to someone interested in doing research in an exciting area than they were in 1963 when I started work. The close relationship with the oil companies that we now have also stops the field from becoming introverted and narrowly academic. I think for these reasons I now have the best group of graduate students that I have every worked with, and look forward to working with them as they get better (and I get worse!) over the next twenty years.

Kaiko Project And Plate Tectonics

Xavier Le Pichon

3.5 km² of new ocean surface are produced every year along the 60,000 km of mid-Ocean Rifts. Accordingly, an equivalent amount of surface must disappear every year. Otherwise, the Earth would double its surface in about 100 million years! The disappearance occurs along the 35,000 kilometers of oceanic deep trenches that are principally situated along the rim of the Pacific Ocean. In 1967, I computed that the speed at which the ocean floor plunges below the Japanese islands along the Japan Trench is 8 to 9 centimeters per year, nearly one hundred kilometers per million years, 20,000 kilometers since Pangea time, 200 million years ago! It is rewarding that space geodesy techniques have now revealed that Japan is indeed getting every year 8 centimeters closer from Hawai. This is a proof of the rigidity of the plates which goes much beyond we ever dreamed in 1967.

We know that subduction of the ocean floor is the cause of earthquakes, tsunamis and volcanic activity on the island arcs. We know that the Japanese islands are the products of 200 million years of active subduction. But subduction is very difficult to investigate. In short, subduction is the disappearance of the oceanic crust and lithosphere inside the Earth within its mantle. How does one investigate a crime in which the body of the victim has disappeared? This difficulty explains why it took so long for Earth scientists to realize that subduction does exist and that it is the most energetic process at the surface of the Earth. Furthermore, subduction occurs below water, at depths of 4 to 11 kilometers, within a relatively narrow trench. Thus, techniques of investigation from the sea surface do not offer enough resolution to properly decipher the marks left by the subduction process on the sea-floor. One needs to lower instruments near the sea-floor using a combination of unmanned vehicles and deep sea submersibles coupled, if possible, to drilling programs.

High resolution exploration of the trenches using deep sea submersibles was the rationale for Project Kaiko that we conceived in 1975 with Professor Nori Nasu. We had to wait for nine long years before the actual exploration of the Japanese trenches by a French-Japanese scientific team took place. In 1984 and 1985, with Professor Kazuo Kobayashi, we first mapped from the surface several critical targets and then we dove with the French Ifremer submersible Nautile 27 times to the sea-floor to depths of up to 6,000 meters.

The northern Japan trench turned out to be a gigantic erosional feature with steep slopes modeled by major slumping and avalanches. We investigated in detail the remarkably smooth subduction of large seamounts and followed the trails they leave on the wall of the trench as they are being swallowed.

The Nankai trench, on the other hand, is filled with a thick cover of mud and subduction piles up this mud to form a very large submarine mountain belt that we call accretionary prism. We investigated this accretionary prism near the Izu peninsula, at a plate where compressional deformation affects the oceanic lithosphere seaward of the subduction, producing scales of oceanic crust which will later be incorporated within the Japanese margin.

The most remarkable discovery of the Kaiko dives was the ubiquitous presence of fluid venting on the walls of the trench, the venting being maximum near the bottom of the trench and decreasing upward. Large colonies of clams take their food from these seepages and enabled us to rapidly identify the locations of the vents. The venting is due to the fact that the muds that are accreted to the wall of the trench are saturated with fluid which becomes trapped, resulting in high fluid pressure. We realized at this time that the high fluid pressure may well be modulated by the earthquake cycle and that consequently, monitoring the fluid outflow could be a significant step forward in our understanding of the earthquake cycle. In any case, the high fluid pressure reduces the frictions between the subducted plate and the overlying margin and is consequently an essential element of the system.

This is why another submersible cruise, during the Summer of 1989, was entirely devoted to the fluid problem. We explored a small portion of the Eastern Nankai trough, south of Shizuoka prefecture, in the area of the expected future large earthquake. The aim was to map the different vents, measure the fluid outflow, establish a fluid budget and monitor the variation of the venting with time. We only have quite preliminary results but we already know that venting is much more important than was thought and that the fluid outflow is much larger than the amount of water entering the margin with the subducted muds. Thus, there must be a system to pump additional water within the margin.

We also monitored the outflow during a full month and discovered significant variations.

However, we are still far from understanding the incredibly complex system that we call subduction. We need much more exploration and monitoring of the fluid outflow to understand its possible relationship with the earthquake cycle, as elastic energy is progressively loaded within the continental margin to be suddenly released during the earthquake. I believe that Kaiko was a first modest step in this direction. It is vital for science, especially in Japan, that the deep sea processes related to subduction and the earthquake cycle undersea manifestations be thoroughly monitored, understood and modeled. In this respect, the International Drilling Program will soon bring additional very important data. But much more need to be done. I am sure that Japan will continue to play an important role in this research.