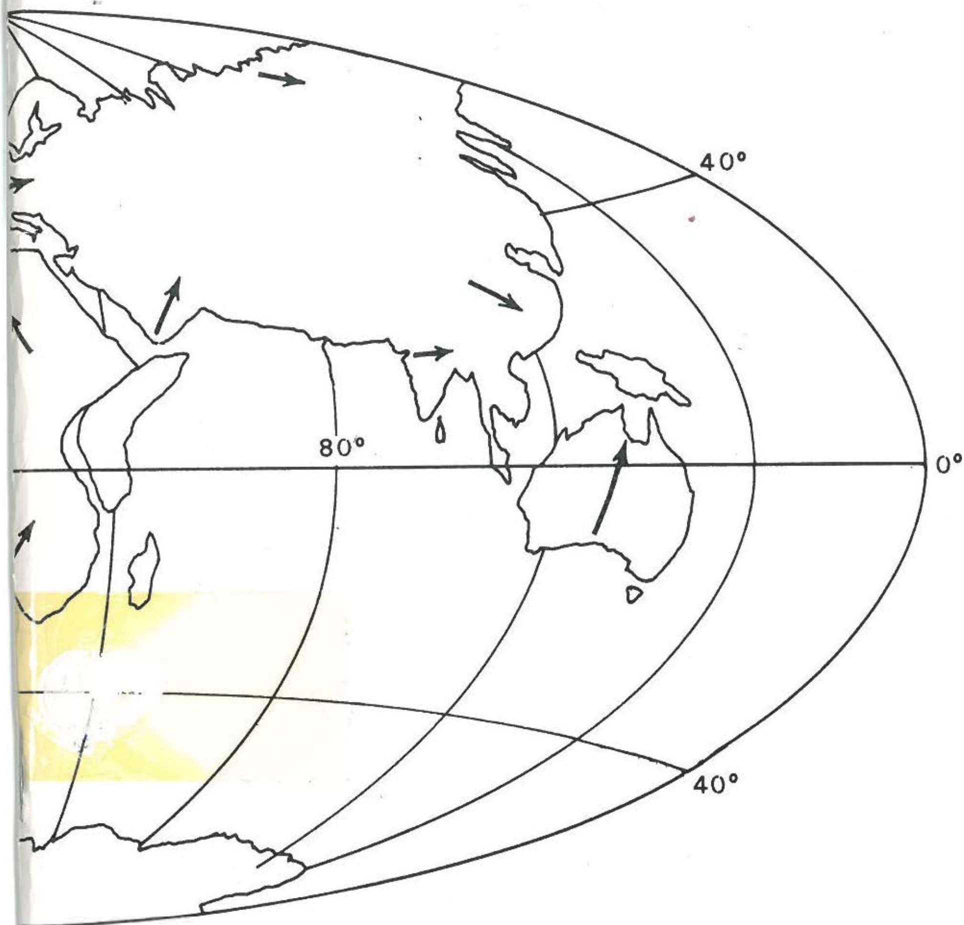
T. R. Owen

Geology '77—
A New Exciting Science



University College of Swansea

UNIVERSITY COLLEGE OF SWANSEA

GEOLOGY '77—A NEW EXCITING SCIENCE

Inaugural Lecture

Delivered at the College on 6th December 1977

by

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INAUGURAL LECTURE

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Just over 40 years ago, a timid schoolboy came down from Merthyr Tydfil to compete for one of the scholarships awarded by the University College of Swansea. He little thought then that he would gain that scholarship and become a student at the College. Even less did he imagine that he would later return to that same college as a lecturer and that he would be giving this inaugural lecture there this evening.

During all these years, first as a student and then as a teacher, he has seen his subject—geology—change appreciably, but these changes have been particularly exciting during the last fifteen years. A new Revolution has taken place, a revolution in Geology "comparable in scale and effect to the revolution of Darwin's theory of evolution and Einstein's theory of relativity". The subject has had to be relearnt and retaught; the books have had to be rewritten.

As with other revolutions, this geological revolution was not a sudden one, but had a long period of growth which goes back almost to the start of this century. Moreover it often happens that two thinkers stumble across a new theory at virtually the same time. It happened in the theory of evolution with Darwin and Wallace. The geological revolution began with Wegener and Taylor. Moreover it also happens that pride of place is given to one of the two thinkers. With evolution this was Darwin, with geology it was Alfred Wegener.

In 1915 Wegener published an expanded version of a 1912 paper in his book "The Origin of Continents and Oceans". He suggested that the continents had once formed a single supercontinent—"Pangaea", and that about 200 million years ago Pangaea began to split up in various stages into the separate continents as we now know them, the opening of the North Atlantic being accomplished in relatively recent geological times (fig. 1).

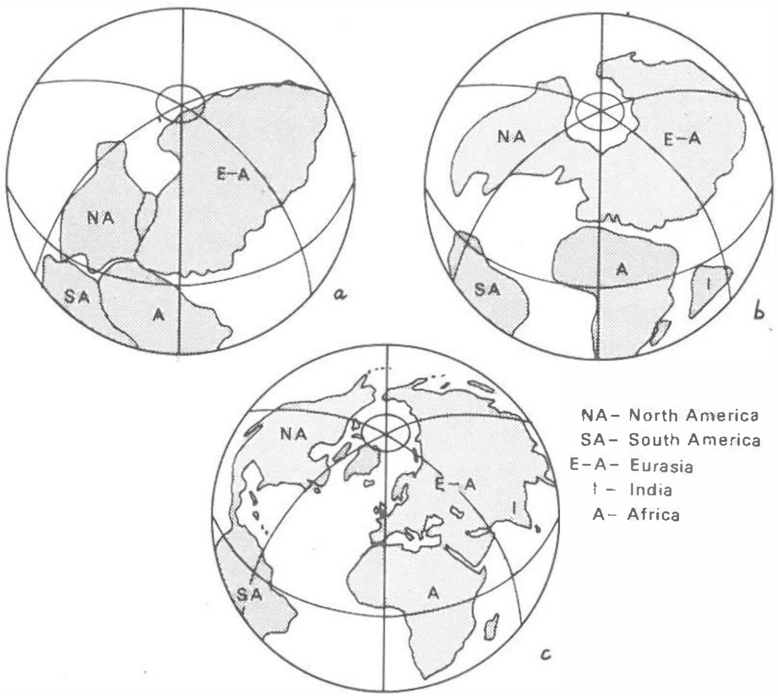

Fig. 1. The drifting contents. (a) 200 million years ago; (b) 65 million years ago; (c) today. (After Wyllie).

Wegener and his followers compiled an impressive list of evidence in support of this theory of continental drift, but a fierce debate had begun. The main opponents were the physicists who argued that what was known of the physical properties of the earth just would not permit the proposed movements. Moreover they could not accept Wegener's belief that it was the pull of the Moon that had caused the continents to move apart.

The debate went on and then gradually subsided. Wegener was to meet his death on the Greenland ice sheet in 1930, and by the 40's it looked as if his theory had died with him.

Geology was to suffer in the 30's and 40's from this setback. The subject was a collection of topics—earthquakes, volcanoes, mountain building, thick geosynclinal sedimentary piles, changing climates, etc., but lacking a framework that pulled everything together. For example, if continental drift had not occurred, how then could one explain the great changes of climate which had occurred in Britain, such as from the equatorial forested swamps of the Carboniferous to the hot deserts of the Permian (fig. 2)?

The great revival began in the 50's and it was the physicists who made the breakthrough. Two names stand out, those of P. M. S. Blackett and S. K. Runcorn. These eminent geophysicists introduced the idea of palaeomagnetism, the main tool that was to eventually vindicate Wegener. Lavas and some sediments become magnetised at their time of formation and thereby retain a "fossil" record of the direction of the magnetic field at the time and place of origin. From the orientation of the magnetised particles in a rock it is possible to determine the latitude at which that rock formed—its "palaeolatitude". The position of the earth's magnetic poles can be determined for different times in the past. Blackett, Runcorn and others showed that the positions of the earth's magnetic poles had changed relative to the continents back through hundreds of millions of years of geological time. The evidence of European rocks, for example, shows that the magnetic North Pole was situated in the Western Pacific Ocean from Cambrian to Triassic times (570 to 200 million years ago). There is evidence that the direction of the earth's magnetic axis remains approximately coincident with its rotational axis and it thereby follows that the palaeomagnetic data could be interpreted in terms of relative movements of the continents. Moreover the paths of polar wandering as determined by, for example, Eurasian as against North American palaeomagnetic data, clearly showed that these two great landmasses had once been joined but had later gradually separated.

The breakthrough had been made! More was to follow in the 50's. Ocean floor exploration was by now well under way. The configurations of the ocean floors were being charted and great submarine mountain chains were being discovered, forming systems that virtually girdled the world. One such

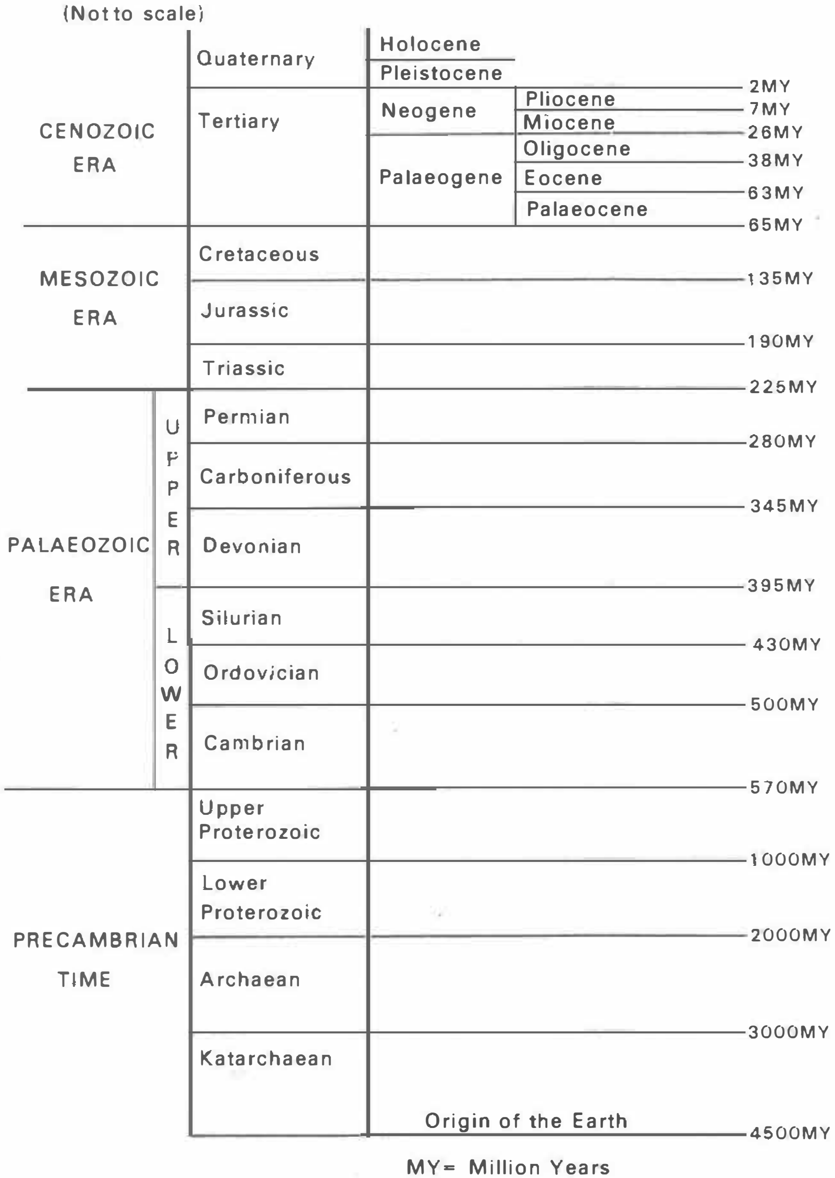

Fig. 2. The Geological Time Scale.

tremendous mountain chain runs down the centre of the Atlantic. Its highest peaks break through the ocean surface as islands such as the Azores, Tristan da Cunha, etc. If all the oceanic waters were drained away from the earth's surface, fantastic mountain festoons, rivalling the Alps and the Himalayas, would be seen in the Atlantic, Pacific, Indian and Arctic oceans. In the Western Pacific, these mountain festoons make a really complex network. Their summits include almost every island captured by John Wayne during the last war! In this story of ocean floor charting, names such as Ewing, Heezen and Menard stand out. Besides these topographical anomalies, various geophysical anomalies were also being noted—variations in gravitational pull, magnetic anomalies, etc. Geological age assessments of rock samples from the ocean floors were being studied. One puzzling fact emerging from such calculations was the unusually young age of the ocean floors (young in a geological sense, that is). No part of the Pacific Ocean's floor appeared to be more than 200 million years old (so much for the idea that the Moon had come from the Pacific hollow!). Rates of heat flow were being measured over the ocean floor. Bullard and others were showing that heat flow rates were unusually high along the crests of the submarine mountain ranges. Measurements of magnetic force across parts of the North Atlantic and again in the N. E. Pacific were showing that patterns of magnetic anomaly existed, forming remarkable parallel linear strips of ocean floor (fig. 3d). These strips could be up to 30 kms wide and 1000 kms long. Moreover the continuity of strips was frequently broken by major fractures with possibly considerable lateral displacements, especially in the region west of the Californian coast (see fig. 4). No explanation for the strips was at that time forthcoming.

Attention had then now switched from the lands to the oceans, but it was the right step. At last, geologists and geophysicists were first *studying the present,* before they *guessed at the past.* "The present is the key to the past" and this was the right way to do it.

If the work of Blackett and Runcorn was the first breakthrough in this geological revolution, the second important event must be a paper read in 1960 by the late

Professor H. H. Hess of Princeton. This paper, entitled "History of the Ocean Basins" was published in 1962. Hess called his idea "geopoetry" and introduced the theme of "sea-floor spreading". Hess claimed that whenever continental crustal slabs split up and moved apart, then molten material ("magma") would well up from the underlying mantle to fill the widening crack with new ocean crust material of basic composition (of the same chemical composition as the rock type "basalt"). The ocean floors were therefore formed of the molten magma welling up from below. For example, as America has moved away from Europe and from Africa (during the last 180 million years) so new ocean floor has been made from upwelling molten material to form the floor of an ever-widening Atlantic Ocean. (This molten material is even today upwelling along the central crack running like a figure S down the middle of the Atlantic, the so-called Mid-Atlantic Ridge—see fig. 4). Hess in this theory of "sea-floor

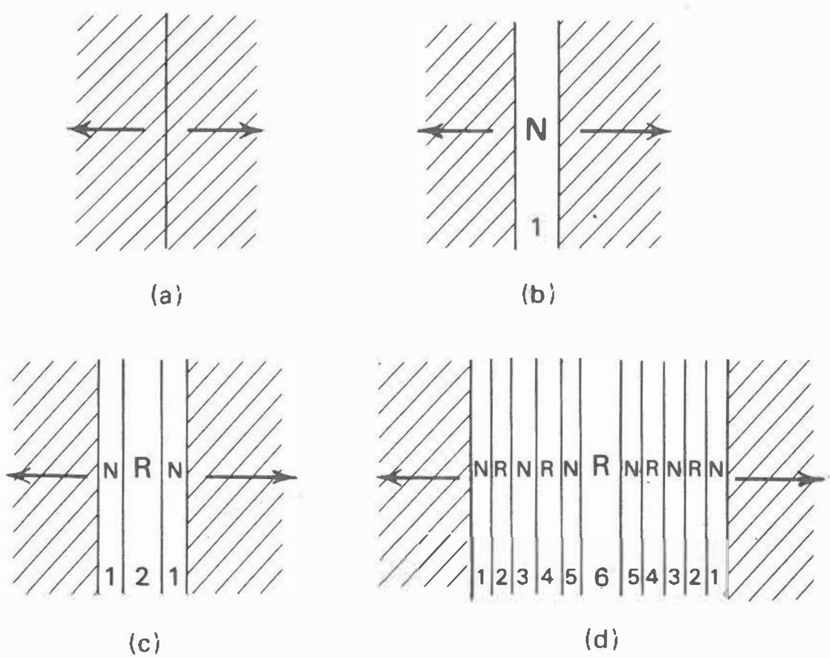

Fig. 3. Sea Floor Spreading. N—Normal; R—Reversed polarity.

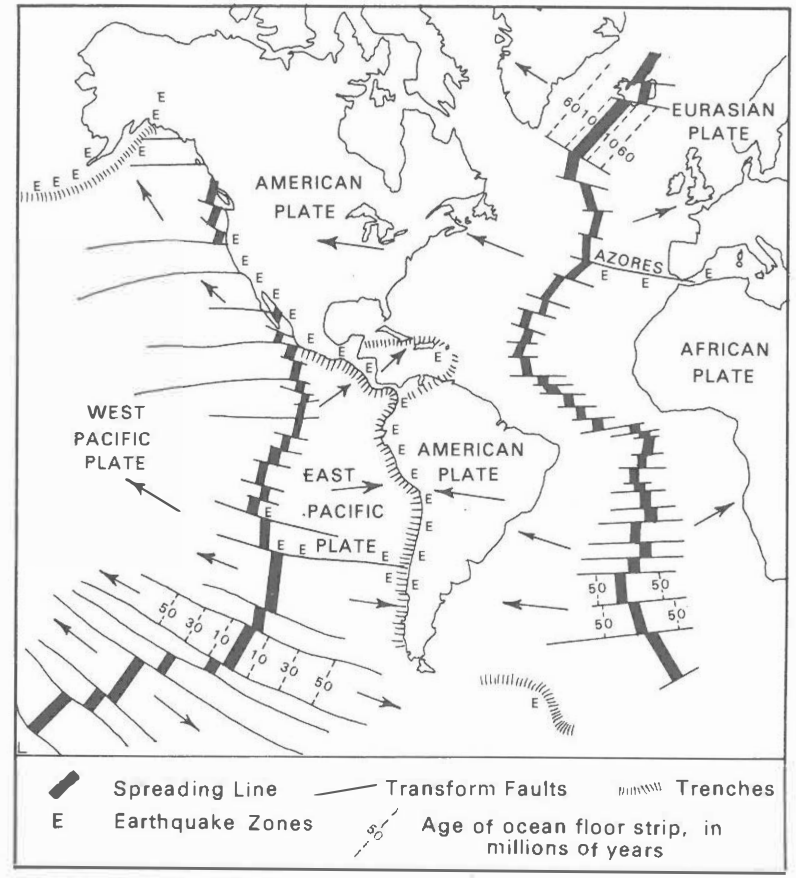

Fig. 4. Sea Floor Spreading in the Atlantic and Pacific oceans (after Heirtzler).

spreading" made one other important point. He maintained that if new ocean floor was being made today from upwelling molten material, then older ocean floor elsewhere must consequently be removed and destroyed in order to make room for the new oceans. In other words, all ocean floor is temporary, it is made and it is destroyed. Oceans are temporary features whereas continental crust is permanent. It may be split up into slabs and put together again (even in a different pattern) but it cannot be destroyed.

Yet a third important breakthrough was to occur—the next vital step in the geological revolution. In 1963, a young postgraduate student at Cambridge, F. J. Vine, collaborating with D. H. Matthews, gave an explanation (in "Nature") for the magnetic anomalies that occurred as parallel strips of ocean floor, as for example in the N.E. Pacific. Vine and Matthews suggested that when molten material comes up to form new ocean floor between two outward moving continental plates, then that molten material takes up (and records) the magnetism at that time. (Changes occur in the Earth's magnetic field from time to time. Today the field is normal and the magnetic North Pole is in the Northern Hemisphere, but at many times in the geological past the position has been reversed with the magnetic North Pole in the *southern* hemisphere). Studies of magnetised lava sequences on land areas were at this time showing these periodic reversals of polarity and by 1966 Vine had shown that the magnetic reversals formed strips of ocean floor parallel to and on either side of the crests of submarine mountain ranges (the mid-oceanic spreading lines). The "geopoetry" of Hess was proved correct by Vine.

Fig. 3 shows the sequence of events when a slab of continental crust splits and separates (3a). As the crack begins to widen, hot molten magma wells up from the "mantle" below and fills the crack with basic material that cools and crystallises into hard rock, taking up the imprint of the earth's magnetic polarity during this cooling process (normal "N", for example, in fig. 3b). Further separating movement then splits this initial infilling, with perhaps the new magma upwelling now recording a reversed polarity R (fig. 3c). With continued separation of the continental margins, a succession of magnetised strips of ocean floor will record the polarity reversals (3d). Studies of these strips of ocean floor can record not only their magnetic polarity (normal or reversed) but also their geological age (using uranium-lead, rubidium-strontium or potassium-argon methods). These age assessments confirm the theory of sea-floor spreading, with the oldest formed strips being outermost (1) and the latest formed infilling being central (6) in fig 3d. From the arrangement of these age-determined strips over the ocean floors, on either side of the mid-ocean ridges, it is then possible to work out the *average* rate

of spreading. In fig. 4 some of the known age assessments are shown for a part of the S.E. Pacific, a part of the S. Atlantic and the area south of Iceland. To give some examples of spreading, during the last 4 million years the South Atlantic has widened by an *average* of 4 cms per year (its widening is actually much more erratic than this average implies) and the North Atlantic at an average of 2 cms per year. At this 4 cms per year widening, the South Atlantic would therefore have taken 138 million years to open up to the 5500 kms width that it now has—suggesting a late Jurassic initial opening (stratigraphical and palaeontological evidence more or less confirms this time of separation). The most remarkable crustal movement was achieved by the Indian continental slab which moved from about 46°S to 12°N in the last 180 million years. Between 100 and 50 million years ago the average rate of this northward movement of India actually increased to 16 cms per year!

From 1965 onwards, many other advances were being made, especially with earthquake studies. Earthquakes were shown to be associated with fractures that displaced the spreading line (figs. 4 and 6)—the "transform faults" of J. T. Wilson. Deep seated earthquakes were shown to occur along inclined planes ("subduction zones") near deep oceanic trenches (see fig. 7). The revolution had been virtually accomplished and the theory of Plate Tectonics virtually accepted. On a January day in 1970 Time magazine proclaimed "Geopoetry becomes Geofact".

The theory of Plate Tectonics asserts that the outer shell of the Earth (the Lithosphere, about 70 kms thick) is divided into a number of irregular segments or "plates". There are some 7 major plates and a large number of small plates (fig. 5). These plates are moving, the general direction of movement being indicated by the arrows in fig. 5. Boundaries between plates can be of 3 types. "Divergent" plate margins are typified by the Mid-Atlantic Ridge. Here new ocean floor is being introduced as plates move *away* from one another. "Convergent" or "destructive" plate margins occur where previously formed ocean floor is being destroyed as two plates move towards each other. In this case the denser of the two plates slides down beneath the lighter segment, the plane of sliding ("subduction

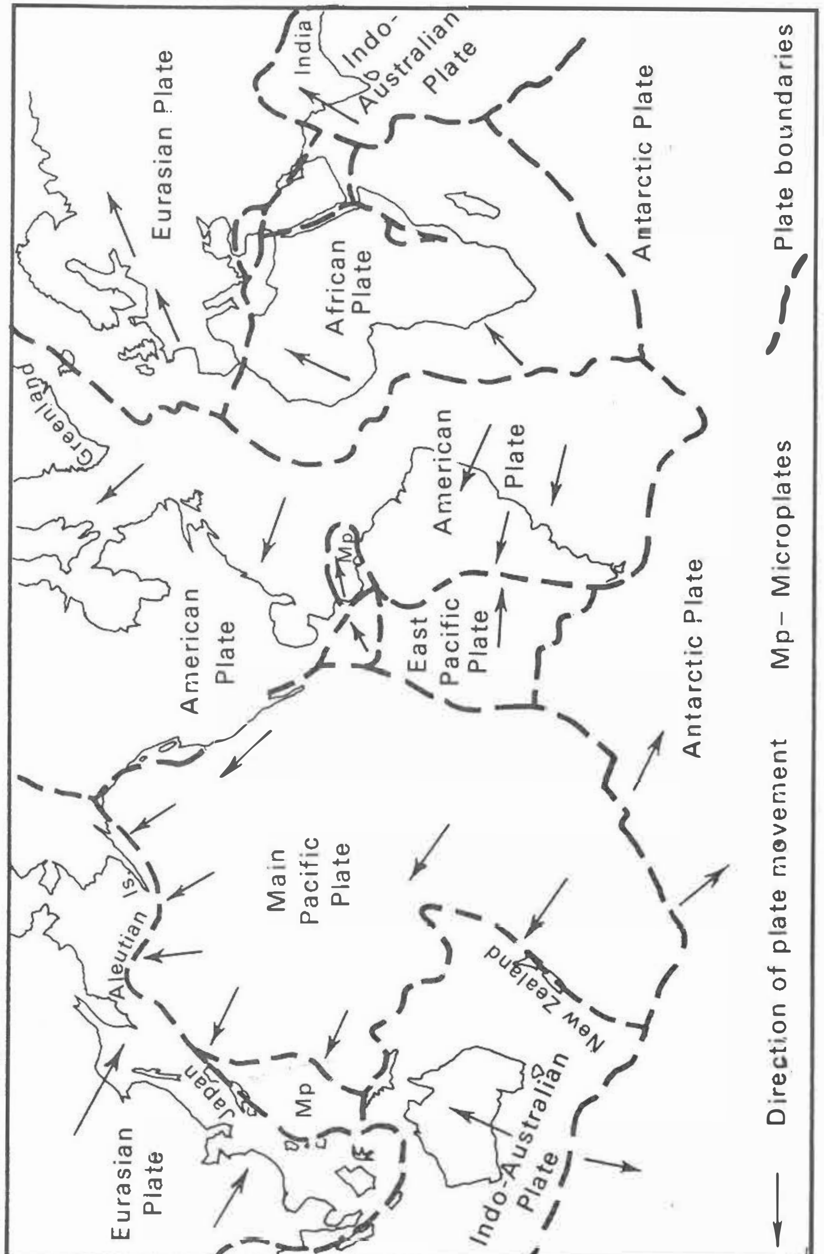

Fig. 5. Major plates of the World.

zone'' or ''Benioff zone'') being inclined at about 45° to the horizontal (see figs. 6, 7 and 8). Such subduction is particularly common where the leading edge of one plate is formed of continental material of lighter density and which therefore overrides the denser oceanic crust of the disappearing plate front. The best example is the situation along the western seaboard of South America (fig. 6). Whereas *new* oceanic crust is being added at the Mid-Pacific ridge (it's actually nearer to S. America than the centre of the Pacific), so at the same time older oceanic crust is disappearing and descending underneath the western margin of S. America. Deep-seated, intense earthquakes occur as the plate descends. The Peru earthquake of 1970 killed 50,000 people in a space of 5 minutes. Moreover the descending plate melts as it descends and the molten material rises up through the overriding continental crust of S. America, forming the long lines of active volcanoes that characterise the Andes (fig. 6), and the mountain ranges of Central America. The lava emitted by these volcanoes is frequently of a mixed chamical type called ''andesite'' (after the Andes). It is the result of melted basic oceanic crust rising up through the more acid (''granitic'') continental crust of South America. Yet a third effect of this South American subduction (and also of other destructive plate boundaries) is the presence of a well-marked deep oceanic trench along the western seaboard of S. America (fig. 6). Very deep subduction trenches occur especially in the western Pacific (near Japan, the Philippines and south of Sumatra and Java) and in the northernmost Pacific (south of the Aleutian Islands).

There is an important difference between the theory of Plate Tectonics and the original theory of Continental Drift. The latter envisaged only the *continents* moving, ploughing their way through the ocean material. In the newer theory, a moving plate can consist of partly or even wholly oceanic material (the Main Pacific plate, in fig 5, is an example of the latter). In some cases of destructive plate boundaries, oceanic material actually descends beneath oceanic material (there has to be some density contrast here). The result is an ''island arc'' (figs. 7 & 8)—a line of volcanic islands. The Japanese and Tonga islands are examples. Earthquakes and frequent volcanic eruptions again characterise island arcs.

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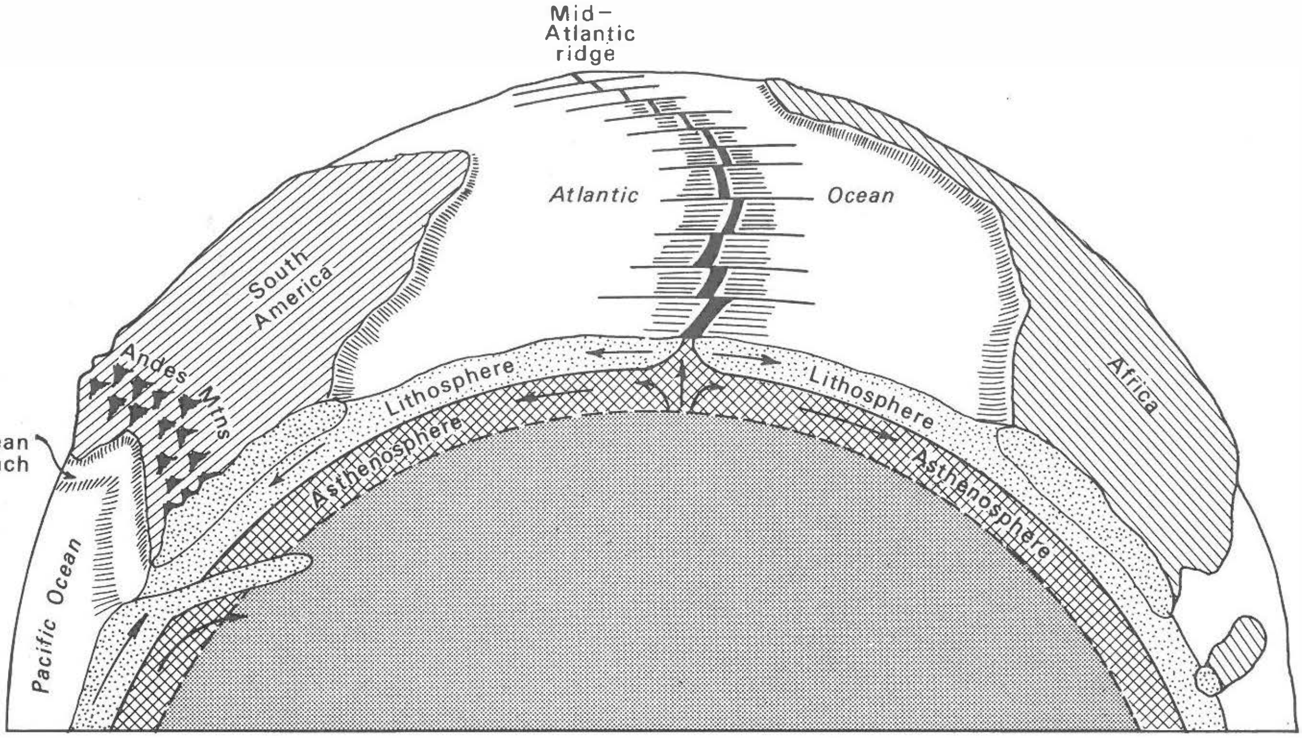

Fig. 6. Plate movement in the S. Atlantic and S.E. Pacific. (After Wyllie).

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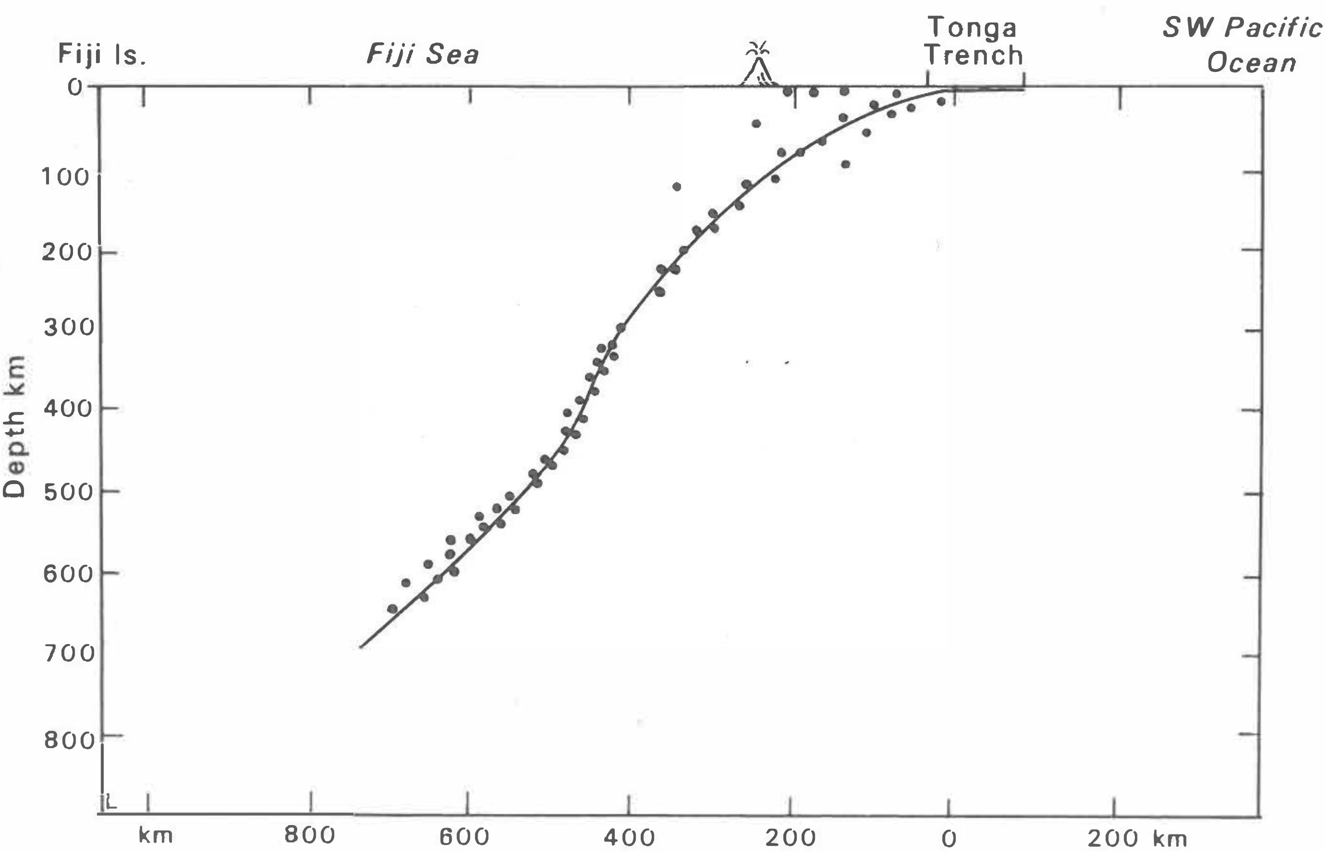


Fig. 7. Distribution of deep-seated earthquake focii beneath the Tonga Islands (after Sykes).

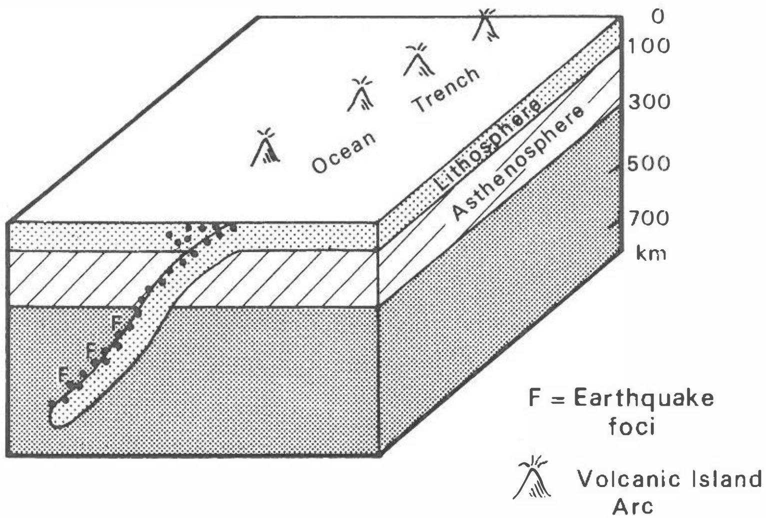


Fig. 8. Island arc subduction (after Wyllie).

The third plate margin situation is where plates are moving *sideways* against one another. These important earth fractures usually have long histories of movement. The two best known examples are the great Alpine Fault of South Island, New Zealand and the famous San Andreas fault system of California. These Californian fault complexes have been moving since late Cretaceous times (80 million years ago). Between 1906 and 1971 California has experienced 18 destructive earthquakes, a particularly memorable one being that in 1906. Even as recently as February 9th, 1971, 64 people died in Los Angeles.

We know then that widespread crustal movements occur today and have occurred in the geological past, but what makes these crustal segments move? The true explanation still eludes us but it is generally thought that the moving force comes not from *without,* as Wegener believed, but from *within* the Earth. This force is circulating heat, circulating in convective systems or patterns in the upper portions of the Earth's mantle and more particularly in a layer known as the "asthenosphere" a weak plastic layer immediately underlying the outer shell or "lithosphere" (figs. 6 and 9). The outer layer of the Earth, the Lithosphere, is about 70 kms thick (but is

thinner beneath the spreading lines, i.e. the mid-oceanic ridges). This layer is relatively cool, rigid and brittle. It comprises the outer crust (down to the Moho) plus the topmost part of the mantle. Under big continents the continental crust makes up most of the lithosphere's thickness whereas under oceans, oceanic crust is very thin (often less than 20 kms) the bulk of the lithosphere here therefore being uppermost mantle. This is why oceanic plates are denser than continent-carrying plates and descend beneath the latter when the two collide. The asthenosphere, with an average thickness of 150 kms, is a layer of weakness that is capable of flow. It is sometimes called the "low velocity zone" because certain earthquake waves slow down temporarily as they pass through it.

Due to the different convective cells in these upper regions of the Earth's mantle, there are some areas of the Earth where heat is rising and then diverging outwards (dragging the lithosphere apart) whereas elsewhere heat is descending and pulling lithospheric portions towards one another. The former

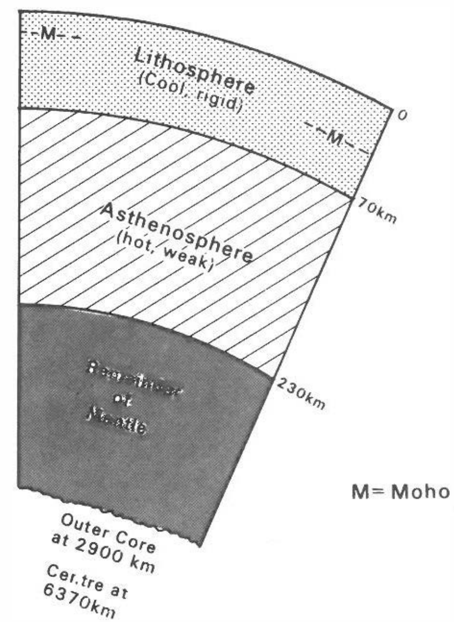


Fig. 9. The outer shells of the Earth. M—Moho (shallow beneath oceans, deeper under continents). (After Wyllie).

situation is that of sea-floor spreading and the making of new ocean crust, the latter is the site of subduction. Where two continental crustal slabs are being carried towards one another, with the intervening oceanic crust being destroyed by subductions, this can eventually cause the two continental parts of the lithospheric plates to actually collide. The effect is to ruck up the thick sedimentary piles which had accumulated in the continental marginal seas into highly folded zones, rising to form mountainous belts. In this way have been formed the modern mountain ranges such as the Alps and the Himalayas (the latter by the collision of a northward-drifting India into the southern "underbelly" of continental Asia.)

The great attraction of the Plate Tectonic theory is that it brings together what were previously a number of disconnected phenomena. It can explain the volcanic and earthquake belts of the World, the great oceanic trenches, the festooned belts of mountain ranges, and volcanic oceanic islands. By reconstructing past positions of continental masses, it is possible to explain the variety of past climates with their variety of life. Important mineral-rich zones can be related to plate margin activity.

It has been stated earlier that by the 70's the new Revolution had been virtually accepted, but there were still some sceptics, in particular the Russian geologist, Beloussov and the Americans, A. A. and H. A. Meyerhoff. They attacked the

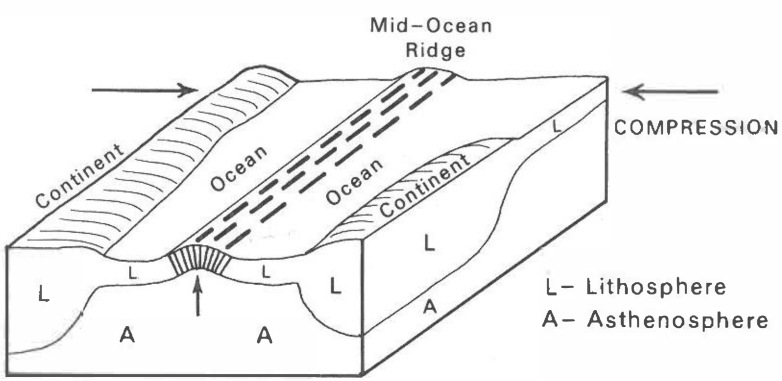


Fig. 10. Alternative explanation for mid-oceanic ridges (after A.A. and H.A. Meyerhoff).

modern theory as being too "cut and dried". Beloussov, for example, put forward an alternative explanation for the age pattern of the polarity reversal strips parallel to the central rifts of mid-ocean ridges. He pointed out that successive lava emissions from the ocean ridge could occur as flows arranged as tiles on a roof (fig. 11). Again the Meyerhoffs interpreted the ocean ridges as areas of compression rather than extension, with fractures opening up along an up-arched central ridge, (fig. 10). This compression was part of the history of a *contracting* Eearth (said the Meyerhoffs).

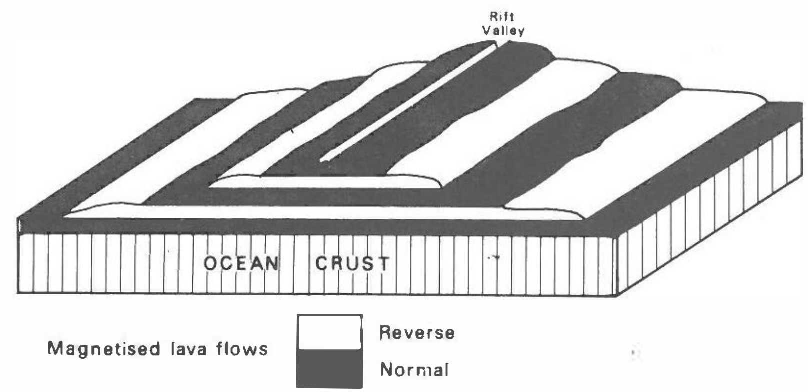


Fig. 11. Alternative explanation for the oceanic strips (after Van Andel and Beloussov).

An exciting and stimulating aspect of the Plate Tectonic theory is its application to past geological history. One can now appreciate more clearly the changes which have occurred in the geological evolution of an area. It is now believed that plate movements have occurred at least as far back as 2000 million years ago. Palaeo-magnetic evidence suggests that continental slabs have been migrating in all sorts of directions in this far-off geological past. The map of the World for about 700 million years ago looks very different from that of today. Such a map, based on palaeomagnetic positions, is shown in fig. 12. Australia and the Antarctic were in the Northern Hemisphere with the Antarctic in a tropical position! Greenland lay on the Equator! Africa and South America (joined together then) were "upside down" with the South

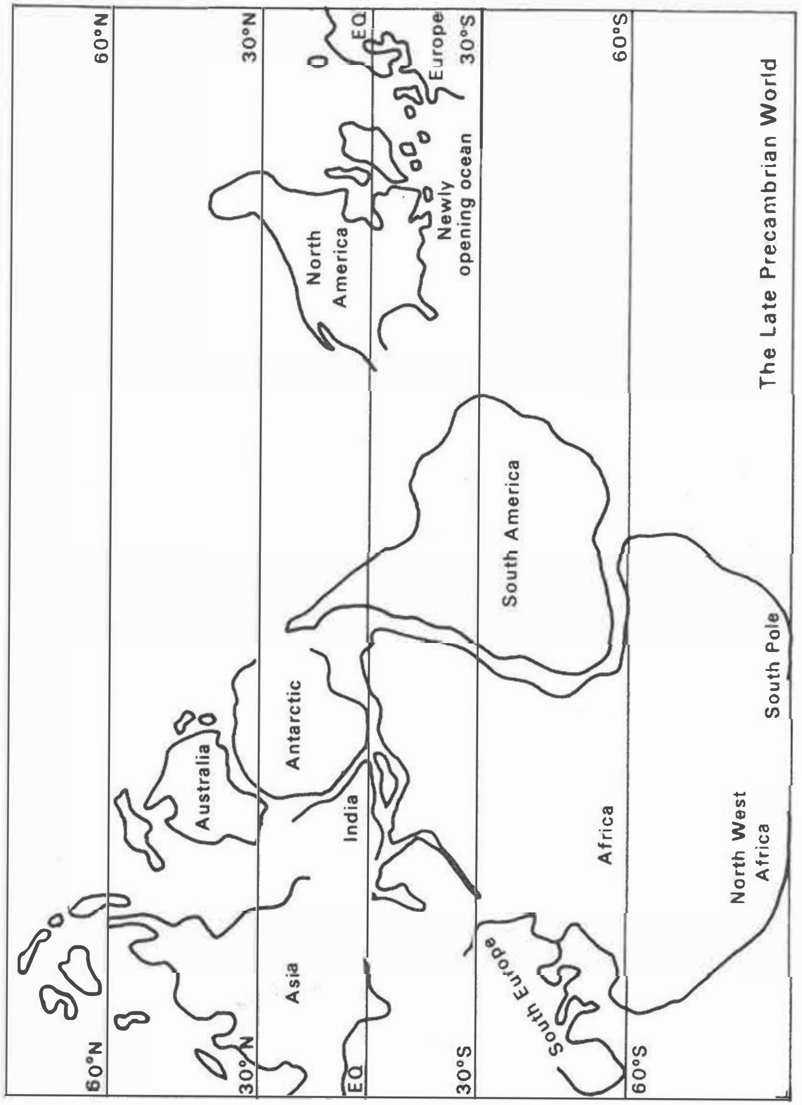


Fig. 12. The late Precambrian World (based on Smith, Briden and Drewry).

Pole over N.W. Africa. These two joined continents were later to drift over the South Pole and up "the other side" thereby righting themselves to their present orientation!

Before these times, there may in the very early history of the Earth have been a very much larger number of smaller continental crust nucleii. How these first came into being is a matter of great debate. One theory involves very early plate tectonics—perhaps as far back as 4000 million years ago (the Earth began 4500 million years ago). This suggests that early heat convective cells may have been small in size but very active due to steeper thermal gradients then. The result was subduction occurring in a large number of zones producing island arcs (fig. 13a), which with continued drifting coalesced to form nucleii of continental crust. These nucleii in turn collided with others to form larger continental slabs (fig. 13b).

One particularly exciting contribution of Plate Tectonics to geological evolution is the reconstruction of an *earlier* "Atlantic" ocean between Europe and N. America. This ocean dominated British geological history from about 1000 to about 400 million years ago. This ancestral ocean (later to completely disappear) has been called the "Proto-Atlantic Ocean"

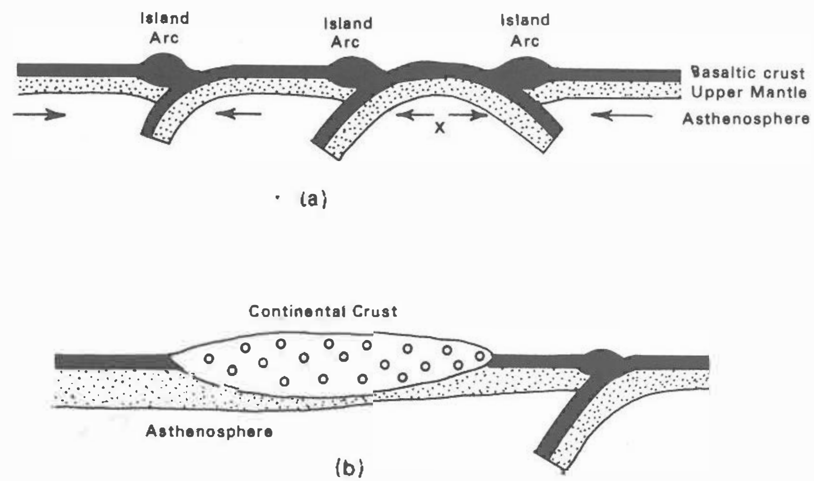


Fig. 13. Possible mode of formation of early continental crust (after Wyllie).

or "Iapetus" (fig. 14). At its widest, what are today N.W. Scotland and England (with Wales) were separated by a considerable distance (as much as 2000 kms according to one view). N.W. Scotland was then close to Greenland. Northern Newfoundland was separated from Southern Newfoundland, again perhaps by as much as 2000 kms. A mid-ocean ridge, forming new ocean crust, must have lain between Scotland and the rest of Britain. With the approach of Lower Palaeozoic

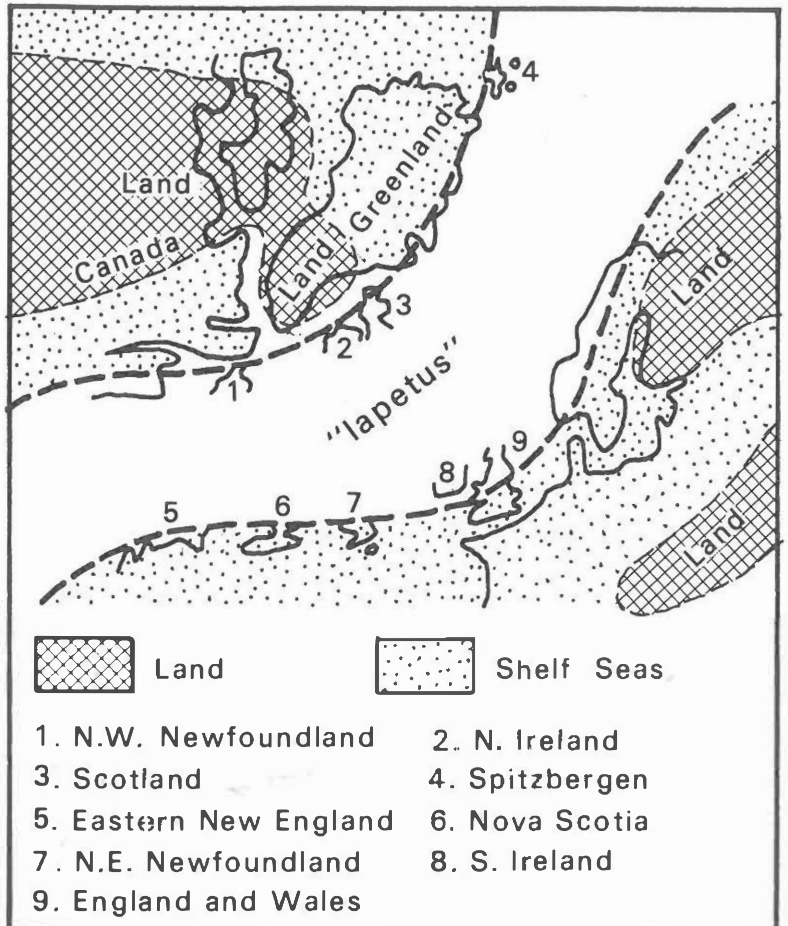


Fig. 14. "Iapetus"—the Lower Palaeozoic ocean (after Cowie and Marshall Kay).

times, however, subduction began to occur on the ocean's margins and these subductive processes gradually began to shrink the width of "Iapetus" causing at the same time the great volcanic episodes of the Ordovician Period and producing the spectacular volcanic piles of Snowdonia and the Lake District. By the close of Silurian times, the British part of this ancestral ocean had come to an end with the collision of its continental crust margins. The suture of this collision is believed to be somewhere near the Scottish border (the "devolution" of Scotland must now happen all over again!).

The British area by this time (Devonian times) was situated well *south* of the Equator (perhaps as far as 30 degrees south) but it was then to steadily drift northwards, passing over the Equator by Upper Carboniferous times. This explains the extensive Equatorial environment in which the Coal Measures (with their valuable coal seams) were formed. Continued northward movement brought the British area into desert latitudes by Permian and Triassic times (280-200 million years ago). By Triassic times initial splits were beginning to open a new Atlantic Ocean between N.W. Africa and U.S.A. Waters began to flood towards Britain in the Jurassic and, as more and more new Atlantic spreading occurred, especially in the Upper Cretaceous (the great extensive submergence in which the Chalk accumulated over vast areas). The final (northernmost) opening of the Atlantic, between Scotland and Greenland, saw extensive basalt lava eruptions flood over N.W. Scotland (Skye and Mull) and Antrim (the Giants Causeway) about 60 million years ago.

Convective heat cells must have changed their position somewhat during these Triassic to Cretaceous times and the results have been particularly beneficial to Britain's present economy. Abortive attempts at stretching and spreading appear to have taken place along the North Sea and other British waterways (Celtic Sea, Irish Sea, Porcupine Bight, Rockall Trough, etc.) but particularly along the North Sea. Geophysical investigations and subsequent deep drilling have proved the presence of major graben (rift) faulting and subsidence along the central line of the North Sea (virtually astride the International Line between us on the one side and Norway-Denmark on the other). Fig. 15 shows this deeply

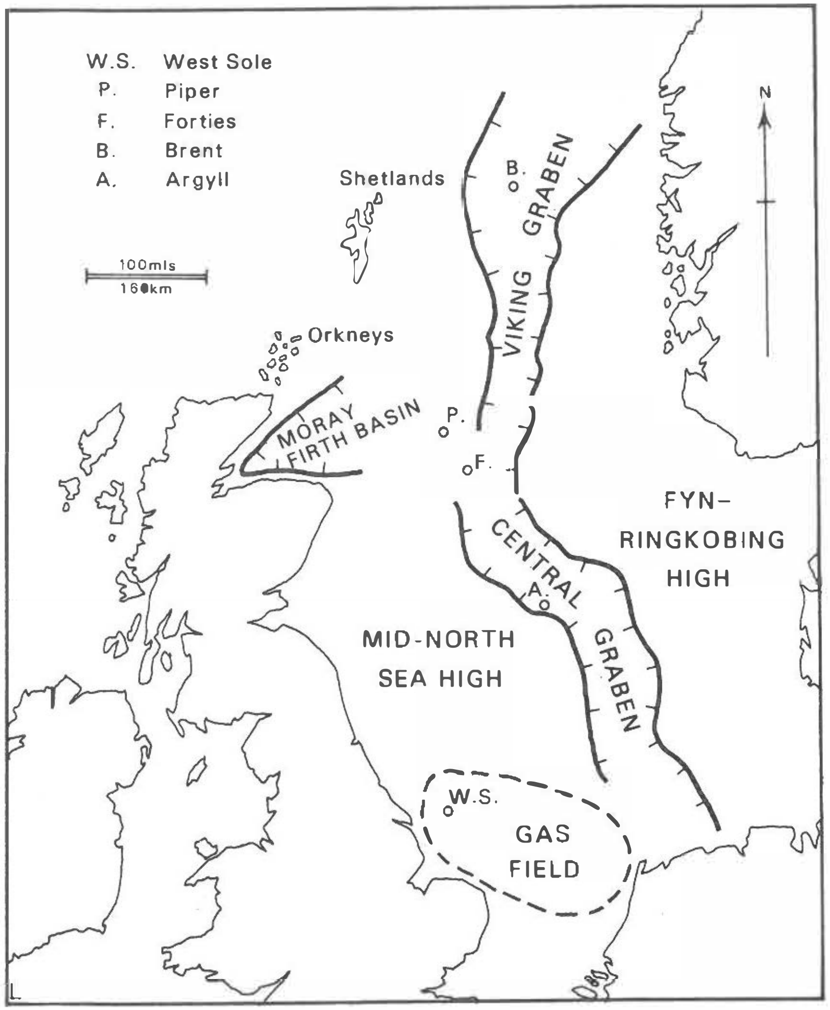


Fig. 15. The graben structure of the North Sea (after Kent).

buried structure. Within it are to be found thick Mesozoic sediments and a thick Tertiary sedimentary wedge (up to over 10,000 feet in places) overlies it (fig. 16). Because of the fortunate faulted and tilted attitudes and relations of the various Mesozoic formations, hydrocarbons have flowed from Jurassic source rocks into thick sand bodies of Jurassic, Cretaceous and

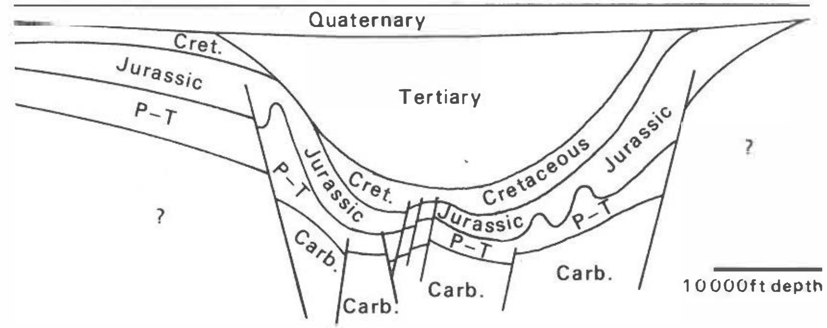


Fig. 16. General structure of the central North Sea (after Evans and Coleman).

even lowest Tertiary age, there to be trapped by special structural situations (fig. 17). Important oil reservoirs have thereby been proved at a large number of points (Brent, Forties, Piper, etc., see fig. 18). These oil reserves could be bringing in 6000 million pounds per annum by the mid 1980's. Brent field alone could supply a total estimate of 2250 million barrels of oil and Forties 2000 million barrels.

In the southern parts of the North Sea, important reserves of natural gas occur, mainly in Lower Permian sandstone reser-

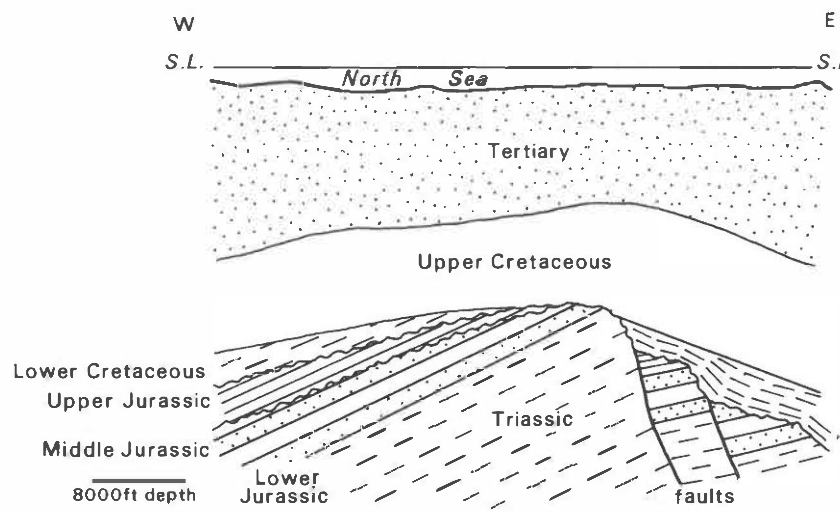


Fig. 17. Section across Brent Field (after Kent).

voirs. Fortunately here these porous sandstones were deposited as an area of Permian desert sand dunes directly over thick Coal Measures. The gasses being driven off coal seams found their way into these Permian sand bodies. It is fortunate for Britain that the western portions of both the oil-bearing grabens and of the great gas field occur in British waters. It could so easily have been otherwise.

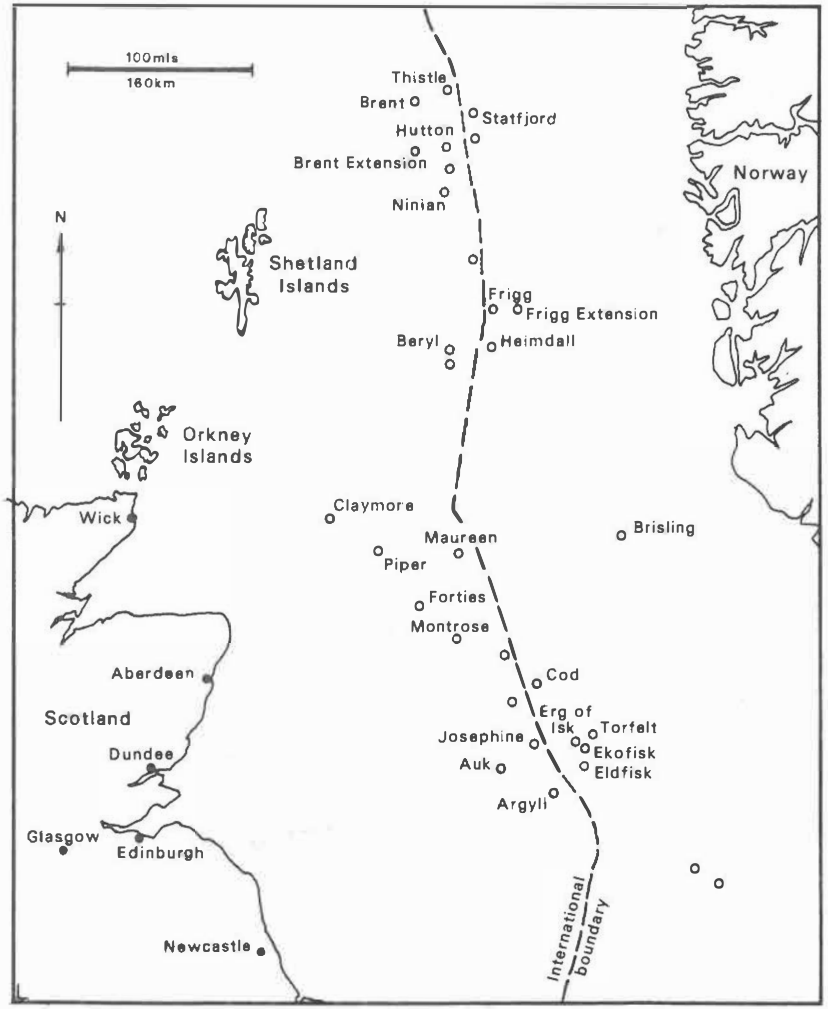


Fig. 18. The oilfields of the North Sea.

These investigations beneath the British seas have not only been beneficial to our economy. They have been a tremendous stimulus to our geological reconstructions of the British past. The British geological map now incorporates all the sea areas and has given us a wealth of new vital evidence. Changes in our thinking have had to be made. For example, an important borehole drilled in the late 60's on the coast of Merionethshire, at Mochras (fig. 19), proved the thickest Lower Jurassic marine sequence in Britain and this in an area that was previously thought to have been a land area during Jurassic times!

What now of the future? The new theory has provided many explanations and helped to pull the subject together, but it has at the same time posed new problems and offered new challenges. Herein lies the work for the future. Let us briefly look at some of these problems and challenges.

Much work needs still to be done with regard to magnetic polarity reversals. A start has been made and a geomagnetic polarity reversal time scale has been calibrated back to about 4½ million years, using volcanic lavas and deep sea cores. This length of time has been divided into four major epochs, each of roughly 1 million years in length. There are possibilities here for extending backwards even further in time a new geological

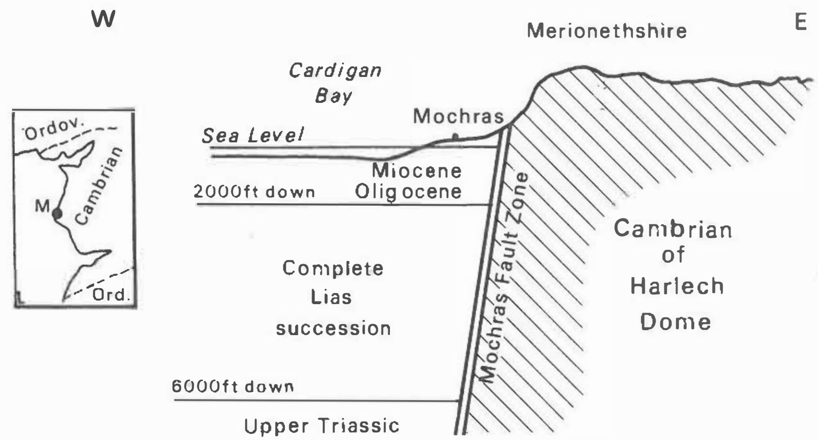


Fig. 19. The Mochras Borehole.

time scale, which will strengthen, by correlating with, the normal methods of dividing geological time.

Attempts have been made to correlate *major* polarity reversals with geological events. As far as one can assess, the polarity tendency has been as follows:-

Tertiary and Quaternary times:-	Mixed normal and reversed
Cretaceous:-	Mainly normal
Jurassic:-	Normal becoming mixed
Triassic:-	Mixed becoming normal
Permian:-	Mostly reversed becoming mixed in later Permian times
Carboniferous:-	Mainly reversed
Devonian:-	Mixed
Silurian:-	Mainly normal
Ordovician:-	Mostly mixed becoming normal in late Ordovician times

A long period of mainly reversed polarity characterised the Carboniferous and Permian periods. Has this any significant correlation with events? This was the time when, after having been wandering appreciably, the continental masses collected together into Wegener's "Pangaea". Could it explain peculiar climatic circumstances—the luxuriant Coal Measure forests of Europe and N. America and at the same time the widespread glaciations of the southern continents (plus a then more southerly positioned India)? Cretaceous times was largely a normal polarity time but at the close of the Cretaceous rapid reversals began to occur. Could this explain the extinction of the giant Dinosaurs? What happens when the polarity reverses? From detailed studies which have been made of deep sea sediment cores the intensity of the magnetic field appears to change as shown in fig. 20. The intensity appears to be reduced by a factor of about ten immediately before the reversal. The magnetic poles then swing right across the globe to their changed positions and the field intensity is rapidly restored in the next 10,000 years. What happens during the 2000 critical years when the earth's magnetic field is very low in intensity and when the actual swing over takes place? It has been suggested by some that charged particles fall from the outer atmosphere to the surface of the earth and that more cosmic rays reach that surface. Could these effects cause changes in or extinctions of living species? One British scientist believes that ice ages may *cause* changes in the earth's magnetic field.

The Plate Tectonic Theory has helped to understand the causes of earthquakes and volcanic eruptions. By progressing with research will man one day be able to *predict* the onset of an eruption or the time of a major earthquake? At the moment, this seems a far cry but man should persevere. Lines of investigation appear to involve the study of animal behaviour prior to an earthquake tremor, the use of satellites for observing mass changes of topography, the studies of P and S wave

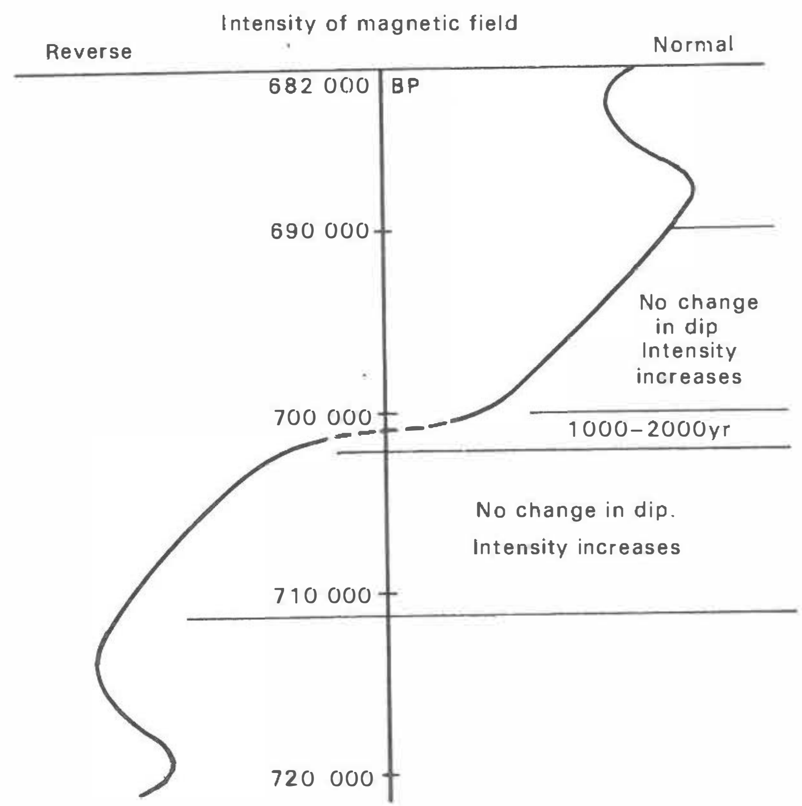


Fig. 20. Polarity reversal (after Wyllie).

velocities through rocks in the time preceeding and succeeding the occurrence of an earthquake. It has been noted that the duration of anomalously low VP is a function of the magnitude of the earthquake and of the length of the warning period. The expected point of return of the Vp curve to its original track (Y in fig. 21) is the approximate time of the earthquake. The longer this gap (from X to Y), the more intense the earthquake. (It can go wrong. A Californian earthquake predicted for 1969 didn't occur until 1971). Much further laboratory

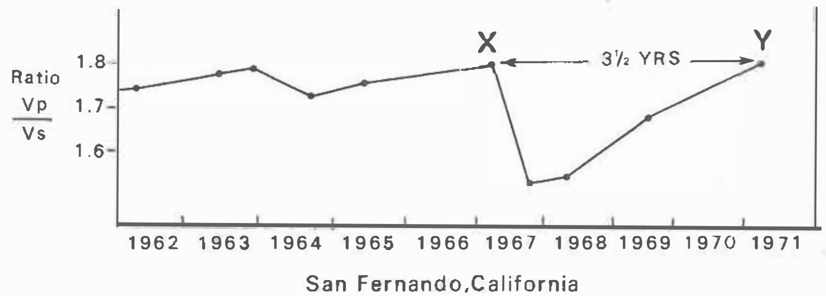


Fig. 21. Variations in $\frac{Vp}{Vs}$ at San Fernando, California (after Wyllie).

and field studies are also needed, especially in rock fracture and changes in rock porosity and dilatancy. Earthquake control is another challenging problem for the future. An earthquake really happens when fault blocks are *locked,* not when they can move freely. If one can therefore facilitate movements —on a small and gradual scale—then the possibility of a major earthquake may be thwarted. Experiments involving the injection of waste fluids into fractured rocks have been initiated. It has been estimated that 500 boreholes costing 1 million dollars each would be required to tame the San Andreas Fault in California.

The application of modern plate tectonics to past geological history is very much in its infancy, and one must guard in suggesting solutions which are too simple and too glib. One challenging facet is the recognition of preserved ancient ocean crust (ocean floor) in the geological record. Subduction should of course completely destroy any ancient ocean floor. For-

tunately however, during subductive processes some oceanic lithosphere may become thrust upwards on to the edge of the opposing plate and be preserved. Such a process is called "obduction". Obducted slices have been identified as "ophiolite complexes" in Newfoundland, S. W. Scotland and more importantly in the Troodos Mountains of Cyprus, where sections through preserved oceanic lithosphere shows an 8 km sequence down from pillow lavas through sheeted intrusive complexes to gabbro and eventually to ultrabasics which may even represent sub-Moho material. The Americans and the Russians were some years ago thinking of spending billions of dollars or roubles in drilling super-deep holes down to the Moho. They never did and it's just as well because today one can examine the same sequence on land in Cyprus! Nature has there hurled the crust up for us to see.

Reconstruction of ancient sea floor spreading patterns again offer a challenge, and one may be in for surprises as more data is forthcoming. Already different schools of research are suggesting that the Earth once had an extra continent, called "Pacifica" (situated perhaps near Australia) which suffered splitting at about the beginning of Triassic times and then drifted off in portions towards China, E. Siberia, N. America and S. America respectively. These "Pacifica" fragments are now embedded in the circum-Pacific mountain belts and help to explain the formation of these rucked up folded ranges. There is undoubtedly a mass of geological, geophysical and biological evidence to link the Western Cordilleras of N. America with N.E. Asia.

Geochemical and mineralogical research is also concentrating on active plate boundaries and on deep oceanic mineral deposits. "The extension of plate tectonic concepts to exploration has so far been limited to providing general guide lines to likely new areas of mineralisation, but further refinements to the hypothesis should eventually be of great value in making more precise predictions of the location of specific types of ore body" (Mitchell and Garson, 1976). Metallic sulphide deposits are closely linked with present day or former convergent plate boundaries (subduction or collision type). Important areas include the Kuroko deposits of Japan, the sulphide ores of the Philippines and the deposits of the

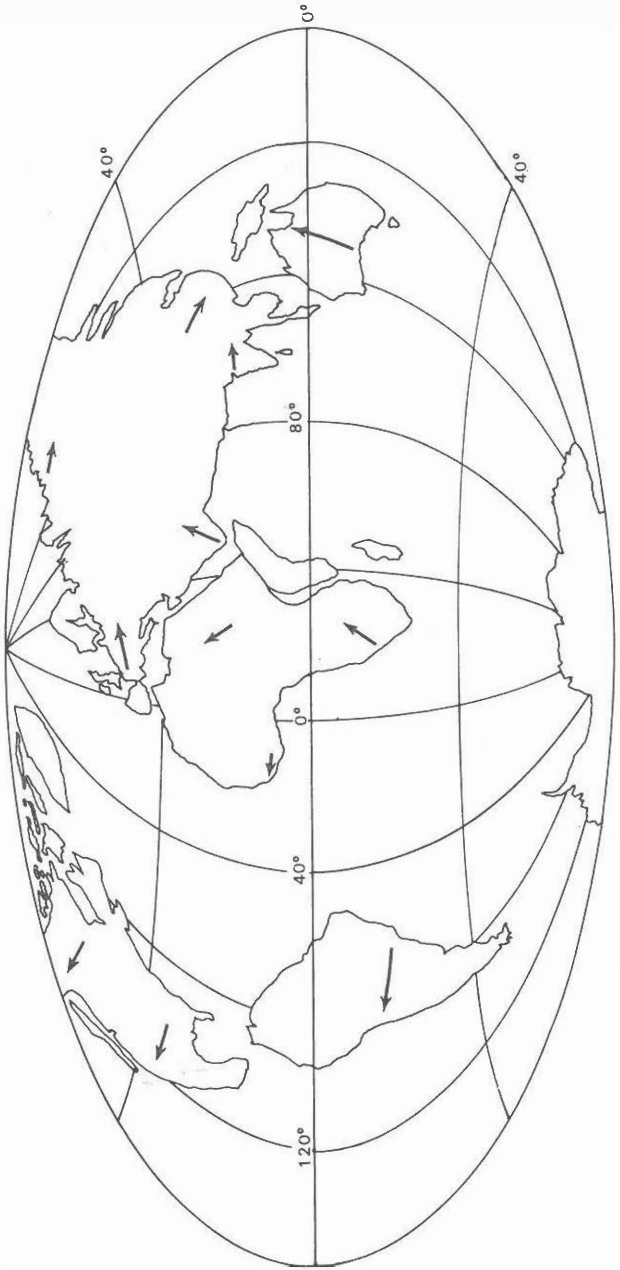


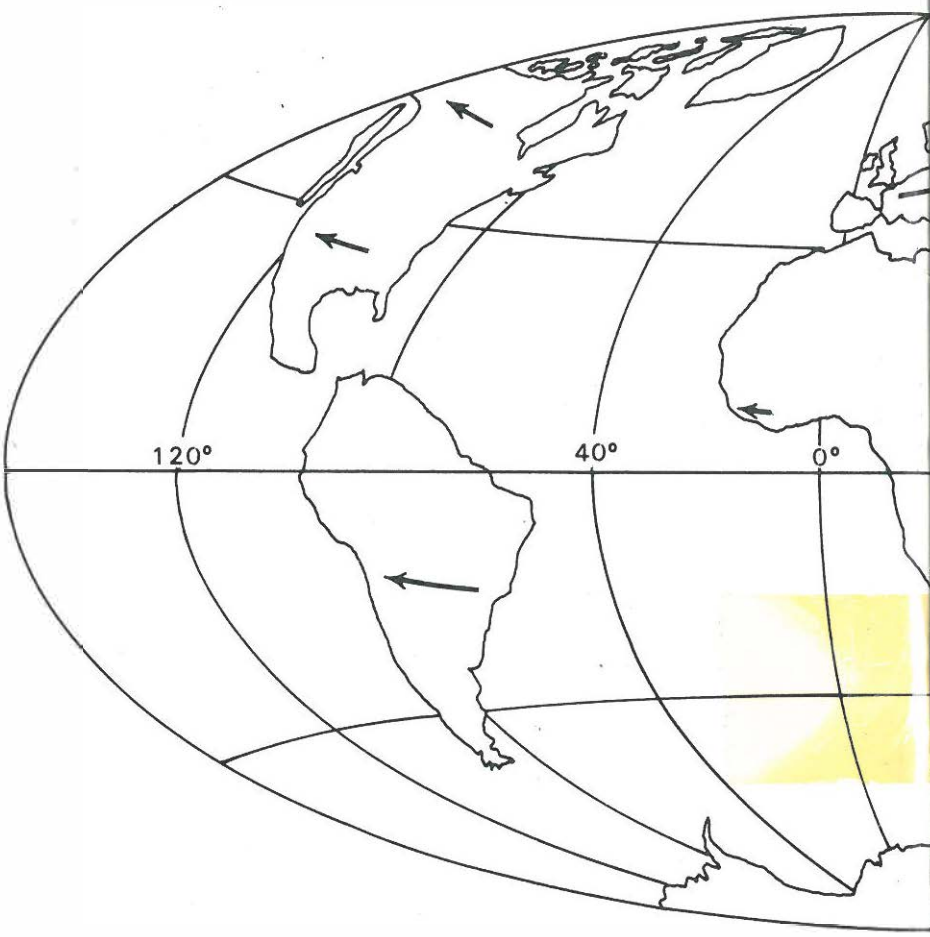
Fig. 22. The World of 50 million years hence (after Dietz and Holden).

Coast Ranges, the Rockies, the Andes and the eastern Mediterranean (Cyprus and Turkey). Gold-bearing deposits often accompany sulphide minerals and many of the important gold areas of the world occur in rocks that can be associated with former convergent plate boundaries.

Divergent plate boundaries too are the sites of important mineral potential. About ten years ago rich submarine sulphide deposits were found at depth along the centre of the Red Sea, a present day initial stage of oceanic opening. Mid-oceanic ridges are believed to be other mineral enriched areas, rich in iron, manganese, copper, nickel, lead, uranium and mercury and will be the scene of active exploration and drilling in years ahead. Mineral deposits originally formed in an isolated position on a spreading line may in fact eventually form long zones parallel to the direction of spreading.

Finally, what of future plate positions? In order to make any sort of prediction one must of course assume present-day rates. This gives a picture something like fig. 22 for 50 million years hence. The Americas will have moved well westwards, South America especially so. India will have turned eastwards. Australia will have moved its whole length northwards. The first Test match at Brisbane will take place on the Equator? Swansea will be in Germany! Last but not least, New Zealand will have been completely sheared out of existence by continued slip along the great Alpine Fault. Llanelli's record against the All Blacks would be secure for all time!

[*My sincere thanks are due to Mrs. V. M. Jenkins for typing the manuscript and to Mr. G. Lewis for drawing the illustrations*].



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