# C. CONVECTION CURRENTS AND CONTINENTAL DRIFT

## XIII. Evidence from ocean islands suggesting movement in the Earth

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Oceanic islands increase in age from the mid-ocean ridges towards continents and the andesite line reaching a maximum known age of Upper Jurassic. The Seychelles appear to be a continental fragment.

Several pairs of lateral aseismic ridges extend from islands on the mid-ocean ridge to adjacent continents. Their continental junctions mark points on opposite coasts which would also fit if the continents were reassembled according to the criteria used by Wegener. As Holmes has shown each pair of ridges tends to have distinctive chemical characteristics.

One possible explanation is that convection currents in the mantle rising along the mid-ocean ridges and sinking beneath trenches have carried the crust apart across the Atlantic, India and East Pacific Oceans. The lateral ridges may be approximately streamlines.

Although Darwin showed that most volcanic islands sink, a few have been uplifted. Most of these lie a few hundred kilometres in front of deep trenches, suggesting that they may be on the crest of a standing wave in front of the trenches and that the crust is rigid.

Of eleven straight chains of young islands in the Pacific ten get older away from the East Pacific Ridge. They could also be streamlines, fed by lava rising from deep within convection cells with stagnant cores. The regularity of ridges suggests non-turbulent flow.

### 1. Introduction

If the continents have moved, then they have drifted like rafts and formed the ocean floors in their wake. It is to this wake that we should look first for evidence of past motion. This paper reviews some of the information about ocean basins, islands and cores of bottom sediments which provides evidence of the nature of that motion.

This study suggests which coasts, now separated, once fitted together. Their geology is then examined to try to confirm these ideas and to find when separation occurred. Geophysical data are also pertinent, but they are not discussed here.

The conclusions suggest a pattern of surface movement which is not very symmetrical, and certainly less so than the patterns of deeper movement suggested by physicists on theoretical grounds. This raises the question of how closely the surface pattern is likely to follow and reflect the deeper flow. Some conclusions are drawn about the probable nature of deeper flow.

### 2. The Atlantic Ocean

#### (*a*) *Ages of islands and cores*

In the Atlantic Ocean fossils have been found, and described, on at least nine islands and three sea-mounts which lie beyond the continental shelves. Isotopic age determinations have been published for the Tristan da Cunha group and other geological reasoning has been used to date five more islands. These ages have been plotted on figure 1 which is revised from Wilson (1963*a*) with additional ages for Caryn Peak Seamount (Miller & Ewing 1956), Great Meteor Seamount (Pratt 1960) and Muir Seamount

(Tolstoy & Ewing 1949). Not all the ages agree with those in the previous compilation. This is in part a reflection of the uncertainties and arguments about the ages of some islands. In part it is due to plotting the age of the beginning instead of the middle of any epoch to which fossils were assigned. Thus fossils described as Miocene are here given the date 25 instead of 20 My. This seems justified because a considerable length of time must have been required to build any of these islands. The ages are still regarded as minimum ages.

FIGURE 1. Sketch of the Atlantic Ocean. The numbers are maximum recorded ages (in millions of years) of islands and sea-mounts (●) and of cores ( • ).

Ericson, Ewing, Wollin & Heezen (1961) and Northrop & Heezen (1951) have reported pre-Pleistocene ages for fossils from forty-six cores collected by themselves and others. The ages of fourteen of the older cores have been plotted. The other cores were omitted because they are either too young or too close to other cores to provide additional information of consequence.

It is obvious from this map that the greatest ages are towards the margins of the ocean basin and that there are no old ages in the centre. This is not from any lack of islands or cores there, nor is it because the sedimentary layer is thick and has buried the older rocks there, for Ewing, Ewing & Talwani (1964) have shown that the central zone of the Mid-Atlantic ridge is bare across a width of 75 miles and that sediment is thin over most of the ocean floor. At intervals around the coasts of the Atlantic Ocean marine invasions have left coastal plains or infaulted patches of rock of various Jurassic, Cretaceous and Tertiary ages. The significance of these ages will be discussed later.

The evidence supports the views of Wegener (1924) and Holmes (1928–29) that the Atlantic Ocean has been spreading away from the mid-ocean ridge.

### (*b*) *Possible fit of continents before separation*

If the continents have separated, the problem arises of finding the precise pattern in which they were fitted together before separating.

In the South Atlantic only one fit is likely. This excellent match between Africa and South America cannot be directly extended to the North Atlantic because of uncertainties about possible Cenozoic movements in the Mediterranean and Caribbean, nor can the fit of North America and Europe be uniquely determined on the basis of topographic fit. Palaeomagnetic observations offer a guide but are imprecise.

A different criterion for fitting continents is based upon an observation about the Walvis and Rio Grande lateral ridges which extend across the South Atlantic. If the shoreward ends of those ridges are placed in juxtaposition the same fit is obtained between Africa and South America as by matching the coast lines (Wilson 1963 *a*). If one assumes that this method is generally applicable one can use the lateral ridges from Iceland to Scotland and to east Greenland, and from west Greenland to Baffin Island to derive a unique reconstruction of Europe and North America. According to this method Kangerdlugssuak, east Greenland, must be placed beside the Shetland Islands and Disco Island, west Greenland, beside Cape Dyer, Baffin Island. The latter ridge is rather broad, but precision can be given to the fit if the channels between northwest Greenland and Ellesmere Island are regarded as a shear. Wegener suggested this and evidence of faulting has been found (Christie 1962) on the Ellesmere side of the channel.

To fit the combined Europe and North America to the combined Africa and South America, one must rely on topographic fit, but this gives a fairly obvious solution, with northwest Africa fitting against the eastern coast of the United States. The Caribbean is largely closed and the Tethys seaway opened to the east. Spain is displaced.

The adjacent coasts of the reassembled continents may now be compared. Spitsbergen (Harland 1961) is thus placed so that its present north coast abuts against the present northeastern end of Ellesmere Island (Douglas, Norris, Thorsteinsson & Tozer 1963) and the two present many similarities (figure 2).

The nature and origin of the Lomonosov Ridge has been a problem. Russian geologists have regarded it as a sedimentary fold belt, unique in the ocean basins. Others have considered that it is likely to be a basaltic ridge, as are many other submarine features. Ostenso (1960) found a lack of magnetic anomalies and hence regarded it as sedimentary in nature. It can be seen on modern atlases that the Lomonosov has a shape which replicates that of the edge of the Siberian platform and it has been suggested by Heezen & Ewing (1961) that the two have moved apart. That view is accepted and it is here proposed that the Lomonosov Ridge is an old continental shelf of gently dipping sedimentary rocks, which was detached from Siberia probably along the original fault margin of the continental block.

The entire northwest coast of Norway would have lain alongside of the northern part of the east Greenland coast north of Scoresby Sound. Both are Caledonian mountain systems for which isotopic age determinations by the potassium-argon method give minimum ages of 490 to 375 My for eight specimens scattered along the northern half of the east Greenland coast (Haller & Kulp 1962; Kulp, Kologrivov, Haller & Koch 1962*a*, *b*)

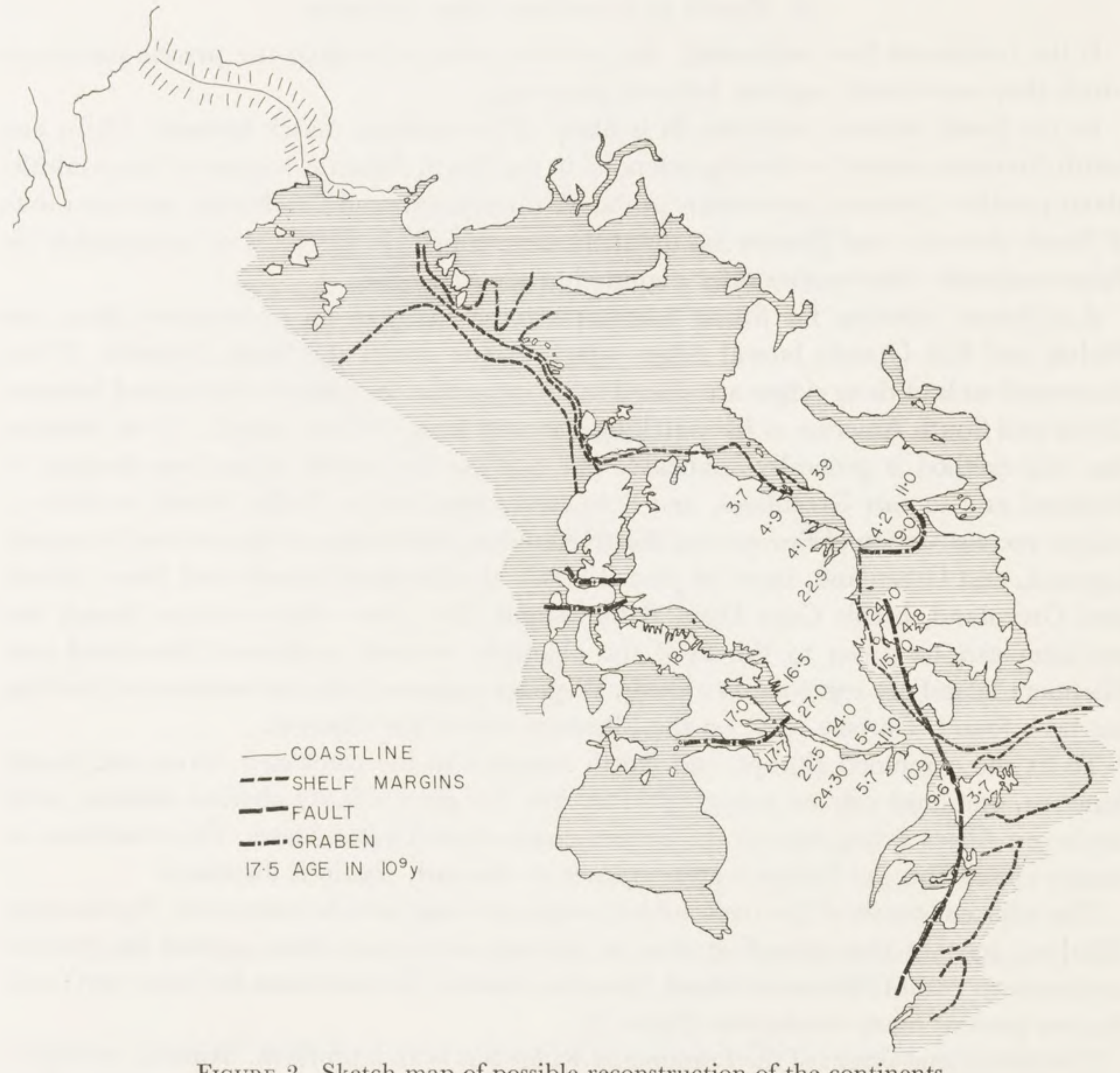


FIGURE 2. Sketch map of possible reconstruction of the continents before the opening of the Atlantic Ocean.

and 575 to 385 My for eight determinations from the northwest coast of Norway (Kulp & Neumann 1961). A single determination south of Scoresby Sound (Kulp *et al.* 1962*b*) gives a rubidium-strontium determination of 2290 My which is comparable with the Scourian ages obtained by Giletti, Moorbath & Lambert (1961) for northwestern Scotland at the conjugate point in our reconstruction.

The match of ages across Baffin Bay is again striking. South of Cape Dyer the three ages closest to the coast are 1605, 1700 and 1715 My (Leech, Lowden, Stockwell & Wanless

1963). Opposite to these is an age of 1650 My in the Nagssugtoqides (Armstrong 1963). The greatest ages in the Nain province of Labrador of 2250, 2395 and 2430 would lie opposite the Ketildes on the Greenland coast which have ages of 2700 and 2400. These are followed by a determination of 570 My for the Aillik lamprophyre dikes in Labrador opposite to 560 My for a pegmatite from Ivigtut in Greenland. The Grenville Province of 960 to 1095 My lies opposite to the Garder Intrusives of 1100 to 1200 My. This fit also brings the Great Glen and Cabot Fault into alinement (Wilson 1963*b*), so that the whole reassembly fits remarkably well.


FIGURE 3. Sketch map of possible reconstruction of continents before the opening of the central and southern part of the Atlantic Ocean. The Americas have been drawn together. Spain has probably rotated.

The possibility that the Caledonian and Hercynian mountain belts of Europe are continued in the Appalachians of Canada and United States has often been raised, but a new aspect has been added by the discovery that the fold belt along the northwest coast of Africa is also of Hercynian age (Sougy 1962). In our reconstruction this feature lies against the North American coast from New England to Georgia and forms the hypothetical land of Appalachia (figure 3). This part of the Appalachians has always seemed too narrow. The Avalon and Meguma rocks of eastern Newfoundland and Nova Scotia which add width to the northern Appalachians may once have been continuous with the fold belt in northwestern Africa.

When South America is brought into the position against Africa traditionally assigned to it by proponents of drift then the Caribbean Sea and Gulf of Mexico and the South

Atlantic are closed. The geological similarities across the South Atlantic between Africa and South America are so striking and have been so thoroughly discussed by du Toit (1937) and Martin (1961) that they do not need to be reviewed here.

### (*c*) *History of formation of the Atlantic Ocean*

If continents have moved, the evidence suggests that they were joined together in the Triassic period, producing the widespread desert and continental conditions so evident in the geological record. There is no marine Triassic anywhere along the Atlantic, but it is abundant along the Pacific coasts, in the Tethys region and in the western part of the Arctic basin. So far as the Atlantic is concerned, the breakup of the continent began in two places; from the Pacific Ocean eastwards through the Caribbean and from the Arctic Sea southwards between Spitsbergen and Greenland.

Of the evidence for the spread of the Atlantic Ocean from the Arctic Sea southwards, Nielsen (1961) has stated: 'the fish-bearing Triassic sediments in east Greenland were deposited in shallow ocean basins whose connexion with the open sea was highly variable...close relatives of the Greenland forms play an essential part in the upper Scythic marine fish fauna from Spitsbergen'.

Trumpy (1961) also writes: 'The Eotriassic sea of central east Greenland formed a narrow arm opening to the northeast into the Arctic Ocean and having a blind southern ending in the vicinity of Scoresby Sound. Detritus from the west was predominant during desposition of the *Glyptophiceras* and *Ophiceras* beds. Later on, the main supply came from a land mass to the east, of which Liverpool Land and the Canning Land are remnants. There is no direct proof for the existence of a North Atlantic Ocean in the Triassic (or, indeed, up to the Cretaceous).'

Concerning the history of the Jurassic period, Arkell summarized his findings in the statement: 'All the occurrences of Jurassic formations chronicled in the preceding chapters amount to little more than relics of marginal lappings of the sea around the edges of the continents; the sole exception being the Tethys, a sea which stretches across southern Asia from west to east along the band that was destined to influence the great Tertiary mountain chains' (Arkell 1956, p. 595).

Only one modification may be needed. At the time he wrote little was known of the Verkhoyansk Range which has since been shown to be another great geosyncline (Markovsky 1961) and which has been postulated to form the connexion between the Arctic Sea and the Pacific (Wilson 1963*a*).

At times, the Jurassic seas which lapped the northern coasts of the continents of Europe and Asia extended far inland. For the most part they were epicontinental, shallow seas and the question to be resolved is to what extent there is evidence that the Atlantic Ocean existed or became open during that period. Donovan (1957) who studied the east coast of Greenland, did not believe in drift and stresses the differences between the faunas and times of sedimentation in Greenland and in Scotland and Norway. On the other hand, he states that the first signs of disturbance along the faults which bound Jurassic and Cretaceous deposits in east Greenland were in Upper Jurassic time.

Arkell (1956) who also did not believe in drift describes the Jurassic rocks of east Greenland as 'a series of transgressions of the "Scandic Ocean" over the block-faulted, irregularly down-sinking continental margin. They were laid down on the opposite shore of the same ocean as that which to the eastward overspread the Barents Shelf, leaving its deposits in Spitsbergen and Ando (Norway) and both sides of the Scottish Highlands.'

Although Arkell speaks of the need for western seaways in the site of the present Atlantic, no Jurassic rocks are preserved, on the coasts of northern Europe, but all the deposits across England, France, Russia and Germany are those of shallow epicontinental seas. Evidence of deep water is only seen in the Alpine or Tethys region and in southern Spain.

Along the Atlantic coast of Europe, there are deposits in Portugal and on the north coast of Spain. Those of the Asturias are linked by Arkell with other Iberian deposits which are said to be 'essentially epicontinental and contain a succession of faunas similar to those of the Pyrenees, France and intra-Alpine Europe'. In Portugal, the Jurassic rocks, although on the coast, are said to have been deposited in a north–south gulf between Europe and 'the suppositious North Atlantic continent which may be represented by the tiny islands of Berlengas and Farilhoes, of ancient granite'.

Thus in spite of Arkell's opinion against continental drift, he offers no definite evidence that the North Atlantic was open in the Jurassic. A shallow, epicontinental seaway extending across Europe as far as Portugal would suffice to explain the lithology of all the known deposits and, at least, most of the faunal connexions, but the great block faults which let down the coast of East Greenland suggest that the rifting of the future Atlantic Ocean may have been beginning in the north towards the close of the Upper Jurassic epoch.

Turning now to the Cretaceous, rocks of that period are only found along the north-western coast of Norway overlying Jurassic in the infaulted basin at Ando. Holtedahl (1950) has drawn attention to evidence from submarine contours 'that the high north-western part of the Scandinavian Peninsula is bordered by fractures along which dislocations probably took place during the Tertiary uplift of the land mass'. He suggests that these faults extend from the northern part of Norway south to the Norwegian Channel. This is a submarine trough following the coast of southern Norway from the edge of the continental shelf for 800 km up the Skaggerak to an abrupt termination against post-Cretaceous faults south of Oslo fjord. It has parallel sides about 60 to 80 km apart. It is a region of present seismicity and perhaps Eocene volcanicity and is generally believed to be due to faulting. It is suggested that it may be a similar structure to the Bahia graben on the Atlantic coast of Brazil.

There seems to be general agreement about the youth of the southern half of the coast of east Greenland. Donovan (1957) who did not favour drift agreed that it was young. Wager (1940) states that 'In late Cretaceous much of the coast was at sea level and marine Senonian sediments were laid down. Up to 7 km of basalts followed. During middle Eocene, powerful uplift of mountains and sinking of Denmark Strait. During the resulting flexuring, a dike swarm was intruded parallel to the coast.'

Wager & Deer (1939) found that the latest flows were late Eocene or Oligocene and the fauna bears a closer relation to Arctic and boreal forms of the old world rather than to the new. In 1938, they noted a close relation between the dip of the lavas, the density of the swarm and the dip of the dikes. Lava extrusion was a slow process and gave time for dikes to cool and flows to be eroded before adjoining dikes and overlying flows followed. There is evidence that neither flows nor dikes ever extended into the interior.

In Skye, Harker (1904) found similar flexuring and dikes and suggested that the flexure was the result of events of large order 'such as the formation of the Atlantic'.

Wager considered that the coastal mountains of east Greenland were rapidly uplifted by 3·5 km along 800 km of coast, and pointed out that this must have involved subcrustal flow, possibly due to convection currents.

It was formerly believed (Hawkes 1916; Holmes & Harwood 1918; Noe-Nygaard 1946; Tyrrell 1949) that the thick lava piles of Greenland, Iceland, the Faeroes, Scotland, Ireland and Jan Mayen were all parts of a vast pile of flood basalts which had been faulted, tilted and eroded. Walker (1960, 1963) has shown that this is not true, but that the Tertiary volcanic piles 'represent more or less elongated lava lenticles of exceptionally great thickness rather than the eroded remnants of an originally continuous lava flows'. He considers that the flows are arranged like two piles of overlapping shingles extending towards Greenland, and Scotland from Iceland and both dipping towards the centre.

In the middle of Iceland, the flows are recent and flat-lying, but as the flows are slowly buried by successive eruptions and as the two halves of Iceland are slowly pulled apart so the beds are tilted to dip inwards. Walker (1960) holds that the 'crustal flexure along the east coast of Greenland may be an extreme example with steep-dip due to an unusually rapid increase in thickness'. It thus appears that the same process has been operating in Greenland, Iceland, and Skye and that it may be the splitting of the Atlantic basin.

Good dating and proof of the youth of Iceland and the Faeroes would do much to corroborate this hypothesis, but the ages of both are uncertain and the subject of divergent views. No marine fossils older than Pliocene are known in Iceland. Some plants from Iceland are regarded as Miocene, but may be older.

Presumably, the history of the opening of Baffin Bay can be regarded as being similar. At Disco Island on west Greenland, there is a well-dated marine succession from Upper Cretaceous to Eocene (Munch & Noe-Nygaard 1957). On the opposite coast of Baffin Island are lavas and sediments, but unfortunately, they have only been briefly described by Kidd (1953).

Fortier & Morley (1956) and Gregory, Bower & Morley (1960) found evidence from an airborne magnetometer profile that the basement beneath Lancaster Sound had been depressed and possibly offset by faulting. They regarded the coast of Baffin Island and the valleys which cross it through Cumberland, Frobisher and Chorkbak inlets as features formed by faulting and tilting, presumably in Tertiary times. It is possible that both Lancaster Sound and Hudson Strait not only follow faults, but are also rifts like the Norwegian Channel.

Farther south off Godhaab, both Holtedahl (1950) and Dibner, Drylov, Sedova & Vakar (1963) have pointed to the bathymetry as evidence of downfaulting off the coast and the latter described Cretaceous and Paleocene fragments dredged there.

Kranck (1939, 1947) has discussed the dikes which are a well known feature of the coast of Labrador and which also occur on the coast of Baffin Island. Unfortunately detailed descriptions of these coasts have never been published and the problem is confused by the presence of little altered Precambrian dikes in addition to those of possible Cenozoic age. Kranck suggests that Hamilton Inlet may be a graben of Tertiary age.

After referring to the uplifted Labrador surface and the continental shelf up to 1500 m and below it, Tanner (1944) states: 'It is therefore scarcely possible not to assume that the eastern border is formed by a fault zone stretching in the main parallel with the coast.'

These views are given support by Bidgood & Harland (1961) who interpreted palaeomagnetic studies of some Greenland rocks as follows: 'This would be consistent with a movement of Greenland relative to North America which increased the separation of the two areas to give their present positions, that is, mainly by the opening of the Davis Strait and Baffin Bay and some spread among the Canadian Arctic Island. The movement would be post-Triassic in date.'

The margins of all these northern coasts of Greenland, Norway, Baffin Island and Labrador were lifted up by as much as 3·5 km, apparently by faulting. For each case, the land slopes gently to the interior, so that the highest elevations are close to the coast. Thus Greenland is saucer-shaped. This type of structure resembles that of the African rift valleys in which the down-faulted rifts are bordered by raised margins. The east coast of Brazil is similar.

On the other hand, the coasts of Great Britain, southern Europe and United States are not uplifted at the margins. On the contrary, the Cretaceous seas lapped progressively farther inland on the Atlantic and Gulf coasts of United States. Beginning with Lower Cretaceous beds, these coastal deposits form a great shelf and fill a deep trough along the whole east coast of United States which probably extends off the coast up to the banks off Newfoundland. They have been described by Drake, Ewing & Sutton (1959) and by Murray (1961).

Engelen (1963) has reinterpreted these data and suggested that the troughs and the rapid changes in depth of basins along the coast are due to faulting. He believes that tectonic disturbances started off Newfoundland in early Cretaceous time and has continued there ever since, but that the activity began at later times farther south. He implies that the Blake submarine plateau is due to late Tertiary downfaulting, which seems a reasonable explanation.

In the Gulf Coast area nepheline syenite stocks, other small intrusives and volcanic ash beds of late Cretaceous age show that it was a period of igneous activity.

In Scotland and Ireland, thin beds of Cretaceous chalk crop out beneath the base of the flood basalts, but residual flints provide evidence that most of Ireland was once so covered by chalk (Charlesworth 1953). The basalt flows, of presumably early Tertiary age, were soon followed by block faulting which lowered the coasts of northeast Ireland.

The second channel by which the Atlantic Ocean was opened was from the Pacific Ocean across the Caribbean. The start of this has been mentioned by Vaughan (1918) who pointed out that land conditions probably prevailed throughout Mexico and Central America in Lower and Middle Triassic, but that during the Upper Triassic submergence of central Mexico very probably gave rise to an inter-oceanic connexion.

During the Jurassic, the mountain ranges and fold axes of Southern Mexico and Central America had an east–west strike according to Arkell and the 'Lithology and fauna in southern Mexico indicate that in the Jurassic, the same grain was followed by a seaway which at times linked the Gulf of Mexico with the Pacific and afforded a migration route across southern Mexico.... A more permanent connection between the Atlantic and

Pacific Oceans lay farther south through the Caribbean and across Costa Rica and Panama.'

These seas penetrated as far east as Trinidad, Cuba and Alabama, but there is no trace of Jurassic rocks along the east coast of North America south of Greenland nor any on either coast of the South Atlantic Ocean with two small exceptions.

Haughton (1963) states that the only Jurassic formation in West Africa is the Amisian which is found in graben within the Precambrian of Ghana, but he and Furon (1963) both agree that these sediments are not marine, nor are any of the Jurassic beds of central Africa.

Pires Soares (1948) has described siliceous marine limestones on Maio Island in the Cape Verde Islands as belonging to the latest Jurassic. This isolated occurrence is at the most westerly part of Africa. According to our reconstruction the Guianas then lay against the southern coast of the United States and both would be close to the Cape Verde Islands. The seas which reached Trinidad and the northern coast of the Gulf of Mexico would then have needed but a slight extension to reach the Cape Verde Islands and that appears to be the limit of marine penetration from the Pacific during the Jurassic period.

Arkell has maintained on palaeontological grounds that there was no direct link during the Jurassic between the Caribbean and the Mediterranean which fits the proposed reconstruction. There is not a single outcrop or any other evidence to suggest that the North Atlantic between Africa and United States or the South Atlantic from Patagonia to Trinidad had started to open before Cretaceous time.

Furon (1963) states explicitly that 'The modern Atlantic Ocean and the west coast of Africa were formed in the Cretaceous'.

The seas which had already reached the Cape Verde Islands have left records of a continuously marine facies there from earliest Cretaceous times. By Aptian times, the sea had spread south along the coast to Cameroons, Gabon and Angola and during the Albian, it penetrated Nigeria. After a regression, Upper Cretaceous seas returned along the coast all around the Gulf of Guinea and penetrated through Nigeria across the Sahara. These basins have been described by Haughton (1963). Across the southern tip of Africa, are other basins of Cretaceous rocks which have been emplaced along faults with throws as great as 12 000 ft.

At Dakar, the Cretaceous and Tertiary beds form a deep basin which is bounded to the east by great faults. The close of the Cretaceous was marked by uplift and volcanic activity which occurred in the Maestrichtian (Furon 1963).

Of major faults, Furon has drawn attention particularly to three which perhaps had their origin in Cretaceous time. He has suggested the existence of a large tectonic trough or rift valley extending northeast through the Cameroons. The four islands in the Guinea Gulf which have Cretaceous rocks on them lie on its continuation. Another tectonic trough believed to be of Cretaceous age, crosses it and is followed by the Lower Niger River. Furon also states that an important fault lies parallel to and off the coast for 2000 km from Liberia to the Cape Verde Islands. It is marked by straight and closely spaced bathymetric contours.

Cretaceous seas left similar deposits along the coasts of Brazil. At the mouth of the Amazon River, borings in the Marajo tectonic trough traversed a thick sequence of clastic, generally continental and deltaic sediments. The abundance of idiomorphic quartz grains indicated derivation of the clastic material from volcanic rocks, probably associated with late Cretaceous volcanism. The occurrence of marine zones within the sequence increases progressively northwards (Amaral 1955). The presence of Cretaceous volcanic rocks near the eastern tip of Brazil has been mentioned by Almeida (1960).

A little farther south, the Bahia graben has been drilled for oil. Moura & Fernandes (1953) have stated that the Reconcavo oil basin, Bahia, Brazil, is composed essentially of Cretaceous (or Upper Jurassic) sediments whose deposition took place in a closed continental basin under conditions of differential subsidence. It has been suggested that both of the Marajo and Bahia grabens may have been formed like those in the Norwegian Channel and the Canadian Arctic Archipelago during the fracturing of the Atlantic Ocean.

Near Rio de Janeiro, a small downfaulted basin has been described which is filled with calcareous and clastic sediments of Paleocene or Late Cretaceous age (Beurlen 1956), but Couto (1958) regards the limestones as probably Upper Cretaceous and terrestrial in origin.

There are abundant Jurassic deposits in Patagonia, but the relationship of Patagonia to the rest of South America at that time is uncertain and no evidence of any early spreading of the Atlantic Ocean has been recorded from the south.

In summarizing, one must distinguish between mere transgressions of shallow seas and the break-up of continents by faulting to form ocean basins. In the north, shallow transgressions began in the Triassic, and during the Jurassic extended right across western Europe. The first evidence of faulting was along the coast of east Greenland in Upper Jurassic time. There seems to be no evidence for wide opening of the North Atlantic before Late Cretaceous when Scotland and Greenland started to move apart and so did Baffin Island and west Greenland. Starting in the Lower Cretaceous epoch, the sea overlapped the east coast of United States.

The second channel, that across Central America, first became apparent during the Upper Triassic transgression. It has been suggested elsewhere that this spreading might have been caused by the East Pacific Ridge, if at that time, it had continued across what is now Central America instead of turning north into the Gulf of California as it does now (Wilson 1963*a*). Apparently, this opening formed true oceanic crust during the Upper Jurassic because the Cape Verde Islands are true oceanic islands with topmost Jurassic beds on them. By the same token, by Lower Cretaceous time, the ocean proper had spread to the Bahamas and the Gulf of Guinea.

This involves a problem. For the ocean to open from the Caribbean as far as the Gulf of Guinea, means that there must also have been movements between either Africa and South America or between Africa and North America. Because the transgressions in the north are so much greater, some rifting to the north seems to be more likely; but the main spreading of the ocean may not have started until near the close of the Cretaceous, for there is evidence then of faulting or volcanism in the Gulf coast, at the mouth of the Amazon, at Bahia, at Rio de Janeiro and at Dakar.

It is interesting to note how many apparent grabens open off the Atlantic; in the Norwegian Channel, among the Canadian Arctic Island, at the mouth of the Amazon and at Bahia. In each case, the geologists who described the features regarded them as highly unusual. All that can be dated seem to have formed about the Cretaceous period.

Thus, the evidence from the margins of the continents is quite compatible with that obtained from the ocean islands and cores and both suggest that spreading began in one or two places during the Jurassic and led to the main spreading of the Atlantic Ocean in Cretaceous time. The main movements seem to have begun in Upper Cretaceous time and were accompanied by widespread volcanism. Spreading continued throughout the Cenozoic to the present time.

### (*d*) *Comparison of the petrology of certain pairs of islands*

If the ocean has moved apart in the manner suggested by figure 1, then certain pairs of islands and pairs of volcanic eruptions on ocean coasts now far removed from one another on opposite sides of the ocean basin, must once have been together and formed at the same time. It is to be expected that such pairs of islands would have very similar rock types.

The close resemblance between the Tertiary volcanic rocks of east and west Iceland and between the Kangerdlugssuak district of east Greenland and the British Isles is as well known as to need no further comment. Indeed, the similarities of all these rocks are so great that until Walker's work (1960, 1963), they were all regarded as remnants of a single vast area of flood basalts. Holmes (1918) for example, drew attention to the very high $TiO_2$ values found in analyses he reported from Greenland, Iceland, Faeroes and to a less striking degree, Scotland.

Farther north, Jan Mayen is often included in the Brito-Arctic petrological province, but in fact the lavas are somewhat different and Tyrrell (1949) has shown that they are marked by unusually high quantities of alkalis. The same is true of the volcanic rocks of the northern coast of east Greenland, north of Scoresby Sound. If the ocean spread apart in an east–west direction, this could be explained.

If this thesis is correct, we might venture to predict that when the rocks of Baffin Island are investigated, they should have similar composition and be of the same Upper Cretaceous and Eocene age as those opposite to them on Disco Island, Greenland.

The Azores are still too close together to provide any significant check, so the next pair which we might expect to be similar are Bermuda and the Canaries.

Bermuda, or the Bermudas, are a group of islands formed of detrital and aeolian limestone. That these limestones rest upon a volcanic peak has been shown by the geomorphology, by aeromagnetic surveys, and by a single borehole which penetrated melilite-basalt beneath Eocene limestone (Pirsson 1914).

The single analysis of this rock was compared by Pirsson with six other analyses of similar types from Baden, Hawaii, Wurtemberg, Arkansas and Quebec. These were the closest he could find but five analyses given by Hausen (1956) of the 'ancient basaltic rocks' on the Anaga Peninsula of Teneriffe are all quite similar to the Bermuda example. They may be of the same age being probably Lower Tertiary and almost certainly Pre-Miocene. This similarity between the Bermuda analysis, two of the analyses chosen by Pirsson and one of the Teneriffe analyses are shown in table 1.

Drilling in Bahamas is not known to have reached any volcanic rocks and the composition of the volcanics buried under central Florida is not known. The next comparison is, therefore, between Fernando de Noronha and the islands of the Guinea Gulf. There can be little question but that this pair of islands lie in the same relation to one another. There is a long and thorough report on Fernando (Almeida 1955), but the African islands have only been partially investigated. In tables 2 and 3, I have reproduced two analyses published by Part (1950) of rocks from Annobon Island. Beside each are two matching

Table 1. Comparison of basalts from Bermuda and Canary Islands

| | melilite-basalt, Bermuda | ouachitite, Arkansas | fourchite, Arkansas | mela-analeime basalt, Teneriffe |
|---|---|---|---|---|
| $SiO_2$ | 38·79 | 36·40 | 42·03 | 40·86 |
| $Al_2O_3$ | 14·55 | 12·94 | 13·60 | 13·40 |
| $Fe_2O_3$ | 5·67 | 8·27 | 7·55 | 7·60 |
| FeO | 6·68 | 4·59 | 6·65 | 5·89 |
| MgO | 7·78 | 11·44 | 6·41 | 7·74 |
| CaO | 14·65 | 14·46 | 14·15 | 11·71 |
| $Ne_2O$ | 2·78 | 3·01 | 1·83 | 2·20 |
| $K_2O$ | 2·54 | 0·97 | 0·97 | 2·40 |
| $H_2O^+$ | 1·99 | 2·36 | 1·08 | 1·21 |
| $H_2O^-$ | 0·67 | — | — | 0·89 |
| $TiO_2$ | 0·80 | 0·42 | 0·57 | 5·31 |
| $CO_2$ | 3·56 | 3·94 | 3·70 | — |

Table 2. Comparison between analyses of trachytes from Annobon and Fernando de Noronha

| | Annobon biotite-trachyte | Noronha alkali trachytes | | Pisani trachytes | Teneriffe trachytes |
|---|---|---|---|---|---|
| $SiO_2$ | 61·55 | 60·81 | 59·13 | 60·20 | 59·40 |
| $Al_2O_3$ | 21·15 | 18·88 | 19·62 | 20·50 | 19·49 |
| $Fe_2O_3$ | 1·24 | 2·57 | 1·57 | 1·58 | 1·45 |
| FeO | 0·84 | 0·00 | 0·72 | 1·01 | 2·30 |
| MgO | 0·30 | 0·61 | 0·41 | 0·39 | 1·05 |
| CaO | 0·65 | 1·70 | 2·71 | 1·96 | 1·66 |
| $Ne_2O$ | 5·31 | 6·20 | 5·94 | 4·75 | 9·34 |
| $K_2O$ | 5·55 | 5·80 | 4·65 | 5·57 | 4·34 |
| $H_2O^+$ | 1·92 | — | 3·81 | 3·00 | 0·26 |
| $H_2O^-$ | 0·86 | 2·22 | 0·27 | — | 0·21 |
| $TiO_2$ | 0·40 | 0·05 | 1·01 | 0·51 | 0·45 |
| $CO_2$ | nil | — | 0·00 | — | — |

Table 3. Comparison between analyses of basic lavas from Annobon and Fernando de Noronha

| | Annobon oceanite | Fernando limburgites | | Baden limburgite |
|---|---|---|---|---|
| $SiO_2$ | 39·20 | 42·18 | 40·80 | 41·14 |
| $Al_2O_3$ | 12·49 | 11·91 | 12·89 | 12·67 |
| $Fe_2O_3$ | 3·47 | 7·91 | 5·00 | 4·72 |
| FeO | 9·48 | 5·81 | 9·05 | 7·25 |
| MgO | 16·52 | 13·23 | 11·00 | 11·30 |
| CaO | 9·88 | 11·12 | 11·48 | 12·02 |
| $Ne_2O$ | 1·98 | 2·21 | 4·04 | 2·80 |
| $K_2O$ | 1·05 | 1·32 | 1·63 | 1·27 |
| $H_2O^+$ | 0·27 | 3·02 | 0·10 | 2·60 |
| $H_2O^-$ | 1·00 | 0·53 | 0·60 | 0·74 |
| $TiO_2$ | 3·70 | 1·43 | 2·20 | 3·46 |
| $CO_2$ | nil | nil | nil | 0·08 |

analyses from Fernando and other analyses from different parts of the world, chosen by Almeida because they closely resembled those from Fernando. Again, it can be seen that the Annobon analyses are quite as similar to the Fernando rocks as any which Almeida could find with the whole world to choose from.

These relations, therefore, suggest the general conclusion that, whereas the Atlantic Ocean may be longitudinally divided into zones each having the same age, it may be divided latitudinally into zones each having a characteristic composition.

## 3. Indian Ocean

The same principles should be applicable to the Indian Ocean. Students of Gondwanaland believe that it opened during late Mesozoic and Tertiary times and Ewing & Heezen (1960) have traced mid-ocean ridges through it. I have already suggested four aseismic, lateral ridges with two large faults postulated by others, provide a guide to reconstructing the former continent (Wilson 1963*a*). Inasmuch as the history of the Indian Ocean is believed to be more complex than that of the Atlantic, and because a great deal of new information has recently been obtained, which is not yet published, it seems better to wait before discussing the history of the Indian Ocean further.

## 4. Pacific Ocean

### (*a*) *Spreading from the East Pacific Rise*

Evidence has been given to show that the Atlantic Ocean has spread nearly symmetrically from a mid-ocean ridge and that the Indian Ocean may have done the same. The seismically active mid-ocean ridge continues across the Pacific Ocean where it has been called the East Pacific Rise, but it is far to the southeast of a median line across the Pacific Ocean Basin (Menard 1960). Consistency suggests using the name East Pacific Ridge.

The region which it crosses has too few islands and is too little explored for any useful attempt to be made to plot its possible growth in the manner used for the Atlantic. It has been shown that, of eleven linear chains of islands which contain active or recently active volcanoes, in the eastern part of the Pacific, ten get progressively older in the direction away from East Pacific Ridge (figure 4). The only exception, Samoa, is located in a special tectonic position beside a sharp bend in the Andesite Line. The islands are in fact arranged like plumes of smoke which are being carried down-wind from their sources (Wilson 1963*c*).

All the marginal faults for which the direction of motion is known are similarly arranged. The concept that the Pacific Basin is being rotated in a counterclockwise direction is not supported by the available evidence. The conclusion is that the Pacific Ocean appears to be spreading in either direction away from the East Pacific Ridge.

### (*b*) *Age of the Pacific Basin*

One obvious explanation of the asymmetrical arrangement of East Pacific Rise is that, whereas the other oceans started to spread from a rift in what had been the central part of a pre-existing continent, the Pacific began to spread from a rift within a pre-existing ocean basin or at its margin.

According to this view, the northwestern part of the Pacific basin is older than the southeastern part. Such few dates as have been published support this view. The only Cretaceous rocks dredged or drilled in the Pacific lie in the northern or western parts, but there is another criterion for age.

Darwin pointed out that volcanic islands sink slowly. Those sea-mounts, whose flat tops show that they were once at sea level and which are now deeply submerged are presumably old. Cretaceous fossils have been dredged from the tops of some between Wake and Johnston Islands (Hamilton 1956). Menard (1959, figure 6) has published a map showing that all deeply submerged guyots lie in the northwestern half of the Pacific Ocean basin. There are about 150 of them scattered rather widely (Fisher & Hess 1963).

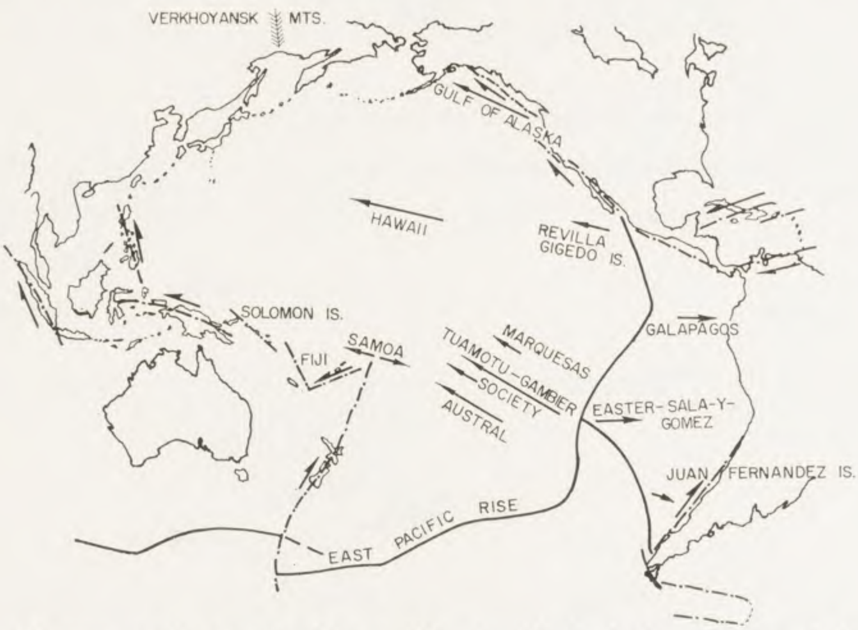


FIGURE 4. Sketch map of the Pacific Ocean. The double-barbed arrows mark linear chains of islands or sea-mounts which get older in the direction of the arrows. Single-barbed arrows indicate directions of motion on major fault systems.

The fact that no fossils older than Cretaceous have yet been dredged from any of these sea-mounts does not necessarily mean that none of them were older. For comparison, consider the effect of the Pleistocene transgression on sea-mounts. Owing to the rapid recent melting of ice sheets, the sea has risen so rapidly that a number of sea-mounts and atolls have been drowned. This has certainly happened for the dozen or so shallow table-mounts described by Almeida (1960) off the coast of Brazil. It is very likely to be the cause of the drowning and near-drowning of the large coral banks in the Indian Ocean between Rodriguez Island and the Seychelles and around the Chagos Archipelago.

The Cretaceous is well known to have been another period marked by great transgressions of the sea. These transgressions may have caused simultaneous drowning of many atolls and today they would appear as deeply submerged guyots with Cretaceous fossils on their tops. Drilling into such table-mounts might reveal older rocks beneath.

It therefore appears that the northwestern Pacific and the North American side of the Arctic Basin are the only two parts of the oceans of the world which may be older than Cretaceous or latest Jurassic.

That the western part of the Arctic Basin is old is shown by the great Franklinian geosyncline which from Pennsylvanian to Cretaceous time appears to have been a coast shelf resembling the Gulf Coast of today. Until the opening of the Atlantic Ocean in Cretaceous time, it seems probable that great rivers flowed from the Appalachians across North America to it (Douglas *et al.* 1963).

One curious difference between Arctic and Pacific basins is that whereas in the Arctic the old and new parts are separated by the great Lomonosov Ridge, no ridge has been


FIGURE 5. Sketch map of the Pacific and part of the Indian Ocean showing islands believed to have been uplifted (●). The uplift in meters is given where known. Except for the group of islands from Niue to Henderson, all uplifted islands lie between 200 and 750 km in front of island or mountain arcs.

found between the old and new parts of the Pacific. This can be understood if the East Pacific Ridge was broke across the floor of an ocean basin whereas the opening of the eastern Arctic basin began by separating a continental shelf from its parent continent.

### (*c*) *Uplifted islands of the Pacific*

In a note on uplifted islands, attention has been drawn to two groups of islands for which there is evidence of considerable uplift (Wilson 1963 *d*). Some of these were discussed by Dietz (1954). One group lies in the central Pacific and probably owes its uplift to tectonic causes. The others all lie at distances of from 200 to 750 km in front of island arcs.

A third group may now be suggested and is comprised of those islands lying at similar distances off the trenches and coast of South and Central America. They are shown in figure 5. Because none of them has any coral or sediments upon them, the extent and, in some cases, the proof of uplift is lacking, but the systematic arrangement of eight islands and small archipelagoes at a regular distance in front of a trench is striking in a vast part of the ocean which is otherwise devoid of islands for more than 3000 km offshore.

The explanation offered for both the later groups is that the floor of the ocean is rigid enough to be bent upwards at a distance of a few hundred kilometres in front of ocean deeps. Any islands which may be there tend to be uplifted. All islands tend to sink, so that the uplift will not always exceed the sinking and not all islands will appear to have been raised. Perhaps fracturing may increase the chance for new islands to be formed there.

(*d*) *Some features of the Hawaiian islands*

Eaton & Murata (1960) have shown that the Hawaiian lavas rise from at least depths of 50 km, but the source may be still deeper.


(*a*) section (*b*) plan

FIGURE 6. Sketches showing that, if there has been a source of lava in the relatively stable core of a convection cell, motion of the convecting current could have given rise to a chain of progressively older islands.

Dietz & Menard (1953) have published profiles taken across the Hawaiian chain. These suggest that the Hawaiian Islands are sinking, forming a moat around their base; but it can also be observed that the outward flow of deep-seated rock from beneath the sinking islands and from beneath the moats has produced an arch or rim around the moat which is raised to a maximum reported height of 172 m above the bottom of the moat at a distance of 180 km from the moat. The upward flexure begins at a distance of about 420 km from the moat.

Iceland and Tristan are considered to be over hot rising currents which maintain them in a median position. The concept that ready sources of lava under Iceland and Tristan could, during the spreading of the ocean, have given rise to pairs of lateral ridges extending to either continent is thus easy to understand.

It is not at all so obvious why a source of lava under Hawaii, which is not on the mid-ocean ridge should remain relatively fixed and so give rise to a chain of older islands like a plume on the downstream side. One suggestion which has been offered is that the source of the Hawaiian lava is in the stable core of a convection cell and that the more rapidly moving upper part of the cell moves over and past the source (figure 6).

## 5. Suggestions from a study of islands about the nature of motion within the Earth

If newly exposed ocean floors have been spreading out from the mid-ocean ridges in all three oceans, then either the Earth has been expanding or some other parts of its surface have been diminishing or disappearing. The second alternative is considered to be taking place where down-currents carry the ocean floor down into the deep ocean trenches which are the most seismically active regions on Earth. In two places table-mounts—the two deepest in the world—appear to have been tilted and to have been carried part way down the slope into the Aleutian trench (Menard & Dietz (1951) and Dietz (1954).

It is a curious fact that normal acid lavas, base metal sulphide ores and gold ores are entirely lacking over that half of the Earth's surface forming the ocean basins. The only trace of base-metal sulphides on an oceanic island is reported from Macquarie Island (Mawson 1943) which may in fact be on the Andesite Line and the only gold is found on Fuerteventura which may be part of Africa rather than an oceanic island like the other Canary Islands.

Apparently primary partial melting of the mantle does not produce either normal acid lava or ores. (Iceland although as large as Ireland or Newfoundland and deeply eroded has none.) Coats (1962) has suggested that in the case of the Aleutian Islands that it is the carrying down of basalts and submarine sediments to depths of at least 100 km that produced andesitic lavas by secondary melting. Perhaps this process also concentrated the sulphide ores.

This suggests that the ocean floors spread from the mid-ocean ridges and are swallowed up again in the trenches off island arcs and continental mountain systems.

Such a motion might be due to convection but it is clear that one cannot from any study of islands rigorously prove that convection has taken place within the Earth, but the proposals of Wegener, Holmes, and others that since the end of the Jurassic period the oceans have spread away from the mid-ocean ridges offers a reasonable explanation of the evidence available. Jeffreys (1929) has shown that a viscosity of $10^{26}$ or $10^{27}$ would be necessary to stop convection in the Earth. Runcorn (1963) has repeated the argument and pointed out that such a high viscosity is unlikely.

An alternative view that the Earth is rigid to great depths has most recently been stated by MacDonald (1964). This view depends upon observations and assumptions which he admits are uncertain. In his own words 'observations of heat flow and gravity suggest...preliminary studies of surface waves tentatively confirm...the distribution of earthquake foci along continental borders and the concentration of deep-focus earthquakes at the borders similarly imply'. These indefinite foundations of calculations must be weighed against the precise geological observations already quoted.

If convection does occur it must be laminar. Reynold's criterion for the onset of turbulence is that

$$vl\rho/\mu > R,$$

where $v$ is a typical velocity, $l$ a typical length, $\rho$ is density, $\mu$ viscosity, and $R$ a number between 1 and 10000 depending upon circumstances.

If in the Earth we assume that the order of magnitude of $v = 1$ cm per year, $l = 3000$ km, $\rho = 5$ and $\mu = 10^{21}$ then $R = 3 \times 10^{-19}$ so that inertia and turbulence play an entirely negligible role.

If convection is assumed one is faced with the problem of discussing the most probable distribution of currents which cannot be directly observed. Those who approach the problem from the point of view of mathematical analysis or theory based upon any of the Earth's physical properties usually arrive at regular patterns of convection cells, to which the surface pattern shown in figure 7 does not conform.

One must therefore assume either that the analytical approaches do not take enough factors into account to be correct and accept the surface indications or one can hold that

FIGURE 7. Sketch map of the world showing the type of surface flow required if convection currents are supposed to rise under the mid-ocean ridge and sink under the continental mountain system. The convecting system appears to be a single elongated cell with both ends on the west coast of North America.

the surface is divided into rigid blocks separated by zones of weakness and these greatly modify the effects of the deep currents so that the surface pattern does not reveal it well. Probably both ideas have some merit, but one can perhaps choose which is dominant by considering the surface pattern.

The surface pattern of postulated currents is based upon the mid-ocean ridges which are taken to represent rising currents and upon the direction of motion of large transcurrent faults. It seems that there may be only one great continuous cell wound about the Earth. It is tempting to regard chains of islands like the Hawaiian Islands and lateral ridges like the Walvis and Rio Grande ridges and those in the Indian Ocean as flow lines. This may be approximately correct, but it involves the assumption that the sources of these ridges have not themselves been moving.

These ridges are divisible into three classes. Those of the Pacific Ocean which like the Hawaiian chain are straight and parallel with one another. This is the behaviour to be expected in laminar flow with no interference from crustal blocks and no motion of the sources of lava. The ridges through Iceland may be similar.

It will be noticed that the straight ridges were formed in the Pacific which has a vast area of oceanic crust. This is held to be able to slide down freely into the surrounding trenches. It is therefore suggested that these ridges may well be flow-lines.

The second class are those pairs of ridges which are not straight, but in which the members are each a mirror image one of the other. The Amsterdam–Kerguelen–Gaussberg ridge and the Amsterdam–Cape Naturaliste ridge are one such pair and the Walvis and Rio Grande ridges form another. The fact that they are mirror images of one another suggests that surface blocks on either side have not moved relative to the other, but that the source has moved along the ridge distorting the ridges which are not true flow lines.

The second group formed in the southern oceans where movement was perhaps less free but not greatly impeded.

The third class are ridges which are irregular, particularly the Rodrigues–Seychelles and Chagos–Laccadive ridges. Both of these have been held to terminate in large faults and to be very much involved in the postulated collision of Africa and India with Eurasia (Wilson 1963*a*).

It is therefore suggested that the flow in the deep mantle may be approximately shown by the lateral aseismic ridges, and that interference between continental, but not oceanic blocks of crust may distort the pattern. If this is true there is but a single convection cell about the Earth.

For the reasons suggested in the section on the Hawaiian Islands, it is held that the currents have stagnant cores. Gutenberg and others have shown that the Earth has a low velocity layer at a depth of from 50 to 200 km. The source of Hawaiian lava has been suggested to come from a greater depth than the axis of this layer, perhaps from a depth of about 100 km. The layer of low velocity seismic waves is probably also a layer of lower rigidity which may be part of the explanation for the more rapid flow in the near surface layers.

By an independent method based upon a study of rate of recoil of land formerly covered by ice sheets, R. K. McConnell (1963) has shown that the upper 100 km of the Earth are more rigid than the region below. No doubt this is because it is cooler. Immediately in front of a zone where a rigid plate resting upon a more fluid medium is being bent downwards, the plate can be expected to be raised.

Such a reaction seems observable for the moat and arch around the Hawaiian Islands. It has been suggested that it is also the explanation for the uplifted islands which are found in front of trenches in the Pacific and Indian Oceans.

It is held that the present system of convection currents was initiated during the Mesozoic period. If it remains stable, the continents will all slowly move until they form a continuous belt over the descending currents where they will presumably stay until the pattern of convection changes. Most, if not all, the continents are now moving at the same rate as the convection currents, but when the continents meet (as in Tibet today?) the currents either have to stop or else shear past the base of the continents. This may produce a discernible difference in the nature of continents so involved.

The continent which broke up in Mesozoic time is not considered to have been primeval. On the contrary, it, in turn, was assembled when convection currents brought earlier continents together, and the Urals and Caledonian–Appalachian systems have been suggested as junctions.

This periodic break-up of continents and then their slow progression to a new pattern may have happened several times. If so it explains why old mountain systems are shorter than present ones, being only broken fragments of the original systems.

To trace the history of the Earth and unravel the geology according to this mobile interpretation of its history is a much more formidable task than that for a static geography. It is made more difficult because nothing that has been said conflicts with the view that the continents have been growing as well as moving by release of basalt and its remelting and conversion to andesite and hence to greywackes and granodiorite.

A better knowledge of the geology and age of oceanic islands would be helpful.

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