Continental and Oceanic Rifts

G. Pálmason
Editor

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Edited by G. Pálmason

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Geodynamics Series

The Final Reports of the International Geodynamics Program sponsored by the Inter-Union Commission on Geodynamics.

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FOREWORD

After a decade of intense and productive scientific cooperation between geologists, geophysicists and geochemists the International Geodynamics Program formally ended on July 31, 1980. The scientific accomplishments of the program are represented in more than seventy scientific reports and in this series of Final Report volumes.

The concept of the Geodynamics Program, as a natural successor to the Upper Mantle Project, developed during 1970 and 1971. The International Union of Geological Sciences (IUGS) and the International Union of Geodesy and Geophysics (IUGG) then sought support for the new program from the International Council of Scientific Unions (ICSU). As a result the Inter-Union Commission on Geodynamics was established by ICSU to manage the International Geodynamics Program.

The governing body of the Inter-Union Commission on Geodynamics was a Bureau of seven members, three appointed by IUGG, three by IUGS and one jointly by the two Unions. The President was appointed by ICSU and a Secretary-General by the Bureau from among its members. The scientific work of the Program was coordinated by the Commission, composed of the Chairmen of the Working Groups and the representatives of the national committees for the International Geodynamics Program. Both the Bureau and the Commission met annually, often in association with the Assembly of one of the Unions, or one of the constituent Associations of the Unions.

Initially the Secretariat of the Commission was in Paris with support from France through BRGM, and later in Vancouver with support from Canada through DEMR and NRC.

The scientific work of the Program was coordinated by ten Working Groups.

WG 1 Geodynamics of the Western Pacific-Indonesian Region

WG 2 Geodynamics of the Eastern Pacific Region, Caribbean and Scotia Arcs

WG 3 Geodynamics of the Alpine-Himalayan Region, West

WG 4 Geodynamics of Continental and Oceanic Rifts

WG 5 Properties and Processes of the Earth's Interior

WG 6 Geodynamics of the Alpine-Himalayan Region, East

WG 7 Geodynamics of Plate Interiors

WG 8 Geodynamics of Seismically Inactive Margins

WG 9 History and Interaction of Tectonic, Metamorphic and Magmatic Processes

WG 10 Global Syntheses and Paleoreconstruction

These Working Groups held discussion meetings and sponsored symposia. The papers given at the symposia were published in a series of Scientific Reports. The scientific studies were all organized and financed at the national level by national committees even when multinational programs were involved. It is to the national committees, and to those who participated in the studies organized by those committees, that the success of the Program must be attributed.

Financial support for the symposia and the meetings of the Commission was provided by subventions from IUGG, IUGS, UNESCO and ICSU.

Information on the activities of the Commission and its Working Groups is available in a series of 17 publications: Geodynamics Reports, 1-8, edited by F. Delany, published by BRGM; Geodynamics Highlights, 1-4, edited by F. Delany, published by BRGM; and Geodynamics International, 13-17, edited by R. D. Russell. Geodynamics International was published by World Data Center A for Solid Earth Geophysics, Boulder, Colorado 80308, USA. Copies of these publications, which contain lists of the Scientific Reports, may be obtained from WDC A. In some cases only microfiche copies are now available.

This volume is one of a series of Final Reports summarizing the work of the Commission. The Final Report volumes, organized by the Working Groups, represent in part a statement of what has been accomplished during the Program and in part an analysis of problems still to be solved. This volume from Working Group 4 (Chairman, J. Sutton) was edited by G. Pálmason.

At the end of the Geodynamics Program it is clear that the kinematics of the major plate movements during the past 200 million years is well understood, but there is much less understanding of the dynamics of the processes which cause these movements.

Perhaps the best measure of the success of the Program is the enthusiasm with which the Unions and national committees have joined in the establishment of a successor program to be known as:

Dynamics and evolution of the lithosphere: The framework for earth resources and the reduction of the hazards.

To all of those who have contributed their time so generously to the Geodynamics Program we tender our thanks.

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A. L. Hales, President ICG, 1975-1980

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PREFACE

During the past decade of the International Geodynamics Program many publications dealing with specific rift areas of the Earth's surface have appeared. Most of them followed symposia that were held in the respective rift zones. Among the rifts thus treated are the Rhinegraben, Afar, Iceland, the Baikal rift, the Oslo paleorift, the Rio Grande rift and the Dead Sea rift. Furthermore, publications dealing with studies of the ocean floor have discussed many oceanic rift areas.

In view of the recent growth of publications dealing with specific rift areas, the Working Group 4 (Continental and Oceanic Rifts) decided at its meeting in Santa Fe, New Mexico, in 1978, that this volume should emphasize comparative studies on topical subjects rather than focus on geographical areas. It is hoped that this will prove to be a useful approach to reviewing the present state of knowledge of the rift zones of the Earth.

The papers in this volume deal with many aspects of rift systems that have received attention in recent years. An introductory paper gives a much needed overview of the history of rift studies from the early work in East Africa at the end of the 19th century to the present time, when the main features of the World Rift System have been recognized. Subsequent papers deal with various physical aspects of rifts, including ground deformation, seismicity, gravity and heat flow. One paper deals with hydrothermal systems, which seem to be as integral a part of active rift systems as e.g. volcanism and seismicity. Magmatism is the subject of three papers, and metallogenesis in relation to rifting is discussed in one paper. Two papers deal with certain aspects of the Iceland rift zone and the Rhinegraben system. Finally, one paper gives some thoughts on unsolved problems of the continental rifts.

It is hoped that this collection of papers will prove a valuable source of information for rift studies during the decade of the International Lithosphere Program.

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HISTORY OF RIFT STUDIES

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Introduction

The great fault systems of the continents have been known for more than a century but it is only in recent years that the rifts in the ocean floor have been reasonably well mapped. The years following the second world war saw a spate of ocean exploration with many new instruments. Previously, there had been the suggestion of Wiseman and Sewell (1937) giving the results of the John Murray expedition that the rift along the Carlsberg Ridge in the Indian Ocean might be connected to the rifts of East Africa via the Gulf of Aden. This connexion turned out to be fundamental and today most people accept that the continental and oceanic rifts are closely interconnected and that continental rifts can evolve into ocean rifts and eventually into ocean basins.

The evolution of rifts into ocean basins implies large horizontal movements of the lithosphere. As is well known, the whole concept of continental drift was for many years unfashionable. It was not until the advent of palaeomagnetism in the 1950's that it became at all respectable. In some ways, this was surprising as the observational evidence for large scale relative movements between continental blocks has been documented for a long time, for example, the movements along the Great Glen fault of Scotland, the Dead-Sea - Jordan rift valley, the San Andreas fault of California and the Alpine fault of New Zealand. It is difficult to ascertain when horizontal displacements were first recognized but the large shear along the Dead Sea rift was discussed by Lartet (1869).

Strangely, the problem of accepting continental drift seems to have been associated with the mechanism rather than the evidence for it. The Polflucht forces of Wegener were hopelessly inadequate. The large scale mantle convection currents advocated by Arthur Holmes and Vening Meinesz were difficult to conceive in a so called solid mantle and the expanding Earth of Halm and Hilgenberg did not explain the large horizontal shear along adjacent pieces of continent.

The situation may be summarised in the words of Sir Edward Bullard (1965) : "There are phenomena, such as ice ages and thunderstorms, for whose occurrence there is incontrovertible evidence, but for which there is no theory that is not open to substantial objections. Difficulties of accounting for a phenomenon do not provide a proof of its non-existence, though they may give a strong indication that the evidence is being misinterpreted".

Early Studies (Pre-1940)

Early studies of rifting were necessarily confined to land areas. Field observations indicated normal faults, often with throws which seemed enormous. For example, Joseph LeConte (1889) in an article on the origin of normal faults and of the structure of the basin region of North America states "The vertical displacement on the north side of the Uinta Mountains according to Powell is 20,000 ft. (6.1 km)., that on the west side of the Wahsatch according to King is 40,000 ft. (12.2 km). In the plateau region according to Dutton there are faults extending for 200 miles (322 km) with a vertical displacement of 2000 ft. (0.6 km) to 12000 ft. (3.6 km)."

To the early workers, including LeConte, it was impossible to account for such faults unless there is a "subcrust liquid" and the idea became prevalent of a series of crustal blocks floating at different levels in accord with Archimedes' principle. It is always difficult to find the earliest references to such ideas but some of the earliest must be Mr W. Hopkins' "Researches in Physical Geology" published in the Philosophical Transactions of the Royal Society. In the third series (1842), Hopkins speaks of subterranean reservoirs and an elevatory force, produced by expansion of the fluid matter to raise the superincumbent solid mass and to form in it a system of fissures. The plane of these fissures will scarcely ever be parallel and diagrams are shown to demonstrate how crustal blocks float at different levels according to their shape.

With these observations and ideas on normal faults and the observations of Lartet (1869) of horizontal shear along the fault system in Palestine, it might be said that the embryo of the so called modern plate tectonics was already born in the middle of the last century.

The enormous horizontal extent of rift systems became appreciated with the works of John Walter Gregory. Gregory first visited East Africa in 1892-3 and his monumental book (405 pages) entitled "The Great Rift Valley" appeared in 1896. In this he describes the Great Rift Valley as extending from Palestine in the north to beyond the Zambesi in the south, a distance of some 5000 miles. He attributes the recognition of the extension of the Red Sea fractures into Africa to H. Douvillé(1886). Gregory visited Africa again in 1919 and as a result his more often referenced book appeared in 1921. It is perhaps worth quoting its full title viz. "The Rift Valleys and Geology of East Africa, an account of the origin and history of the rift valleys and their relations to the contemporary earth-movements which transformed the geography of the world with some account of the prehistoric stone implements, soils, water supply and mineral resources of the Kenya Colony." A quote from Gregory's preface is also appropriate viz: "Pioneer geology has to choose between the rashness of using imperfect evidence or the sterility of uncorrelated, unexplained facts. "Gregory was the first to suggest the name "Rift Valley" using the term to denote the sinking of material between parallel fractures. He cites a long, comprehensive bibliography but he seems to have been unaware of the works of Hopkins, independently formulating his own theory for the origin of rifts which was very similar. He envisaged the formation of a long, low arch which ruptured as the lateral supports gave way. The top then sank "as the keystone of a bridge sinks if its buttresses slip or settle. The sinking of the keystone of the East African arch into the plastic layer below forced some of it up the adjacent cracks, through which the material was discharged in the volcanic eruptions. Each renewal of the subsidence was followed by fresh eruptions".

At the turn of the century, there was also some indication of the larger extent of the rifts in the ocean floor. The Danish "INGOLF" expedition of 1895-1896 discovered and named the Reykjanes Ridge running for 1100 Km south west of Iceland. A report of the expedition by Wandel (1898) suggested that the ridge must be young and of volcanic origin. The arguments were (a) earthquakes had been felt by ships crossing the ridge and (b) volcanic activity must have taken place after the Ice age as not a single ice strewn boulder was recovered in dredge hauls on the axis of the ridge whereas the regions to the east and west of the ridge were strewn with boulders.

The significance of this discovery was commented upon by Th. Thoroddsen (1901 , 1908) who pointed out that the Reykjanes Ridge seemed closely related to the active rift zone on land. In particular, many volcanic eruptions occurred in the vicinity of Eldeyjar and the ridge was narrow and volcanic with its surface covered by volcanic debris and scoriae. He also noticed that the volcanic line across Iceland has the same trend (S.W. - N.E.) and the volcanic island of Jan Mayen is probably located on its continuation although at that time no volcanic ridge was known to extend north of Iceland as far as Jan Mayen. Some twenty years later, Sieberg (1923) on his seismicity map, shows the Reykjanes Ridge and the mid-Atlantic Ridge as seismically active but not in continuity.

Some of the most remarkable work in Iceland was that of Niels Nielsen from Denmark (Nielsen 1929, 1930, 1933) who was a supporter of the ideas of Wegener at a time when they were hotly debated. Nielsen envisaged the fissure eruptions and fault structures as being "the result of a pull from west to east which has simply split the land into innumerable fissures". He recognised two profoundly different types of tectonics, the Alpine pressure tectonics and the Icelandic tensional tectonics. His concept of tensional processes causing rifting and magma intrusions is very similar to that envisaged in recent models.

The tension hypothesis seems to have been almost generally accepted (e.g. Suess, 1904 Cloos, 1939) but in the 1920's an alternative hypothesis relating the rifts to compression was proposed. the chief proponents were E.J. Wayland (1929) and Bailey Willis (1936) working in Africa. In this hypothesis the normal step faults at the surface were considered to be secondary. The main faults at depth were postulated to be reverse (at 45°) and a consequence of lateral compression, the two opposing overthrust faults holding down the block in between. The overhangs of the thrusts adjusted by gravity giving a series of inslipping normal faults at the surface and obscuring the major faults beneath.

The compression hypothesis found temporary support in the interpretation of the gravity deficiency over the rift valleys of East Africa. In a monumental paper, Bullard (1936) gave the results of 56 gravity measurements made with pendulums in 1933 and 1934 and included the work of Professor Kolschütter's 1899-1900 expedition. The suggestion of a wedge shaped block forced down between reversed faults provided the light matter to explain the gravity deficiency. At this time, the large volumes of light sediments and light volcanics infilling the rifts were unknown, and this interpretation was abondoned when it was recognised that the light sediment could account for a large portion of the negative Bouguer anomaly.

The exploration of the oceans was severely limited by the apparatus and techniques available. In the 1920's, the development of the sonic echo sounder greatly increased the amount of sounding data although matching of the transceiver with an accurately timed recorder was not achieved until the 1950's. Professor F.A. Vening Meinesz developed his pendulum apparatus for use in submarines leading to more accurate gravity measurements and there was little else. It is perhaps hard to realise that seismic work at sea was extremely experimental. Encouraged by Dick Field and William Bowie, Maurice Ewing made the first trials in 1935 and Teddy Bullard succeeded in obtaining reflexions and refractions using two Brixham trawlers in the English channel in that last bright summer before the war.

The only data available were therefore gravity measurements and ocean depths. These reinforced the conclusion of Wegener (1924) that the crust beneath the oceans is quantitatively different from that beneath the continents. This seems obvious now but since the turn of the century the oceans had been considered to be foundered continents (Haug 1908, Suess 1904) and it was hard to abandon this view. Even prior to 1950, many considered that only the Pacific Ocean is truely oceanic and lacking a sialic layer, the Atlantic and Indian Oceans having such a layer thinned by plastic flow (Umbgrove 1947, Gutenberg, 1939). Although stretching and thinning through plastic flow were suggested, there was no concensus on the nature of the mechanism.

As previously mentioned Wiseman and Sewell (1937) noted the connexion and similarity of the Carlsberg and Murray ridges (considered to be upper Tertiary) in the Indian ocean to the East African rift system observing that the former are almost a mirror image of the latter. The distribution of earthquakes (Heck, 1938) strengthened the comparison, implying that simlar rifting processes might be taking place in the Indian ocean as in Africa.

Some progress towards the recognition of rifting on the scale of ocean basins had also been made. For example, Du Toit (1937) identified many coastlines as faultline coasts from their topographic expression and suggested rifting and listric faulting as the mechanism by which the continental margins were created and the sialic crust thinned. He envisaged the ocean basins to be "merely rift valleys of unusual width" and floored by sialic crust. Some words of Umbgrove (1947) probably reflect the thinking at the outbreak of war viz: "an examination of the Atlantic and Indian Oceans, and a comparison with the available geological and seismic data, shows that the bottom probably consists of sialic material. Internal forces caused similar events to occur in this sialic layer and the surrounding continents (e.g. basins and ridges were formed and eventually rift valleys)".

1940 to 1970

During the second world war, studies of the rifts came virtually to a standstill. There was one noteable exception: 1944 saw the publication of the first edition of Arthur Holmes' "Principles of Physical Geology". In it, Holmes describes the concept of sea floor spreading which was to have such a profound influence on rift studies in the 1960's. The germs of the idea can be found in his earlier papers of 1928-9 and 1933 when he was searching for a mechanism for continental drift and invoking large scale mantle convection. There has been some debate as to whether full credit should be given to Arthur Holmes for the idea of sea floor spreading. In the 1944 edition of his book he updates his earlier diagrams and shows the evolution of "new ocean" as the continents move apart: the figure caption describes "ocean floor development on the site of the gap" and leaves little doubt that he understood fully the concept of ocean floor spreading which was destined to become so important.

At about this time, Bernauer (1943) was interested in explaining the young tectonic activity of Iceland having been a member of a German expedition there in 1938. He was a follower of the mantle convection ideas of Holmes, Griggs (1939) and Vening Meinesz (1934) and envisaged Iceland to be formed of new crust consisting of "sima": the new crust forming over an uprising mantle convection current and continuing to develop by the process of dilation, rupture and sideways transport as long as the convection continues.

After the war, the so called "tension hypothesis" for rift formation became generally accepted and the "compression hypothesis" abandoned. Goguel (1949) and Vening Meinesz (1950) suggested that the negative Bouguer gravity anomalies found over the floors of the continental rift valleys could be explained if the valleys have normal faults. With the development of electronic computing techniques in the late 1950's it became possible to quickly compute models to satisfy the gravity and to establish whether the faults become reverse at depth and hence to distinguish between the two hypotheses (Girdler 1964). For normal faulted valleys the gradients quickly diminish to zero over the sides whilst for reverse faulted valleys, the gradients should be quite large 40 to

50 Km from the valley. The latter are not observed and hence the more obvious idea that the faults continue as normal faults at depth was supported. The conclusion later found further support from earthquake mechanism studies (e.g. Fairhead and Girdler 1971, Sykes 1968) the present day motion along the faults being a combination of dip-slip and strike slip.

In the post war period, work on the rifts in the ocean floors expanded at a much more rapid pace than work on the continental rifts. There were two main reasons for this: first, partly as a result of the war, many new instruments became available for exploring the oceans and secondly, the general growth in scientific research meant more financial support and opportunities for visiting unexplored parts.

The new techniques which became available included markedly improved echo sounders with more accurate timing devices and expanded scale recorders: radio sono buoys and hydrophones for seismic refraction work; new energy sources such as airguns for seismic reflexion work; magnetometers for towing behind ships; continuous recording gravimeters and stable platforms: probes for measuring heat flow and later greatly improved positioning of survey ships with the introduction of satellite navigation systems. With all these new techniques and the boost given to research by the International Geophysical year (1957-8) a wealth of new data became available with which to test old and new ideas on the origin of rifts and the evolution of ocean basins.

The sea seismic refraction experiments started just before the war were continued by Maurice Ewing of Columbia University and Maurice Hill of Cambridge University. Maurice Hill developed a system in which charges were fired from a ship and the shock waves were recorded by hydrophones suspended from buoys and the signals transmitted by radio to the ship. The first results in deep water were obtained from a weather ship 500 Km west of Ireland and were most successful. For the first time the now standard section for the crust beneath the oceans of layers 1, 2 and 3 was obtained (Hill and Willmore 1947, Hill and Swallow 1950, Hill 1952). Early in 1949, Maurice Ewing managed to get two ships in the hopes of finding the depth to the Mohorovicic discontinuity (the Moho). A reversed line 56 Km long was shot and the Moho found 5 Km beneath the ocean floor. (Ewing et al 1949, 1950). These results showed that the structure of the ocean floor is completely different from that of the continents as predicted many years previously by Wegener.

The introduction of precision echo sounders (Luskin et al 1954) coupled with the enthusiasm of Maurice Ewing for exploring the oceans and collecting as much data as possible led to the construction of a series of magnificent physiographic maps of the ocean floors by Marie Tharp and Bruce Heezen in the 1950's and 1960's. At last there were maps of the sea floor which could be compared with maps of the continents. Early on, it was noticed that the valley at the crest of the mid-Atlantic ridge is a continuous feature (Ewing and Heezen 1956, 1960, Hill 1960). At a meeting about the floor of the Atlantic Ocean held at the Royal Society in February 1953, J.P. Rothé discussed the distribution of earthquake epicentres in the Atlantic and Indian oceans and showed that the line of epicentres following the mid-Atlantic Ridge continues around the Cape of Good Hope to join with the epicentres marking the central ridge of the Indian Ocean. It became apparent that the earthquakes occurred in the central valley and their distribution could be used to trace the course of the ridge and its central valley where there were no echo sounding records. In their 1956 paper Ewing and Heezen took the logical step and extended this on a world wide scale. The world wide extent of the rift system was gradually confirmed (Ewing and Heezen 1960). This was a remarkable discovery. The recognition that the rifts of Africa and western North America are parts of a world wide system largely in the floors of the oceans has been central to the development of subsequent tectonic theories.

A further technical advance of the greatest importance was the development of the marine magnetometer. At first, the airborne fluxgate magnetometer developed during the war by Victor Vacquier for submarine detection was converted and towed behind a ship. The first trans-Atlantic profile of total magnetic intensity was obtained from Dakar to Barbados aboard the R.V. Atlantis in 1948. An account of the work and the historic profile are given in Heezen, Ewing and Miller (1953). The instrument was somewhat troublesome and cumbersome and was replaced by the proton precession magnetometer (Hill, 1959) which is free from drift and has no moving parts. It became easy to continuously measure the total intensity of the Earth's magnetic field to an accuracy of 1 part in 10^5.

Crossings of the mid-Atlantic rift revealed a large magnetic anomaly (Heezen et al 1953, 1959, Hill 1960, Talwani et al 1961, Girdler 1964) often in excess of 1000 nT. A similarly large anomaly was found on a flight across the Gulf of Aden by W.B. Agocs (Girdler 1958) and large anomalies were observed over the axial rift of the Red Sea (Drake and Girdler 1964). It soon became apparent that a large magnetic anomaly is a characteristic feature of the axial rift zones (U.S. Navy Hydrographic office 1962, British Admiralty Hydrographic office 1963, Keen 1963, Ostenso 1965) and this has been used together with bathymetry and the distribution of epicentres to map the rifts.

There are also many smaller anomalies on either side of the large anomaly associated with the axial rifts. The next interesting discovery was made by contouring these anomalies using many profiles. This was done for a survey conducted from the USCGS vessel Pioneer in the north east Pacific (Mason 1958) which revealed that the anomalies are remarkably linear, the lineations extending for thousands of kilometers. Similar magnetic lineations were found over the western Gulf of Aden (Girdler and Peter 1960), the Red Sea (Drake and Girdler 1964) and the mid-Atlantic (Heirtzler and Le Pichon 1965).

At first, these anomalies proved difficult to interpret. Apart from the large axial anomaly there is no obvious relationship to the bathymetry and the usual practice of assuming the direction of magnetization to be parallel to that of the Earth's present field frequently seemed to fail. A very clear example was seen in the western Gulf of Aden where a simple minimum is expected for a body striking west-east. Large maxima as well as large minima are observed and this led Girdler and Peter (1960) to infer the presence of reversely magnetizated dykes suggesting that remanent magnetization is very important when interpreting oceanic magnetic anomalies. The complete interpretation had to await the work of Vine and Matthews (1963) when they associated their cause with the idea of sea floor spreading which had been revitalised by Hess (1962) and Dietz (1961).

Vine and Matthews argued that if new oceanic crust is formed along the rift zones, it will be magnetized in the current direction of the Earth's magnetic field. It is a corollary of sea floor spreading and geomagnetic reversals that blocks of normally and reversely magnetised material would be carried away from and parallel to the centres of the rifts thus explaining the magnetic lineations. On land, Cox, Doell and Dalrymple (1963, 1964, 1968) had been painstakingly establishing the times of the reversals using the palaeomagnetic method and radiometric (potassium - argon) dating. In a masterly paper, Vine (1966) applied this to the interpretation of the marine magnetic anomalies near the rifts. Knowing the distances from the anomalies and the times from the dating of reversals it was possible to estimate the speeds of formation of the rift zones. The rifts were found to be evolving at rates from 2 to 11 cm/yr. It was obviously important to check the association of these ideas and this has been achieved mainly by examining the ages and magnetic properties of the sediments overlying the magnetized oceanic crust. The sediments have been drilled in many places by the Deep Sea Drilling Project (e.g. : Maxwell et al 1970) and the ages of the oldest sediments agree in a most gratifying way with the ages predicted from the interpretation of magnetic anomalies. It therefore became necessary to adjust to the idea that the rift zones can evolve at remarkably rapid rates on a geological timescale.

The discovery of the magnetic lineations has enabled the oceanic character of the Gulf of Aden and Red Sea to be confirmed. From the early pendulum measurements of Von Triulzi (1898, 1901) Vening Meinesz (1934) and Girdler and Harrison (1957), the Red Sea was known to have a positive Bouguer gravity anomaly in contrast to the negative anomalies found over the rifts in East Africa. This indicated that the Red Sea is underlain by dense material with the physical properties of basalt (Girdler 1958). Later work by the research vessels Atlantis and Vema supported this interpretation with the discovery of high seismic velocities at shallow depths beneath the axial trough (Drake and Girdler 1964). It was suggested that the dyke like bodies with high density, strong magnetization and high seismic velocity were formed as Africa and Arabia moved apart.

This work was complementary to that along the Dead Sea Rift. Quennell (1958, 1959) found further support for the shear proposed by Lartet (1869), Dubertret (1932) and Wellings (1938) ingeniously suggesting that the Dead Sea and Lake Tiberias are rhomboidal gaps in between en echelon faults due to the northward movement of Arabia with respect to Sinai which also opened the Red Sea. In modern terminology the Dead Sea rift is a transform fault transforming the Red Sea in the south to the Taurus - Zagros mountains in the north. Quennell (1959) further noticed that the wrench faults (as they were then known) must follow either a great circle on the Earth's surface or a small circle. The faults forming the Dead Sea rift zone were described as arcs, all arcs having centres at approximately 33°N., 24°E. The movement along the Dead Sea rift was supposed to have taken place in two stages, the first stage being 62 Km corresponding to a rotation of 3° and the second stage 45 Km corresponding to a rotation of $2\frac{1}{2}^{\circ}$. This seems to be the first use of the concept of poles of rotation and rotation angles, a concept which was to become so important in the late 1960's (e.g. Bullard et al 1965, McKenzie and Parker 1967). Further support for the shear along the Dead Sea rift came with the work of Freund (1965) and Freund et al (1970).

To many, this horizontal displacement of more than 100 Km seemed outrageous but meanwhile even larger displacements were being proposed for the ocean floor. The patterns of magnetic lineations previously described were found to have several interruptions and these were related to the fracture zones of Menard (1955). The fracture zones were interpreted as strike - slip faults with displacements of the order of 1000 Km (Vacquier et al 1961) and curiously with an apparent change of magnitude and sense of the displacements along the faults (Menard, 1960). Similar faults were found in the equatorial Atlantic displacing the mid-Atlantic rift (Heezen and Tharp 1961) and these were presumed to be old as they are not seismically active along their lengths (Heezen 1962).

The problem of the relationships between the rifts and the fracture zones was tackled by Wilson (1965) who generalised the lucrative concept of "transform" faults. He developed the