Geophysics & Astrophysics Monographs

Sea Floor Spreading and Continental Drift

J. Coulomb

SEA FLOOR SPREADING AND CONTINENTAL DRIFT

by

JEAN COULOMB

D. REIDEL PUBLISHING COMPANY

DORDRECHT-HOLLAND

L'EXPANSION DES FONDS OCÉANIQUES ET
LA DÉRIVE DES CONTINENTS
First published by Presses Universitaires de France, Paris, 1969
Translated from the French by R. W. Tanner

Library of Congress Catalog Card Number 79–179891

ISBN 90 277 0238 1

Printed in The Netherlands

SEA FLOOR SPREADING AND CONTINENTAL DRIFT

GEOPHYSICS AND ASTROPHYSICS MONOGRAPHS

AN INTERNATIONAL SERIES OF FUNDAMENTAL TEXTBOOKS

VOLUME 2

FOREWORD

Studies of the magnetic anomalies paralleling ocean ridges have furnished partisans of continental drift with decisive arguments. To take stock of this important question, my colleague Thellier and I decided in the early summer of 1967 to make it the subject of the annual seminar on Earth physics for the school year 1967–68. Although research was still developing rapidly, the General Assembly of the International Union of Geodesy and Geophysics held in Switzerland in September, particularly some of the meetings in Zurich under the auspices of the International Committee for the Upper Mantle, appeared to confirm that we had made no important omissions. At the conclusion of the seminar, where I had been responsible for most of the lectures, I resolved to write the present volume for the non-specialized scientific reader.

The project turned out to be a good deal more ambitious than I had thought. It is quite an undertaking nowadays to try to survey a rapidly growing subject, first of all because of the difficulty of gathering material; publication delays are now nearing one year, with the result that specialists communicate largely through a selective distribution of reports, as well as verbally in frequent colloquia. I warmly thank those who helped me in getting unpublished literature, especially Xavier Le Pichon. Even so, some essential work came to my knowledge only lately.

Finally, from the viewpoint of this Series, the subject here dealt with is certainly Living Science, and seems ripe for exposition without too much fear that premature interpretations may be rapidly superseded, for the probable lines of development are fairly clear.

It may appear that not much would be needed to make the book into an introduction to original research by adding to the already long bibliography, giving the principles behind some of the calculations, and tempering each assertion with a statement on the conditions of its validity. But in fact this would have taken me far afield to satisfy a restricted public without perhaps answering the particular questions which always occur to enquirers from another discipline. For despite the number of general surveys published every year, scientists who can use it still prefer the time-honored method of consulting a university colleague or quizzing a neighbor at a colloquium when they need information on some particular aspect not in their field.

The book has been kept relatively small then, for these reasons, and I hope that its readers will find as much interest in the wonderful recent discoveries about the ocean floor as I did in coming to know them fully.

INTRODUCTION

The author of a scientific account is always tempted by the inductive procedure; facts first, followed by interpretation. But he quickly finds this approach slow and cumbersome and soon he is putting out hypotheses. This will be my course, and I reluctantly give up, as well, attempts to follow historical development or to indicate systematically priorities of discovery, with all the difficulties attendant on the preprint system. Specialized bibliographies may be consulted (Fox, 1967).

Let me mention, however, four lines of approach to present knowledge:

(1) Location of seismic epicenters and surveys of the ridges by echo sounders, from which comprehensive results have been available since 1959;

(2) Seismic refraction, by whose aid Maurice Ewing showed in 1959 the presence of anomalous mantle under the Atlantic ridge, and Menard in 1960 the absence of crustal thickening under the East Pacific ridge; the complementary gravimetry (from 1948 to 1965, roughly);

(3) From 1952 onwards, heat flow studies initiated by Bullard; first results connected with the ridges date from 1959;

(4) Finally, and most important, magnetic studies, facilitated by the invention of the proton magnetometer (1954) which led to the discovery of the first aligned anomalies and the great transverse fractures by Mason and Raff in 1961, then, thanks to the ideas of Hess and Dietz, to the theory of Vine and Matthews in 1963, starting point of a new era.

From this geophysical break-through the subject has spread out explosively into neighboring disciplines, especially geology. It would be hard to pass over petrography and stratigraphy in this account, but conscious of my shortcomings, I say as little as possible about them.

Two notes in conclusion; year is abbreviated y. and million years m.y. Durand (1965) or (Durand, 1965) refers to the references, but mention of what Durand wrote in 1965 does not.

Addendum to the English version: I express my warmest thanks to Mr. Tanner for his excellent translation.

TABLE OF CONTENTS

CHAPTER I

SEISMIC GEOGRAPHY AND OCEAN BATHYMETRY

Almost all earthquakes are tectonic; they originate as a fracture at a point in the Earth's interior called the *focus;* the nearest surface point is the *epicenter*. The break is then propagated along the surface of a fault. Determinations of epicenters and depths of focus are carried out regularly in various institutions, such as the Bureau Central Sismologique of Strasbourg, using the times of arrival of the seismic waves at several hundreds of stations more or less well distributed around the world.

Until about 1930 when Wadati established the existence of deep focus earthquakes beyond a doubt, fractures were not thought to occur elsewhere than in the crust. In fact deep focus earthquakes are not very frequent, constituting less than 10% of the total. Their number falls off rapidly down to 300 or 350 km, this depth may be taken as a limit between the 'intermediate' and really deep earthquakes. Earthquakes become rare around 600 km and cease completely around 720 km. But these are averages; the distribution varies greatly from region to region.

In Figure 1 the epicenters of 'normal' focus earthquakes, that is, not deep focus, are plotted on an equal-area projection, using only larger magnitude events. They are seen to fall almost exclusively into two kinds of seismic zones: on one hand regions of Tertiary folding, on the other a group of elongated submarine shallows sometimes continued into the heart of the continents by regions of fracture and collapse. Epicenters are rare in the central Pacific and in the continental shields, which are stable regions surrounded by the zones previously mentioned. Earthquakes corresponding to ancient folding may be numerous (Scotland), but they are very weak.

1. Tertiary Folding, Transcurrent Faults, Island Arcs

The Tertiary foldings fall mainly into two great zones; the Pacific Belt (open at the south from Patagonia to Macquarie Island) contains four-fifths of the known epicenters. The Mediterranean or Alpine belt bordering Eurasia on the south branches from the first around the Moluccas and ends at Gibraltar.

These two belts are characterized by numerous arcuate structures; the island arcs of the western Pacific or eastern Mediterranean, the arcs of the Antilles or the South Sandwich Islands (Figure 2), the Himalayan, Carpathian ranges and so on. Most of these arcs outline closed areas: epicontinental seas such as the Sea of Japan, or sedimentary basins such as the Pannonian; but the Bonins and Marianas, or the South Sandwich Islands apparently have one free end, and the structure is very complex in the region of the Melanesian arcs.

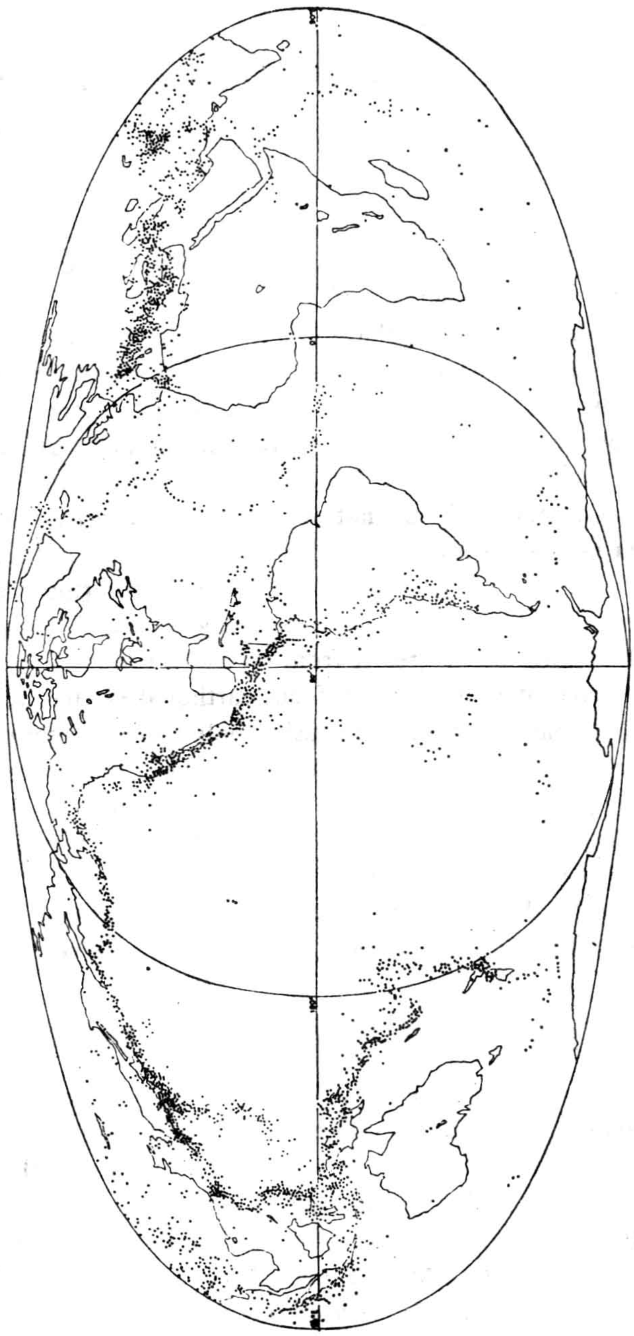

Fig. 1. Geographical distribution of the epicenters of normal earthquakes 1930–1941. (From International Seismological Summary determinations. Equal area projection Eckert and Thomas, *La Terre*, Gallimard "Encyclopédie de la Pléiade", 1959.)

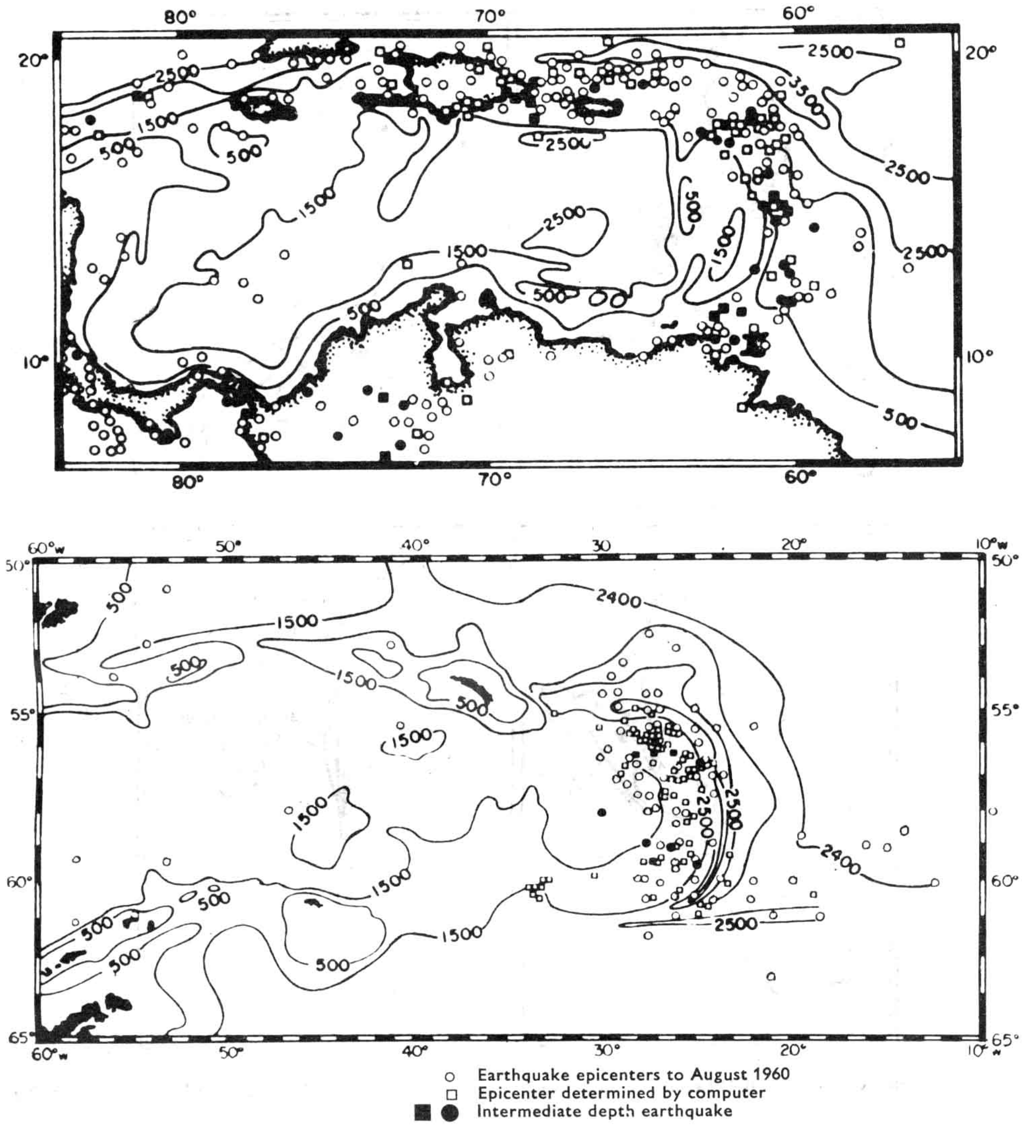

Fig. 2. Seismicity of the Antilles and South Sandwich arcs. (Heezen and Johnson, The South Sandwich Trench, Deep Sea Research, 1965.)

The movements causing earthquakes in the circum-Pacific belt, and perhaps also certain quakes of the Mediterranean zone (North Anatolian scar) are often connected with very large faults or systems of faults in which the horizontal displacement or slip is much greater than the vertical displacement or throw. The most striking feature of these faults is their approximate linearity over hundreds of kilometers. The prototype is the San Andreas fault, responsible for many known earthquakes including the much-studied one which destroyed San Francisco on April 18, 1906. During the 1906 event displacements of up to several meters at some places occurred

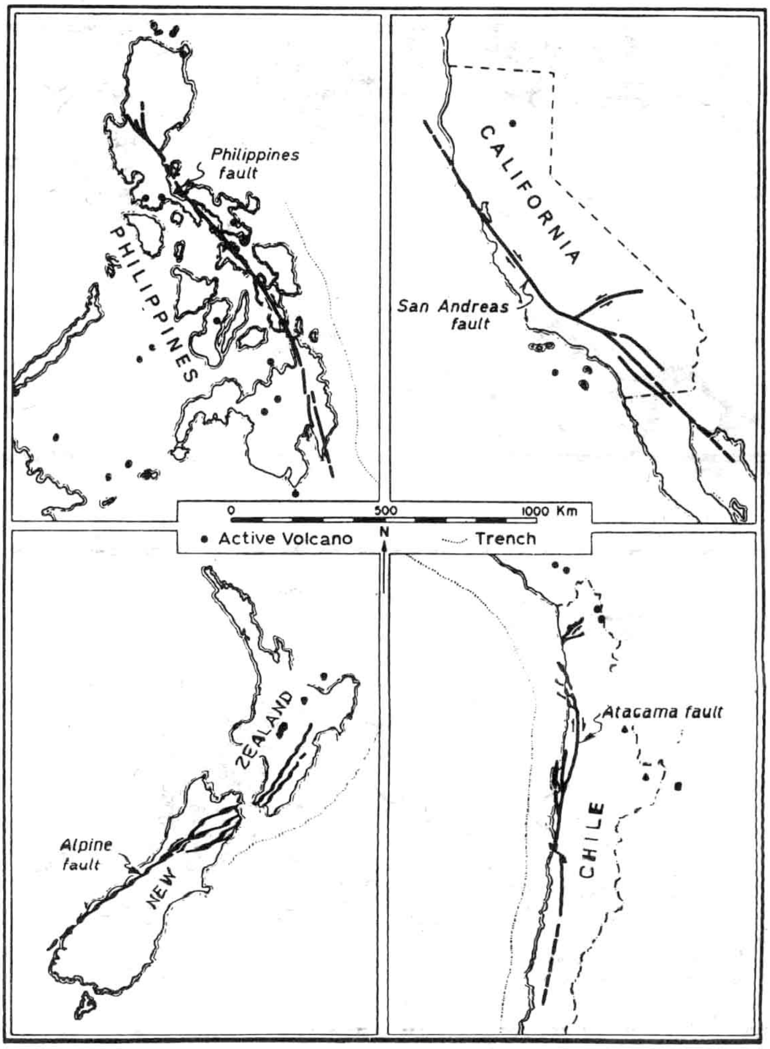

Fig. 3. Great Circumpacific faults: Philippines, California, New Zealand, Chile. (Allen, 1965.)

on two sections of 320 and 150 km length; the fault can be followed for at least 900 km. Recent displacements, all in the same direction, are revealed by repeated triangulation; they are rarely continuous in time and generally result from large or small earthquakes; rates average several centimeters per year. From study of the terrain on opposite sides of the fault, horizontal displacements of several hundreds of kilometers since the Cretaceous are indicated (Noble; Hill and Diblee; Crowell) corresponding to a mean rate an order of magnitude smaller than this.

Along the Pacific belt, Allen (1965) has systematically investigated large transcurrent faults with visible displacement to see whether they were associated with historical earthquakes. The principal examples are given in Figure 3. Study of thalwegs deformed by the fault gives the direction of motion. The Philippine and Formosan faults are exceptions to an alleged curious rule that the motion on all faults corresponds to a counterclockwise rotation of the central Pacific.

Deep focus earthquakes are confined to regions of Tertiary folding, as far as is known, but they do not occur in all such regions, being absent for example from the North American coast of the Pacific rim. Their presence is generally associated with that of an ocean trench, that is, a long narrow steep-flanked depression (order of magnitude: over 1000 km long, 100 km wide at the top, 10 km at the bottom). Trenches are generally asymmetric, the slope being steeper on the side bordering the island arc or continent. The bottom is sometimes flat, but this seems to be due to filling by turbidity currents. The trenches accompanying the island arcs in the western Pacific, where the ocean is already very deep, contain the greatest known depths, often greater

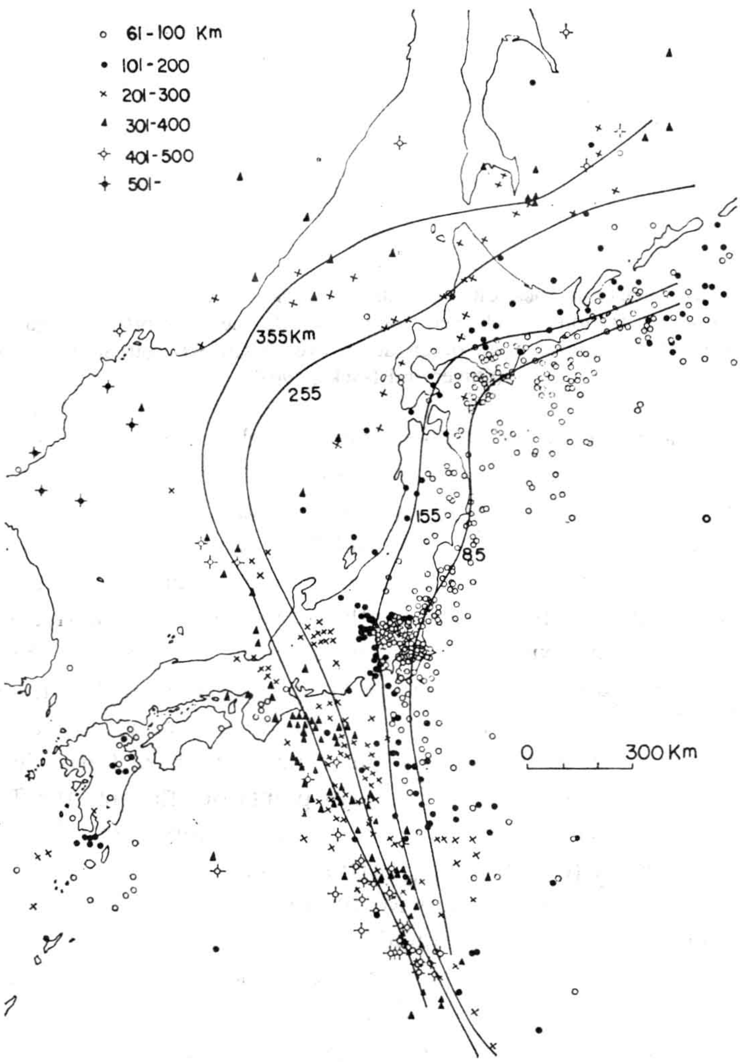

Fig. 4. Epicenters of deep-focus earthquakes from 1926 to 1956 determined by the Japanese Meteorological Service. (Contours from Sugimura and Uyeda, *Japanese national report on the upper mantle*, 1967.)

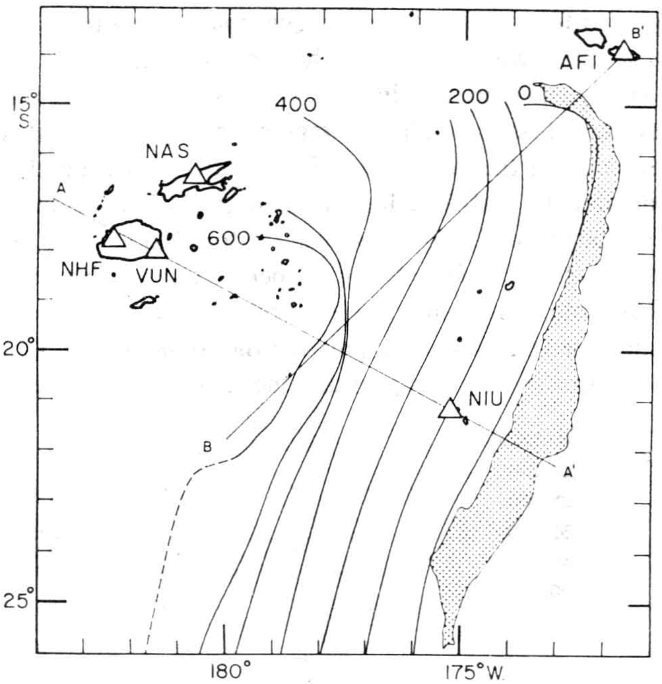

Fig. 5. Deep-focus surface in the Tonga trench region. Triangles denote the Lamont Geological Observatory temporary stations which were used to locate the foci: NIU, Tonga; AFI, Samoa; NAS, NHF, Fiji. Stippled area: ocean depth over 6 km. Contour interval 100 km. (Oliver and Isacks, 1967.)

than 10 km, while those of the Mexican coast rarely exceed 5 km. All are readily distinguishable from the great aseismic depths of the North Pacific.

Except for the region of the New Hebrides and the Solomon Islands, or the re-entrant angle near the boundary of Chile and Peru, the trench is concave toward the neighboring continent. In this direction, about 100 km distant, occurs a chain of volcanoes producing acid lavas. Focal depth increases fairly regularly; normal focus earthquakes are near the axis of the trench but more numerous on the continental side; intermediate foci are largely under the chain, and the really deep quakes notably beyond it. The foci as a group lie thus on surfaces inclined at about fifty degrees, usually only occupied at certain depths, but which have been fairly clearly defined in at least two cases (Figures 4 and 5). Sykes points out that for the Tonga earthquakes (Figure 5) the curvature of the trench in the horizontal plane is followed down to 600 km despite the intervening perturbations.

In the Tyrrhenean Sea and the eastern Mediterranean with similar arcuate structures, intermediate depth earthquakes are found with an analogous pattern. A surprisingly deep focus at 640 km has been observed for the earthquake of 29 March 1954 in the concavity of the Betic Cordillera. Finally, in the continental regions of the South Asian rim, great arcuate structures, including the Himalayas, are not accompanied by deep earthquakes throughout their length. The observed earthquakes, all intermediate in depth, cluster where the belt changes direction, in Burma, the Hindu Kush and the Carpathian arc. Under each of the two latter regions, the quakes oddly recur in the same place and at the same depth (225 and 150 km respectively).

2. The Crests of Ridges

The lines of ocean epicenters are sparser but more clearly traceable than the lines of Tertiary foldings. Their real width probably does not exceed 20 km (Sykes). All of the

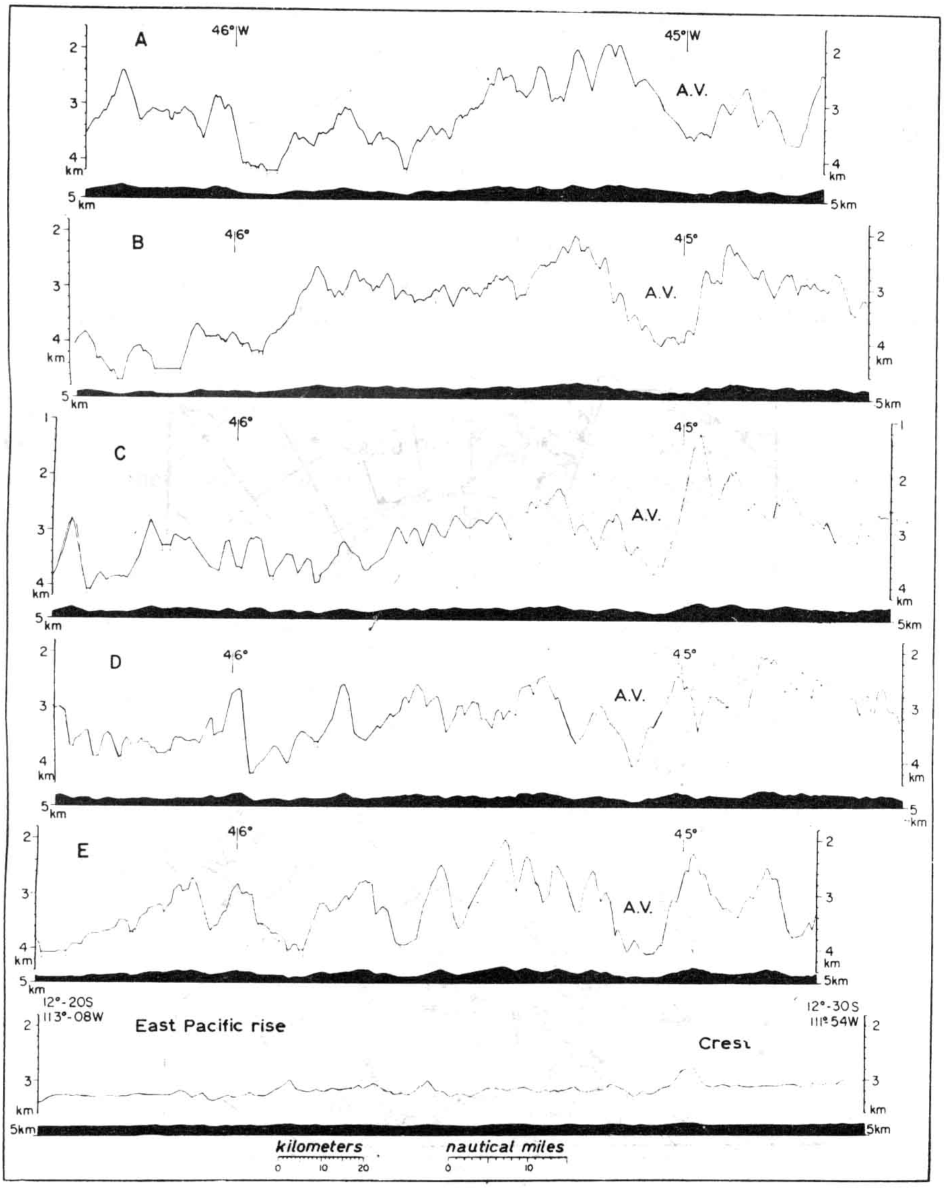

Fig. 6. Profiles of the Atlantic ridge between 22°N and 23°N, and of the East Pacific rise around 12°S. The variability of relief in the crestal region of the former is shown, particularly in the peaks and plateaus to the west of the axial valley (A.V.). (Van Andel and Bowin, 1968.)

corresponding tremors are of normal depth, and rarely very large. These lines of seismicity follow elongated shallows, rises or ridges. The typical example is the mid-Atlantic ridge discovered over a century ago in laying the first telegraph cables. The line of seismicity divides the ocean down the middle, following the curvature of its opposite coasts. The average width of the ridge exceeds 1000 km, but the earthquakes are located right on the crest (de Vanssay in 1939). The ocean depth over the crest is around 2 or 3 km, while the adjoining basins on either side are about 5 to 6 km deep. Ewing and his colleagues have found (Heezen *et al.*, 1959) that the 'crest' corresponds to a rift valley with a maximum depth of 2 km and a width of 30 km lying between two very uneven regions (Figure 6). To be exact, the median valley may be bifurcated, obstructed by volcanoés, displaced laterally, or even disappear (as for example south of Iceland on the Reykjanes ridge).

Let us start from the equator, along which the Atlantic seismic zone runs roughly from St. Paul Rocks to the Romanche trench. Going north the zone describes a large arc as far as the Azores, paralleling the African coast. From there a branch runs towards Gibraltar or Cape Saint Vincent along a poorly defined rise. Between the Azores and Iceland, another branch may connect several epicenters situated between

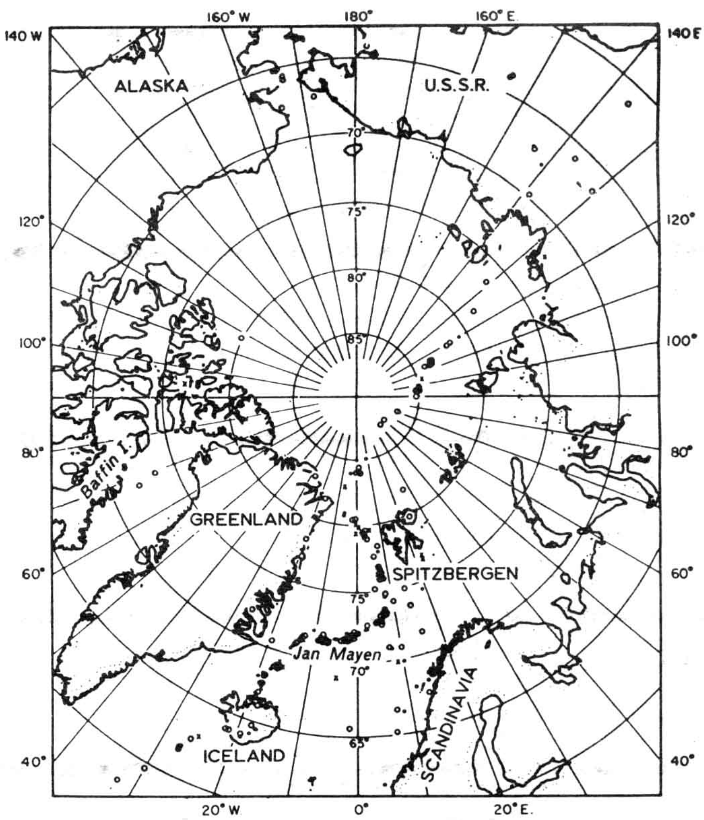

Fig. 7. Arctic epicenters, January 1955–March 1964. Circles represent epicenters determined by the author from 10 or more seismic stations, smaller circles from less than 10, crosses recent determinations by the U.S. Coast and Geodetic Survey from 10 or more stations. (Sykes, 1965.)