DAVIES
RUNCORN

Mechanisms of Continental Drift
and Plate Tectonics

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Edited by

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School of Physics, The University, Newcastle upon Tyne

1980 · ACADEMIC PRESS

A Subsidiary of Harcourt Brace Jovanovich, Publishers

London · New York · Toronto · Sydney · San Francisco

ACADEMIC PRESS INC. (LONDON) LTD
24/28 Oval Road
London NW1

United States Edition published by
ACADEMIC PRESS INC.
111 Fifth Avenue
New York, New York 10003

British Library Cataloguing in Publication Data

Mechanisms of continental drift and plate tectonics.
1. Plate tectonics—Congresses
I. Davies, P A II. Runcorn, Stanley Keith
551.1'3 QE511.4 80–41582

ISBN 0–12–206160–8

Printed in Great Britain by
John Wright and Sons Ltd. at The Stonebridge Press, Bristol BS4 5NU

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Preface

The question first considered by Wegener concerning the nature of the processes in the Earth bringing about continental drift and sea-floor spreading (or major displacements of the lithosphere) in the last 100–200 myr, is probably the most important one in geoscience at the present time. The concept of plate tectonics has integrated the evidence for continental drift, sea-floor spreading and global seismicity in a way most stimulating for geology and geophysics. The process has been rightly called by J. T. Wilson the "revolution in the Earth sciences." The global distribution of earthquakes, the world oceanic ridge system, the global pattern of the Tertiary mountain building and the ocean trenches are all generally understood in terms of the parting or collision of plates. Plate tectonics, however, is kinematic and geometrical and is not a theory in the sense of identifying the forces responsible for the plate motions. Thus, while the solution of the geometrical relationships of plate tectonics has absorbed the energies of geophysicists and especially geologists (who have reinterpreted the geological record in the new way, with stimulating effects in the subject), and dynamical questions have been discussed in lively speculative papers, no consensus of opinion has been reached.

We thought it timely to arrange a meeting to examine critically the various theories which have been put forward: gravity sliding of the plates away from the ocean ridges, the pulling of the plates by the sinking of lithospheric slabs in the trenches, mantle plumes, tidal effects, general expansion of the Earth and thermal convection in the mantle. The validity of the physicochemical processes to which these theories appeal need critical examination and the ideas now require formulation in terms of fundamental physics and chemistry. The geophysical and geological evidence which may be used to test them must also be examined thoroughly.

The geotectonics of the geological record prior to Wegenerian continental drift and especially in the Precambrian must be considered. Although the speed and nature of plate movements in recent times are so well documented by the palaeomagnetic record in the ocean floor, no theory of plate motions is satisfactory unless it explains the Earth history record prior to Wegenerian drift – over 20 times as long. Nor can geoscience today ignore the evidence brought back from space missions to the Moon and planets. How does the very different tectonic history of the Moon, Mars and Mercury fit in with ideas developed for the Earth? Does the evidence from Venus reveal continental drift there? Can a theory of continental drift which requires a dynamical model of the mantle provide a basis for understanding?

The Advanced Study Institute on "The mechanism of continental drift and plate tectonics" was held in the School of Physics from Tuesday 27th March until Tuesday 10th April, 1979, and this volume includes a full and representative collection of papers given at the meeting. We are most grateful to NATO who provided generous financial support to the Institute. Such support enabled a large group of Earth scientists (particularly graduate students) from many countries to attend. Their active participation assured the success of the meeting. Not least, we acknowledge the contributions made to the organization of the Institute by Mr W. F. Mavor, Mrs J. Roberts, Mrs D. Orton, Miss Anne Codling and Miss Maureen Hopkinson.

During the preparation of this volume we were all saddened by the death of Dr Raphael Freund – a distinguished Earth scientist who contributed most enthusiastically to the scientific and social activities of this meeting.

Raphael Freund was born in Breslau, Germany and after six months his family emigrated to Israel. After graduating with distinction from high school in Haifa he went on to the Hebrew University in Jerusalem to read geology, obtaining his M.Sc. in 1959 and his Ph.D. in 1963. He was to remain based at the Hebrew University for the rest of his life, becoming successively Instructor (1959), Lecturer (1963), Senior Lecturer (1966), Associate Professor (1972), Full Professor (1977) and first Director of the Institute of Earth Sciences.

As he lived almost on top of the Dead Sea rift, it is not surprising that this became his main object of study. He searched for and found an enormous amount of geological data for elucidating the timing of the shear movements along the Dead Sea rift zone. He was an enthusiastic field geologist and it was fortunate that he was still well enough to be able to show a great deal of the evidence for horizontal shear to the international gathering last year. Further afield, he made contributions to the studies of strike slip faults in New Zealand, and in his last year worked on dynamic models of subduction zones.

November 1980

P. A. Davies
S. K. Runcorn

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The Mechanisms of Continental Drift and Plate Tectonics: Some Boundary Conditions from Surface Phenomena

R. W. GIRDLER

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Introduction

The object of this introductory chapter is to present some boundary conditions which may be inferred from surface phenomena for theories of mechanisms of continental drift and plate tectonics.

In 1914, J. Barrell introduced the concept of "lithosphere" and "asthenosphere" for the outermost layers of the Earth. The "lithosphere" was considered to be a shell with high strength overlying the "asthenosphere" with relatively very low strength.

It is now generally accepted that the outer skin of the Earth consists of a number of thin, relatively rigid plates or spherical caps. The margins of these plates are seismically active as a consequence of their moving relative to each other. The seismicity of the Earth, therefore, may be used to give an idea of the size and shape of the plates. Figure 1 shows two faces of the Earth. The regions of deep focus earthquakes (shown as black) are somewhat restricted and mark where the plates are descending into the asthenosphere ("subduction zones") or where the plates are colliding. These regions, of course, also have shallow seismicity. The regions where *only* shallow earthquakes occur locate the rifts (i.e. where the plates are separating) and transform faults (i.e. where the plates are sliding past each other). In the oceans, these regions of shallow earthquakes are very narrow but on the continents they tend to be more diffuse (Fig. 1), presumably reflecting the long history of the continental crust and the presence of many faults and fractures.

Size, thickness and fragility of the plates

As can be seen from Fig. 1, the plates have areas of the order of 10^6–10^7 km^2. By contrast, their thickness is very small. Early workers, studying the gravity anomalies over Fennoscandia and eastern Canada, arrived at estimates of less than 100 km. Tozer (1973), in emphasizing the importance of the temperature dependence of creep processes, obtained even lower estimates. From a consideration of heat transfer processes, he obtained estimates for the thickness of the "quasi-elastic" lithosphere of 7 km for the oceans and 39 km for the continents, noting the continental lithosphere is 5–6 times thicker than the oceanic lithosphere.

If we take a working figure of 50 km for the thickness of the plates, and estimates of 1000–5000 km for their length dimensions, we obtain thickness/length ratios of 20/1 to 100/1. The plates are therefore wafer thin and may be expected to be fragile.

Age of the plates

In addition to the contrast in thickness of the continental and oceanic parts of the plates, there is a tremendous contrast in their relative ages. The continental lithosphere has had a very long history and the oceanic lithosphere a very short history.

The continents are composed of light sialic material which has been at the Earth's surface for thousands of millions of years. This is due to the relatively low density, the material being light enough to escape being recycled into the asthenosphere at the subduction zones.

In contrast, the oceanic lithosphere has all formed within the last 200 Myr and the young lithosphere covers more than two-thirds of the Earth's surface. If we take 4600 Myr for the age of the Earth, we see that the present oceanic lithosphere has formed in less than 5% of the history of the Earth. On the time-scale of Earth history, therefore, we have a process of considerable rapidity.

Creation of the oceanic parts of the plates – development of the idea of sea-floor spreading

The way in which the continents break up and the oceanic lithosphere forms is obviously very important. Considerable progress has been made towards understanding these processes, in particular the evolution of oceanic lithosphere by sea-floor spreading. This concept (and the observational support for it) has probably contributed more than anything towards the understanding of the mechanism of continental drift and plate tectonics.

The idea of sea-floor spreading may be attributed to Arthur Holmes, a Northumbrian who was born at Hebburn-on-Tyne (a few miles from Newcastle) in 1890. The idea is simple and elegant. As the continents drift

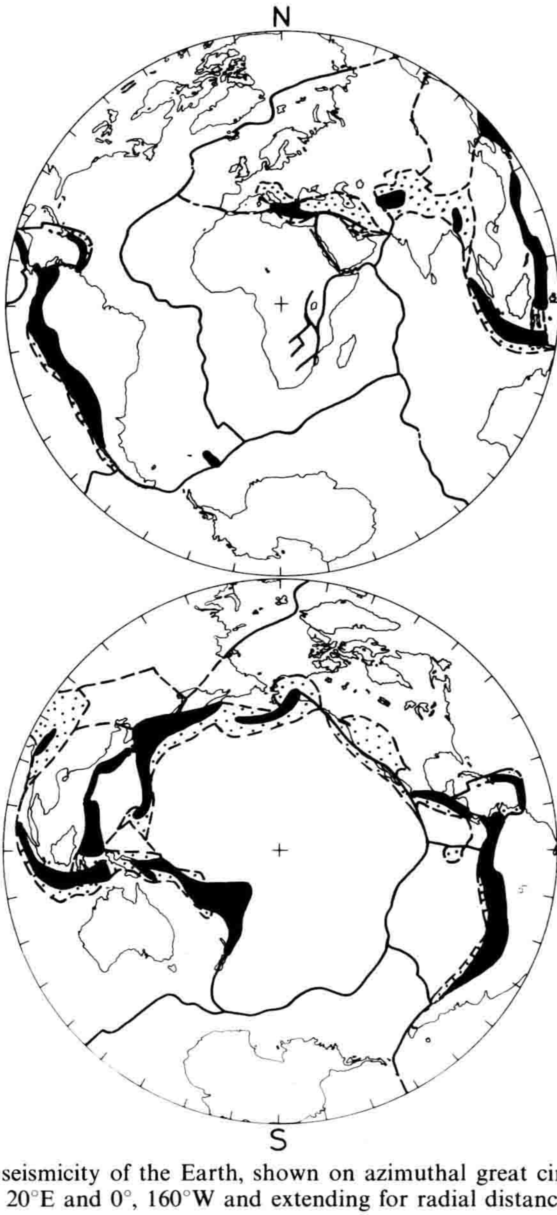

Figure 1. The seismicity of the Earth, shown on azimuthal great circle projections centred on 0°, 20°E and 0°, 160°W and extending for radial distances of 110°. The regions with deep earthquakes (focal depth greater than 100 km) have black shading and the diffuse regions with shallow earthquakes (focal depth less than 100 km) have stippled shading. The narrow regions of shallow seismicity are shown by thick lines.

apart, new ocean is formed by the injection of igneous material at the site of the ever expanding gap. The newest ocean is therefore, found at the middle and the oldest at the margins.

There has been some debate (*J. Geophys. Res.*, 1968) as to whether full credit should be given to Arthur Holmes for what has turned out to be one the most fruitful ideas in the Earth sciences. It is of interest therefore to see how Holmes' ideas evolved. Figure 2 is compounded from two of his publications. Figure 2(a) shows his ideas in the late 1920s; the continents are shown as being carried along by convection currents and an island or "swell" composed of light continental material is shown left behind as an ingenious way of explaining the height of the ridge. The words "new ocean" appear twice between the continents and the island or "swell". Figure 2(b) is taken from Holmes' *Principles of Physical Geology* published fifteen years later in 1944; here the continental relic is replaced by an oceanic island or swell and the words "new ocean" appear only once. By this time studies of rocks dredged from the mid-Atlantic had shown the ridge to be composed of oceanic basalts. The figure caption for the 1944 version describes "ocean floor development on the site of the gap" and leaves little doubt that Holmes fully understood the sea-floor spreading concept. The idea was further developed by Hess and Dietz in the 1960s.

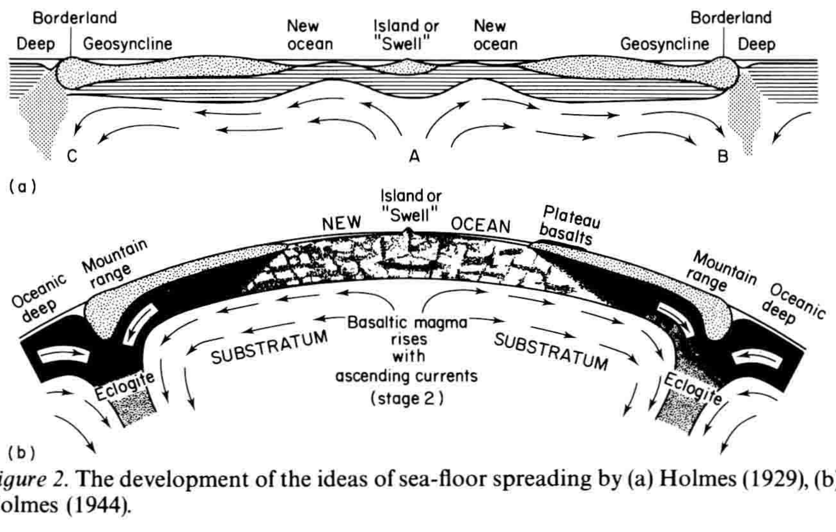

Figure 2. The development of the ideas of sea-floor spreading by (a) Holmes (1929), (b) Holmes (1944).

The remarkably short history of the present day oceanic lithosphere has been inferred from studies of magnetic anomalies following the suggestion by Vine and Matthews (1963) that the sea-floor spreading process should record the reversal history of the Earth's magnetic field. The way in which this happens is depicted in Fig. 3. The early time-scales for reversals were obtained by Vine (1966) and Heirtzler *et al.* (1968) by extrapolation using the radiometric data of Cox, Doell and Dalrymple (1964) for normally and reversely magnetized rocks on land of up to 4 million years old as calibration. The extrapolations, although outrageous, were remarkably successful!

When the observed and computed anomalies are compared, it is possible to deduce the spreading rates as illustrated in Fig. 3. It is found that new oceanic crust is being created at remarkably fast rates of up to 10 cm/yr, the East

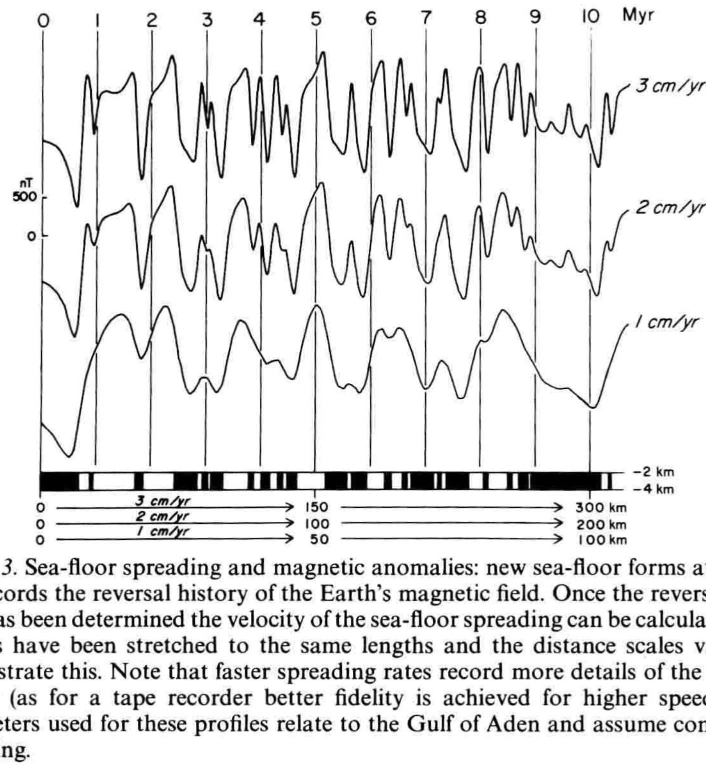

Figure 3. Sea-floor spreading and magnetic anomalies: new sea-floor forms at the left and records the reversal history of the Earth's magnetic field. Once the reversal time-scale has been determined the velocity of the sea-floor spreading can be calculated. The profiles have been stretched to the same lengths and the distance scales varied to demonstrate this. Note that faster spreading rates record more details of the reversal history (as for a tape recorder better fidelity is achieved for higher speeds). The parameters used for these profiles relate to the Gulf of Aden and assume continuous spreading.

Pacific Rise being one of the fastest spreading centres. This sets a further condition on possible mechanisms of continental drift and plate tectonics as presumably the velocities of any driving mechanism must be at least of the order of the magnitudes of the half spreading rates, i.e. greater than about 5 cm/yr.

The reversal time-scale for the Earth's magnetic field has now been constructed back to 160 million years. As mentioned, this is by extrapolation using the radiometric dates of rocks on land over a few million years. It is clearly important to have some check on such extrapolations. This has been done by drilling through the sediments at various locations on the sea-floor and comparing the age of the sediments immediately overlying the magnetic layer with that predicted by the magnetic time-scale. The age of the sediments may be determined independently by examining the fossils contained in them. In nearly all cases the agreement is remarkable, as can be seen from Fig. 4.

Figure 4 shows that the assumption of uniform spreading seems vindicated. In some ways this is not surprising as presumably with the plates having such large areas, the momentum involved in their movement must be considerable. With large momentum, once the plates are set in motion it is likely that they

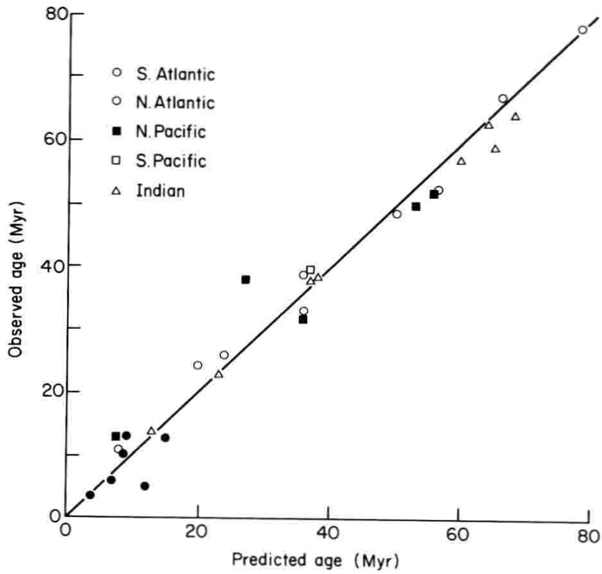

Figure 4. Comparison of the age of oceanic lithosphere as predicted by the magnetic reversal time-scale of LaBrecque *et al.* (1977) and that observed from the age of overlying sediments in Deep Sea Drilling Project (DSDP) boreholes. The 45° line indicates a perfect correlation (Diagram by courtesy of D. J. M. Noy).

will continue to move fairly smoothly. However, evidence is accumulating to suggest that the plate motions may not be so simple.

Possible go–stop–go motion of the plates

A completely different impression is presented by continental geology. Here evidence for the motions of the plates comes mainly from the mountainous regions or collisions zones. Several quite distinct orogenic revolutions have been recognized. To illustrate this, a futher diagram from Arthur Holmes is presented in Fig. 5. It shows graphically how he envisaged the orogenic revolutions to occur with time. Several orogenic phases are seen, some major and some minor, separated by quiet periods of the order of 40 million years. Further, within each major orogenic revolution such as the Alpine, further subdivisions into dynamic and quiet phases can be recognized. This is based