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PRINCIPLES OF GEODYNAMICS

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Preface

Geodynamics is an old science. Most of the basic theories have been conceived in principle during the 19th century and not many fundamental ideas have been added since. Some progress has been made in the following-up of these concepts and, in some instances, in the determination of some important facts about the Earth. Nevertheless, geodynamics has been a highly speculative subject for about a hundred years and it is not likely that this situation will change during the next hundred. It is also unlikely that many *basic* new ideas will be added in that time interval. The reason for this lies in the extreme difficulty of obtaining really relevant data about the mechanics of the Earth, partly due to the impossibility of probing into the depths of the Earth by direct means to any considerable extent and partly due to the fact that the time intervals in which "something happens" are of the order of millions of years, which is much too long for any human being to wait and experiment with.

The situation in geodynamics is therefore much akin to that which existed when the ancient Greek philosophers were speculating about the possibly atomic structure of matter: there was, at that time, absolutely no hope to either confirm or to reject the hypothesis. The subsequent historical developments proved indeed that two thousand years of technological advances were required before the question could be settled. Geodynamics is much in the same position now as the physics of matter was two millennia ago: the basic ideas that one can think of have all been thought of, but there seems to be no chance of settling the fundamental questions for a long time to come.

It seems, therefore, that the time is ripe for an evaluation of the existing ideas in the light of presently available facts. This, in spite of the early recognition of the subject, has never been done. All existing books, monographs and papers (of which there is legion) have been written to advance one or the other of the hypotheses as the "true" one. This led, in consequence, to much wishful thinking; to the inadvertent ignoring of unpleasant facts, and to the straining of others to fit preconceived ideas. The writer admits that he has been guilty of the same offense, falling in with the general trend and type of geodynamic speculations. It was only after much thought and disappointment that he arrived, so to speak, at being an "agnostic" on the subject. It is, however, his conviction that any real advances can only be expected if one starts with such a frame of mind. Otherwise, too much energy is needlessly wasted in the zealous promotion of concepts for which there can realistically be no hope of "proof" in the foreseeable future.

The present book represents, therefore, the writer's notes and ideas on the principles of geodynamics. It is not a comprehensive literature survey, but rather a compilation of the most competent presentations of each one of the,—usually very old—, basically possible hypotheses. Much of the material has been taken from the writer's own earlier attempts at struggling for the "proof" of one or the other of the ideas in which he was inclined to believe at the time, some of it from similar attempts of other geophysicists. He has particularly heavily drawn from those of his earlier articles which appeared in the Canadian Journal of Physics, in the Transactions of the American Geophysical Union, in Geofisica Pura e Applicata and in the Bulletin of the Geological Society of America. Permission to do this has kindly been granted by the editors of the journals in question and this is here gratefully acknowledged.

The first two chapters of the book give a brief summary of the physical facts about the Earth as far as they are known, the third puts together the principles of the theory of deformation of continuous matter which is the basic mechanical background of geodynamics, and the rest represents a synoptic view of the subject, much in the same way as one might present a synoptic view of the world's philosophies, without taking sides for one or the other.

The writer is indebted to many colleagues and friends for helpful discussions and stimulating criticism. It was Dr. J. TUZO WILSON in Toronto who started him off on the subject of theoretical geophysics in the first place. Many of the ideas presented here, especially on the physiography of the Earth, can therefore be backtraced to Dr. WILSON's stimulating influence. The writer owes much to Dr. J. A. JACOBS, of the University of British Columbia in Vancouver, for the discussion of mathematical matters, and especially to Dr. EGON OROWAN of the Massachusetts Institute of Technology whose influence on the writer's conception of fracture and failure has been great. The Springer Verlag has been most coöperative in effecting a speedy publication of the manuscript. The writer wishes to acknowledge his sincere gratitude to all these people.

Calgary, Alberta, Canada, February 10, 1958

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I. Physiographic and Geological Data Regarding the Earth

1.1. Introduction

The science of geodynamics aims at an explanation of the present-day surface features of the Earth. Geodesy, geology and geophysics have accumulated a wealth of information about our globe. Since the Earth is a physical object, it would be quite inconceivable that its present-day physiography would not be the result of well-defined physical processes. Since it is one of the most fundamental postulates of modern science that the laws of physics be universally valid, such changes of the surface features of the Earth as may have occurred, must have taken place in strict conformity with these laws.

The Earth is part of the solar system, the solar system is part of the universe. Ultimately, therefore, the surface features of the Earth are conditioned by the manner in which the evolution of the universe took place. Whether there is a mountain in a particular spot on the Earth's surface depends in the end on how the universe was created. However, it is quite obvious that a mountain on the Earth's surface is only a minute detail in the universe as a whole. It stands to reason, therefore, that processes can be defined which are not too intimately tied up with the universe as a whole, but which would be sufficient to explain the Earth's surface features. That these processes do have *some* connection with the evolution of the universe, is just one more instance demonstrating that there is in reality only one single nature.

Geodynamics confines itself to the study of the Earth's crust. Because of the unity of all nature, reference will have to be made occasionally to conditions above or below the crust, i.e. to conditions obtaining in the universe or in the interior of the Earth. However, we indulge in such diversions only if it is necessary for the understanding of the mechanics of the Earth's crust.

A serious handicap in the study of geodynamics is connected with the fact that it is extremely difficult to encompass geological data in terms of numbers. Traditionally, physical laws can be most easily applied to such phenomena which can be expressed by numbers. On the other

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hand, geology traditionally has been a descriptive science whose findings cannot easily be encompassed in numbers. Much space in the present book is therefore devoted to the discussion of this difficulty and to the task of abstracting numbers or simple geometrical shapes from the wealth of physiographic facts.

The principal physical processes governing the evolution of the Earth's crust are not yet definitely known. The approach is therefore one of trying out various theories and checking their consequences with regard to features accessible to observation. Sometimes, much mathematics is needed to follow up a particular hypothesis to its ultimate conclusions, particularly if reference has to be made to the mechanics of deformation of continuous matter. It is therefore expected that the reader is familiar with infinitesimal calculus, and in some sections, also with tensor calculus. However, pains have been taken to supply all the necessary *physical* background in sufficient detail to make the book, in this regard, self-contained. In general, the writer aimed at presenting the material in such a fashion that the reader who is interested in a particular topic can seek out the corresponding chapter, read it and understand it if he follows up the cross-references. It will be found that many topics can be understood without the necessity of referring to *all* that has been said on previous pages. Some of the theories have reached only a descriptive stage and can therefore be understood without any reference to mathematical analysis at all.

It is hoped, therefore, that the book will represent a useful work of reference for all those who are interested in any aspect of geodynamics.

1.2. Geological Evolution

1.21. The Basic Rock Types. The domain of geology is the investigation of the origin and evolution of rocks, i.e. of the material which constitutes the solid surface of the Earth.

First of all, one finds two principal types of rocks: sedimentary rocks and igneous rocks. Sedimentary rocks are separated into more or less distinguishable parallel layers, whereas no such structure is evident in igneous rocks.

The appearance of rocks is the result of their geological past. Lava, for instance, may be thought to have been exuded from the deeper parts of the Earth during volcanic activity. Other types of igneous rocks, such as the granites and granodiorites, were at one time thought[1] to have a similar history as lavas, with the difference that the cooling process had a much longer duration and took place at great depth.

[1] NEUMAYR, M.: Erdgeschichte, 3rd. ed. by F. E. SUESS. Leipzig: Bibliographisches Institut 1920.

Hence the name "batholiths" (from Greek $\beta\acute{\alpha}\vartheta o\varsigma$, depth and $\lambda\acute{\iota}\vartheta o\varsigma$, stone) for masses of such granites found in the interior of mountain ranges. However, the present-day[1] view inclines toward assuming that the batholiths were formed *in situ* by a process called *metamorphose*. In the case of batholiths, this process must have been very complete as it must have involved melting of the present rocks in order to give them the igneous appearance. In other metamorphic rocks, it has been less complete.

The rocks on the surface of the Earth are continuously subject to detrition by the action of wind and water. Ground down by atmospheric influences, the débris is carried in rivers to larger bodies of water where deposition takes place. The accumulation of such débris, under further consolidation, gives rise to the sedimentary rocks mentioned above. The process of accumulation itself is called *sedimentation*. Sedimentary rocks, in accordance with their mode of formation, are "stratified". Corresponding types of strata can often be traced to various parts of the world.

One thus arrives at a cycle of evolution of rocks. Sedimentary rocks become gradually metamorphosed, possibly even entirely molten, until they have the appearance of igneous rocks. Then the process of detrition starts, the débris are deposited somewhere and eventually, new sedimentary rocks are formed.

The Earth is generally assumed to have begun as a hot, molten body. (For a more detailed discussion of this point, see Sec. 5.13.) If this be true, all "first" rocks must have been igneous. However, no such "first" rocks can be found. It appears that even the oldest known igneous rocks are not "first" rocks, but show signs of having been metamorphosed from even earlier sedimentary rocks (cf. HOLMES[1]). The beginning of the evolution of rocks is therefore not known.

1.22. Geological Time Scale. The fact that sedimentary rocks have been formed by deposition of débris yields a powerful means of dating them, at least relative to each other. During the process of deposition, it is inevitable that living and dead organisms become entrapped which are then preserved as fossils. It is thus possible not only to obtain an idea of the age of a stratum in which a fossil is found, but also to obtain a picture of the evolution of life. A drawback of this method of dating is that it is naturally confined to such times from which traces of life have been preserved to the present day. The traditional geological time scale, therefore, begins with that epoch from which the oldest fossils were found.

[1] HOLMES, A.: Principles of Physical Geology. New York: The Ronald Press Co. 1945.

The traditional time scale is shown in Table 1. The absolute ages shown there are after MARBLE[1] who made use of all presently known means, including radioactive age determinations (cf. Sec. 2.4).

Table 1. *Geological Time Scale*

Era	Epoch	Approx. age in millions of years
Quaternary	Pleistocene	0
Tertiary	Pliocene	
	Miocene	20
	Oligocene	40
	Eocene	60
Mesozoic	Cretaceous	130
	Jurassic	155
	Triassic	185
Paleozoic	Permian	210
	Carboniferous	265
	Devonian	320
	Silurian	360
	Ordovician	440
	Cambrian	520

1.23. Paleoclimatic Data. From a geological investigation of the various sedimentary strata it becomes evident that various parts of the Earth must have undergone large climatological changes. During the Carboniferous epoch, Europe as well as part of North America must have lain in a belt of rain forest (as evidenced by the fossilized tree-ferns found in coal seems of that age) whereas South Africa and Brasil appear to have been buried beneath ice caps. On the other hand, during the Pleistocene, Europe and North America experienced an ice age whereas Patagonia and Northern Siberia were much warmer than they are to-day. If one combines these (and other) observations, one is led to assuming as a plausible explanation, that the geographic position of the North Pole underwent changes during geologic history[2].

The first to investigate the climatological evidence comprehensively in this fashion was KREICHGAUER[3]. Later KÖPPEN and WEGENER[4] and KÖPPEN[2] made thorough investigations of paleoclimatic data. This yielded three attempts at a reconstruction of the polar paths which are shown in Fig. 1. The trace of the pole runs in all three attempts from somewhere near Hawaii in the Carboniferous to its present position.

Accordingly, in the Carboniferous, Western Europe and North America would have lain in an equatorial belt of rain forest. In the Permian Epoch they belonged to the adjacent dry zones so that the large deposits of salt found in these regions could be formed. At the same time, the glaciations of Brasil were replaced by forests giving rise to the formation of coal seams there. During the Mesozoic, Europe was in the dry area whereas the pole proceeded through the North East

[1] MARBLE, J. P.: Rept. Ctee. Measur. Geol. Time 1949/50, 18 (1950).
[2] KÖPPEN, W.: Meteor. Z. **57** 106 (1940).
[3] KREICHGAUER, D.: Die Äquatorfrage in der Geologie, 1. Aufl. Steyl 1902.
[4] KÖPPEN, W., A. WEGENER: Die Klimate der geologischen Vorzeit. Berlin: Gebr. Bornträger 1924.

Pacific Ocean. In the Oligocene and Eocene the position of the pole caused the formation of fossil ice in Alaska and Siberia. The large loop in the polar path during the Pleistocene is suggested by the astonishing

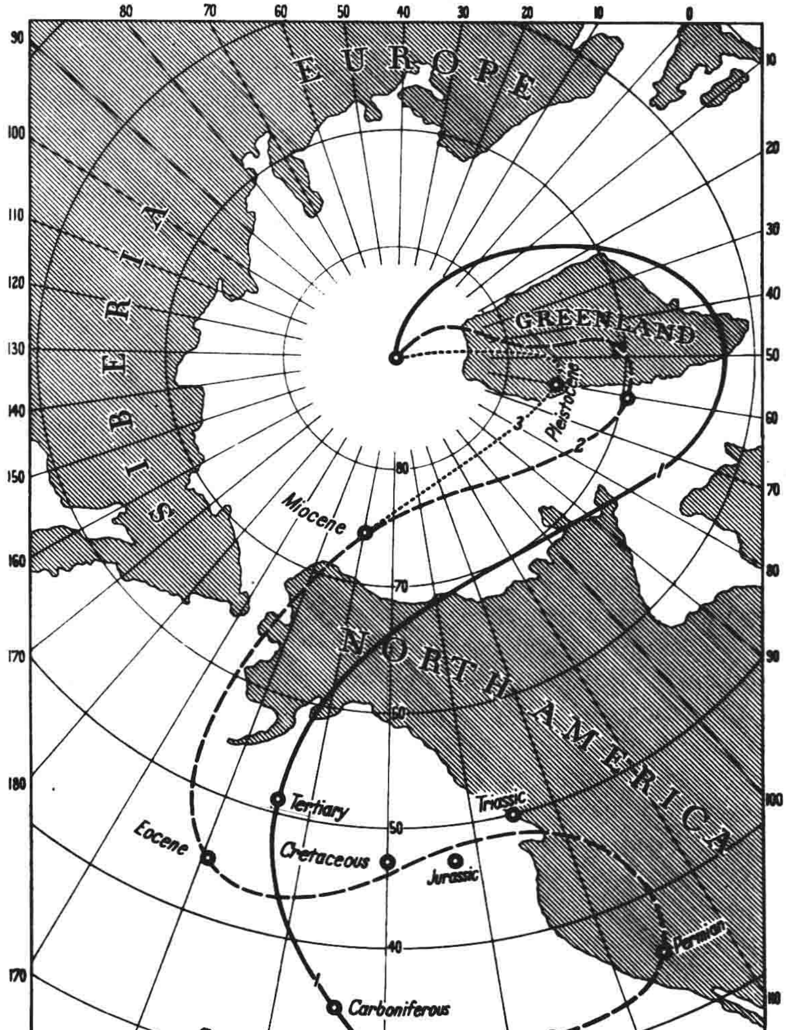

Fig. 1. Path of the North Pole as indicated by paleoclimatology. *1* after KREICHGAUER[1]; *2* after KÖPPEN and WEGENER[2]; *3* after KÖPPEN[3]. (After KÖPPEN)[3]

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[1] KREICHGAUER, D.: Die Äquatorfrage in der Geologie, 1. Aufl. Steyl 1902.

[2] KÖPPEN, W., A. WEGENER: Die Klimate der geologischen Vorzeit. Berlin: Gebr. Bornträger 1924.

[3] KÖPPEN, W.: Meteor. Z. **57**, 106 (1940).

finds of plants on the Seymour-Islands which are now covered with ice and the Quarternary sediments containing fossil subtropical mollusci as far south as the Rio Negro in South America. Similarly, the much more extensive glaciation in North America as compared with that of Europe during the Pleistocene ice ages is a pointer in the same direction.

It is therefore seen that it is possible to postulate a reasonably coherent path of the pole to explain various geological and climatological observations. However, as the dating of strata relative to each other in different parts of the world is not easy to achieve, it is very difficult to establish as a certainty that glaciation in one part occurred concurrently with tropical growth elsewhere. Therefore, the alteration of glaciations and tropical growth in any one area can also be explained by surmising that the climate of the *whole* Earth underwent such changes wherein the evidence in other areas might be assumed to have been obliterated for one reason or another. Nevertheless, the fact that the path of the pole as postulated by paleoclimatic investigations turns out to be more or less coherent, certainly lends considerable support to the hypothesis of polar wandering.

1.3. Geography of Continents and Oceans

1.31. Geometrical Arrangement. A remarkable fact about the physiographic disturbances of the Earth's crust consists in the distribution of continents and oceans. Though quite irregular, it shows a few systematic features. The continents are nearly everywhere antipodic to oceans, and they are all roughly triangular, touching each other in the North and pointing suthwards. Four old shields have their position, roughly speaking, at the corners of a tetrahedron.

However, it may not be correct to simply talk about "oceans", as the Pacific basin seems to be geologically somewhat different from the other oceans. The most striking evidence along this line is the fact that the coasts on the Pacific are obviously different from those on the Atlantic. Furthermore, eruptive magmas in the true Pacific basin are predominantly basaltic, in other areas andesitic (cf. Sec. 2.72).

A remarkable observation is that the continental structures on the Earth's surface can be made to fit together rather well like a jigsaw puzzle. The fit of the western shore of Africa with the eastern shore of South America is quite obvious, but the rest of the continents can also be made to fit with more or less ease. This has already been observed as early as 1911 by BAKER[1] who showed the composition of the continents reproduced in Fig. 2. However, more recently (cf. DU TOIT[2])

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[1] BAKER, H. B.: See DU TOIT[2].

[2] DU TOIT, A. L.: Our Wandering Continents. Edinburgh: Oliver & Boyd 1937.

it has been the practice to fit the Earth's continents together into *two* groups, called *Laurasia* and *Gondwanaland*, rather than into one as done by BAKER. Laurasia is the complex of Europe, Asia and North America, which is even at the present time not very widely dispersed; Gondwanaland is the combination of all the southern continents fitted together. In this sense, one arrives at the picture shown in Figs. 3 and 4.

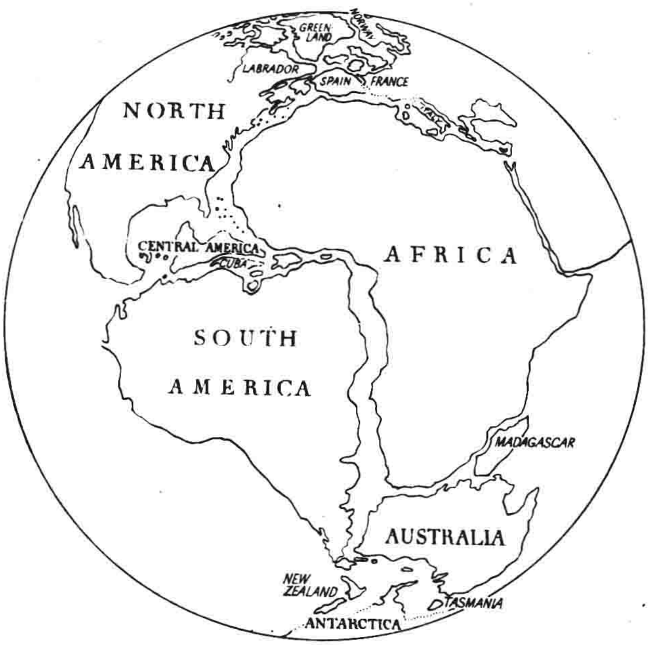

Fig. 2. BAKER's[1] composition of the continents. After DU TOIT[2]

From the artificial arrangement of the continents into two big blocks, it is an easy step to postulating that the continents actually *were* formed originally as such blocks and that they subsequently "broke up" and "drifted" into their present position[3]. We shall discuss the dynamical possibilities for this having occurred later, and at the present time only mention the physiographic evidence bearing thereupon as exhibited by the fit of the continents. In addition to this physiographic indication, many geological data have been collected, mainly by DU TOIT[2] with the intention to find features common to the various continents which might indicate whether or not and when they moved apart from the two original blocks. This evidence is of

[1] BAKER, H. B.: See DU TOIT[2].

[2] DU TOIT, A. L.: Our Wandering Continents. Edinburgh: Oliver & Boyd 1937.

[3] WEGENER, A.: The Origin of Continents and Oceans. Translated from 3rd German ed. by J. G. A. SKERL. London: Methuen 1924.

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