ALLÈGRE

The BEHAVIOR of the EARTH

HARVARD

The BEHAVIOR of the EARTH

Continental and Seafloor Mobility

CLAUDE ALLÈGRE

Translated by
DEBORAH KURMES VAN DAM

HARVARD UNIVERSITY PRESS
Cambridge, Massachusetts, and London, England 1988

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

This book is printed on acid-free paper, and its binding materials have been chosen for strength and durability.

Library of Congress Cataloging in Publication Data

Allègre, Claude J.
The behavior of the earth.

Translation of: L'écume de la terre.
Includes index.
1. Plate tectonics. I. Title.
QE511.4.A4513 1988 551.1'36 87-31102
ISBN 0-674-06457-7 (alk. paper)

THE BEHAVIOR OF THE EARTH

PREFACE

SCIENTIFIC theories are like talented artists: once recognized their merits seem so obvious that their success is assumed to be due only to their excellence. In science especially, new ideas are seen as an inevitable and unshadowed enlightenment, and the fact that the process of discovering them was slow and chaotic is forgotten. The newer an idea, the more shocking it is, and the more it disturbs those who established their reputation before its emergence, as well as those whose intellectual security is upset by it. Originality is a highly esteemed virtue as long as it is not *too* original. Any innovation that goes beyond a certain threshold tends to be pushed to the sidelines, even discounted. To paraphrase René Girard's notion of imitative behavior, the only tolerable originalities are those that are differentially original (in a mathematical sense). The quantum jump in the evolution of scientific ideas is taboo because it violates the principle of *mimesis.*

The idea of continental drift was just such a quantum jump. Although it was not new when it took root in the earth sciences in 1961, it set off a fierce and passionate battle, in many ways comparable to the one that accompanied the emergence of evolutionist ideas in biology. As Darwinian theory is central to all of modern biology, so the theory of continental mobility is the pivot of the revolution the earth sciences have experienced in the past three decades. Without it modern geology would not be conceivable today. Few disciplines have in so short a time undergone such a radical transformation in mode of thought, concept, or method of approaching data.

Continental drift entails the idea of the re-creation of the ocean floor, and therefore of dynamism in the mantle and a coupling between the interior and the surface of the earth. In light of this theory the earth becomes a living, changing entity whose "physiology" can be understood only by studying it globally. Traditional geology consisted mainly of rock classifications, the timetable of geologic eras, cross sections and maps. Its vocabulary was as barbarous as it was esoteric. Today's geology is much more vivid and less static.

For a long while it was thought that movements of the earth's crust were essentially vertical, causing a trench to open here, a mountain to rise there. The only lateral displacements taken into account were those of the sea. Since the birth of geology it has been recognized that during certain epochs the sea covered vast areas of the continents, depositing sedimentary strata containing fossils. For example, the sea invaded the Paris and Aquitaine basins 200 million years ago (in the Triassic period) and did not retreat until a few dozen million years ago (at the end of the Tertiary). On an even more grandiose scale the sea invaded the entire African shield 500 to 150 million years ago. Only a few archipelagoes in the Ahaggar and in the south of Morocco stuck out from the vast expanse of water. Then, under the influence of factors that even today are not well understood, the sea retreated, allowing the continents to emerge. Marine transgressions and regressions were sometimes local, affecting only a small fraction of the land area, and sometimes general, affecting most of the continents.

The length of time the sea remained in a given region is indicated by the depth of sediments deposited one on top of another. The presence of animal and vegetable remains in them makes it possible to specify the age of a stratum and the ecological conditions that prevailed at the time of its deposition. Sedimentary layering thus constitutes the "text" from which a person who understands the language can decipher geologic history.

Because marine transgression and therefore sedimentation was episodic, the record on every continent is fragmentary and scattered. Traditional geology attempted to reassemble these archives, to match them up with one another and to read the messages they contain. This difficult, often tedious work made it possible for geologists to reconstruct the successive geographies of the earth. The continental massifs—blocks of hard, ancient rocks as are found in the north of Canada, a good part of Africa, the center of Australia, Scandinavia, and Central Asia—were assumed to be fixed. Around them the advances and retreats of the sea extended or restricted the continental land area. Episodes during which sediments were folded and carried to high altitudes—this is called orogenesis, or mountain building—were superimposed on this overall scenario. According to the traditional view, these movements were essentially vertical, horizontal displacements being restricted to between a few dozen and a few hundred kilometers.

Because their duration is so short, volcanic eruptions and earthquakes were considered autonomous events that have little relation to other objects of study in the earth sciences. The internal activity of the planet, of which earthquakes and volcanoes are the most spectacular manifestations, was decoupled from what took place on the surface. Each level, each depth was assumed to obey its own particular laws. Surface geologic activities such as erosion, sedimentation, and shoreline changes were thought to have their own causes. The activity of the deeper layers, the area called the "mantle," was thought to be governed by obscure laws in which temperature and pressure no doubt played the decisive roles and whose surface effects were limited. These laws were unrelated to the phenomena of marine transgression and regression and only slightly related to orogenesis.

Continental drift and plate tectonics changed all that. The ancient shields were no longer fixed in relation to one another, shorelines moved with their continents, successive geographies changed not only as a result of the sea's advances and retreats but also because the very framework of these movements was constantly changing. Earthquakes, volcanoes, and mountain building were directly connected to the continuous but variable mobility of the earth's surface. Earth was not a dead planet whose only geologic activity was engendered by the presence of water on its surface, but a dynamic and evolving planet whose constantly changing surface appearance, distribution of land and sea, heights and depths, and archipelagoes and platforms were the surface reflections of large-scale movements that animated its depths.

The earth is now seen as a *system* in the modern sense of systems logic; its dynamics are regulated by multiple interconnected and interregulated causes, and its behavior is as complex and global as that of a living being. Plate tectonics not only had implications for the study of causes and effects, it also furnished concrete answers to a whole series of questions that have been asked since we began observing the planet. Why are there active volcanoes in Iceland, Japan, and Indonesia, but not in Yugoslavia or Siberia? Why are California, Yugoslavia, Japan, and Indonesia ravaged by earthquakes while central and south Africa are exempt from them? Why is oil found both in Venezuela and in the Gulf of Guinea? Why is the Andean Cordillera situated along the edge of a continent while the Himalaya is located in the center of Asia? Why are there great trenches, such as those near the Puerto Rico and Kurile islands, more than 10 kilometers deep in the ocean floor? Why are the sedimentary layers deposited in Brazil so similar to those in Angola? I could fill pages and pages of equally fundamental questions that have been given clear answers since the advent of the theory of global tectonics. Furthermore, the influence of these new theories has changed the attitudes of the earth scientists and, in that way, their very organization.

The term *earth sciences*—it is important to stress the plural—refers to the totality of disciplines whose object of study is our planet; it emphasizes the multiplicity and diversity of disciplines, a vestige of the neat divisions that existed before the development of mobility theory. Before 1970 each earth scientist devoted himself or herself either to the study of a particular region of the earth or to a specialized method of approach: paleontology or geophysics, oceanography or geochemistry.

The geophysicist studied the earth's interior using the methods, tools, and measurements of physics. Since the interior offered only brief episodic exterior signs (earthquakes and volcanoes), suggesting a sort of quiescence interrupted by fits of violent activity, the geophysicist preferred to study the structure of the depths rather than their movements, their anatomy rather than their physiology. Thus fields such as seismology or gravimetry developed, specialties whose object was to determine the internal structure of the earth. Persuaded that the surface structures in no way reflected the deep structures, geophysicists remained indifferent to geology. Laboratories for geophysical research often belonged to applied physics departments, not to those of the earth sciences. The geologist studied rock formations, their distribution, and their history but considered his work isolated from that of the geophysicist. The oceanographer believed his work to be unconnected to that of the pedestrian terrestrial geologist. So continental geology and ocean geology developed in parallel, without any real links between them. Even within geology the different specialties tended to be dissociated from one another. The petrologist who studied rocks and their mode of formation did not feel concerned with the problems of marine transgressions and regressions and therefore neglected stratigraphic geology. The paleontologist who studied the evolution of life on earth considered his progress quite independent of other aspects of geology. Only the tectonic geologist, preoccupied by the difficult problem of mountain ranges, tended to use the results of other disciplines. Advances in research created new specialties, which in turn became isolated, and the tree of geologic science increasingly tended to branch out.

Because mobility theory furnished a framework for many of the great questions in the earth sciences and because it was constructed from varied and distant disciplines, it was immediately able to reconcile all the fields within the earth sciences. A phase of fragmentation was followed by one of unification and accretion. Earth scientists who thought they were investigating separate problems suddenly realized that they were all studying a common subject, the earth. In the same way that a biologist's subject is not limnology, elephants, or bacteria, but *life,* that of the geologist is not fossils, the Alps, paleomagnetism, or granite, but the *earth.* Thus a mosaic of specialists who had ignored one another became a group of earth scientists each of whom had his own outlook but pursued the same goal: to understand the earth, its functioning, and its history.

Those who passed up thematic specialization for the sake of regional studies will be forced to realize that they have chosen the wrong scale. A region is nothing unless it takes its place in a more general framework or unless the mechanisms and structures it illustrates are significant for the functioning of the earth as a whole. So, in a draconian intellectual revolution, the regional catalogue gave way to the region as a model or symbol, an example of a phenomenon. Regionalists will be even more upset when they perceive that participation in the common progress requires each person to keep his specialty, of course, but also to know enough about the others to enter into dialogues and cooperative efforts. No more living in an ivory tower! The magnetician realizes that micropaleontologists exist and that he should work with them to date the ocean floors. The petrologist perceives that unless he has some knowledge of geothermal phenomena, unless he is able to understand the geophysicist, he cannot decipher the messages in the rocks he is studying. The tectonophysicist who specializes in mountains understands that he cannot ignore discoveries about the ocean or the results obtained by oceanographers, and so forth. Thus a new, multidisciplinary scientific community is built up, one that brings together specialists who use different techniques but whose approaches and goals are more and more homogeneous.

In the midst of this intellectual banquet geology was to accomplish more in ten years than it had in the previous one hundred years; it experienced an incredible acceleration in development, a sudden crystallization of ideas that had ripened slowly, often without being formulated, and a restructuring into new chapters.

Some geologists, such as J. Tuzo Wilson, have spoken of this development, which in a few years has brought a bountiful harvest of scientific results and metamorphosed the community of the earth sciences, as a revolution. It is certainly that. The earth sciences were as radically transformed by global tectonics as chemistry by the atomic theory, physics by quantum mechanics, or biology by the theory of evolution and, more recently, by molecular biology. The appearance of mobility theory is no doubt a key moment in the history of scientific thought. This great leap forward took place in a few decisive years, but progress continues with undiminished vigor to this day.

In this book I attempt to trace in an uncomplicated manner the evolution of the ideas connected with continental mobility. This object is combined inextricably with the goal of explaining mobilist geology and its essential concepts. I have purposely simplified the work to give it a manageable size, make it accessible to the general reader, and place it in its proper sociological context. No one can understand the great adventure of our time, the development of the sciences, without also comprehending the context in which it occurs.

CONTENTS

THE WEGENERIAN SYNTHESIS

In 1912 the German meteorologist Alfred Wegener, struck by the similarity of the shapes of the coastlines of Africa and South America, proposed the theory of continental drift. In a paper entitled "Die Enstehung der Kontinente und Ozeane" (The origin of continents and oceans), Wegener suggested that Africa and South America, formerly a single block, broke apart, the two halves moving away from each other and leaving a space to be filled by the ocean. Thus, he said, the Atlantic Ocean was created by continental drift.

Wegener was not the first to state this idea. It was set forth in 1858 by Antonio Snider-Pellegrini in *La Création et ses mystères dévoilés* (The creation and its mysteries explained). After that several authors, especially Frank B. Taylor of the United States, took up the idea, but without attracting much notice in the scientific world. Wegener's contribution was to substantiate the hypothesis with the scientific arguments needed to overcome the skepticism that greets any new idea. He transformed a working hypothesis into a compact, coherent, and synthetic body of doctrine that encompassed extremely diverse aspects of earth's history in a global vision. He defended his theory firmly, but without pugnacity, until the end of his life. Wegener, therefore, must be considered the true father of the theory of continental drift. As the French historian Georges Duby said, in questions of precedence one ought to distinguish clearly between an idea put forth more or less casually among others and a work that has been constructed, argued, and developed around an idea. The first is anecdotal, whereas the second is central and obligatory.* I will follow this rule.

Isostasy

In Wegener's time the great Austrian geologist Eduard Suess, in an immense work entitled *Das Antlitz der Erde* (The face of the

* Georges Duby, *The Three Orders: Feudal Society Imagined*, trans. Arthur Goldhammer (Chicago, 1980).

earth), had popularized the idea that the continents, made of light granite (density 2.8 grams per cubic centimeter), "float" on underlying denser (density 3.2 grams per cubic centimeter) and more viscous basaltic rock that forms the ocean bed. Because the granitic rock is rich in silicon and aluminum, Suess called that layer SIAL; the silicon- and magnesium-rich basaltic rock he called SIMA. Like icebergs floating in water, the sialic continents are in equilibrium on the SIMA. According to Archimedes' principle, the pieces of SIAL move vertically in hydrostatic equilibrium with the SIMA. When erosion removes a surface layer of a continent, the continent tends to rise, as a barge rides higher in the water when it is unloaded. This theory, which had been developed by John Henry Pratt, Clarence Dutton, and George Airy in the nineteenth century, is known as *isostasy.*

The isostasy of the crust can be proved in various ways. Let us imagine that we remove all the water from the oceans. If we plot

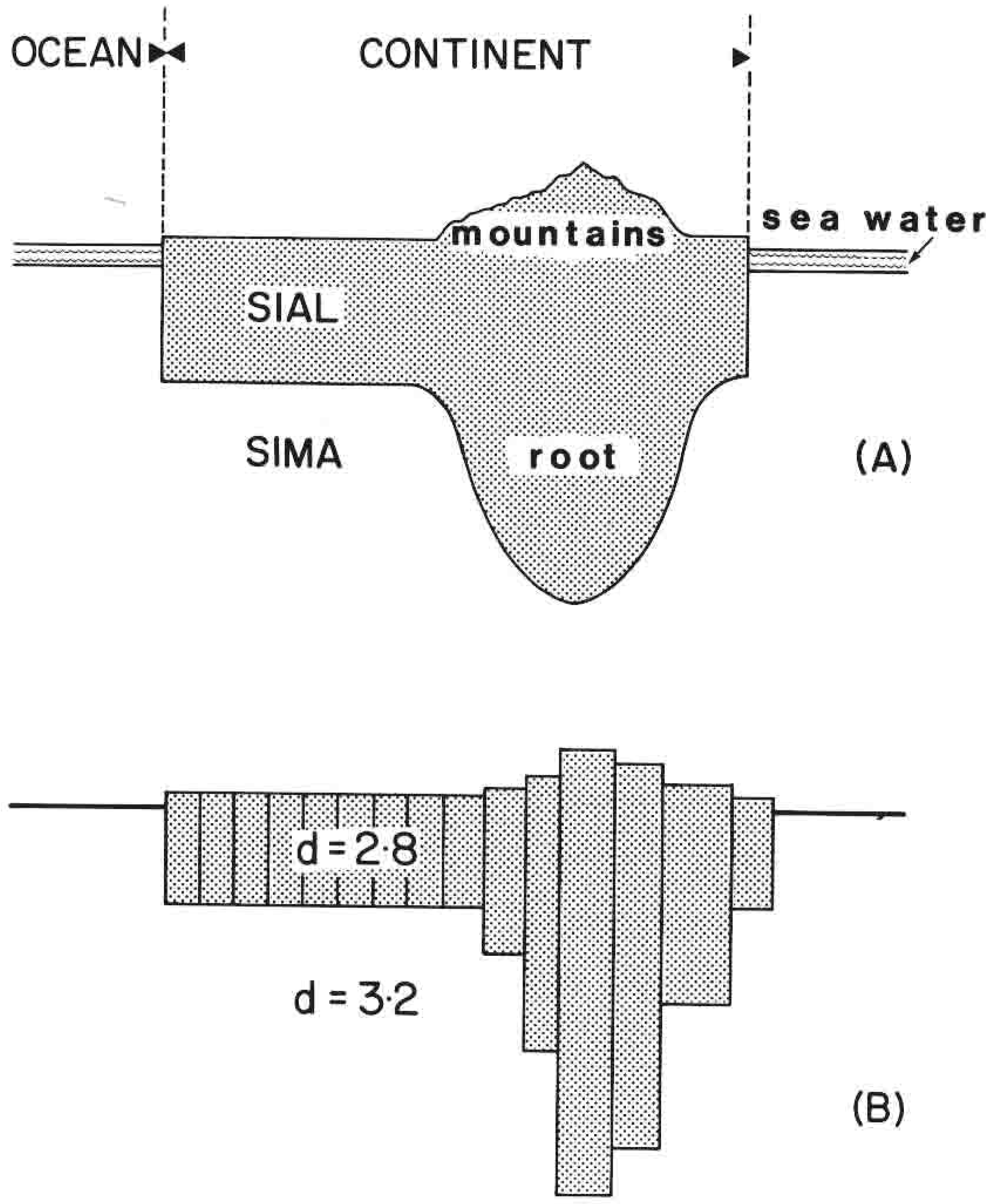

FIGURE 1 (*A*) The continent (SIAL) is lighter than the mantle (SIMA) and thus floats upon it. The weight of mountains is supported by a "root" of thickened continent. (*B*) Model of the heights of continental blocks (of density 2.8 grams per cubic centimeter) floating on a liquid mantle (density 3.2).

the percent of the earth's surface that is at a given height above or below sea level, we get a curve with two maxima corresponding to the hydrostatic equilibrium level for each of the two materials, the SIAL and the SIMA: one at 100 meters above, the other at 4,500 meters below sea level. The continents play the role of the lighter iceberg.

Proof also comes from observations made by numerous geologists, including Gerard Jacob de Geer of Sweden, on the rise of the Scandinavian shield. In the Pleistocene epoch (12,000 years ago) Scandinavia was covered by an ice cap. Since then the glacial covering has retreated northward for climatic reasons, thereby lightening the shield. We know that the shield has risen little by little, because the altitude of known points on the shield has increased over time. This rising motion recalls the image of the floating barge: lightened by the melting of the ice, the shield is returning to its original level.

Finally, a more complex study of the variation of surface gravity shows that mountain ranges, like icebergs, have deep roots that counterbalance their high elevations. This too confirms the analogy between a continent floating on the ocean bed and an iceberg floating on the ocean.

Wegener supported his theory by invoking the principle of

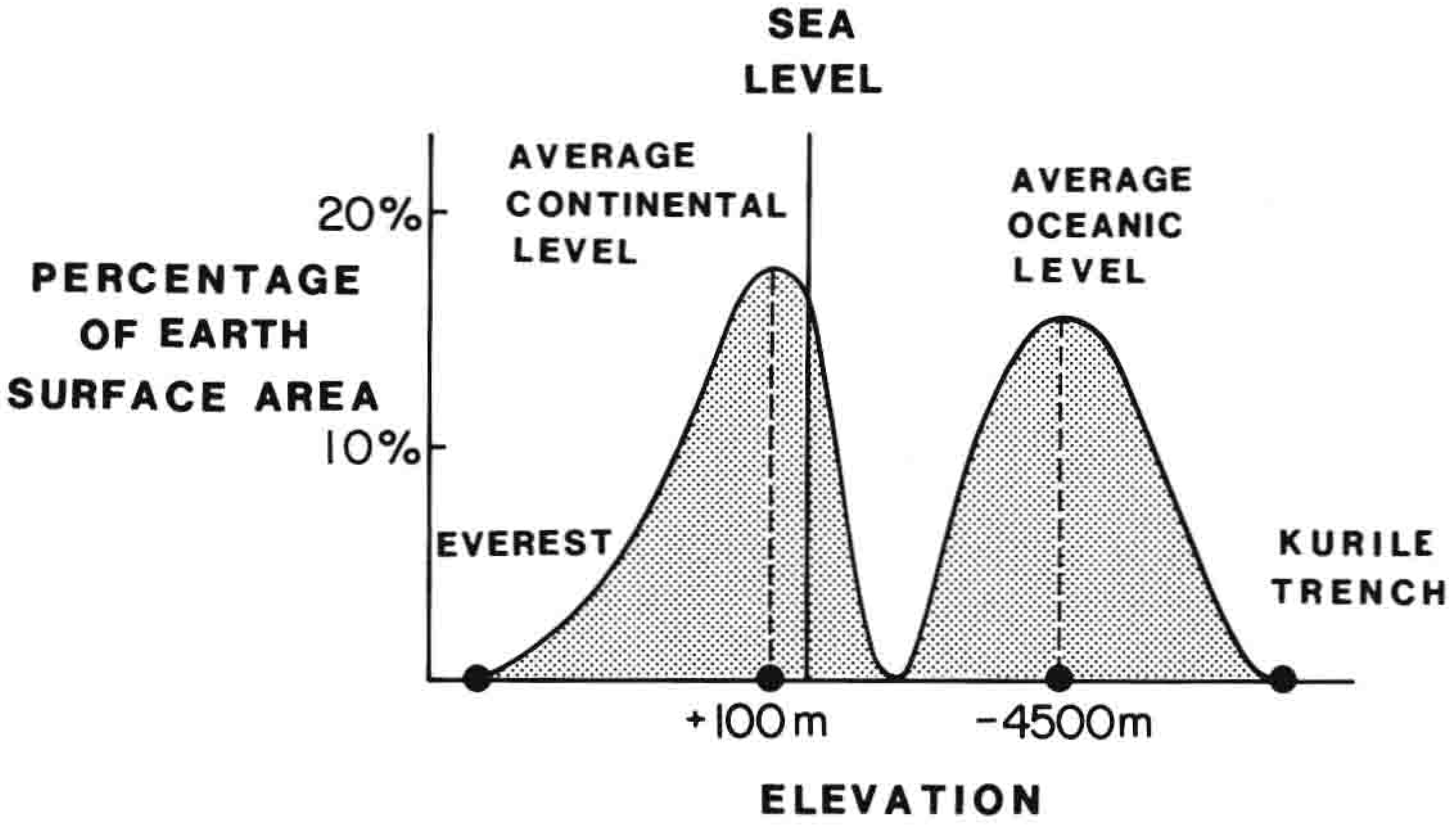

FIGURE 2 Hypsometric curve plotting the percentage of the earth's surface (with the oceans removed) that lies a given distance above or below sea level. The graph has two peaks—one at 100 meters above sea level (reflecting the average height of continents), the other at 4500 meters below sea level (showing the average depth of the oceans)—because continental and oceanic materials have different densities.

isostasy and asked: if vertical movements are possible for the continents, why not horizontal displacements? Icebergs in water are not stationary with respect to one another. Why couldn't Africa and South America have moved progressively away from each other? And why restrict continental drift to the South Atlantic? Wegener proposed to apply the theory to all continents.

Wegener's Scenario for Continental Drift

At the end of the Carboniferous period, about 270 million years before the present (M.Y.B.P.), there existed a single continent named Pangaea. In the following period, the Permian, this supercontinent

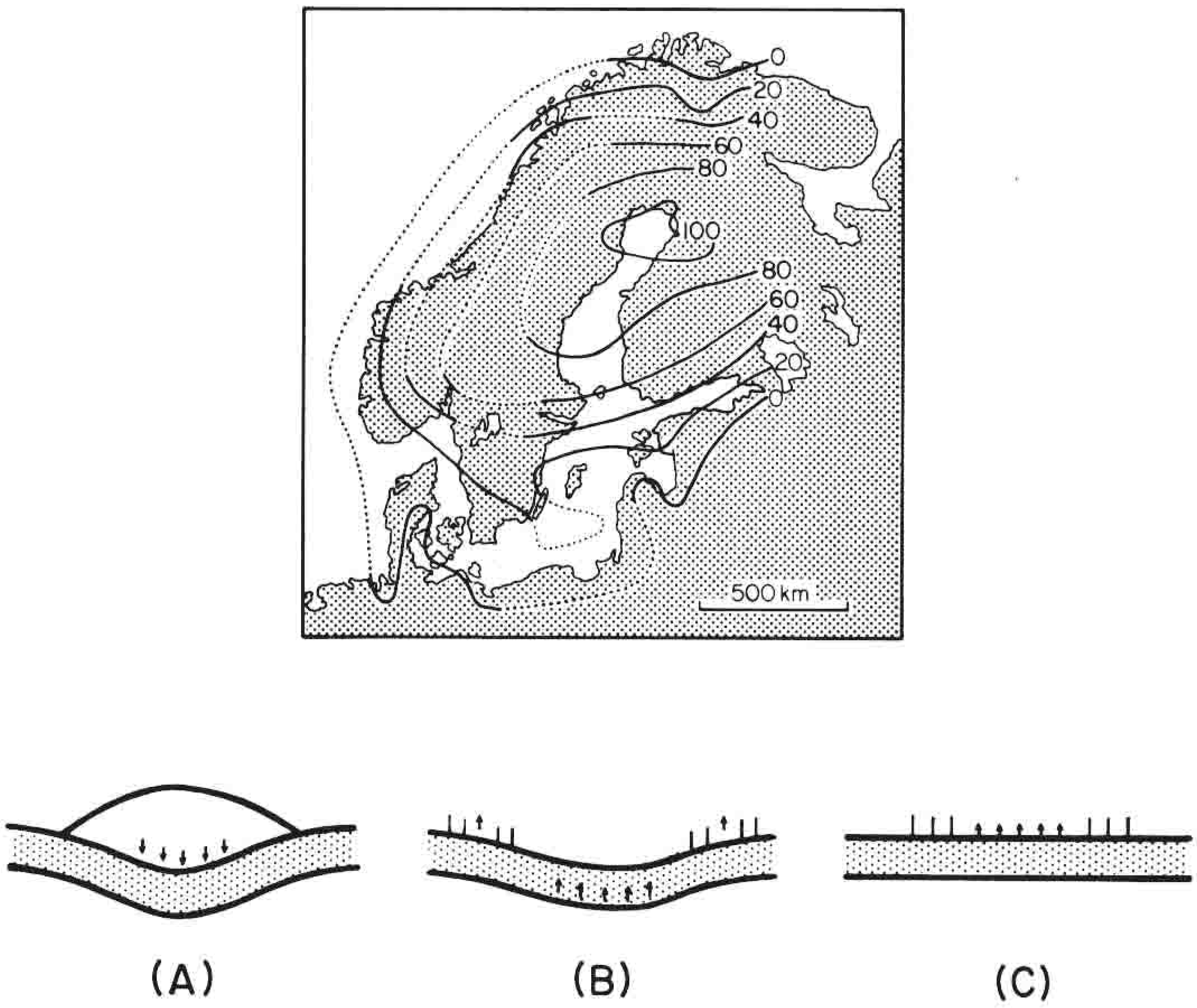

FIGURE 3 The Scandinavian shield has been rising since the removal of a giant ice sheet that covered the area during the last ice age (contour lines show centimeters of uplift per hundred years). The center of the shield is rising at a faster rate than the edges because the center region was pushed down farthest by the ice sheet. Suppose a circular ice sheet forms on the elastic Scandinavian crust. The weight of the ice will push down the crust (*A*). When the ice is removed (*B*), the crust will elastically rebound to its original height (*C*). Because the underlying mantle is a viscous fluid, the rebound occurs gradually and thus is still observable today.

broke apart, its pieces moving away from one another. After millions of years, in the Eocene epoch (50 M.Y.B.P.), a Eurasian continent, attached to North America through Scandinavia and Greenland, formed the northern supercontinent, Laurasia. In the south a series of blocks, called Gondwanaland, contained South America, Antarctica, Australia, and Africa, which, although it was still attached to Asia, had begun to separate from it by means of the Mediterranean Sea. More recently Eurasia moved completely away from Africa. The Atlantic, Indian, and Arctic oceans are the result of continental migrations.

For Wegener these continental movements did not simply represent the destruction of a supercontinent, they were the driving force of great geologic phenomena. The drift of continental rafts manifests itself geologically in what he called "bow and stern effects." Gigantic wrinkles were pushed up on the leading edge of a drifting continent to form mountain chains. Thus the collision between the westward-moving American continent and the Pacific SIMA produced the Andes and the Rocky Mountain chains, and Australia's eastern coastal ranges were formed by the continent's eastward movement. The leading-edge folds were accompanied by important internal repercussions, which produced the intense volcanic and magmatic activities of these regions.

At the trailing edge the phenomena were no less spectacular. The drifting continents left fragments of their borders in their wake, giving birth to island chains. In its westward drift, America left behind the arc of the Antilles. Asia's drift to the northwest created the Sunda, Kurile, and Japan island arcs. In these regions too, the movement of the leading edge had repercussions in the SIMA, setting off volcanic activity and the rise of magma.

Briefly stated, such is Wegener's theory, which I will examine here using the arguments that he and his disciples accumulated over the course of his life and that he published in the final revision (1929) of his main work, *Die Enstehung der Kontinente und Ozeane.* I will not put them in the same order or give them the same degree of importance as he did, for time has emphasized some and toned down others.

Wegener's argument was not syllogistic; it did not rely on a powerful and systematic deductive logic. As is always the case in natural science, he constructed a model, a paradigm that suggested a single explanation for numerous observations made over the course of time. These observations were diverse in nature and of varying degrees of importance.

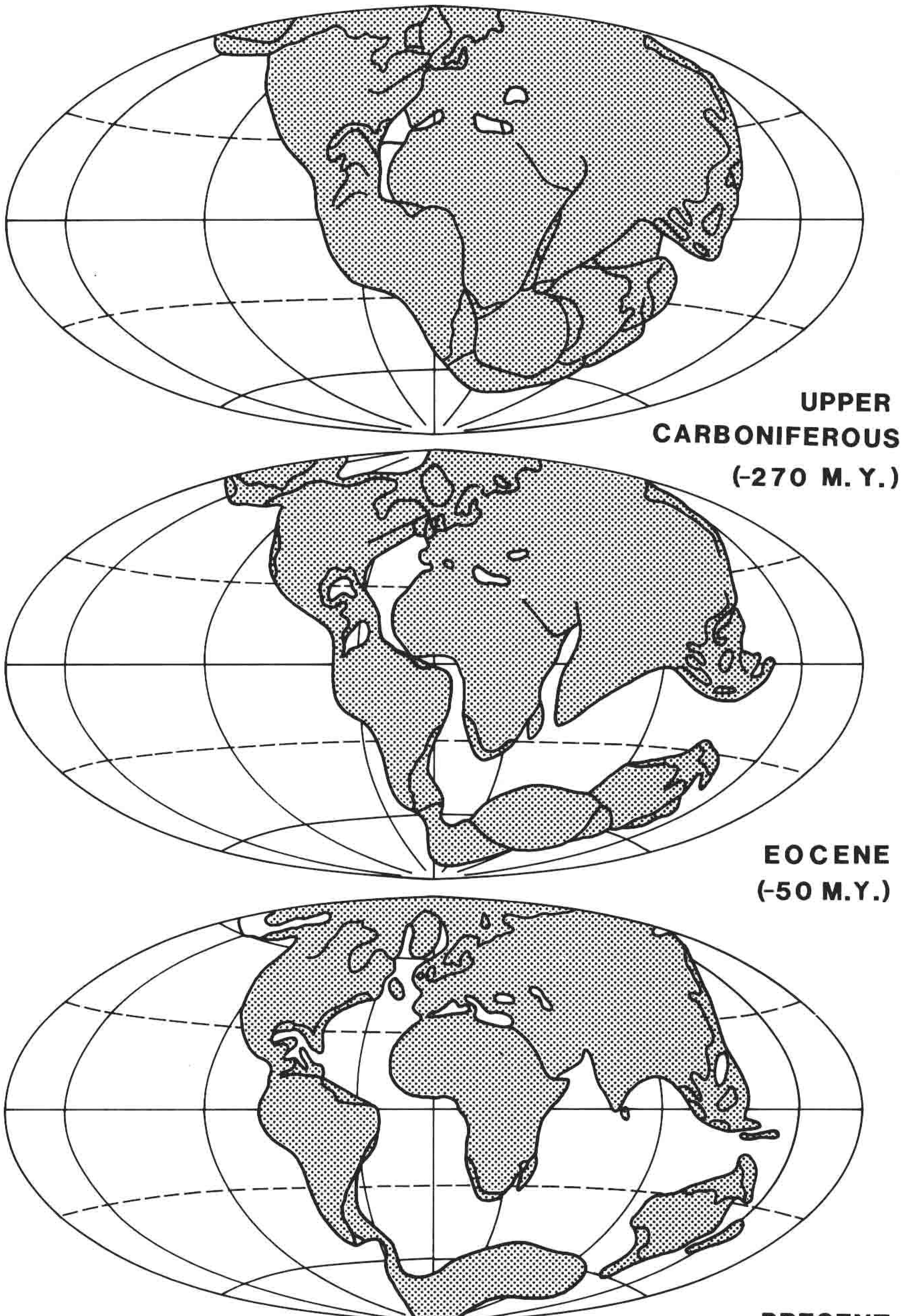

FIGURE 4 Wegener's illustration of continental drift. Continental locations are shown for the present, 50 million years before the present (Eocene epoch), and 270 million years before the present (Carboniferous period). In these illustrations the African continent has been arbitrarily fixed.