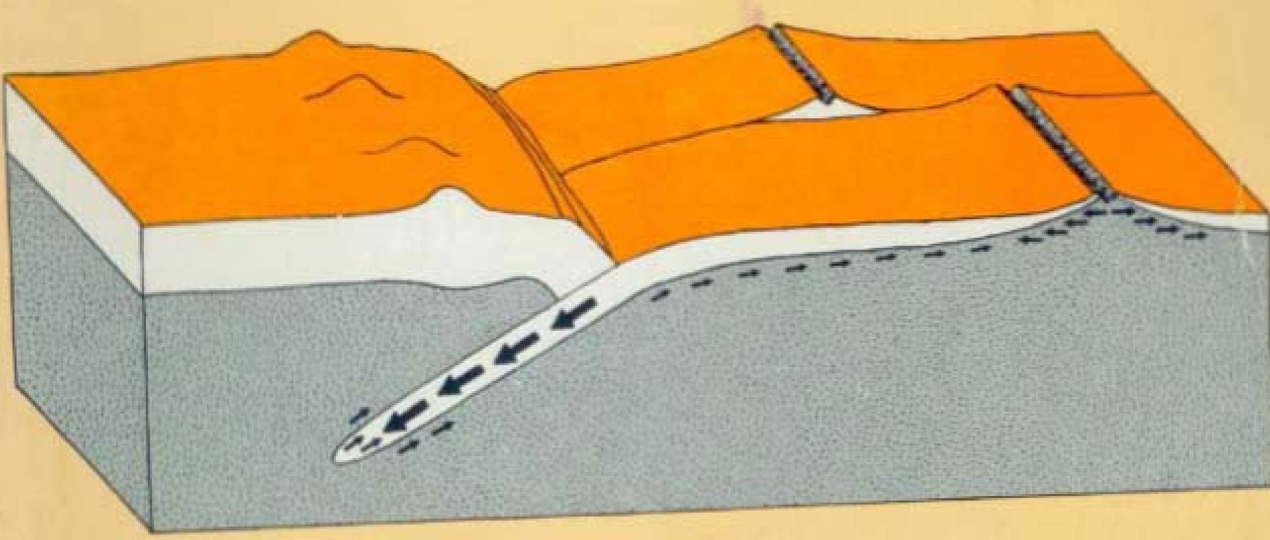
PLATE TECTONICS

How It Works



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BLACKWELL SCIENTIFIC PUBLICATIONS

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Blackwell Scientific Publications, Inc.

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Distributors

USA and Canada
Blackwell Scientific Publications
% PBS
P.O. Box 447
Brookline Village, MA. 02147

Australia
Blackwell Scientific Publications (Australia) Pty Ltd
107 Barry Street, Carlton
Victoria 3053

UK
Blackwell Scientific Publications
Osney Mead
Oxford OX2 0EL

Sponsoring Editor: John Staples

Manuscript Editor: Andrew Alden

Production Coordinator: Robin Mitchell

Interior and Cover Design: Gary Head

Composition: Graphic Typesetting Service

89 90 91 543

Library of Congress Cataloging in Publication Data

Cox, Alan, 1926–
Plate Tectonics.
Includes index. 1. Plate tectonics. I. Hart, R. Brian. II. Title.
QE511.4.C683 1986 551.1'36 86-6138
ISBN 0-86542-313-X

British Library Cataloguing in Publication Data

Cox, Alan
Plate tectonics: how it works.
1. Plate tectonics
I. Title II. Hart, R. Brian
551.1'36 QE511.4

ISBN 0-86542-313-X

Contents

Preface

This book is intended for the reader whose imagination has been captured by reading a popular account about plate tectonics and would like to know more. It concentrates on the quantitative side of plate tectonics because most scientifically literate people are already familiar with the qualitative side. The book will enable the reader to answer questions like the following:

How fast is London moving away from New York?

How fast was Los Angeles moving toward San Francisco 50 million years ago?

How are the motions of plates described in mathematical terms?

What geophysical observations are used to determine plate motions?

How are earthquakes related to plate motions?

How are the magnetic poles related to plate motions?

What drives the plates?

The guiding philosophy of this book is that in plate tectonics, as in chess, more insight comes from playing the game than from talking or reading about it. This is a hands-on, how-to-do-it book. Most students find that through learning the nuts and bolts of plate tectonics, they gain new insight into its power and its limitations.

The basics of quantitative plate tectonics can be mastered in a few months. Even less time is required to understand how plates would move if the surface of the earth was a plane instead of a sphere. All the reader needs to get started is a little knowledge of geometry, a piece of paper, a pair of scissors, and a logical mind.

We begin in Chapter 1 by representing the Earth's surface as a plane and by representing plates as pieces of paper with simple boundaries made up of straight lines and circular arcs. These simple pieces of paper are used to present the main elements of plate tectonics. In Chapter 2 we look at the velocities of these pieces of paper as they move over the surface of a plane. By the end of Chapter 2, the reader will have mastered most of the key ideas of plate tectonics on a two-dimensional, planar earth.

Doing plate tectonics on the spherical earth is a little more complicated and a lot more interesting. To move from the plane to the sphere, the student will need to know something about drawing and moving circles on a sphere. Techniques for doing this using an intuitive, graphical approach are introduced in Chapter 3. No prior knkowledge of spherical geometry or stereographic projections is required.

In Chapter 4, plate tectonics is moved from a plane onto the spherical earth using the geometrical techniques of Chapter 3.

In Chapter 5, as a prelude to seismology, techniques are developed for plotting planes and lines on projections. The approach taken is a direct extension of what was learned in Chapter 3, where a sphere was used to represent the Earth. The same sphere is now used to describe the space around some local point of interest—an earthquake epicenter, for example, or a point on a fault.

Having mastered the techniques of Chapter 3 and 5, students are generally pleased to discover that the same basic set operations can be used to find the great circle distance from San Francisco to Tokyo, to rotate continents, to calculate plate velocities, to locate the epicenters of earthquakes, to interpret the stress fields of earthquakes, and to find paleomagnetic poles. The same graphical techniques can be used to solve many of the problems the student will encounter in courses in structural geology, crystallography, and observational astronomy.

Chapter 6 develops the strong link that exists between plate motions and earthquakes. Plate tectonics provides a conceptual framework for understanding earthquakes. Conversely, earthquakes are a primary source of information about plate motions. After finishing this chapter, the reader will understand the familiar black-and-white "beach balls' that are used to describe the orientation of fault planes and the directions of slip of earthquakes along plate boundaries. He or she will also understand how this information is used to determine the relative motions between pairs of plates.

In Chapter 7 we show how to move a point on a sphere along a small circle. This simple operation of "finite rotation," which is at the geometrical heart of plate tectonics, is described from several viewpoints with lots of examples. Handling a sequence of finite rotations is quite tricky—so tricky, in fact, that mistakes in performing this operation have produced a number of errors in the plate tectonic literature. The goal of Chapter 7 is to help the reader develop insights and techniques that will make such errors less likely.

Chapters 8 and 9 are a mini-text in paleomagnetism. Chapter 8 shows the scientific basis for interpreting the famous marine magnetic anomalies, which provided the magnetic key that unlocked plate tectonics. Chapter 9 describes how rocks get magnetized, how the magnetism of rocks is used to find paleomagnetic poles, and how paleomagnetic poles are connected to plate motions.

In Chapter 10 we turn from the techniques of plate tectonics to some broader issues of current interest in plate tectonic research: the cause of plate motions, hotspots, absolute plate motion, and true polar wander.

The intended reader of the book is a college undergraduate whose appetite for plate tectonics was whetted by an introductory course in geology. However, to make the book accessible to a larger, scientifically literate audience, we have defined expressions like "sinistral faulting" covered in beginning geology courses—the knowledgeable geology student will quickly skip over these with a superior smile.

The required mathematical background is minimal: some trigonometry, elementary calculus on the level of knowing what is meant by "*dx/dt*," and familiarity with vectors. The latter are defined when they are introduced. As a reminder, examples are given showing how vectors add.

For students interested in computers, we show how to translate the basic geometrical operations used throughout the book into algebraic operations suitable for programming. In Chapter 7, for example, we show how to do finite rotations using standard matrix equations. These will be of interest mainly to students who wish to go on to advanced work in plate tectonics. We hope that even hackers will first do problems by hand so they will at least know whether their computer programs are working. As a fringe benefit, doing a few problems the old-fashioned way helps develop an intuitive understanding of how plate tectonics works on a globe. Armed with this insight, hackers have our blessing if they want to go on to create the perfect, all-purpose plate tectonic program.

The hand-drawn figures and cartoons of this work book and its informal style betray its origin as a set of class notes. These notes improved through a decade of use at Stanford, thanks to the criticism and advice of students, especially that of Douglas Wilson, who was first a student and then a teaching assistant in the plate tectonics course. Eli Silver at the University of California at Santa Cruz and Walter Alvarez at the University of California at Berkeley and their students used early versions of the notes and provided useful feedback. We thank Gary Head, the designer, for encouraging us to use our original handmade figures, both in order to reduce the final cost for the student and also to retain the work-in progress feeling of the original notes. The editor, Andrew Alden, helped us on many levels from elements of style to the flow of logic; he even checked some of the math. The catalyst who brought the book together was John Staples, whose love of books and patience with authors makes him more than a publisher's agent.

Introduction

Plate tectonics is a major new paradigm, or scientific world-view, that profoundly changes our ideas about how the earth works. It has been compared to the Bohr theory of the atom in its simplicity, its elegance, and its ability to explain a wide range of experiments and observations.

Tectonics is the study of the forces within the earth that give rise to continents, ocean basins, mountain ranges, earthquake belts, and other large-scale features of the earth's surface. A revolution in tectonic thinking was brought about by plate tectonics and two closely related ideas, seafloor spreading and the use of geomagnetic reversals. The latter is a method for clocking plate tectonic processes. These three ideas were advanced and substantiated between 1962 and 1968 by a handful of scientists working on problems that at first seemed unrelated but which suddenly came together to form a tightly knit fabric. This major revolution was triggered by no more than a dozen key articles that were published during these few years.

Like all revolutions, plate tectonics started with something as fragile as a nest of wild birds' eggs: some tentative ideas in the minds of a few scientists. Today most of these ideas seem obvious. In fact, students sometimes ask their teachers, "Why did it take your generation so long to tumble to the idea of plate tectonics?"

The question is a good one, for ideas closely related to plate tectonics were known long before the mid-1960s. For example, the theory of continental drift, which can be regarded as the grandfather of plate tectonics, was put forward by Alfred Wegener in 1912. The theory of seafloor spreading, which surely is the intellectual father of plate tectonics, was proposed by Arthur Holmes in 1929. A convection current rises up through the earth's mantle, said Holmes, to form the large mountain range or ridge running down the middle of the Atlantic Ocean basin. The rising current then spreads to either side of the ridge, pushing aside the continents and forming the Atlantic basin. David Griggs came even closer to the core idea of plate tectonics in 1939. The mountain ranges and earthquake belts that ring the Pacific basin, said Griggs, are due to convection currents rising in the center of the basin and sinking along its margin. "Such an interpretation," Griggs wrote, "would partially explain the sweeping of the Pacific basin clear of continental material. The seismologists all agree that the foci of deep earthquakes in the circum-Pacific region seem to be on planes inclined about 45° toward the continents. It might be possible that these quakes were caused by slipping along the convection-current surfaces."

These ideas are so close to plate tectonics that, reading them today, it is difficult to imagine that they were not taken seriously at the time they were put forward. Yet until the mid-1960s, few North American geologists accepted any of them. Most regarded the ideas of continental drift and mantle convection as unproven, untestable, or wrong. Some rejected continental drift because they were unconvinced by the argument of the "drifters" that the geology on opposite sides of the Atlantic and Indian oceans matched better if the oceans were closed. Geologists who were impressed by the match across ocean basins still tended to reject Wegener's idea because no known mechanism was capable of forcing continents to move like rafts through the strong rocks that make up the ocean floor.

Students today may find it hard to imagine an intellectual landscape in which almost all geologists and geophysists in the United States were dead set against continental drift. The articles about continental drift and seafloor spreading that we have just quoted were rarely cited before 1962. In North America, these ideas had not entered the mainstream of scientific thought, whereas in Europe and Africa, most geologists were open to the idea of continental drift. Textbooks naturally reflected the view of the profession. In those written between 1930 and 1960 in North America, continental drift either was not mentioned or was dismissed as speculation. For example, the most advanced and influential textbook used in the United States during the 1950s summarized a discussion of continental drift with the statement: "Though the theory is a brilliant tour-de-force, its support does not seem substantial." Being *for* continental drift in North America was as unpopular as being *against it* is today. Recent history has taught geologists that in science, the majority is sometimes wrong—as are the experts and the textbooks.

Plate tectonics was more persuasive than earlier tectonic theories because it was able to make predictions that could be tested against observations. The link to observations was provided by two quantitative elements of the hypothesis, **geometrical precision,** and **accurate timing.** Geometrical precision was the result of several key geometrical ideas that lie at the core of the hypothesis. The first of these is that the earth is distinctly layered. Its outer layer is the lithosphere, a spherical shell about 80 km thick, so rigid and strong that little deformation occurs within it. Beneath the strong lithosphere is the weak, ductile asthenosphere with a viscosity much lower than that of the lithosphere. As the lithosphere moves laterally, little stress is generated in the asthenosphere because the latter is so ductile. The strong contrast in rheology (flow behavior) between the lithosphere and asthenosphere allows stress to be transmitted long distances through the lithosphere. The resulting pattern of motion is quite different from what it would be if the earth were a planet with a single-layer mantle having uniform or nearly uniform rheology. If that were the case, the flow pattern would be an irregular and diffuse pattern similar to the motion of water in a kettle heated from below. On planet Earth with its highly layered structure, the motion of the lithosphere is analogous to the motion of drifting sheets of ice on a pond.

The second geometrical idea is that the earth's lithospheric shell is divided into about a dozen pieces, each of which is rigid and all of which are moving relative to each other. A key step in plate tectonics was to look closely at the boundaries between the plates and to recognize that boundaries can be divided into exactly three classes. **Trenches** are boundaries where two plates are converging. **Ridges** are boundaries where two plates are diverging. **Transforms** are boundaries where two plates are moving tangentially past each other. Each type of boundary turns out to be a major geological feature, the origin of which was poorly understood before plate tectonics.

The third geometrical idea, explored in Chapter 4, stems from recognizing an analogy between lines on a plane and circles on a globe. On a plane an object propelled by a constant force moves along a line. On a globe an object propelled by a constant torque moves along a circle. Because plates move under the influence of nearly constant torques for tens of millions of years, their motions are along circles the locations of which can be deduced from geological and geophysical data. These circles can be described efficiently by specifying the coordinates of the so-called **Euler poles** that lie at the center of the circles.

The other major element of the plate tectonic revolution was based on measuring time. Determining the age of rocks has been a central theme in geology since the beginning of the science. In the early days of geology the first great advance was to use fossils, which are still important for dating today. The next quantum jump in dating came with the use of radiogenic isotopes. By the early 1960s the ages of most parts of most continents had been determined by geologists using these two dating techniques. However, surprisingly little was known about the age of the oldest ocean floor. Estimates ranged from Precambrian (about 600 million years) to late Mesozoic (about 70 million years).

The third quantum jump in determining the age of the earth's surface came in the early 1960s, when geophysicists discovered that they could determine the age of the seafloor through studying the magnetic field at the sea surface. This new dating technique is described in Chapter 8. Its use was a key element in plate tectonics because it provided a clear geometrical picture of the way rocks of different age were created by a process of seafloor spreading. The new dating technique also permitted the rates of plate tectonic processes to be determined much more accurately than had been possible in earlier studies of continental tectonics.

The state of tectonics before the introduction of these four quantitative concepts can be imagined by considering what physics would be like without an appropriate mathematical framework. It would have the quality of the traditional "Physics for Poets" course in a liberal arts curriculum: interesting and stimulating, but not quantitative enough to be tested against observation. Tectonics was like that prior to plate tectonics. In fact, in his classic paper on seafloor spreading, which appeared in 1961 on the eve of plate tectonics, Harry Hess described his study somewhat apologetically as "an essay in geopoetry" (a self-assessment with which many would now disagree). It was only after the introduction of new geometrical concepts and accurate timing that tectonics became a quantitative science characterized by interplay between theory and observation. The main goal of this book is to provide students with the quantitative tools of the plate tectonic trade.

A word of caution may be in order because it is easy to claim too much in the flush of excitement over a new paradigm. Plate tectonics won't tell you everything about the history of the earth any more than evolution explains all of biology. What it does explain is many of the large-scale processes that shape the surface of our planet. Left unexplained are many equally exciting facets of earth science, including the origin and evolution of the earth's atmosphere, the chemical evolution of the crust and mantle, the geology of other planets and their moons, and the evolution of life. Plate tectonics provides an intellectual framework to use in attacking some of these problems, but it doesn't provide the answers. So geology students need not fear that all of the important problems of earth sciences were solved with the advent of plate tectonics. Like other new paradigms, plate tectonics has not produced a winding down of a discipline because all problems are solved. On the contrary, it has provided a solid foundation for attacking a new set of problems.

A subliminal goal of this book is to convey some of the playfulness and lightness that characterized early research in plate tectonics. The originator of the idea, J. Tuzo Wilson, took great delight in using paper cutouts to demonstrate the theory of plate tectonics. Some of us still remember watching Wilson play his embarrassingly child-like games before large audiences of scientists. Now that plate tectonics has become a serious subject, it's hard to remember why we had so much fun doing plate tectonics in those early days. Perhaps it recalled the fun we had as kids making model airplanes and other toys that really worked. In retrospect it seems almost immoral that such enjoyable, childish games should have provided the answer to questions that had puzzled geologists since the beginning of science.

As you shuffle pieces of paper around in the first few chapters, we hope that you can recapture some of Wilson's playful spirit and also, perhaps, some of his satisfaction when it dawned on him that these simple games were, for the first time, explaining the origin of mountain chains, volcanoes, major faults, and earthquakes.

PLATE TECTONICS

How It Works

1

Basics of a Revolution

This chapter has two goals. The first is to develop two of the key ideas of plate tectonics, layering and plate geometry. The second is to give the reader a glimpse of what tectonics was like prior to plate tectonics. A comparison of pre- and post-plate tectonic theories will show how profoundly our views changed. This comparison will also interest those who are curious why so obvious a theory wasn't discovered much sooner. We will see that many of the key ideas of plate tectonics were in the air for a long time before plate tectonics. All that was missing was a few key pieces of data and the imagination and insight needed to put the ideas and the data together.

Earth's Layers

The earth was known to be layered long before the advent of plate tectonics. The layers consist of three concentric shells, the core, the mantle, and the crust, each with a different chemical composition (Figure 1-1). In plate tectonics this model is retained and a new pair of layers is added, the lithosphere and asthenosphere, based not on composition but on rheology, that is, how easily rocks flow. The boundary between the two new layers lies within the mantle.

Core, Mantle, and Crust

The fact that the earth is layered was deduced from two sets of geophysical data. The first clue came from acoustic waves

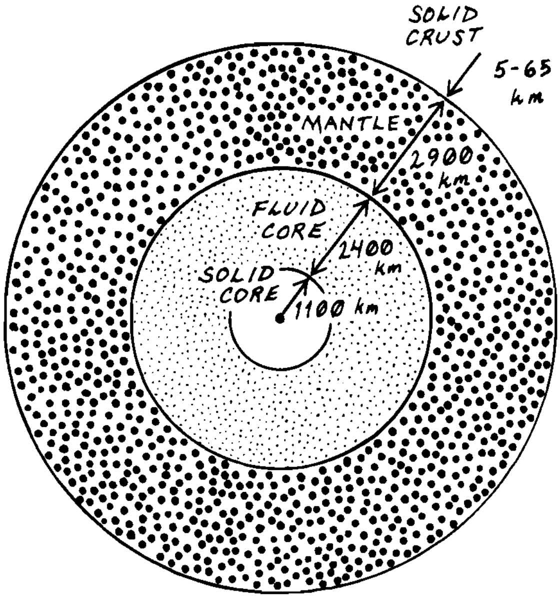


Figure 1-1.
Pre-plate tectonic cross section of the earth.

generated by earthquakes. Because the earth is transparent to these waves, its spherical shells act like lenses that reflect and refract the waves, producing patterns that reveal the earth's internal structure. The earth's layering can be seen in these patterns. The second clue was provided by the earth's gravity field. If the earth's density were uniform and equal to that of the rocks at the surface, the force of gravity would be only half the force observed. The observed strength of the gravity field shows that the earth's density increases with depth.

In trying to come up with a model consistent with both the seismological and the gravitational data, geophysicists were driven to the conclusion that the earth must have an extremely dense **core,** so dense, in fact, that the core must be made of a heavy metal. The best candidate is iron, an element that is abundant in the cosmos. At the very center the inner core is solid metal. The next layer, the outer core, consists of liquid metal. In Chapter 8 we will learn that the earth's magnetic field originates in this liquid layer.

Above the core lies the thick shell called the **mantle.** Pieces of the mantle are sometimes torn loose at depth and blasted from the throats of volcanoes. Hold one of these pieces of peridotite in your hand. You will notice that it is dark green in color, textured like an ordinary rock with transparent crystals, and a little heavier than most rocks you

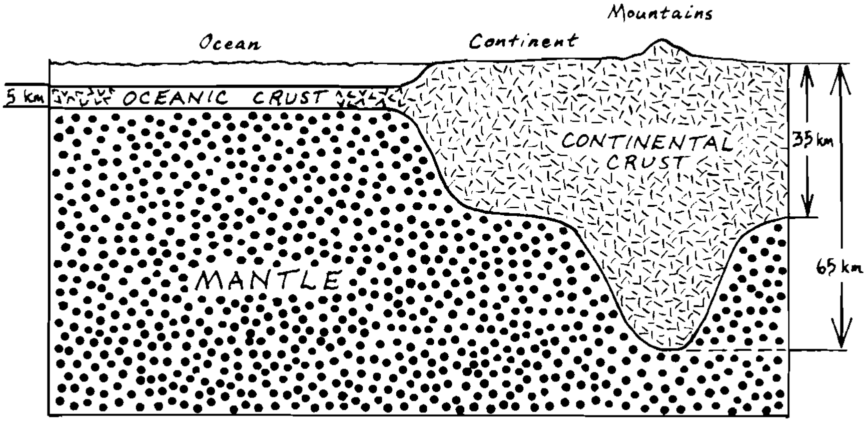


Figure 1-2.
Cross section through thin oceanic crust and thick continental crust—note crustal root beneath mountain range. In classical continental drift, the continent plows through the mantle, deforming and displacing it.

are familiar with. Its minerals incorporate into their crystal lattices silicon and oxygen, light elements that lower the density of the mantle below that of the metallic core.

The **crust** consists of the rocks we walk on every day. Its density is less than that of the mantle because its constituent minerals incorporate even more light elements than do mantle minerals. The most abundant of these elements are silicon, oxygen, aluminum, potassium, and sodium.

The thickness of the crust is not uniform. Typical thicknesses beneath continents are 30 to 50 km, increasing to 65 km beneath mountain ranges. The thickness of the .crust beneath ocean basins is typically 5 km.

Deducing the presence of the core, mantle, and crust from earthquake waves and gravity was one of the great achievements of earth science. The layering tells us that early in its history, planet Earth was hot and soft enough for dense material to sink and for light material to rise. Important as it was, however, knowledge of this layering did not lead to the discovery of plate tectonics.

Strength of the Mantle

The stage was set for plate tectonics during the 1950s by a growing interest in the strength of the mantle. Wegener thought that continents move *through* the mantle, much like a raft moves through water. If Figure 1-2 is viewed as a cross section through western South America looking northward, the continent is moving like a ship to the left through the mantle. Wegener thought that the rocks of the oceanic crust and mantle in front of the moving continent are deformed and displaced. Geologists had difficulty with this idea. The driving forces Wegener proposed were too small to produce stresses as large as those needed to break or deform mantle rocks in the laboratory. This conclusion was reinforced by the observation that the upper layers of the earth are strong enough to hold up mountain ranges, withstanding stresses much larger than those produced by Wegener's driving mechanisms. The mantle appears to be much too strong for continents to plow through it. Therefore continental drift was widely rejected, despite much evidence in its favor, because it seemed to lack a viable mechanism.

A second question closely related to the strength of the mantle is whether the earth's rotation axis is capable of shifting, a process known as polar wander. In a rigid earth, the equatorial bulge provides a formidable element of stability. In a soft earth, the equatorial bulge does not prevent polar wander. By the 1950s it was widely recognized that the question of whether polar wander is possible rests critically upon the question of whether the mantle possesses "finite strength." This refers to a rheology in which rocks deform and flow only above a threshold stress, termed the finite strength. If the mantle has finite strength greater than the driving stresses of continental drift and polar wander, neither is possible. On the other hand, if the mantle flows under an arbitrarily small stress, both continental drift and polar wander are inevitable.

The following quote from an influential 1960 monograph on the subject of the earth's rotation conveys something of the spirit of the times prior to plate tectonics. After a thorough review of relevant theories and observational data, the authors concluded that although the problem of polar wander was unsolved, they favored an earth model with finite strength and no wander: "From the viewpoint of dynamic considerations and rheology, the easiest way out is to assign sufficient strength to the Earth to prevent polar wandering, and the empirical evidence, in our view, does not compel us to think otherwise."

When the importance of the finite strength of the mantle was recognized, geophysicists were eager to try to settle the matter by squeezing mantle rocks in the laboratory. The challenge was (and still is) to reproduce in the laboratory conditions occurring in the mantle, where temperatures and pressures are extremely high, stresses are low, and rates of deformation are excruciatingly slow. By the early 1960s when plate tectonics appeared on the scene, the issue was still in doubt. In the end it was not laboratory measurements that persuaded many geologists that rocks in the upper mantle are soft enough to be deformed. It was the internal consistency of plate tectonics itself, including a new theory showing how South America could move westward without plowing through the mantle beneath the Pacific seafloor.

Plate Tectonic Layering

In plate tectonics, the mantle is divided into two and possibly three layers with different deformational properties. The upper layer is highly resistant to deformation, indicating that it has either high viscosity or finite strength. If the entire mantle were like this, plate tectonics and polar wander would not occur. The **lithosphere** consists of this rigid upper layer of mantle and the overlying layer of rigid crust. Beneath the lithosphere is the soft, easily deformable layer of mantle called the **asthenosphere.** The plates glide as nearly rigid bodies over the soft asthenosphere. The lithosphere is about 80 km thick and the asthenosphere is at least several hundred kilometers thick. Beneath the asthenosphere lies the mesosphere, the innermost shell of the mantle. Its physical properties and the location of its upper boundary are not well known, although it appears to be less deformable than the asthenosphere and more deformable than the lithosphere.

The theory of plate tectonics is largely based upon the presumed contrast in the rheological (deformational) properties of the two outer layers. Because of this contrast in rheology, stresses exerted along one part of a plate can be transmitted to distant parts of the plate much as a force exerted on one side of a floating raft is transmitted across the raft. How this works may be seen in the following thought experiment. Start with two ponds, one frozen solid to the bottom and one with a layer of ice 10 centimeters thick floating on water. Across both ponds make two parallel cuts 1 meter apart and 10 centimeters deep. Now stand on the bank at one end of the cuts and push horizontally on the ice between the two cuts. On the completely frozen pond, the shallow cuts have little effect and the stress is transmitted from the spot where you are pushing through the entire body of ice to the sides and bottom of the pond. Now go to the other pond and push on the ice between the cuts. This time the 1-meter-wide strip of ice floating on water moves easily because there is little friction on the sides or along the bottom of the strip. Most of the stress is transmitted to

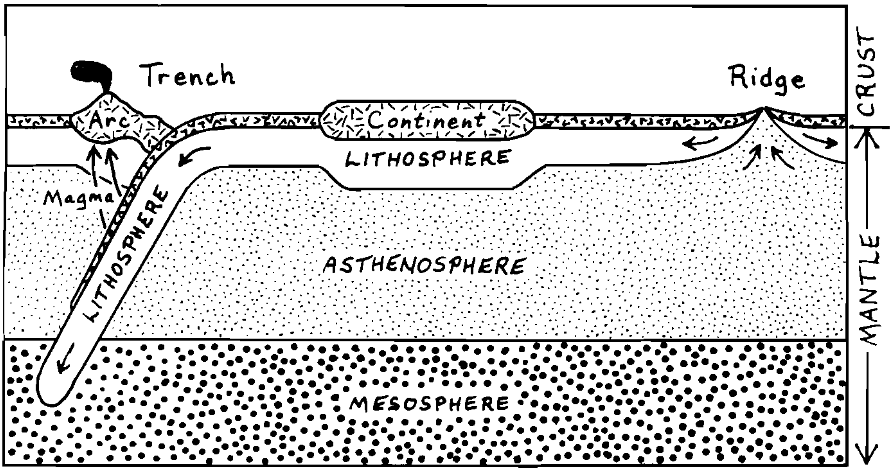


Figure 1-3.
Rigid, cold lithosphere slides over the soft asthenosphere until it encounters a trench, where it sinks. Plate tectonic cross section: continent does not plow through the lithosphere but rides with it.

a region 1 meter wide on the opposite bank, where the strip of ice will probably be pushed up onto the bank. Almost no stress is transmitted through the water to the bottom and sides of the pond because of the low viscosity of the water. In these two experiments exactly the same driving forces applied to bodies of exactly the same geometrical shape produce vastly different styles of deformation because of the difference in the rheology of the two bodies.

Before plate tectonics, most tectonic models were based on a rheologically homogeneous mantle analogous to the completely frozen pond. After plate tectonics, the pond with ice over water became the proper analogy. This change in rheological models brought about a profound change in our ideas about how the earth works.

Instead of continents plowing through the mantle, as in Wegenerian tectonics, continents are embedded in the lithosphere (Figure 1-3) and move with the lithospheric plates in which they are embedded. Where two plates converge, one plate usually slips beneath the other and sinks into the soft asthenosphere without large-scale deformation of either plate.

Why are the rheological properties of the lithosphere and asthenosphere so different? As in the case of ice and water, the difference is a matter of temperature and not composition. However, the analogy is not a perfect one. In the case of ice and water, the layering reflects a simple phase change from solid to liquid. In the case of the lithosphere and asthenosphere the situation is more complicated. Temperature increases with depth in the earth until, at depths of about 80 km in the mantle, the temperature reaches about 1400°C, which is close to the melting temperature of mantle rocks under the pressures at that depth. Materials made of a single mineral melt and lose their strength when heated through a temperature range of only a degree or two. Materials made of several minerals soften over a broader range of temperature. The mantle, composed of an assemblage of minerals with different melting temperatures, is not completely molten at any depth. However, at the depth of the asthenosphere, the temperature is very close to the melting temperature of the lowest melting mantle minerals, with the result that these crystals either melt or become soft, rendering the asthenosphere easily deformable. The sharpness of the boundary between the lithosphere and asthenosphere reflects the fact that minerals at temperatures close to melting lose their strength when heated over a very small range of temperature.

The shape of the isothermal surface that defines the boundary between lithosphere and asthenosphere is an important element of plate tectonics. In a static earth it would be horizontal. However, the earth is in motion, and we know from physics that when pieces of matter move rapidly from one thermal environment to another, they tend to carry their isotherms with them. Recall what happens when you put cold feet into warm water—they do not warm instantly. Similarly, when lithosphere plunges into the asthenosphere, it carries its cold isotherms with it, producing a downward deflection of the isothermal boundary between the lithosphere and asthenosphere. The opposite situation occurs in places like the marginal basins between the Japan Arc and the Asian continent, where the lithosphere is getting thinner as plates on either side pull apart. The asthenosphere moves upward in this case, carrying its hot isotherms with it and producing an upward deflection of the lithosphere-asthenosphere boundary. In Figure 1-3 the heavy line defining the boundary between the lithosphere and the asthenosphere is essentially the 1400°C isotherm. If you knew the shape of this isotherm all over the world and nothing else, then as a plate tectonicist you could make a pretty good guess about what is happening tectonically.

Although the idea that a strong lithosphere overlies a weak asthenosphere is strongly associated with the rise of plate tectonics in the early 1960s, the idea and the very words "lithosphere" and "asthenosphere" were advanced several decades before plate tectonics. This idea originated with geophysicists studying gravity. Analysis of the gravity field over mountain ranges requires that part of the mountains' weight floats upon low-density roots extending down into a weak layer (isostatic compensation) and that part is held up by a strong, outer layer (regional compensation). The word "asthenosphere" was introduced in 1914 by Joseph Barrell in a paper analyzing gravity, and the concept of the lithosphere and asthenosphere was a major element in a 1940 textbook by Reginald Daly. Oddly enough, however, by the time plate tectonics appeared on the scene in the early 1960s, the idea of the asthenosphere had pretty well faded from the geologic literature. That this concept had not become part of the geologic mainstream is shown by the fact that the terms lithosphere and asthenosphere were not used in popular U.S. geology texts of the 1950s. It was only after new insight had been gained into the geometry and timing of tectonic processes that these terms were revived to explain the rheological basis of plate tectonics.

Plate Geometry

The intellectual breakthrough that established plate tectonics was based on a simple new geometrical insight. In a five-page article published in *Nature* in 1965, J. Tuzo Wilson noted that movements of the earth's crust are concentrated in narrow mobile belts. Some mobile belts are mountain ranges. Some are deep-sea trenches. Some are mid-oceanic ridges. Some are major faults. Earlier geologic maps of these long, linear features showed many of them coming to dead ends. Wilson postulated that the dead ends are an illusion: the mobile belts are not isolated lineations but rather are all interconnected in a global network. This network of faults, ridges, and trenches outlines about a dozen large plates and numerous smaller ones, each comprising a rigid segment of lithosphere. The geometrical relationships along the boundaries of these moving plates lie at the heart of plate tectonics and of this book.

We saw earlier that a sheet of rigid ice resting on the water of a pond is an interesting thermal and rheological analog of the rigid lithosphere. A sheet of ice also provides a good introduction to plate geometry. Picture a sheet of ice on a pond. During the winter the ice remains frozen and still. With the spring thaw, as the ice begins to break up, the action starts. Cracks develop that divide the ice sheet into a number of plates. At first these plates remain interlocked; then one plate begins to move. Along its trailing edge a crack opens up and fills with water. Along its leading edge the moving plate of ice overrides or plunges beneath another plate. The plate tectonic process has begun on the surface of the pond. As plates of lithosphere move over the asthenosphere, the geometry of their movement is essentially the same. Much of the beauty of plate tectonics lies in the geometric exactness and simplicity of this geometry of movement. Just as Euclidean geometry provides the mathematical framework for much of science and engineering, the geometry of plate motions provides a mathematical and logical framework within which to describe the motion of the earth's tectonic engine.

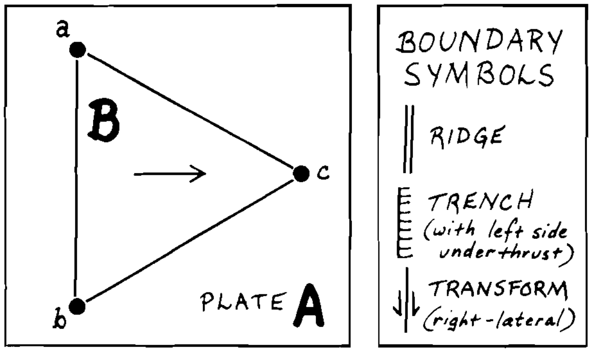
In this chapter we begin by assuming (as our ancestors did) that the earth is a flat plane. We do this, first, because geometry is a little simpler on a plane than it is on a sphere, and second, because, as every surveyor knows, in a local area one may for practical purposes regard the earth's surface as planar. After we've learned the elements of two-dimensional plate tectonics on a plane, we'll wrap the plane around the sphere.

Let us start as Wilson did while writing his 1965 *Nature* article by cutting out some pieces of paper and moving them around on a table top. Glance at Box 1-1 and imagine that the page is a slab of rock 80 km thick. Cut out the triangle labeled B from your paper lithosphere. You've just made your first pair of plates. Now move plate B to the right in a straight line. Along the left side of the triangle a crack is opened up to disclose the asthenosphere beneath. This part of the boundary between the two plates is termed a **ridge** or **rise.** You might well ask whether it wouldn't make more sense to call the crack between the two plates a valley or trench. We will see that in the real world, although a narrow valley sometimes exists between two diverging plates, the regional topography is invariably that of a broad ridge. The reasons for this are discussed later.

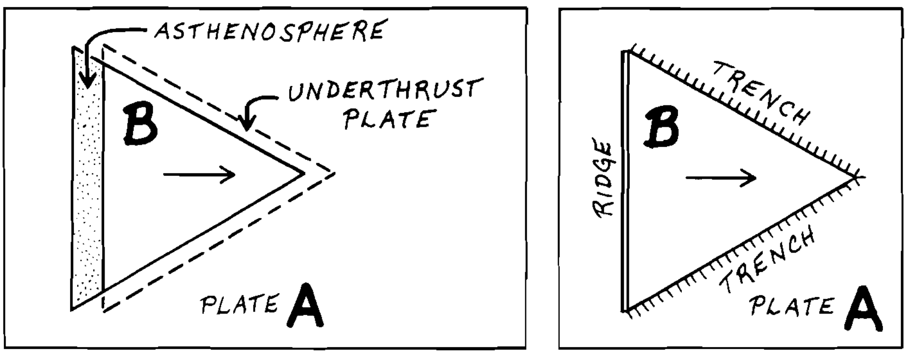
Along the leading edges **bc** and **ca** of the paper triangle the two plates are converging. A boundary where two plates move together this way is termed a **trench.** Again, the choice of this name may appear odd—where plates collide one would intuitively expect a pile of extra-thick lithosphere rather than a trench. Again we find that the earth doesn't always behave like our intuition says it should, for reasons that are discussed below.

Trenches, unlike ridges, are asymmetrical in the following sense: either plate B may be thrust under plate A, or plate A may be thrust under plate B. All trenches have this prop-

Box 1-1. A Triangular Plate.



1. Copy figure and cut out triangle.
2. Move triangle a small distance to right, slipping the point of plate B beneath plate A.
3. Along what part of the perimeter does a gap open? Plot this as a **ridge.**
4. Along what part of the perimeter is there underthrusting? Plot this as a **trench.**
5. Your results should look like this.



erty, which is termed **polarity.** Symbolically the polarity is specified with a "D" on the "down" or underthrust plate and a "U" on the "up" or overthrust plate (Box 1-1). The polarity also may be indicated with short hachure lines or sawteeth on the overthrust plate. (You'll notice when you start reading articles about plate tectonics that the polarity of a trench is represented in several different ways; plate tectonics is still too young to have developed strict conventions.)

Moving the triangular plate has produced ridges and trenches. Is it possible for any other types of boundaries to exist? Try changing the direction of motion of your triangular plate and see what happens. You'll find that two ridges and one trench are possible, as in Figure 1-4. But this does not exhaust the possibilities. Move plate B parallel to one of the sides, so that along this boundary the two plates neither converge nor diverge (Figure 1-5). This is the third and last type of plate boundary, the **transform fault,** or transform for short.

Because boundaries can move only away from each other (ridge), toward each other (trench), or parallel to each other (transform), there are exactly three possible types of boundary between plates. As was true in our example of a triangular plate, several boundaries of different types are commonly found around the periphery of a given plate, as in Figure 1-5.

As was true of trenches, there are two types of transform faults. Consider two points **a** and **b** which are initially opposite each other across a transform. If you stand at point **a** on plate A (Figure 1-6), you will note that point **b** is moving to your right. If you stand at point **b** you will note that **a** is also moving to the right. This type of transform is termed **right-lateral** or **dextral.** Note that the transform is right-lateral no matter which plate you stand on and regard as your fixed reference frame. The other type of transform is termed **left-lateral** or **sinistral.**

Transforms are very common, and many of them have existed for long periods of time. Those bounding large plates are especially long-lived features. What does this observation tell us about earth processes? It tells us that large plates tend to keep moving in the same direction for long periods of time. Recall the special circumstances required for the existence of a transform boundary: the motion between two plates must be exactly parallel to the boundary between them. If the movement of either plate shifts irregularly while the motion of the other plate remains steady (Figure 1-7), a transform will exist only during those moments when the relative motion of the two plates happens to be parallel to a boundary.

Two alternative interpretations can be made from the observations that transforms are common in nature and that they exist for long periods of time. The first is that once transforms are formed, they control the direction of plate motions. An analogy of a transform by this interpretation

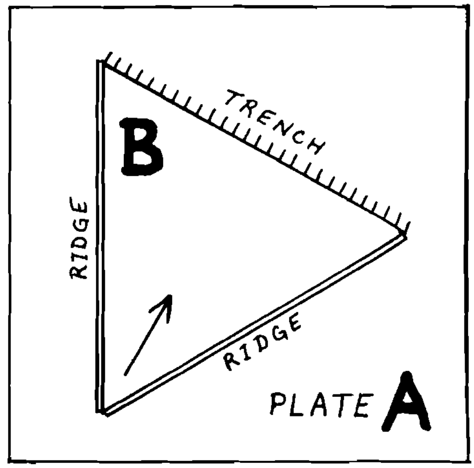


Figure 1-4.
Motion of plate B is oblique to all boundaries, which are either trenches or ridges.

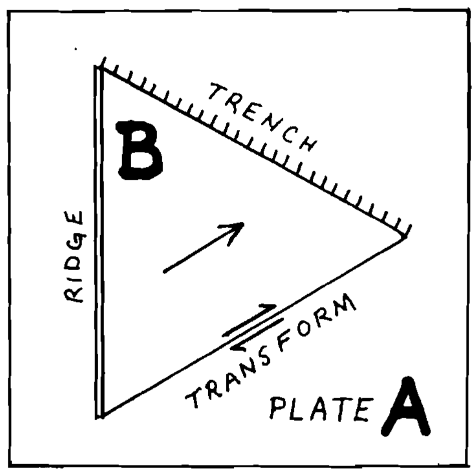
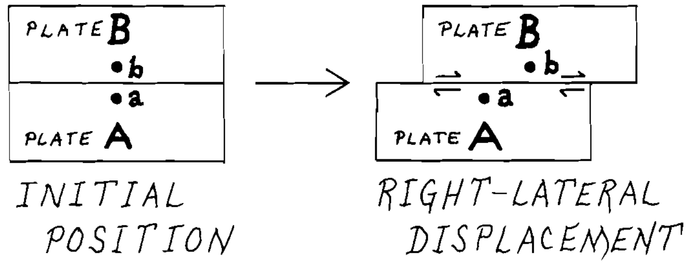


Figure 1-5.
Motion of plate B is parallel to one boundary which is a transform.

Figure 1-6.
Transform fault of the right-lateral or dextral type. If you stand at **a,** you will note that **b** is moving to your right. If you stand at **b,** you will note that **a** is also moving to your right.



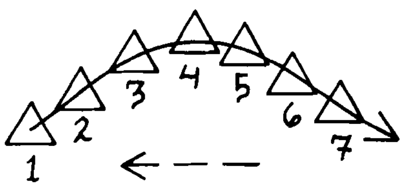


Figure 1-7.
Triangular plate moving along an irregular path. Dashed arrow is direction of relative motion of an adjacent plate. Only at position 4 does the direction of relative motion of the two plates become parallel to a boundary to produce a momentary transform.

would be a long, straight cut made in a sheet of ice on a pond: when the ice starts to move during spring break-up, plates of ice on opposite sides of the cut will tend to move parallel to the cut and to each other. The rationale for this interpretation is that since transforms are cracks or zones of weakness that cut through the lithosphere, they might be expected to guide the direction of plate motion.

An alternative interpretation is that plates are driven by forces unrelated to transforms. Transforms exert no control on the direction of plate motion, but simply align themselves parallel to the direction of motion between the two plates.

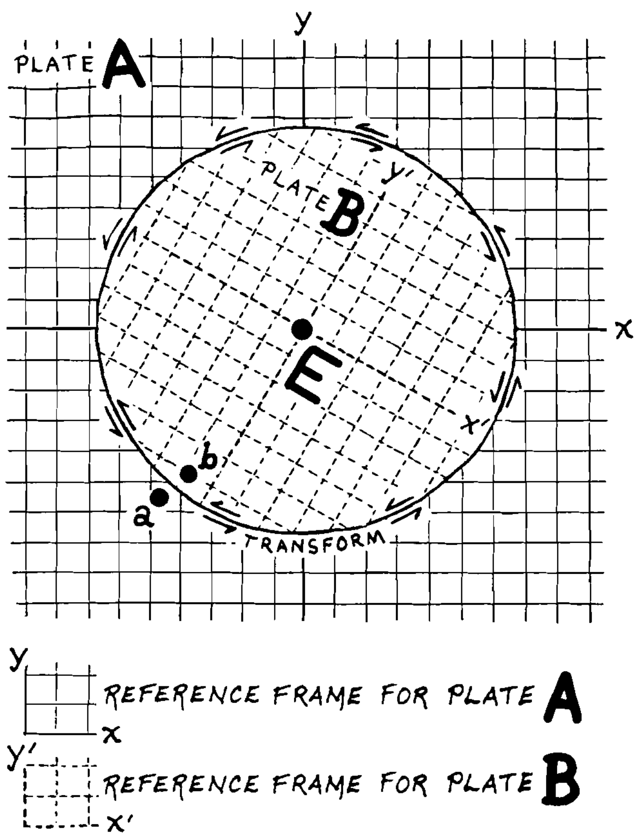
Opinion among plate tectonicists concerning these interpretations is divided. Most favor the view that the stresses generated along transforms are not the main driving forces that determine the direction of plate motion. In other words, the earlier analogy between a transform and a cut in a sheet of ice is inappropriate. Regardless of whether transforms control plate motions or simply record them, they provide our primary source of information about the direction of motion between pairs of plates. Moreover, from their persistence, it is safe to conclude that the process or condition responsible for plate motions, once started, continues in the same mode of operation for a long time.

Euler Poles

Defining Euler Poles

Euler poles play a central role in the geometry of plate tectonics. They are named for the 18th-century mathematician Leonhard Euler, pronounced "oiler." We introduce this important concept with a riddle: the entire boundary of a plate is a transform; what is the shape of the plate? The answer: a circle.

Box 1-2. A Circular Plate.



1. Copy figure and cut out plate B along the circle.
2. Place a pin through **E** to form an Euler pole.
3. Rotate plate B clockwise, keeping plate A fixed.
4. Note that the entire boundary of plate B is a left-lateral transform fault.
5. Note that the Euler pole **E** is the only point that keeps the same coordinates in both reference frames as plate B rotates.

To see how a circular boundary can be a transform, cut the round plate B from Box 1-2. Now place the point of your drafting compass through the center **E** of the circle so that plate B can pivot like a wheel. The pivot point **E** is the Euler pole. Hold plate A stationary so that its reference frame (the grid of solid lines) remains fixed and rotate plate B clockwise. Point **b** is moving past point **a** in a left-lateral sense. Now start again, holding plate B stationary so that its reference frame remains fixed, and rotate plate A counterclockwise. Point **a** is now moving past point **b** in a left-lateral sense. From the viewpoint of plate tectonics these two rotations are equivalent. The choice of the "A" fixed reference system (solid grid lines) or "B" fixed reference system (dashed grid lines) is merely a matter of convenience.

The Euler pole **E** is the pivot point for the motion of the two plates relative to each other. **E** has another interesting property. Keeping the reference frame of plate A fixed and rotating plate B, it is obvious that the coordinates of point **b** in A's grid are constantly changing. This is true for all points on plate B. The only exception is the Euler pole **E,** which keeps the coordinates (x_E, y_E) in the "A" coordinate system. Similarly, if plate B remains fixed while A rotates and if **E** is now viewed as a point on plate A, it is the only point on A that remains fixed in the "B" reference frame. The Euler pole is exactly like the hinge point of a pair of scissors, which is the only point that doesn't move relative to either blade of the scissors. The Euler pole of two plates is the only point that remains stationary relative to both plates.

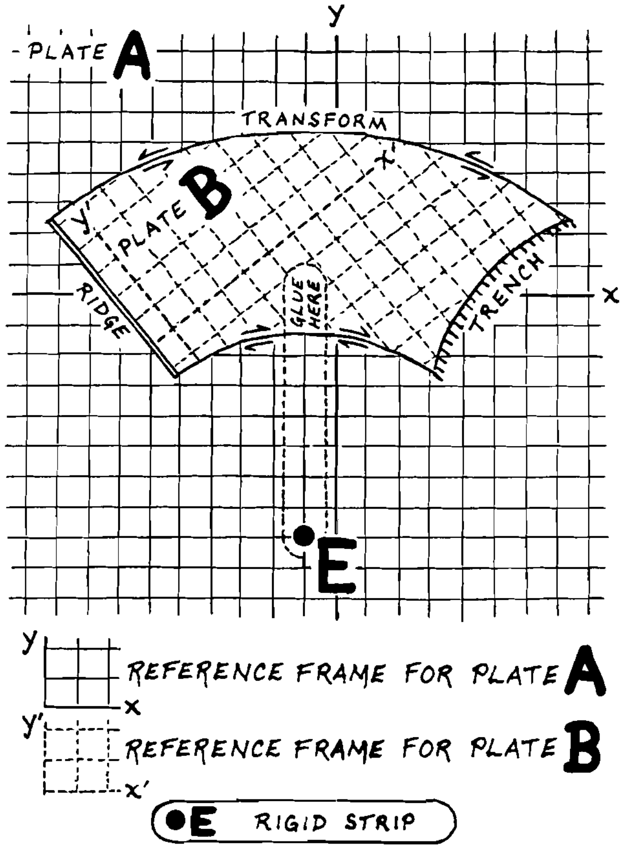
Euler poles can be used to describe the motions of plates with shapes other than round. Box 1-3 demonstrates an Euler pole for a plate with all three types of boundaries. The transforms are segments of circles centered on the Euler pole. In this example, the Euler pole lies outside the boundary of plate B but is still the pivot point for the motion of the two plates. As before, the Euler pole **E** is the only point that remains stationary relative to both plates.

In two-dimensional plate tectonics most transforms are straight lines. Therefore Euler poles are not very useful because they describe the motion of plates bounded by segments of circles. However, we will see that on a sphere, *all* transforms are segments of circles. Therefore all plate motions on a sphere can be described efficiently and compactly using Euler poles. In plate tectonics, the end result of analyzing thousands of observations made over the globe is a table of Euler poles.

Finding Euler Poles

Imagine for a moment that you are an oceanographer surveying a new ocean basin where you have reason to suspect the presence of two plates. How would you go about locating

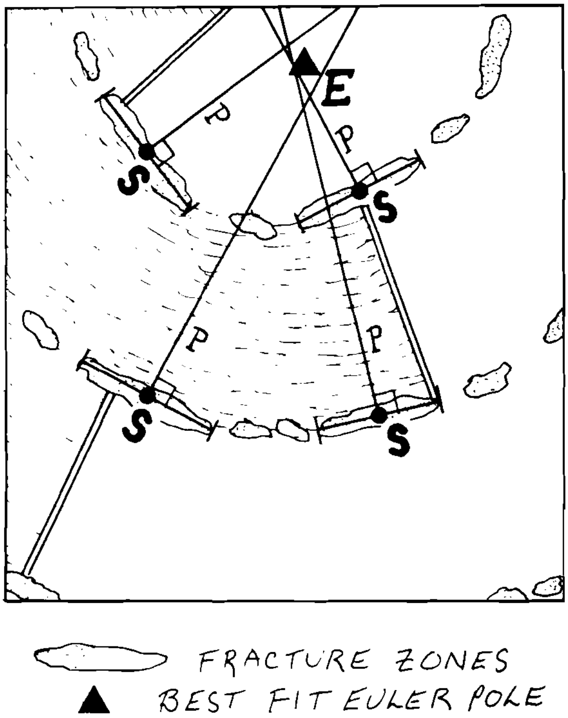
Box 1-3. Plate with Arcs as Transforms.



1. Copy figure and cut along boundary of plate B.
2. Cut out lower RIGID STRIP and glue to plate B as shown.
3. Place pin through **E** to form Euler pole.
4. Rotate plate B clockwise, slipping leading edge beneath plate A.
5. Note which parts of the boundary are ridges, which parts are trenches, and which parts are transforms.
6. Note that as plate B rotates, the coordinates of **E** remain the same in both the coordinate system (or reference frame) of plate A and also in the coordinate system of plate B.

the Euler pole that describes their past motion? You could start by looking for transforms in the form of circles or arcs, but at sea you will quickly learn that most transforms aren't perfect arcs, especially when viewed at close range. However, you may notice some long, narrow mountain ranges

Box 1-4. Finding Euler Pole from Fracture Zones.



1. Identify local linear geologic features.
2. Draw a straight line segment S through each feature.
3. Construct the perpendicular bisector P of each segment.
4. Eyeball the point **E** that is as close as possible to all bisectors P. This is the Euler pole.

across which the ocean floor steps down from a shallower to a greater depth. These mountain ranges are important. Oceanographers recognized these impressive geographic features decades before plate tectonics came along and termed them **fracture zones.** Locally they appear to be linear whereas over great distances they are segments of circles. In surveying your new ocean basin, you will want to plot all such fracture zones carefully on your navigation charts.

We will see later that many fracture zones mark the trace of present or ancient transforms. Having found some fracture zones in your survey, how do you deduce from them the location of the corresponding Euler pole? Box 1-4 shows how to do this, based on the simple idea that lines drawn perpendicular to the arc of a circle all intersect at the center of the circle. You first draw a best-fitting straight-line segment along the trend of each of your fracture zones (Box 1-4). Use a protractor to read the azimuth of these lines, in degrees clockwise (or east) of north, and record these azimuths, together with the coordinates of the midpoints of the line segments. (You'll want to publish these numbers in a table because plate tectonicists will be very interested in your basic data.) Your next step is to construct the perpendicular bisectors of the line segments, repeating this at different localities spaced as far apart as possible. You'll usually find that the perpendicular bisectors don't all intersect, but most of them nearly do. Usually you can eyeball a Euler pole that is fairly close to most of the perpendicular bisectors. In Chapter 4, you will learn how to find Euler poles mathematically on a sphere.

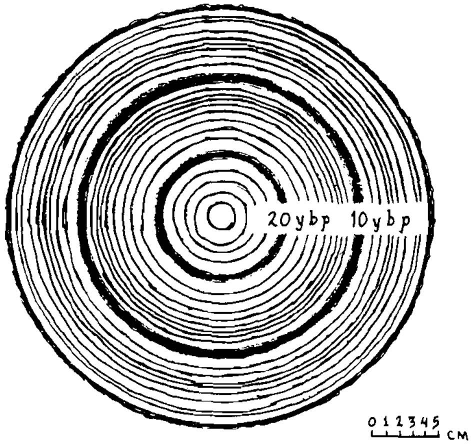


Figure 1-8.
A tree ring is an example of an isochron, a surface or line which marks the location of material which all formed at the same time. If the distance Δx between the 20 yr and 10 yr tree rings is 5 cm, then the bark of the tree is moving away from the center at a velocity $V = \Delta x/\Delta t$ = 5 cm/10 yrs = 0.5 cm/yr. Although this is a fast-growing tree, some plates are moving apart 20 times faster.

Isochrons and Velocities

Magnetic Stripes

Trees grow by generating annual layers or rings just beneath the bark. A geologist would call a tree ring an **isochron,** that is, a surface or line that marks the location of material which formed at some specific time in the past. Imagine that 20 years ago you were a forester investigating tree growth and that you had injected a tree with black dye to mark the ring which formed that year. Then, 10 years ago, you repeated the experiment. A cross section of the tree today would display the two isochrons shown in Figure 1-8 for 20 ybp (years before present) and 10 ybp separated by 10 annual rings. Obviously trees in the forest don't have artificial isochrons, but they do display variations in the thickness of their growth rings which are characteristic of past climatic fluctuations. An expert can readily determine the age of a specimen of wood from an archeological site by comparing its ring widths with those of trees of known age from the same region.

In plate tectonics, the chronometer used to determine isochrons on the seafloor is provided by the earth's magnetic field. The heart of the timing system is located in the earth's liquid core, where the geomagnetic field is generated by electrical currents. This magnetic chronometer is binary in the sense that it has two stable states: a **normal** state in which the magnetic field is directed toward the north, and a **reversed** state in which the field is directed toward the south. For at least two billion years the field has switched back and forth between these two states at irregular intervals that may be as short as 20 thousand years or as long as several tens of millions of years or more. The geomagnetic field aligns the ferromagnetic domains in rocks on the seafloor as they cool from a molten state at a ridge. From sensitive magnetometer readings made at the sea surface, it is possible to "read" the magnetic memory of the rocks on the seafloor.

The seafloor is generally found to be magnetized in stripes of alternating polarity. Like tree rings, the stripes are of varying widths, and ages can be determined by comparison with a standard pattern of known age as determined by isotopic dating. Using this approach, which is described in more detail in Chapter 8, isochrons have now been determined for almost all of the seafloor. Magnetically determined isochrons near an active ridge are almost always parallel to the ridge and usually have mirror symmetry across it. The reason for the symmetry is discussed in Box 1-5. The explanation offered is not completely realistic for several reasons: the crack between the plates is not bounded by vertical planes as shown but rather is narrow at the top and wider at the bottom; moreover, the plates do not move apart in a series of equal, finite steps but rather by a more irregular process. However, the explanation in Box 1-5 starts with the right assumptions, is qualitatively correct, and ends with the right results.

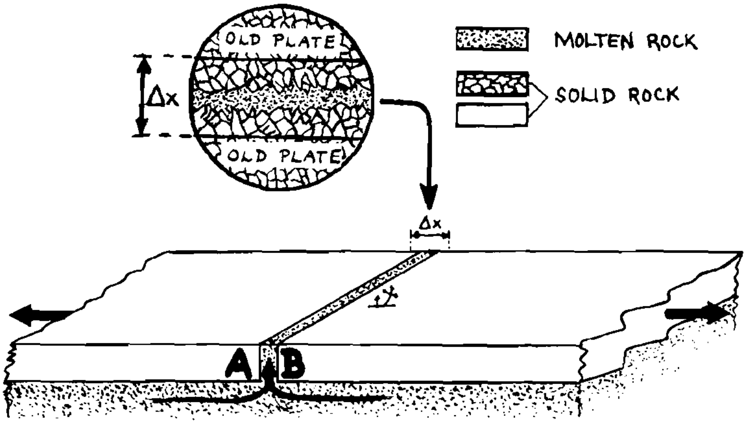
Rates of Spreading

Imagine that as an oceanographer you've learned from your fathometer readings the location of a ridge (Figure 1-9c). From your magnetometer readings you've determined the isochrons as shown. Can you determine from these data the velocity of seafloor spreading? Note first that the 10 my (million year) isochrons are 1000 km apart. Ten million years ago, both of these isochrons were together at the ridge. Thus, during the time span Δt = 10 my a total width of Δx = 1000 km of new oceanic lithosphere formed as the two plates moved this distance apart. The velocity ${}_AV_B$ of plate B relative to plate A is thus

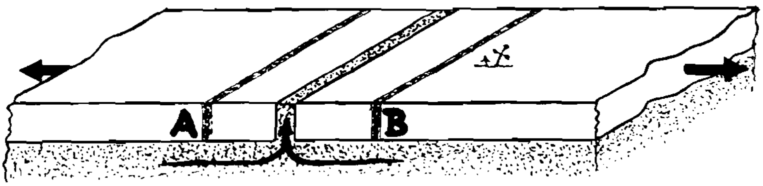
$$ {}_AV_B = \frac{\Delta x}{\Delta t} = 100 \text{ km/my} = 100 \text{ mm/yr} \qquad (1.1) $$

In addition to giving us spreading velocities, isochrons also help us roll back the process of seafloor spreading for the

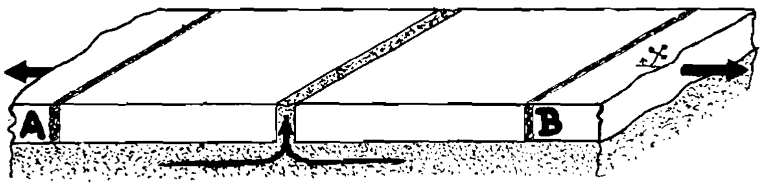
Box 1-5. Symmetrical Ridge Formation.



1. Plates A and B crack apart and separate a distance Δx.
2. Magma rises to fill the opening and begins to solidify inward from the old walls of the crack (inset).
3. Material at the center of the filled crack is the last to crystallize and therefore is the weakest.



4. After time Δt the plates separate another distance Δx.
5. A crack reopens at the weak center of the old opening.
6. Magma again rises from the asthenosphere to fill the opening.



7. The process continues, building both plates.

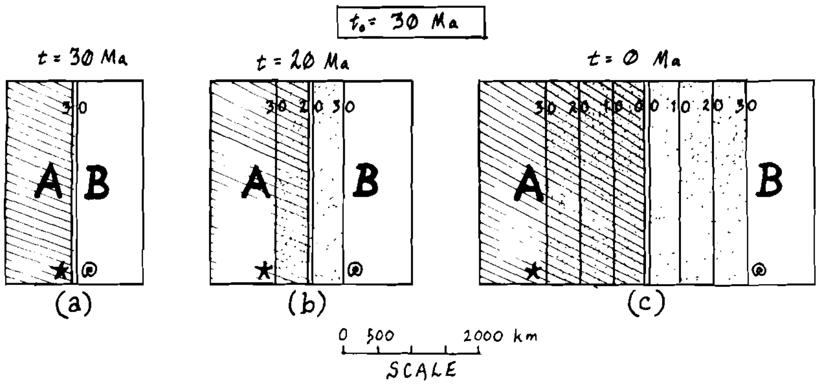


Figure 1-9.
Symmetrical growth of plates A and B by accretion at a ridge. t is the time of the plate reconstruction, $t_0 = 30$ Ma is the time when the plates begin to diverge, and $t = 0$ is the present. The starfish and snail remain firmly attached to the moving seafloor. During the past 30 my each plate has grown by a total width of 1500 km. Both strips of new lithosphere (stippled pattern) were added on the side of the plate adjacent to the ridge.

purpose of finding out where plates were at various times in the past. For example, researchers have been able to accurately determine the ancient position of North America next to Europe by matching up corresponding isochrons. To see how this works, let's start with the simple set of present-day isochrons shown in Figure 1-9c. We know that 20 million years ago (20 Ma) the 20 my isochrons were superimposed at a ridge, as is shown in Figure 1-9b. In showing isochrons as they looked at 20 Ma, the question arises of how to label the isochron that is forming at the ancient ridge, "0 Ma" or "20 Ma." We'll try to avoid confusion by (1) always keeping present-day ages attached to the isochrons when we make reconstructions for earlier times; and (2) labeling as t_0 the time when the ridge first formed and as t the time when a snapshot was taken of the ridge. Figure 1-9b is a picture of the isochrons as they looked at time $t = 20$ Ma, assuming that the ridge started spreading at time $t_0 = 30$ Ma. The isochron just forming at the ridge is labeled "20 my." Figure 1-9a is a picture of the ridge at $t_0 = 30$ Ma.

Velocities determined from isochrons in this way are the true velocities between plates only if the plates are spreading in a direction perpendicular to the ridge. If they spread at some other angle, the true velocity will be greater. In Figure 1-10 the isochrons for plates A and B are spaced the same distance apart as those for plates C and D. The 5 my isochrons are spaced 400 km apart, so the velocity is given by

$$
\begin{aligned}
{}_CV_D &= \frac{\Delta x}{\Delta T} \qquad (1.2)\\
&= 400 \text{ km}/5 \text{ my}\\
&= 80 \text{ km/my}\\
&= 80 \text{ mm/yr}
\end{aligned}
$$