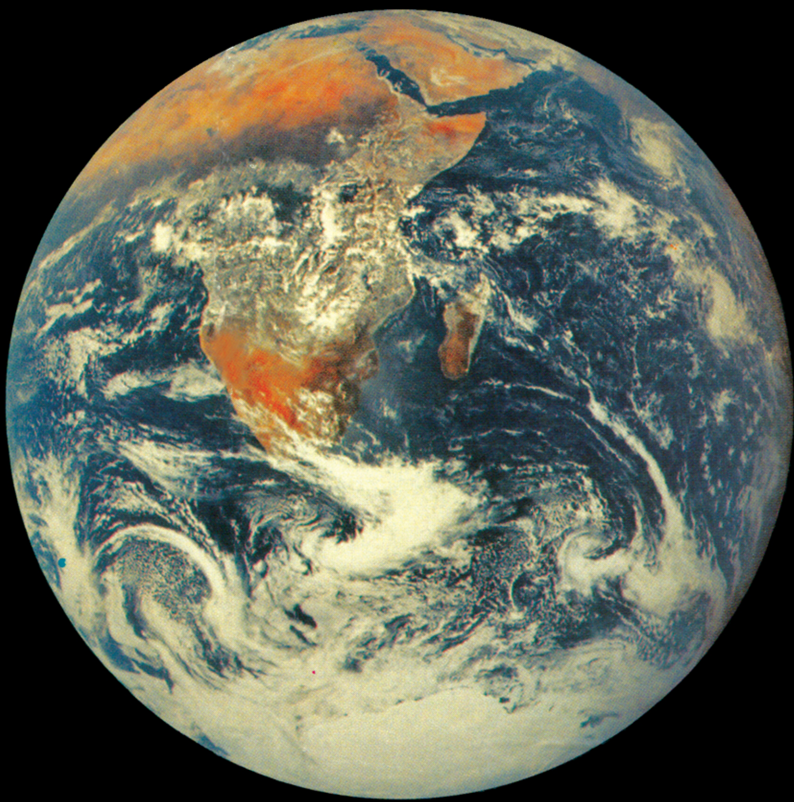
PLATE TECTONICS & CRUSTAL EVOLUTION

Third Edition



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Crustal Evolution

Third Edition

by

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PERGAMON PRESS

OXFORD · NEW YORK · SEOUL · TOKYO

U.K.	Pergamon Press Ltd, Headington Hill Hall, Oxford OX3 OBW, England
U.S.A.	Pergamon Press Inc., 660 White Plains Road, Tarrytown, New York 10591-5153, U.S.A.
KOREA	Pergamon Press Korea, KPO Box 315, Seoul 110-603, Korea
JAPAN	Pergamon Press Japan, Tsunashima Building Annex, 3-20-12 Yushima, Bunkyo-ku, Tokyo 113, Japan

First edition 1976
Second edition 1982
Third edition 1989
Reprinted 1993 (with corrections and additions)

Library of Congress Cataloging-in-Publication Data

Condie, Kent C.
Plate tectonics and crustal evolution/by Kent C. Condie.–
3rd ed.
p. cm.
Rev. ed. of: Plate tectonics & crustal evolution. 2nd ed. c1982.
Bibliography: p.
Includes index.
1. Earth–Crust. 2. Plate tectonics. I. Condie, Kent C. Plate tectonics & crustal evolution. II. Title. III. Title.
QE511.C66 1988 551.1'3–dc19 88–22931

British Library Cataloguing in Publication Data

Condie, Kent C.
Plate tectonics and crustal evolution.
3rd ed.
Lithosphere. Evolution. Effects of
motion of lithosphere plates
I. Title
551.1'3

ISBN 0–08–034874–2 Hardcover
ISBN 0–08–034873–4 Flexicover

Printed in Great Britain by BPCC Wheatons Ltd., Exeter

To Carolyn,
Tamara, Linda and
Nathan

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Contents

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Preface

This book has grown out of a course I teach at New Mexico Tech. The rapid accumulation of data related to plate tectonics and the origin of continents in the past decade has necessitated continued updating of the course. The book is written for an advanced undergraduate or graduate student, and it assumes a basic knowledge of geology, chemistry, and physics that most students in the Earth Sciences acquire during their undergraduate education. It also may serve as a reference book for various specialists in the geological sciences. I have attempted to synthesize and digest data from the fields of oceanography, geophysics, geology, and geochemistry and to present this information in a systematic manner addressing problems related to the evolution of the Earth's crust over the last 3.8 Ga. The role of plate tectonics in the geological past is examined in light of geologic evidence and examples of plate reconstructions are discussed.

Since the first and second editions of the book were published, a wealth of information related to plate tectonics and continental origin has appeared in scientific journals. To accommodate this new information, it was necessary to rewrite more than 75% of the text as it appeared in the second edition. Also, a large number of new figures have been added and the tectonic map of the world has been updated. The third edition includes new sections on meteorites, seismic tomography, mantle convection, accretionary terranes, mantle sources and evolution, continental growth, secular changes in Earth history, Venus, and a new chapter on exogenic Earth systems. In addition, the following topics have been substantially revised: lunar origin, global gravity, origin of the core, metamorphism, plate boundaries, hotspots, tectonic settings, magma associations, Phanerozoic orogenic systems, and crustal origin and evolution.

The general approach is much the same as in the first and second editions. Historical background and major physical properties of the Earth are briefly summarized in Chapter 1 and the origin of meteorites, planets and the Earth/Moon system are discussed in Chapter 2. Chapters 3 and 4 dealing with the mantle (and core) and crust, respectively, are no longer strictly descriptive chapters but include also interpretations. Exciting new constraints on mantle structure from seismic tomography and satellite gravity studies are included in Chapter 3, as well as a discussion of convection and the driving forces of plate tectonics. The origin of the core is also examined. In addition to summarizing geophysical and geochemical properties of both the oceanic and continental crust in Chapter 4, metamorphism and crustal provinces are discussed.

Chapter 5 includes not only the basic factual data that led to the seafloor spreading and plate tectonic models, but also includes new information on magnetic reversals, the evolution and changes of plate boundaries, aseismic ridges and oceanic plateaus, and hotspots and plumes. Major tectonic settings are reviewed in Chapter 6 and the section on collisional orogens is expanded, based on the voluminous literature on this subject that has appeared in the past few years. Mineral and energy deposits are also discussed in light of tectonic settings. Chapter 7 has been completely rewritten and updated in light of major advances in our understanding of magma production and mantle sources from trace element, Sr–Nd–Pb isotope, and rare gas studies of basalts. Chapter 8 includes examples of plate tectonic histories of Phanerozoic orogenic systems. Although emphasis is placed on North American systems, examples are also included from other continents.

Chapter 9 includes a discussion of Archean and Proterozoic crustal provinces and of the possible role of plate tectonics during the Precambrian. In Chapter 10, information is brought together to discuss crustal origin and evolution. Topics include the composition and origin of the primitive crust, magma oceans, crustal growth mechanisms and rates, a summary of the growth of North America, secular changes in crustal composition, and comparative evolution of the terrestrial planets. The new Chapter 11 includes a detailed discussion of the origin and evolution of the atmosphere and oceans and comparison of the evolution of the atmospheres of the terrestrial planets. In addition, the evolution of terrestrial climates, the origin and evolution of life, mass extinctions and impact phenomena are discussed.

In order to keep the book to a reasonable length, and avoid duplicating information that is widely available in other books, some subjects are covered in only a cursory manner and others not at all. For instance, the methods by which geological, geochemical, and geophysical data are gathered are only briefly mentioned, as books on these subjects are readily available. Extensive mathematical treatments are omitted for the same reason. Because the book is designed primarily as a textbook, references are kept to a minimum. I have attempted, however, to reference the major papers and some of the minor ones that have strongly influenced me in regard to interpretations set forth in the text. More extensive bibliographies can be found in these papers and in the references listed under "Suggestions for Further Reading" at the end of each chapter.

I am greatly appreciative of efforts of Debbie Pettengill and Pat Mills who typed and edited the manuscript and dedicated many months to producing the finished copy. The superb figures were drafted by Jessica McKinnis.

KENT C. CONDIE

SOCORRO, NEW MEXICO
MAY 1988

CHAPTER 1

Introduction

A Perspective

THE origin and evolution of the Earth's crust is a tantalizing question that has stimulated much speculation and debate from the early part of the 19th century. Some of the first problems recognized—such as how and when did the oceanic and continental crust form?—remain a matter of considerable controversy even today. Results from the lunar landings and satellite data collected from other planets indicate that the Earth's crust may be a unique feature of bodies in the solar system. The rapid accumulation of data in the fields of geophysics, geochemistry, and geology in the past 25 years has added much to our understanding of the physical and chemical nature of the Earth's crust and of the processes by which it evolved. Evidence favors a source for the materials composing the crust from within the Earth. Partial melting of the Earth's interior appears to have produced magmas that moved to the surface and produced the first crust. The continental crust, being less dense than the underlying mantle, has risen isostatically and has been subjected to weathering and erosion. Eroded materials have been added partially to continental margins, causing the continents to grow laterally, and partially returned to the mantle to be recycled and perhaps again to become part of the crust at a later time. Specific processes by which the crust was created and grown are not well known, but a large amount of data allows important boundary conditions to be invoked. In this book, important physical and chemical properties of the crust and upper mantle are presented and discussed in terms of models for crustal origin and evolution.

The theories of seafloor spreading and plate tectonics that have so profoundly influenced geologic thinking in the past two decades have also provided valuable insight into the mechanisms by which the crust has evolved. One of the major problems regarding crustal evolution is that of when plate-tectonic and seafloor spreading processes began. Some scientists consider the widespread acceptance of sea floor spreading and continental drift as a "revolution" in the Earth Sciences (Wilson, 1968). Scientific disciplines appear to evolve from a stage primarily of data gathering, characterized by transient hypotheses, to a stage where a new unifying theory or theories are proposed that explain a great deal of the accumulated data. Physics and chemistry underwent such revolutions around the beginning of the 20th century, whereas the Earth Sciences entered such a revolution in the late 1960s. As with scientific revolutions in other fields, new ideas and interpretations do not invalidate earlier observations. On the contrary, the theories of seafloor spreading and plate

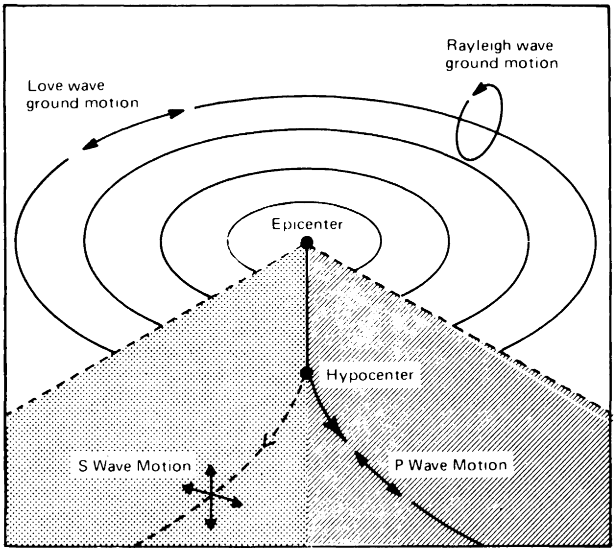

FIG 1.1 Types of body and surface wave motion related to the hypocenter and epicenter of an earthquake. After Davies (1968).

tectonics offer for the first time a unified explanation for heretofore seemingly unrelated observations in the fields of geology, paleontology, geochemistry, and geophysics.

Sources of Data

Seismic Methods

Before discussing the physical and chemical properties of the Earth, it may be useful to review some basic definitions and techniques used in the geosciences. The most definitive information on the structure of the Earth's interior comes from *seismology*. When an earthquake or an explosion occurs in the Earth, two types of elastic waves are produced—body waves and surface waves. *Body waves* travel through the Earth and are reflected and refracted at interfaces. They are of two types: *P waves* (or compressional waves), which are characterized by alternate compression and expansion in the direction of propagation, and *S waves* (or shear waves), with particle motion normal to the direction of propagation (fig. 1.1). P waves are always faster than S waves and S waves cannot be transmitted through a liquid. Surface waves are propagated along or near the surface of the Earth and also are of two types: Rayleigh and Love waves. *Rayleigh waves* exhibit elliptical particle motion confined to a vertical plane containing the direction of propagation, while *Love waves* are characterized by horizontal motion normal to the propagation direction. The region in the Earth where elastic waves are produced by an earthquake (or explosion) is defined as the *hypocenter* or *focus*, and the point on the Earth's surface vertically above as the *epicenter*. Elastic waves are detected by seismometers, which respond to ground movements. Computerized arrays of seismometer stations make it possible to separate interfering signals, to improve signal-to-noise ratio, and to measure wave velocities directly.

Several seismic methods are used in investigating the interior of the Earth. The gross features of the Earth's interior are determined from travel-time distance studies of body waves travelling through the Earth. Detailed structure of the crust and uppermost mantle is determined by seismic refraction and reflection methods. Large underground explosions are particularly useful in these studies because the time and location of such explosions are known more accurately than earthquake times and hypocenter locations. The refraction method, which is used both on land and sea, is based on measuring the travel times of P waves between shot points and seismic recorders located various distances apart, usually along straight-line profiles. The method is limited, in that very detailed crustal structure cannot be determined. Evidence for low-velocity layers is obtained from modeling of surface-wave data and from amplitude studies of refraction data. The use of supercritical reflections (i.e. reflected waves that have incident angles greater than the critical angle) can enhance the interpretation of refraction data. Vertical incidence reflections occur only at sharp discontinuities and may allow a distinction to be made between sharp and gradational discontinuities.

Travel-time anomaly studies are valuable in evaluating upper-mantle structure. A *travel-time anomaly* (or residual) is the difference between observed and calculated body wave arrival times at a given seismograph station. Calculated arrival times are azimuthally corrected and based on idealized models. Maps constructed by contouring travel-time anomalies are useful in relating such anomalies to geological and other geophysical features.

Earthquakes produce natural vibrations in the Earth known as *free oscillations*. Two types of oscillations occur: torsional oscillations, involving particle displacements normal to the Earth's radius, and spheroidal oscillations, which are radial or tangential displacements. Long-period free oscillations are detected with strain seismometers and Earth-tide gravimeters. Free-oscillation studies have resulted in improved resolution and detection of interfaces within the Earth, as well as determination of density and seismic anelasticity of parts of the mantle. Rayleigh- and Love-wave dispersion provide a basis for detailed studies of crustal and upper-mantle structure.

Free oscillations produced by major earthquakes do not last indefinitely and the vibrational energy is gradually converted to heat. The oscillations are attenuated, and the process is known as *anelasticity*. Body waves passing through the Earth are also attenuated. Anelastic attenuation is measured with a unitless factor Q, the *specific attenuation factor*, and low values of Q mean high seismic-wave attenuation. Measured Q values in the Earth range from about 10 to greater than 1000. Anelasticity in the Earth appears to result from some combination of grain boundary damping, stress-induced ordering of crustal defects, and damping caused by vibration of dislocations (Gordon and Nelson, 1966). Q decreases rapidly as temperature and degree of melting increase in the Earth.

Seismic reflection profiling is used both in oceanic and continental areas (Brewer and Oliver, 1980; Stommel and Graul, 1978). In oceanic areas, acoustic sources on ships are used to produce energy to study the stratigraphy and structure of sediments around continental margins and in ocean basins. The major reflection profiling studies on the continents are those of the COCORP research group in the United States and the BIRPS group in the United Kingdom. Vibrating trucks transmit energy into the Earth, and return echoes are recorded by arrays of geophones. Data are collected and computer processed so as to produce a section through the crust as a function of seismic-wave travel times.

Magnetic Methods

The Earth's magnetic field is defined by its strength and direction. The direction is expressed in terms of the horizontal angle between true north and magnetic north, the *declination*, and the angle of dip with the horizontal, the *inclination*. The inclination becomes vertical at the two magnetic poles. The total magnetic field strength is strongest near the magnetic poles (70 μT at the South Pole) and weakest at the equator (about 30 μT). Both short- and long-term variations occur in the direction and strength of the magnetic field. Short-term variations (with periods of hours to years) are related chiefly to interactions of the magnetic field with the strongly conducting upper layers of the atmosphere. Variations with periods of hundreds of years or more are known as secular variations and are interpreted to support an origin for the magnetic field in terms of fluid motions in the outer part of the Earth's core. Approximately 90% of the present field can be described by a magnetic dipole at the Earth's center, which makes an angle of about 11.5 degrees with the rotational axis. A general westward drift of the field is noted at a rate of about 0.18 deg/a.

Local and regional variations in the magnetic field reflect, for the most part, rocks beneath the surface with varying degrees of magnetization. These variations are measured with fluxgate or proton magnetometers on land or sea, or in the air. Significant deviations from a magnetic background either on a local or regional scale are known as magnetic anomalies, the intensities of which are expressed in gammas (γ) or teslas (T) (1 γ = 100 μT). Small-scale anomalies extending over thousands of square kilometers reflect variations in the lower crust or upper mantle.

Rocks may become magnetized in the Earth's magnetic field by several mechanisms, which are described in Chapter 5. Such magnetization is known as *remanent magnetization* and is measured in the laboratory with spinner, astatic, or cryogenic magnetometers. The maximum temperature at which a mineral can possess remanent magnetization is known as the *Curie temperature*. *Paleomagnetism* is the study of remanent magnetism in rocks of various geologic ages. If rock samples can be accurately oriented and the date of magnetization determined, it is often possible to determine the locations of earlier magnetic pole positions. Paleomagnetic studies have shown that the magnetic poles have reversed themselves many times in the geologic past, and such reversals are thought to be produced by instability in the outer core.

Gravity Methods

Gravity is the force of attraction between the Earth and a body on or in the Earth divided by the mass of the body. The average gravitational force of the Earth is 980 gals (1 gal = 1 cm/sec^2). Gravity is measured with a gravimeter and can be determined both on land and at sea. Accuracies are typically about 1 mgal on land and 5–10 mgal at sea. The standard reference for gravity on the Earth is the gravitational field of a spheroid, and is dependent only on latitude. The gravity field on the Earth can be described using data derived from the directions and rates of the orbital shift of artificial satellites. From such data it is possible to determine how much the Earth's average surface, or *geoid*, which is roughly equal to sea level, actually deviates from a spheroid. Data indicate that the Earth is pear-shaped, with an average equatorial radius of 6378 km and an average polar radius of 6357 km. Gravity distribution on the Earth can be calculated from spherical harmonic coefficients of the satellite gravitational data.

Local and regional gravity data must be corrected for latitude and elevation before interpretation. On land, gravity measurements are usually above the geoid surface, and hence an increase in gravity must be added to the observed value to account for the difference in elevation. This is known as the *free-air correction*. If the standard gravity value of the spheroid is now subtracted (i.e., the latitude correction), the *free-air anomaly* remains. If the attraction of rock between the geoid and the gravity station is subtracted (the *Bouguer correction*) and a correction is made for nearby topographic variations, we obtain the *Bouguer anomaly*. Measurements at sea require no free-air correction, since they are made at sea level, and the Bouguer correction, where used, is added to account for the change in gravity that would result if the oceans were filled with rock instead of water.

Early gravity measurements in the mid-1700s indicated that large mountain ranges exhibit smaller-than-expected gravitational attractions. Such data led to the principle of *isostasy*, introduced about 1900 by Dutton. This principle suggests that an equilibrium condition exists in the Earth whereby the load pressure due to overlying columns of rock is equal at some depth of compensation. Two main theories have been proposed to explain isostasy. Pratt's theory assumes that the density of rock columns in the outer shell of the Earth varies laterally above a constant depth of compensation and is expressed as a function of elevation on the Earth's surface. Airy's theory proposes that the outer shell is composed of low, rather constant-density columns, and that the depth of compensation varies as a function of the thickness of the columns. Both mechanisms probably contribute to isostatic compensation. Models suggest compensation depths of the order of 50–100 km for both the Airy and Pratt theories. *Isotatic gravity anomalies* may be calculated by subtracting from Bouguer anomalies the mass distribution within a segment of the upper part of the Earth as determined from some combination of the Airy and Pratt compensation mechanisms.

Electrical Methods

The Earth's magnetic field induces electrical currents, known as *telluric currents*, which flow in the crust and mantle. Most short-period variations in the magnetic field are produced by interactions with the strongly conducting ionosphere (upper atmosphere). A magnetic storm produces large magnetic variations lasting for a few days and is caused by strong currents of high-energy particles emitted by solar flares that are trapped in the ionosphere. Magnetic variations can be used to estimate conductivity in the Earth, since the strength of induced currents depends on electrical conductivity distribution. Short-period variations of such currents penetrate only to shallow depths, while longer periods penetrate to greater depths.

Four methods have been used to estimate conductivity distribution in the crust and mantle (Keller, 1971; Creer, 1980): (a) direct-current sounding; (b) magnetotelluric sounding; (c) electromagnetic sounding; and (d) geomagnetic deep-sounding. Direct-current sounding involves driving a current into the ground between widely spaced electrodes, and the depth of penetration of this method is limited to only several tens of kilometers. In the magnetotelluric method, both electric and magnetic variations in the Earth's field are measured simultaneously. An artificial electromagnetic field is generated, driven into the Earth, and measured in the electromagnetic method. The geomagnetic deep-sounding method involves measuring variations of naturally induced currents caused by magnetic storms. This provides the best method for estimating mantle conductivity distributions.

Geothermal Methods

Heat flow determinations on the Earth involve two separate measurements, one of the thermal gradient (dT/dx) and one of thermal conductivity (K). From these measurements, heat flow (q) is calculated as follows:

$$q = K \frac{dT}{dx} \tag{1.1}$$

Heat flow may be expressed as μcal/cm^2 sec or as mW/m^2 where 1 μcal/cm^2 sec is defined as one heat flow unit (1 HFU) and 1 HFU = 0.0239 mW/m^2. Thermal gradient is measured with thermistors, which on land are attached to a cable and lowered down a borehole, and at sea are attached to core barrels or mounted in a long thin probe that is inserted into deep-sea sediments. In both cases, time is allowed for thermal equilibration before measurements are taken. Thermal conductivity of water-saturated rocks is usually measured with a divided-bar apparatus in which a known heat flow is passed through a sandwich of copper discs, two standards, and a rock sample; thermal conductivity is calculated from the temperature difference across the sample and its thickness. The thermal conductivity of unconsolidated sediments is usually measured with a needle probe, which consists of a thermistor, an electrical heating element, and a hypodermic needle inserted into the sediment. Thermal conductivity is obtained from the rate at which the needle temperature rises for a given energy input to the heater.

In continental areas, significant ground water movement can produce anomalously low heat flow. Also, measured heat flow in areas that were covered by Pleistocene glaciers may be lower than actual heat flow. Although glacial corrections up to 30% have been proposed by some investigators, evidence is conflicting regarding the general importance of this effect.

The radiogenic heat production of a rock or of a geologic terrane may be calculated from the concentrations of U, Th, and K and the heat productivities of ^{235}U, ^{238}Th, and ^{40}K. The concentrations of these isotopes can be determined by counting the natural radioisotopes with a gamma-ray spectrometer in the laboratory. Airborne gamma-ray spectrometers have been used to estimate concentrations of U, Th, and K over large areas of the crust. Radiogenic heat generation (A) is expressed in 10^{-13} cal/cm^3 sec or as μW/m^3. One heat generation unit (1 HGU) is defined as 10^{-13} cal/cm^3 sec and is equivalent to 0.0239 μW/m^3.

High-pressure Studies

For many years it has been possible to reconstruct in the laboratory static pressures up to about 300 kbar, which is equivalent to about 1000 km burial depth in the Earth. A new era of high-pressure research began in 1972 with the development of the double-stage split-sphere apparatus and the diamond-anvil pressure cell (Liu and Bassett, 1986). With these systems it is possible to study phase relations at pressures up to 1.7 Mbar and temperatures up to 3500°C, which allows direct investigation of lower mantle and core compositions. High-pressure experiments can be performed with solid or liquid media at a large range of temperatures. It is also possible to measure a considerable number of properties of rocks at high pressures and temperatures: phase equilibria boundaries, elastic properties including P- and S-wave velocities, electrical and thermal properties, and fracture and flow characteristics are but a few. From such measurements, in conjunction with geophysical data, it is possible to place limitations on the composition, mineralogy and melting behavior of the crust and upper mantle, and to evaluate the origin of magmas. From the results of high-pressure and high-temperature rock-deformation studies, it is also possible to understand more fully earthquake mechanisms and flow characteristics within the Earth.

Possible mineral assemblages and compositions of deeper parts of the Earth, including the core, also can be studied using the results of shock-pressure experiments. The method involves generating a strong shock (up to several megabars) in a material with explosives, producing a wave front that moves through the material at a velocity greater than sound and greater than the particle velocity of the shocked material (Ahrens and Peterson, 1969). The pressure and density within the wave can be deduced by measuring the shock and particle velocities, and results are generally expressed in terms of the hydrodynamic sound velocity plotted against density. Various elements, minerals, and rocks are examined, and the results are compared with hydrodynamic velocity data deduced from body-wave studies of the Earth. Such comparisons provide limitations on the composition of the lower mantle and core.

Geochemistry and Geochronology

Geochemical data from rocks and minerals provide important information bearing on the composition of the upper mantle and evolutionary changes in the crust and mantle. Geochemical and isotopic research have advanced rapidly in the past decade in response to the development of new analytical methods and geochemical modeling. Trace element and radiogenic isotope geochemistry, in particular, have been useful in studying the evolution of the crust and mantle. Important advances in our understanding of planetary evolution also have come from geochemical and isotopic studies of lunar and meteorite samples and of ultramafic inclusions from the Earth's mantle. Isotopic studies are important not only in terms of geochronology but also for identifying and mapping crustal and upper-mantle sources for magmas. Pb, Nd, and Sr isotopes are important in both applications. Geochronology involves the study of time relationships in orogenic belts and in the evolution of continents and ocean basins. Tracer studies make use of daughter isotopes as "fingerprints" to study the origin of igneous rocks and to trace the evolution of the mantle and crust through geologic time (see Chapt. 7).

Refinements in radiometric dating methods have improved estimates of the beginning and duration of the various subdivisions of geologic time. A current version of the geologic time scale is given in table 1.1.

Other Sources of Information

The viscosity of the mantle has been estimated by studies of isostatic recovery rates of large segments of the crust after removal of a surface load such as icecaps or large lakes, and from estimates of the seismic anelasticity Q. The mass of the Earth can be estimated from surface gravity data after a rotational correction. The Earth's two principal moments of inertia—one about the polar axis and the other about an equatorial axis—can be estimated from rotational axis precessional data and the observed flattening of the Earth. Other physical properties as a function of depth within the Earth are estimated from measurements made on the Earth's surface and models of the Earth's interior.

Information from oceanic and continental drill cores allows a reliable projection of compositional data to shallow depths in the crust. The Deep Sea Drilling Project (DSDP), which began in 1968, has now recovered many cores from the sediment layer on the ocean floors, some up to several hundred meters in length. A specially designed drilling ship, the *Glomar Challenger*, is used as a floating drilling platform. Deep holes on the continents, other than oil wells, are rare. However, deep drilling into the continents in a variety of geologic environments is currently in the planning stages.

Last but not least are the conventional and well-established geological methods. Perhaps the most commonly overlooked yet extremely important source of data is field geology. The results of widespread geological mapping on the continents are of critical importance to the evaluation of the roles of seafloor spreading and plate tectonics in the geologic past. Stratigraphy, tectonics, volcanology, experimental petrology, sedimentation, and paleontology are other important fields of investigation.

Seafloor Spreading

Seafloor spreading is the process by which the lithosphere splits at ocean ridges and moves away from ridge axes with a motion like that of a conveyor belt as new lithosphere is created and fills the resulting crack. The lithosphere can be considered as a mosaic of plates bounded by ocean ridges, subduction zones, and transform faults (boundaries along which plates slide by each other) (fig. 1.2), and the study of the interactions of lithospheric plates is known as *plate tectonics*. Oceanic lithosphere is consumed in the asthenosphere at subduction zones to accommodate the newly created lithosphere such that the surface area of the Earth remains constant. The alternate possibility, that the Earth is expanding to accommodate growth of the lithosphere, seems unlikely, as discussed later. Hess (1962) is credited with proposing the theory of seafloor spreading, although the name was suggested by Dietz (1961).

The most definitive evidence for seafloor spreading comes from the study of linear magnetic anomalies on the seafloor (Chapt. 4). Vine and Matthews (1963) first

TABLE 1.1

GEOLOGIC TIME SCALE

CENOZOIC

AGE (Ma)	PERIOD		EPOCH		AGE
	QUATERNARY		HOLOCENE		
			PLEISTOCENE		CALABRIAN
	TERTIARY	NEOGENE	PLIOCENE	L	PIACENZIAN
				E	ZANCLEAN
5			MIOCENE	L	MESSINIAN
10					TORTONIAN
				M	SERRAVALLIAN
15					LANGHIAN
20				E	BURDIGALIAN
					AQUITANIAN
25		PALEOGENE	OLIGOCENE	L	CHATTIAN
30				E	RUPELIAN
35					
			EOCENE	L	PRIABONIAN
40				M	BARTONIAN
45					LUTETIAN
50					
55				E	YPRESIAN
			PALEOCENE	L	SELANDIAN: THANETIAN
60					SELANDIAN: UNNAMED
65				E	DANIAN

MESOZOIC

AGE (Ma)	PERIOD	EPOCH		AGE
70	CRETACEOUS	LATE		MAASTRICHTIAN
80				CAMPANIAN
				SANTONIAN
90				CONIACIAN
				TURONIAN
				CENOMANIAN
100		EARLY		ALBIAN
110				APTIAN
120			NEOCOMIAN	BARREMIAN
130				HAUTERIVIAN
				VALANGINIAN
140				BERRIASIAN
150	JURASSIC	LATE		TITHONIAN
				KIMMERIDGIAN
160				OXFORDIAN
170		MIDDLE		CALLOVIAN
				BATHONIAN
180				BAJOCIAN
				AALENIAN
190		EARLY		TOARCIAN
				PLIENSBACHIAN
200				SINEMURIAN
				HETTANGIAN
210	TRIASSIC	LATE		NORIAN
220				
				CARNIAN
230		MIDDLE		LADINIAN
				ANISIAN
240		EARLY		SCYTHIAN

PALEOZOIC

AGE (Ma)	PERIOD		EPOCH	AGE
	PERMIAN		LATE	TATARIAN
				KAZANIAN UFIMIAN
260			EARLY	KUNGURIAN
				ARTINSKIAN
				SAKMARIAN
280				ASSELIAN
	CARBONIFEROUS	PENNSYLVANIAN	LATE	GZELIAN KASIMOVIAN
300				MOSCOVIAN
				BASHKIRIAN
320		MISSISSIPPIAN	EARLY	SERPUKHOVIAN
340				VISEAN
				TOURNAISIAN
360	DEVONIAN		LATE	FAMMENIAN
				FRASNIAN
380			MIDDLE	GIVETIAN
				EIFELIAN
			EARLY	EMSIAN
400				SIEGENIAN
				GEDINNIAN
	SILURIAN		LATE	PRIDOLIAN
				LUDLOVIAN
420			EARLY	WENLOCKIAN
				LLANDOVERIAN
440	ORDOVICIAN		LATE	ASHGILLIAN
				CARADOCIAN
460			MIDDLE	LLANDEILIAN
				LLANVIRNIAN
480			EARLY	ARENIGIAN
500				TREMADOCIAN
520	CAMBRIAN		LATE	TREMPEALEAUAN FRANCONIAN DRESBACHIAN
			MIDDLE	
540			EARLY	
560				

PRECAMBRIAN

AGE (Ma)	EON	ERA
750	PROTEROZOIC	LATE
1000		MIDDLE
1250		
1500		
1750		EARLY
2000		
2250		
2500	ARCHEAN	LATE
2750		
3000		MIDDLE
3250		
3500		EARLY
3750		

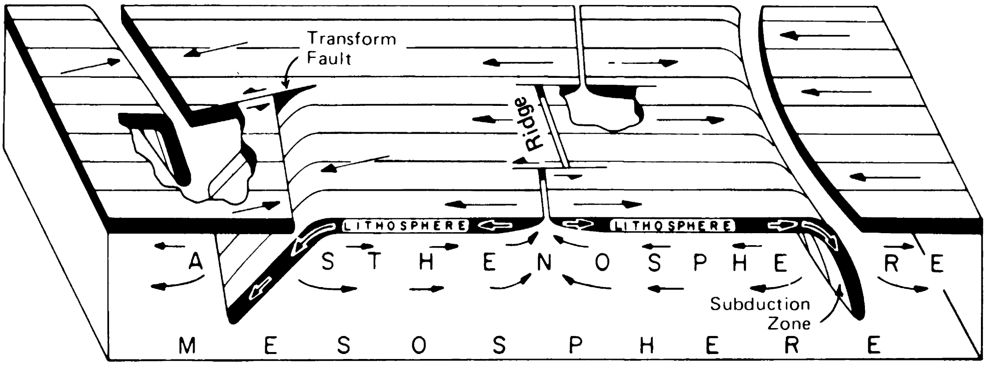

FIG 1.2 Schematic diagram showing the major features of seafloor spreading. After Isacks et al. (1968), copyright by the American Geophysical Union.

suggested that the alternate stripes of positive and negative magnetic anomalies were caused by bands of basaltic rock in the oceanic crust that were alternatively magnetized in normal and reversed directions of the Earth's magnetic field. They proposed that new lithosphere is formed over convective upcurrents beneath ocean ridges by magmatic processes. As magmas emplaced in the axial rifts cool through the Curie temperature of magnetic minerals, they acquire a magnetization in the direction of the existing magnetic field of the Earth. The newly magnetized crust then splits and is forced apart to make room for fresh injections of magma.

Many seemingly unrelated facts from the fields of geology, paleontology, geophysics, and geochemistry are consistent with, and find a unified explanation in, the seafloor spreading model. For instance, the observed increase in age and thickness of deep-sea sediments with distance from ocean ridges is predicted by the model, as are the compositional changes found in basalts retrieved from the oceanic crust. First-motion studies of earthquakes (see Chapt. 5) are also consistent with the model. The absence of deep-sea sediments older than Jurassic reflects seafloor spreading rates of a few centimeters per year, which indicates that the ocean floors should be completely renewed every 150–200 Ma. Satellite laser measurements verify plate motions (Christodoulidis et al., 1985) and results agree in magnitude and direction with those deduced from seafloor spreading reconstructions. Data indicate that Hawaii on the Pacific plate and locations on the North American plate are separating at about 1 cm/a, Hawaii and Australia are converging at a rate of 4.6 cm/a and Australia and North America are closing on each other at about 1.8 cm/a.

Continental Drift

Although continental drift was first suggested in the 17th century it did not receive serious scientific investigation until the beginning of the 20th century. Wegener (1912) is usually considered the first one to have formulated the theory precisely. In particular, he pointed out the close match of opposite coastlines of continents and the regional extent of the Permo-Carboniferous glaciation in the Southern Hemisphere. DuToit (1937) was the first to propose an accurate fit for the continents based on geological evidence. Continental drift, however, did not receive wide acceptance among geoscientists, and especially among Northern-Hemisphere geoscientists, until the last two decades. The chief reasons, aptly summarized by MacDonald

(1964), related to lack of an acceptable mechanism and to geophysical data that indicate that continents have roots in the mantle (Chapts. 3 and 4) and hence could not be moved at the Moho, as was commonly proposed. The breakthrough came in the early 1960s, when the seafloor spreading theory became widely accepted. Seafloor spreading offers a mechanism for continents to drift and yet retain their deep roots, by drifting at the base of the lithosphere, not at the Moho.

It is possible, using a variety of geological and geophysical data, to reconstruct the positions of continents prior to their last break-up about 200 Ma ago. Matching of continental borders, stratigraphic sections, and fossil assemblages are some of the earliest methods used to reconstruct continental positions. Today, in addition to these methods, we have polar wandering paths, seafloor spreading directions, and hotspot traces. The geometric matching of continental shorelines was one of the first methods used in reconstructing continental positions. Both Wegener (1912) and DuToit (1937) employed this method. Later studies have shown that matching of the continents at the edge of the continental shelf or continental slope results, as it should, in better fits than the matching of shorelines, which reflect chiefly the flooded geometry of continental margins. The use of computers in matching continental borders has resulted in more accurate and objective fits. As an example, figure 1.3 shows a computerized, least-square fit of continents on both sides of the Atlantic Ocean at 500 fathoms depth. Areas of overlap and gaps are minimal. Many areas of overlap can be explained by additions to the edges of the continents after their rupture. Examples are the Niger Delta and the carbonate reefs of the Bahama Bank and Blake Plateau. Similar computerized fits have been proposed for Australia, Antarctica, India, Madagascar, and Africa.

Similarities in age and stratigraphic sections on opposite continental margins is another feature used by early investigators to support continental drift. One of the most striking similarities is that of the late Paleozoic (Gondwana) sections on continents in the Southern Hemisphere. When continents in the Southern Hemisphere are considered in their predrift positions, late Precambrian–Paleozoic terranes define a continuous belt from eastern Australia through Antarctica into southern Africa and Argentina. A belt of Triassic and Jurassic basalts and diabases of similar composition, which extends from South Africa through Antarctica into Tasmania, and a clustering of Precambrian anorthosites in East Africa, Madagascar, and India also support the geometric fit of the continents in the Southern Hemisphere. Radiometric dating of Precambrian terranes bordering the Atlantic Ocean provides strong evidence for continental drift. The fit of South America to Africa suggested by the matching of crustal provinces and structural trends is very close to the 500-fathom computerized fit of these continents shown in figure 1.3. Most striking is the continuation of the late Precambrian provinces from west-central Africa into eastern South America. Also, the Archean provinces in western and central Africa continue into South America. Precambrian provinces around the North Atlantic are considerably more complex and appear to involve extensive reworking of older terranes.

The Expanding Earth Hypothesis

An alternate explanation for some of the evidence of continental drift is that the Earth has expanded, with new surface area created at ocean ridges (Carey, 1976).

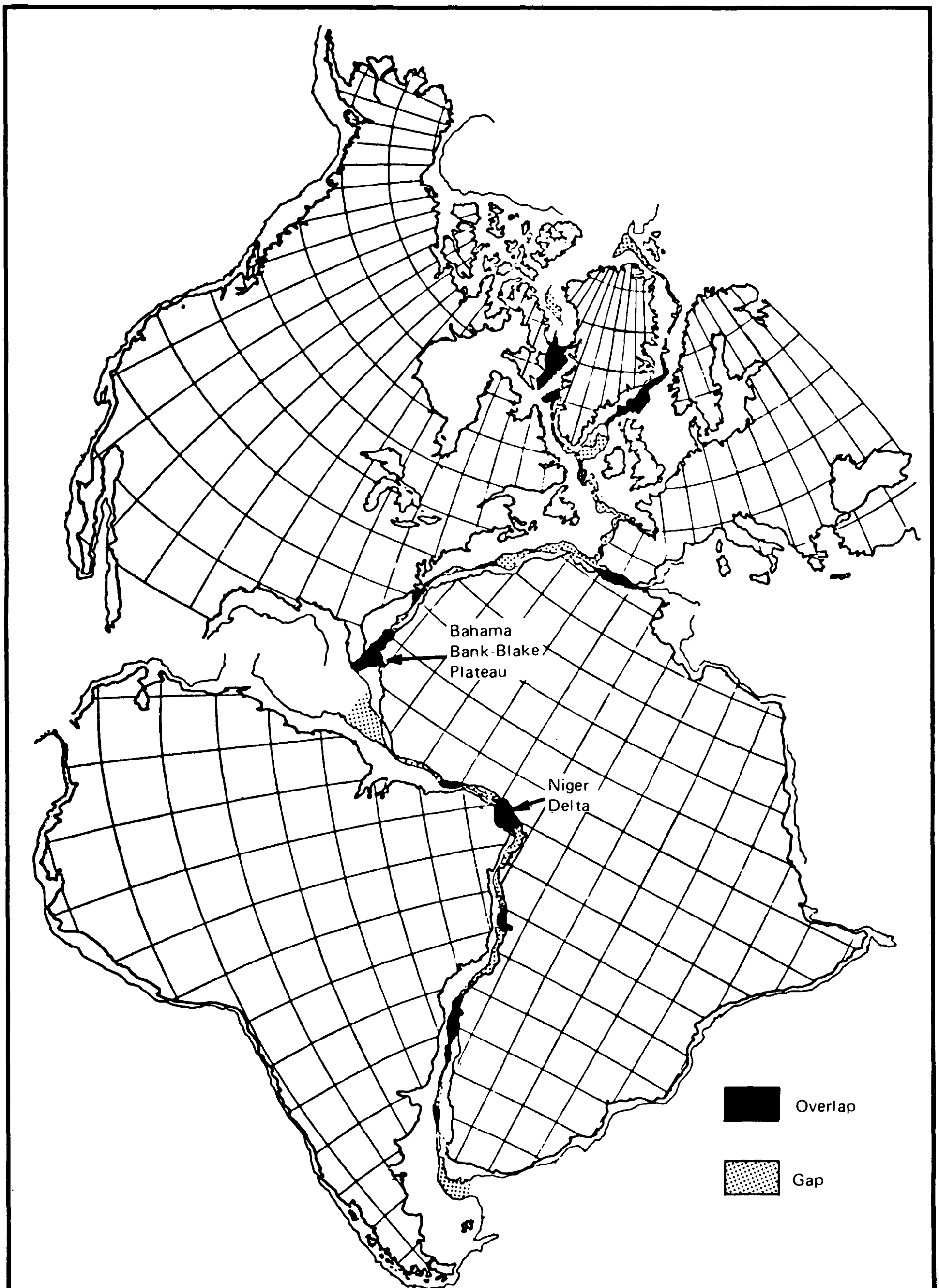

FIG 1.3 Computerized least-square fit at 500 fathoms of continents around the Atlantic Ocean. After Bullard et al. (1965). Used with permission of the Royal Society of London.

This hypothesis generally presumes that the area of the continents has remained constant and that ocean basins have grown as the Earth expands. An expanding Earth and seafloor spreading are not mutually exclusive processes, however, and the overwhelming evidence for seafloor spreading and continental drift seems to necessitate that, if the Earth expanded, these processes have gone on concurrently.

Evidences for an expanding Earth are either ambiguous or are based on tenuous and ad hoc assumptions. One of the earliest evidences cited is the idea that the continents have become progressively emergent with time, necessitating an increase in the Earth's radius of about 0.5 mm/a (Egyed, 1956). These results, based on data collected from paleogeographic maps, suggest that the percentage of the continents flooded by shallow seas has decreased with time. Some investigators have interpreted this to indicate that the Earth is expanding and causing seawater to move off the continents into growing ocean basins. However, several sources of inherent error render this interpretation uncertain. First, the continents are only 88% emergent today, and some seawater is tied up in polar ice caps. Also, determining the emergent area of continents by scaling data from paleogragraphic maps has many sources of error, including inadequate maps for most continents. Estimates of the areas covered by seawater as a function of time in North America indicate a rather constant relationship between average elevation of the continents and sea level since the Cambrian (Wise, 1973). It is also likely that the volume of ocean ridges, which has changed with time, is the most important factor in controlling flooding of the continents. Data are not sufficient to document progressive emergence (or submergence) of continents with time.

Carey (1958, 1976) has discussed a variety of geometric arguments for an expanding Earth. For instance, large gaps are left on some reconstructions of the Permian supercontinent Pangaea, which disappear on a globe of smaller radius. Such problems, however, may or may not be real, in that other investigators have managed to obtain acceptable reconstructions. Glikson (1980) has suggested that the lack of evidence for extensive oceanic crust in the Proterozoic can be explained by having an Earth with a smaller radius and Proterozoic supercontinents covering nearly the entire surface.

Major obstacles to an expanding Earth, however, seem to outnumber evidences in favor of expansion (McElhinny et al., 1978; Schmidt and Clark, 1980). New estimates of the radius of the Earth during the last 400 Ma from paleomagnetic results limit the amount of expansion over this time to $<0.8\%$. Also, crater distributions and ages on the lunar surface rule out any significant expansion of the Moon ($<0.06\%$) during the last 4 Ga, and a similar conclusion applies to Mars, Mercury and Venus. By analogy, the Earth would not be expected to have undergone significant expansion during the same time period. Biogeographic distributions of invertebrates during the early Paleozoic are also incompatible with an expanding Earth, in that they demand large expanses of oceanic crust between continental blocks. It also has not as yet been possible to find a satisfactory mechanism for planetary expansion. Results from the Moon seem to limit a decrease in the gravitational constant over the last 4 Ga to $<2\times10^{-10}\ a^{-1}$, which eliminates one of the more popular causes suggested for expansion. Considering all sources of data, it would appear that the Earth has not expanded more than 1% since its formation 4.6 Ga ago.