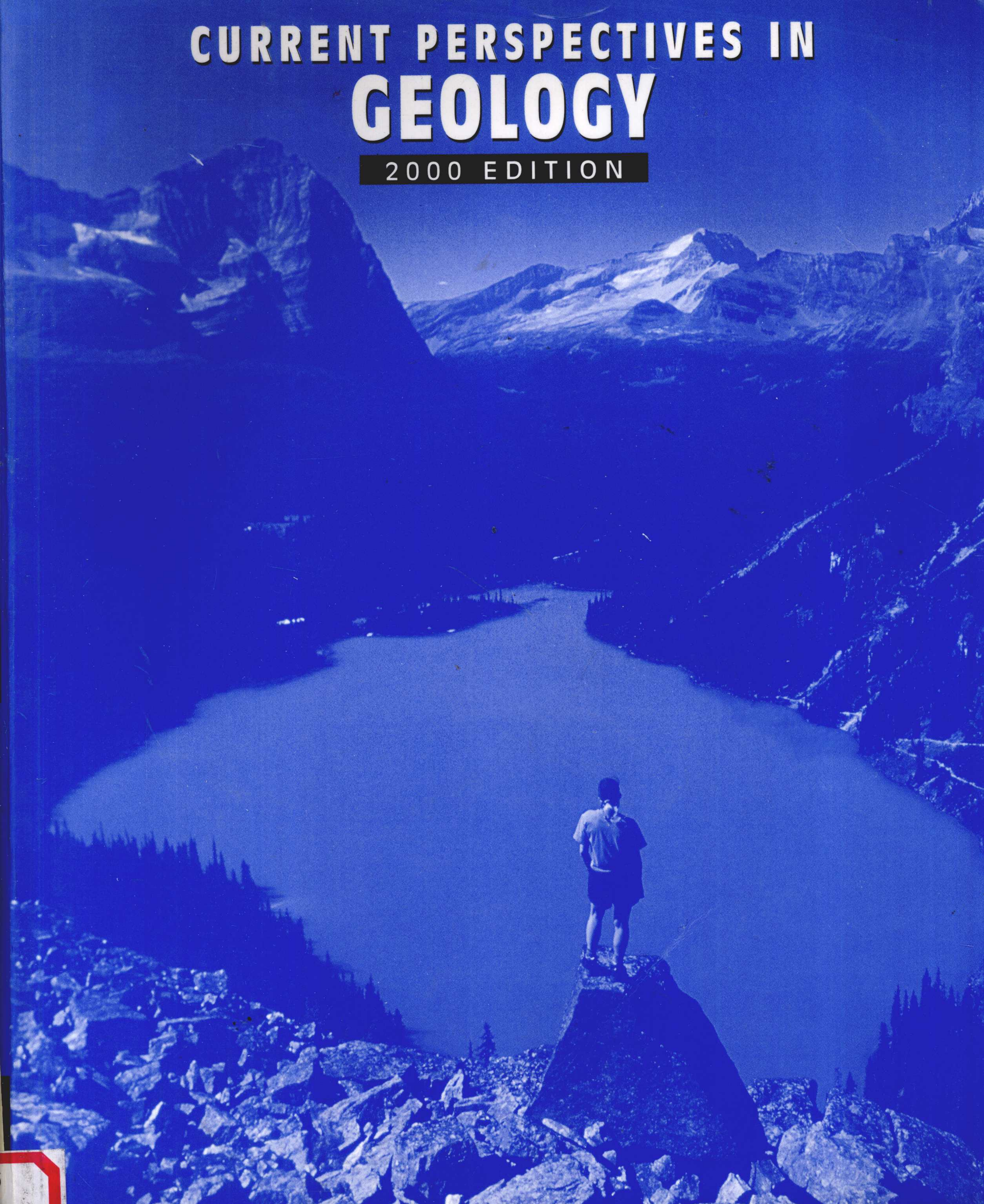
CURRENT PERSPECTIVES IN GEOLOGY

2000 EDITION



Michael L. McKinney • Kathleen M. McHugh • Susan P. Meadows

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Michael L. McKinney
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Preface

The Earth's geologic processes are nearly timeless, but the impact geology has on humans is very much a current issue. To represent the wide variety of topics upon which the study of geology touches human activity and inquiry, the editors of this anthology have collected articles from a number of general interest and science magazines.

The editors have carefully chosen articles to supplement material a student might encounter when taking a course in physical geology, historical geology, environmental geology, dinosaurs, and earth science. Often, there is an overlap of subject areas taught among these courses. For example, a considerable portion of an environmental geology course usually includes material on physical geology. To help readers identify these overlaps, the editors have divided the book into six parts. Parts one through three cover physical geology, parts four and five cover environmentally related topics, and the final part covers historical geology.

Each article opens with a brief overview and discussion of the issues or concerns generated by the topic. Following the articles, the editors then ask a few questions to help the readers focus on the issues and apply what they have learned from their geology classes.

Acknowledgments

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Contents

PART 1
The Origin of Earth and Its Internal Processes

1

Within the last decade and longer there have been significant strides in our understanding of the earth's interior. The controversy over mantle convection seems to be approaching a resolution. Estimates of the outer core temperature are better constrained, and our understanding of the role of the core in the earth's magnetic field has made many progressive strides. Hopefully, the near future will make just as many advances in our understanding of the earth's interior.

Dynamics of Earth's Interior

By Thorne Lay and Quentin Williams

The last 50 years have seen remarkable advances in our understanding of the thermal, chemical, and dynamical state of the Earth's deep interior. A host of observations and techniques, including analysis of many types of seismic waves, experimental determinations of equation of state and phase equilibria of Earth materials over almost the entire range of pressure and temperature conditions inside the planet inversions for the temporal history of the magnetic field, and numerical models of the geodynamic and mantle flow under realistic conditions, have enlightened us greatly about the deep reaches of our planet. While many mysteries remain, some of the most fundamental issues are on the verge of resolution.

In many ways, the late 1940s and early 1950s can be flagged as the start of the modern era in our understanding of the chemical and mineralogical properties of the mantle and core. While the gross layered structure of Earth was determined by seismology in the first few decades of this century, it was about 50 years ago that several fundamental tenets that have underpinned most subsequent studies of the properties of the mantle and core were definitively stated or demonstrated. These include the famous inference by Birch that high-pressure crystalline phase transitions likely generate the anomalous gradients in seismic velocity documented by Jeffreys between 400- and nearly 1000-kilometers depth; Bullen's assessment that the seismic velocity distribution in the lower mantle indicated that this largest region of the planet is homogeneous in chemistry and phase (except for the lowermost 200 kilometers); and a compelling case made from a combination of elastic data on iron, the seismic properties of the outer core, and compositional information on meteorites, that the core of the planet is iron-dominated, confirming a suggestion made by Dana and Wiechert in the late 19th century. The possibility of mantle convection was being promoted by Verhoogen (among others), but general acceptance of this idea had not yet occurred. The idea that permanent magnetization of the interior of the planet is required to generate Earth's dipolar field was in the process of being replaced by the magnetic field-generating magnetohydrodynamic models of fluid flow in the outer core, produced, for example, by Elsasser. Finally, the inner core of the planet (first recognized to exist in 1936) had been proposed to be solid and produced by a pressure-induced intersection of the geotherm with the melting curve of iron, although even the notion that this region is solid was unproven.

In spite of these first-order insights, profound uncertainties existed about the nature of deep Earth at the time that the American Geological Institute was founded. Many views of

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the composition of the upper mantle and the nature of the crust-mantle (Moho) discontinuity differed profoundly from those of today; the manner in which basalt was generated was unclear; the type of crystallographic transitions that might be present within the transition zone were a matter of complete speculation; and the available seismic observations were adequately explained by a laterally homogeneous, onion-like layered planet. Today, a richness of geophysical phenomena have been characterized that could not have been envisioned a half-century ago—from the plumbing systems delivering magma to mid-ocean ridges; to images of apparent mantle upwellings, and downwellings, including global maps of deflections of seismic discontinuities from which lateral temperature variations can be inferred, to continent-sized partially molten features at the base of the mantle; through to anisotropic structure and super-rotation of the inner core.

Upper Mantle

With respect to the upper mantle, the idea that a glassy or magmatic basaltic substratum of ten to hundreds of kilometers of thickness was present at sub-crustal depth had largely run its course by the early 1940s. However, eclogite was frequently invoked as the dominant upper mantle rock, due to its chemical similarity with basalt and general compatibility with the seismic signature of the upper mantle. Given an Earth of meteoric composition, such a calcium and aluminum-enriched upper layer was anticipated to shift to a region dominated by magnesium silicates at depth. Birch, in his classic 1952 paper, actually excluded peridotite from being the dominant upper-mantle rock type based on its elasticity: This likely resulted from a lack of appreciation of the shifting phase assemblages from plagioclase-to garnet-peridotite at pressures below 2.5 GPa (depths shallower than 80 kilometers).

At present, a combination of detailed studies of basalt petrogenesis (spearheaded by Ringwood and co-workers), improved elastic data on minerals, and seismic velocity profiles (particularly of the oceanic crust and mantle) have resulted in a general consensus that the upper mantle is predominantly of peridotitic chemistry. This first-order revision of upper-mantle composition avoids the large degree of mantle melting necessary to generate basalt from eclogite, and limits the fraction of melting needed to generate basalt to ~20 percent and the usual depth of melt initiation to ~100 kilometers. Furthermore, the melting behavior of peridotite provides a natural mechanism for the genesis of harzburgite as the residue of basaltic melt extraction. Also, the appreciation of the importance of peridotite in the upper mantle has removed the gabbro-eclogite transition as a viable explanation for most observations of the Moho discontinuity—a popular interpretation of the late 1950s and '60s. Nevertheless, the gross similarity of the elastic properties of eclogite to the upper mantle continues to produce some ambiguity in the present-day interpretation of mantle structure: It remains difficult to completely preclude eclogite-regions from being at depth within the mantle of the planet.

Deep Earth

Concepts about deeper regions of the planet have undergone even more profound revisions in the last half-century. In the 1940s, the transition zone of the planet was defined as a region of anomalous seismic velocity gradient between 400- and 1000-kilometers depth—a zone where the change in velocity with depth could not be explained by the effects of self-compression alone. The reasons for this shift were unclear, with the possibilities existing that a change in chemistry might occur or that phase transitions could shift the elasticity and density in this region. In 1936, the chemist J.D. Bernal had made the insightful proposal that olivine might convert to a denser spinel structure at high pressures; Birch followed in 1952 with the suggestions (acknowledged as from J.B. Thompson) that $MgSiO_3$-pyroxene might adopt the corundum (Al_2O_3) structure and SiO_2 might adopt the rutile (TiO_2) structure at high pressures. Remarkably, each of these ideas would ultimately prove to be correct (although the cation-ordered version of the corundum structure, $MgSiO_3$-ilmenite, has a rather small stability field relative to that of the perovskite-structured polymorph). Determining the phase equilibria of magnesium silicates at transition-zone conditions, however, required extensive developments in high-pressure technology.

Experimental capabilities in 1948 encompassed only crustal-level conditions, but today the full pressure range and most of the temperature range of deep Earth conditions can be stably achieved in laboratory experiments, with detailed structure and properties of the sample being characterized by X-ray diffraction and spectroscopic methods. In doing so, a sound physical and thermochemical basis has been provided for both the detailed seismic structure of the transition zone and the lack of structure in the bulk of the lower mantle: Essentially no phase transitions have been observed in mantle constituents at depths greater than ~900 kilometers. The synthesis of the high-pressure phases relevant to the transition zone was accomplished in the 1960s and 1970s, with high-pressure phase equilibria results continuing to the present day.

The high-pressure experimental results have advanced in tandem with improved seismic characterization of the transition zone. The refinement of the seismic structure of the transition zone into discrete seismic discontinuities at 410- and 670-kilometers depth (beginning with work in the 1960s) was readily placed into a mineralogical context—the former is associated with the transition from olivine to ß-phase (a phase with structural similarities to spinel), and the latter with a transition from (Mg, Fe)$_2$SiO$_4$-spinel to (Mg, Fe)O-magnesiowüstite and (Mg, Fe)SiO$_3$-perovskite. The depth of the former of these transitions provides, in conjunction with the pressure-temperature slope of the olivine to ß-phase transition, a key reference point for the temperature within the transition zone. Accordingly, the view of the transition zone of the planet has progressed from a featureless, high gradient zone of seismic velocities with poorly constrained mineralogy, temperature, and chem-istry to a zone whose complex mineralogy is well-understood, with the absolute temperature having fixed points, and for which there are only modest uncertainties in the bulk chemistry.

In turn, the recognition of plate tectonics coupled with improved observational and experimental constraints on the rheologic properties of mantle materials has moved mantle convection from the realm of speculation to one of the truly fundamental concepts in our understanding of deep Earth. Today, ideas about possible episodic material exchange between the upper and lower mantle of the planet, the genesis of plume-like upwellings, and the ultimate fate of subducted slabs each hinge on the critical recognition that Earth's mantle is an actively convecting dynamic system. The advent of seismic tomography in the 1980s profoundly impacted our understanding of mantle convection, as this procedure for imaging three-dimensional variations in seismic velocities revealed for the first time the deep structure underlying surficial plates. Today, the global resolution of lateral variations of upper-mantle velocity (controlled primarily by thermal variations but also by chemical variations) is approaching 500-kilometer-scale lengths, with 50-kilometer resolution in regions of dense seismic instrumentation. Patterns of high and low seismic velocity have been revealed throughout the mantle, with the strongest variations found in the upper 300 kilometers. Unexpected features, such as deep roots of high-velocity material extending 300-400 kilometers below cratons, have radically modified initial notions about plate tectonics and continental formation. Deep-seated upwellings under ocean ridges and beneath major volcanic hot spots are indicated by low-velocity regions and by deflections of transition zone discontinuities. Subducting lithosphere, illuminated only by deep seismicity in 1948, is now imaged as high-velocity tabular downwellings extending throughout the upper mantle, with possible aseismic extensions to depths of at least 2,000 kilometers. Numerical models of mantle flow that utilize the seismic images to constrain the distribution of buoyancy sources have accounted for long-standing mysteries about the shape of Earth's geoid, and detailed models of the entire mantle viscosity structure are beginning to converge. The unexpected observation that mantle heterogeneity is dominated by very large-scale structures has ironically provided support for some of the earliest conceptual models of a mantle convection system dominated by large patterns. Geochemical evidence for distinct reservoirs in the mantle persists, emphasizing the importance of plume flows from internal boundary layers as distinct from large-scale flows associated with oceanic plates. While the debate over whether the mantle has a layered convective system or not continues, a consensus seems to have emerged of significant material transport across the upper mantle-lower mantle boundary.

Core-Mantle Boundary

Since the 1940s, ideas about the structure above the core-mantle boundary (CMB) have perhaps evolved more than those about any region of the planet. The view of this zone has shifted from an area characterized by a minor flattening of velocity gradients in Jeffreys' models (in 1949, Bullen inferred the presence of chemical heterogeneity of the lowermost 200 kilometers of the mantle based on this feature) to a zone recognized today to contain two laterally variable seismic discontinuities, at 5–50 kilometers and 130–400 kilometers above the CMB, with regions of anisotropic properties that appear to indicate the presence of texturing of material through lateral flow. The continually improving seismic images of the structure near the CMB indicate that it is an area in which the complexity of physical and dynamic processes rival those present in the lithosphere and shallow asthenosphere. Among the most basic of paradigms about Earth's deep mantle is that it is solid—a conclusion that appears not to hold for the absolute basal layer of Earth's mantle, where mantle and core meet. The recent discovery of a 5- to 50-kilometer-thick layer of dramatically depressed seismic velocities just above the core-mantle boundary is most readily explained by the presence of abundant partial melt at this depth—a wholly unanticipated result with profound rheologic implications for the lowermost mantle. Many of the seismologically characterized structural features near the CMB are still not well understood from mineralogic/petrologic or planetary evolution perspectives, but the simple demonstration of their existence has inspired a wide range of ongoing theoretical and experimental efforts to discern the properties of this enigmatic region of the planet—avenues of research that could not have been even dimly foreseen in the 1940s.

Core

The core has long been viewed as a compositionally simpler system than the mantle (as Birch put, it, "predominantly iron"), but there is now certainty that a lighter component or components are alloyed with iron in the outer core at the ~10-weight-percent level. Furthermore, our estimate of the temperature of the outer core is now better constrained than ever before, based on high-pressure experiments, with the present minimum estimate of the temperature at the top of the outer core to be 4000°K, and the likelihood that it is significantly hotter—a result far better constrained than Verhoogen's 1953 range of 1500–6000°C for the base of the mantle or Gutenberg's 1951 estimate that the center of the planet was "probably closer to 2000°C than 5000°C." The elastic properties of high-pressure iron have been utilized to understand the observation that the inner core is anisotropic (seismic waves travel faster along the axis of rotation of the inner core than they do through its equator). As with the mantle, it appears that this lowermost region of the planet must be convecting and this results in sheared orientation of crystals—a realization not hinted at until the last decade.

Finally, the understanding of Earth's magnetic field has mushroomed over the last 50 years, with present-day numerical models of the magneto-hydrodynamics of the core system showing it is actually able to generate predominantly dipolar magnetic fields that undergo spontaneous reversals. The models bear many similarities to actual observations. Both the pivotal role of the solid inner core in modulating the fluid flow pattern of the outer core (and thus the character of the magnetic field) and the large-scale, complex turbulence of outer-core fluid flow are now routinely recognized features of deep Earth dynamics. The magnetic field has thus progressed from a feature whose genesis was only dimly understood to a first-order signature of the pattern of fluid flow within the core. It is fun to contemplate what comparable advances the next 50 years will bring.

Questions:

1. What two things brought mantle convection from just speculation to an actual fundamental concept?
2. At what depth in the lower mantle are there no phase transitions?
3. What is the new understanding of earth's magnetic field?

Answers are at the back of the book.

Activity:

Go to **http: //pubs.usgs.gov/publications/text/unanswered.html**
Read only "What drives the plates?" Write a page summary.

2

Plate tectonics, discovered in the 1960s, changed the view of earth from a static entity to a dynamic planet. It also offered answers to many of geology's questions. In addition, the theory allowed for mantle plumes and hot spots which are responsible for the creation of the Hawaiian Island chain. These two discoveries, together, may explain the Laramide Orogeny, or the Rocky Mountains. The Laramide Orogeny has proven to be an enigma to many earth scientists due to its locality being far inland and its lack of volcanic activity.

Mantle Plumes and Mountains

By J. Brendan Murphy, Gary L. Oppliger, George H. Brimhall, Jr., and Andrew Hynes

Traveling west on Sixth Avenue from downtown Denver, the Front Range of the Colorado Rockies looms 2,500 meters, above the mile-high city. Yet as magnificent as the panorama may be, it fails to do justice to the Laramide Orogeny, the process that started the Rocky Mountains' growth some 75 million years ago. Geologists estimate that the total uplift of the Front Range exceeded 7,000 meters. What drove the western half of Colorado to fracture and pile up to a height seven kilometers greater than that to the east? Earth scientists have long labored for a convincing explanation.

The theory of plate tectonics has offered clues. In a brief 30 years, it has revolutionized our understanding of mountain building. According to this theory, the outermost layer of the earth, the *lithosphere*, is composed of a mosaic of rigid plates that ride on a hot, pliable layer of the earth's mantle, the *asthenosphere*. As a consequence of circulation in the mantle, plates move with respect to each other at rates of a few centimeters per year. Over geologic time, this motion can account for the creation and destruction of oceans, the generation of mountain belts and sedimentary basins, the distribution of volcanic and earthquake activity, and the locations of ore, oil and gas deposits. Yet plate-tectonic theory has a tough time with the details of the Laramide Orogeny.

The conventional explanations of mountain building according to plate-tectonic theory all include horizontal plate motions and directly or indirectly depend on subduction zones, areas where oceanic crust descends back into the asthenosphere. Yet the Rocky Mountains lie 2,000 kilometers to the east of the current coastal margin, many times farther from an active subduction zone than mountain building generally takes place.

We propose that an additional mechanism of mountain building has been largely overlooked and may help explain not only the Laramide Orogeny but also other unusual geological features of the southwestern U.S. Our model involves the interplay of the horizontal motions of traditional subduction-related mountain building processes with vertical plumes of anomalously hot mantle ascending from thousands of kilometers below the earth's surface. Together these mechanisms may offer a convincing explanation for what long has been a geologically puzzling part of the world and may lead to better understanding of mountain building worldwide.

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Horizontal Forces

In plate tectonics, as plates move apart, magma ascends from the asthenosphere, cools and solidifies to generate new lithosphere between the plates. This ongoing activity drives wedges of new lithosphere between the plates, separating them and generating a widening ocean. According to the theory, all oceans form in this way. The northern Atlantic Ocean, for example, has formed and progressively widened over the past 120 million years as the European and North American plates move apart. On a globe of constant radius, however, the divergence of plates and the construction of new lithosphere in some places must be compensated by convergence and destruction of lithosphere in others.

This is neatly accommodated by the recycling of oceanic crust in subduction zones. As it descends, the slab of lithosphere progressively heats up in the warmer ambient temperature of its surroundings. This eventually causes melting in the vicinity of the slab and in the overlying plate. These melts exploit weaknesses (such as fractures) in the overlying plate and ascend to the surface to produce volcanoes. In this way subduction leads directly to mountain building. The Andes are a modern example of mountains formed by such a process, and many of their highest peaks are either volcanically active now or have been in the recent past.

A second form of orogenic activity involves *microcontinents*, small islands or island chains located on oceanic crust. All modern oceans contain these islands; the Hawaiian chain is an example. Ultimately, when the tract of oceanic crust that separates these microcontinents from the continental margin becomes consumed by subduction, they will be swept to the margin and will collide with it. The impact results in deformation of rocks and igneous activity, which combine to form mountains. The coastal mountains of western North America formed in this way. Repeated collisions with many of these small landmasses over the past 400 million years has caused the North American Plate to grow westward by an average of 500 kilometers, extending from Baja California to Alaska.

In some instances subduction and convergence consume an entire ocean, and two continental land masses collide building mountains. Over the past 40 million years an ancient ocean called the Tethys was consumed by the collision of India with southern Asia and of northern Africa with southern Europe. The Himalayas and the Alps were pushed up in the Tethys's place.

None of these processes lends itself readily to an explanation of the Laramide Orogeny. Since the Laramide had no volcanic activity, conventional models of subduction do not apply. Likewise, it is clear that continents did not collide to form the Rockies. Furthermore, although collisions with microcontinents occurred during the time of the orogeny, these collisions were 1,200 kilometers away, at the very least, making this an unlikely explanation.

Geologists have been forced to invoke an unusual sort of subduction zone to explain the Laramide Orogeny, one that had an extensive subhorizontal zone, rather than the more typical angled one. This zone must have extended at least 1,200 kilometers into the continental interior, and the oceanic crust must have been anomalously shallow in order to avoid melting and the generation of magma. Although this mechanism is widely accepted, the reasons why such a subduction zone should exist have been elusive. We may be able to fill in some of those details.

Plumes and Hot Spots

More than 30 years ago, Tuzo Wilson of the University of Toronto proposed mantle *plumes* to explain the formation of island chains. He suggested that Hawaii and several other volcanically active Pacific islands sit atop narrow columns, or plumes, of unusually hot rock and magma that ascend from deep within the earth. The interaction of plumes with the earth's rigid outer crust causes broad bulges or swells, and the melting induced by plumes provides the raw material for some of the world's most famous volcanoes. Volcanic centers above these plumes are known as *hot spots*.

In the example of the Hawaiian chain, the only active volcanoes are on Hawaii and the seamount Loihi, which is to the southeast of Hawaii and working its way toward the surface. Wilson noted that the islands are progressively older, less elevated and more eroded to the northwest along the length of the chain, and he interpreted this progression to be related to the westward motion of the Pacific Plate above "a jetstream of lava." Each volcano was born in the present position of Hawaii directly above the plume. But as the plate moved northwestward, each was cut off from its supply of magma below. As each volcano cooled and aged, it subsided and became progressively more eroded.

Implicit in this analysis is the fact that hot spots are relatively stationary and certainly move more slowly than the plates above them. Building on this idea, Jason Morgan of Princeton University proposed that three parallel island chains in the Pacific Ocean could have been formed by the motion of the Pacific Plate over three different hot spots.

Many investigators also think that the ascent of plumes is intimately associated with the breakup and dispersal of continents to form new oceans. Indeed, hotspot activity may have been an integral part of the breakup and dispersal of the supercontinent Pangea and the formation of the Atlantic Ocean. Don Anderson at the California Institute of Technology thinks that hot spots originate beneath large supercontinental land masses because continental crust conducts heat poorly compared with oceanic crust. By acting as an insulator, blocking the escape of heat from the mantle below, the supercontinent forces temperatures beneath it to rise, causing it to dome upward and eventually crack. Molten lava from the underlying asthenosphere rapidly ascends to fill the cracks, thereby driving the fragmented pieces of the former supercontinent farther and farther apart.

Nonetheless, hot spots are definitely not restricted to the locations of plate boundaries. The active Hawaiian volcanoes sit in the middle of the Pacific Plate at present, and mid-oceanic plate hot spots dot the globe. Thus their direct relationship to plate tectonics is unclear. Most earth scientists do accept that hot spots are the surface expression of hot columns of magma rising from a depth below the realm of plate tectonics, but just how deeply they originate is less certain. Recent evidence, however, suggests that these hot spots represent upwelling from near the core-mantle boundary, about 2,900 kilometers below the earth's surface. (See *American Scientist*, March-April 1995, pp. 134-147.) Thus plumes may be a phenomenon superimposed on plate motion rather than being a consequence of it.

The tell-tale signs of the origin and ascent of such features were recently revealed by seismic tomography, a procedure analogous to computer-aided tomographic (CAT) scanning of the human body by criss-crossing waves from an X-ray generator. This technique, which combines information from a number of seismic waves emanating from earthquake zones that penetrate deep into the earth, allows the construction of a three-dimensional image of much of the inner earth.

Seismic tomography, combined with laboratory and theoretical models, provides insights into the geometry of 9 plumes. An established plume has a relatively narrow central conduit in which hot mantle ascends, but it widens dramatically where it contacts the base of the lithosphere. Evidence from Hawaii and from the Yellowstone Caldera, which also resides above a plume, indicates that the plume's products are ponded at the base of the lithosphere and can "underplate" an area about 1,000 kilometers in diameter. This results in swelling and dynamic uplift of the lithosphere that is sustained as long as the plume remains active. Many of these regions are uplifted by as much as three kilometers above this hot, relatively buoyant material. Volcanic islands such as Hawaii rise more than another six kilometers above the dynamically domed sea floor, making them some of the highest mountains on earth.

Hot Spots and Mountain Building

As a plate moves over a hot spot, the crustal swell is dragged in the direction of plate motion into an eccentric elliptical shape up to nearly 2,000 kilometers in length. Hot spots and their associated crustal swells must inevitably interact with continental margins. More than 40 hot spots lie beneath the modern oceanic crust, and no modern ocean could be consumed without at least some hot spots being overridden by continental crust. In accordance with a basic principle of geology known as *uniformitarianism*, which states that modern processes are typical of those that have occurred throughout much of geological history, no ancient ocean could have been consumed without overriding ancient hot spots. Furthermore, the overriding of hot spots by continental margins must be a common phenomenon.

We think that the overriding of a hot spot and its large, buoyant, elongate swell by a convergent plate margin would dramatically affect the geometry of the subduction process and therefore would profoundly influence the style of mountain-building activity at continental margins.

A Modern Example

The geological evolution of the southwestern U.S. may offer such an example. From about 400 million to 75 million years ago this region experienced relatively normal mountain-building periods, including the Sonoma, Nevada and Sevier orogenies. Then, about 75 million years ago, a cycle of unusual tectonic processes began that continues to the present; we attribute these processes to the overriding of the Yellowstone hot spot by the North American Plate. Further, we conclude that the early manifestations of this event resulted in the Laramide episode of mountain building.

Before going into details, we must briefly review the geological history of western North America over the past 400 million years. During most of this time, mountain belts formed as the result of subduction and the episodic collision of microcontinents. Igneous rocks from that time have similar compositions to those in modern subduction-zone regions, and the style and distribution of rock deformation is also typical of such settings. As oceanic crust was consumed by the subduction zone, microcontinents collided with the margin. Specific collisions produced important and discrete episodes of mountain building known as the Antler (about 400-330 million years ago), the Sonoma (260-210 million years ago) and the Sevier (120-70 million years ago) orogenies. In addition, from about 100 million to 75 million years ago, ongoing subduction resulted in the emplacement of large granitic bodies that make up the backbone of the Sierra Nevada.

The breakup of Pangea, which began 180 million to 150 million years ago, probably accelerated these processes. Since that time, the North American Plate has drifted westward as the Atlantic Ocean formed and has progressively widened. Thus the western margin of the North American continent now lies at a location formerly occupied by oceanic crust of a wider Pacific Ocean.

About 75 million years ago, an unusual succession of tectonic events began. Between about 75 million and 40 million years ago, there was widespread deformation as vast portions of the continental crust were tectonically sliced and heaved on top of one another in the Laramide Orogeny, forming the early Rocky Mountains. The extent of this deformation (nearly 2,000 kilometers from the continental margin) is many times greater than the normal distribution of this type of deformation. During the same time, the region saw an almost complete lack of volcanic activity, a highly unusual situation for a typical subduction zone.

Both of these unusual features have been attributed to the presence of a subhorizontal subduction zone, rather than the more typical steeply angled zone that would have extended at least 1,200 kilometers into the continental interior. The deformation is associated with the interaction of this slab of oceanic crust with the overlying continental lithosphere. Because of the horizontal motion, the oceanic slab remained anomalously shallow and did not warm enough to generate magma. Although this scenario fits the available geological data, determining what would produce such a subduction geometry has proved difficult.

Equally enigmatic is the fact that after about 32 million years of quiescence, voluminous magma generation and associated volcanic activity began about 43 million years ago in northern Nevada and surrounding areas. This event may have had an important impact on modern economic development of the region. Many geologists think that this activity was directly responsible for gold mineralization in the area. Known as Carlin-type deposits (for their location near Carlin, Nevada), they qualify as one of the world's most productive districts, having yielded 50 million ounces of gold ($18 billion at $365 per ounce) since their discovery in 1962. Another 150 million ounces may be accessible over the next 20 years.

Magmatic activity continued in the region until about 6 million years ago. Yet despite the fact that the western margin of North America was still converging with the Pacific Plate, geologists working the vicinity of this magmatism have found convincing evidence that the area was extending dramatically at the time. In the early 1970s, John Proffett, then a graduate student at the University of California at Berkeley, estimated that the crust in the area may have been extended by more than 100 percent, to at least twice its original width. This estimate has been supported by the more recent work of Brian Wernicke at Caltech and his colleagues. One manifestation of this extension is the dramatic block faulting of the Basin and Range