New Theory of the Earth

New Theory of the Earth is an interdisciplinary advanced textbook on all aspects of the interior of the Earth and its origin, composition, and evolution: geophysics, geochemistry, dynamics, convection, mineralogy, volcanism, energetics and thermal history. This is the only book on the whole landscape of deep Earth processes that ties together all the strands of the subdisciplines.

This book is a complete update of Anderson's *Theory of the Earth* (1989). It includes dozens of new figures and tables. A novel referencing system using Googlets is introduced that allows immediate access to supplementary material via the internet. There are new sections on tomography, self-organization, and new approaches to plate tectonics. The paradigm/paradox approach to developing new theories is developed, and controversies and contradictions have been brought more center-stage.

As with the *Theory of the Earth*, this new edition will prove to be a stimulating textbook for advanced courses in geophysics, geochemistry, and planetary science, and a supplementary textbook on a wide range of other advanced Earth science courses. It will also be an essential reference and resource for all researchers in the solid Earth sciences.

Don L. Anderson is Professor (Emeritus) of Geophysics in the Division of Geological and Planetary Sciences at the California Institute of Technology (Caltech). He received his B.S. and D.Sc. (Hon) in Geophysics from Rensselaer Polytechnic Institute (RPI), his M.S. and Ph.D. in Mathematics and Geophysics from Caltech, and Doctors Honoris Causa from the Sorbonne, University of Paris. He was Director of the Seismological Laboratory of the California Institute of Technology from 1967–1989. He is a Fellow of the American Academy of Arts and Sciences, the National Academy of Sciences and the American Philosophical Society. He received the Emil Wiechert Medal of the German Geophysical Society, the Arthur L. Day Gold Medal of the Geological Society of America, the Gold Medal of the Royal Astronomical Society, the Bowie Medal of the American Geophysical Union, the Crafoord Prize of the Royal Swedish Academy of Science and the National Medal of Science. He was installed in the RPI Hall of Fame in 2005. He is a Past President of the American Geophysical Union. Professor Anderson's research centers on the origin, evolution, structure and composition of Earth and other planets, and integrates seismological, solid state physics, geochemical and petrological data. He is also interested in the philosophy and logic of science.

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From reviews of the previous edition, *Theory of the Earth*:

". . . *Theory of the Earth* is one of the most important books of the decade . . . Anderson is one of a very small group of scientists who have managed to achieve success in both fields [geophysics and geochemistry], providing a dual experience that makes his book an invaluable survey. *Theory of the Earth*, then, is in part an extensive summary of our current state of knowledge of the Earth's interior, . . . drawing on a wide variety of scientific disciplines including not only geophysics and geochemistry but solid-state physics, astronomy, crystallography and thermodynamics. . . . Both as survey and synthesis, Anderson's text, the first in its field, will be of great benefit to students around the world."

Peter J. Smith, *Department of Earth Sciences, Open University*

"Anderson can be congratulated for producing a document that will be a standard taking-off point for many a future graduate seminar."

William S. Fyfe, *Department of Earth Sciences, University of Western Ontario*

".. . much to the envy of the rest of us, there are a few people within the Earth-science community who are, well fairly superhuman. Don Anderson is one of them – as close to being the complete geophysicist/geochemist as anyone is ever likely to be. *Theory of the Earth*, then, is an extensive summary of practically everything 'known' about the physics, chemistry and physicochemical evolution of the Earth's interior. . . . Anderson has produced a remarkable synthesis of our present understanding of the Earth's interior."

Nature

"The appearance of this book is a major event in geoscience literature. It is a comprehensive statement on the Physics and Chemistry of the Earth by one of the great authorities of our time. It will occupy a prominent place on our bookshelves for the rest of our professional lives. When we get into an argument with colleagues or face a fundamental problem that we are unsure about we will reach for it: "Let's see what Anderson says about that". . . . a very valuable book."

Frank Stacey, author of *Physics of the Earth*

".. . as in all good scientific books, there is strong concentration on themes with which Anderson has been closely identified over a number of years. . . . The scope of the book is most impressive: it will be a constantly useful as a source of information that is otherwise extremely time-consuming to track down."

Joe Cann, *Times Higher Education Supplement*

Pre-publication praise of *New Theory of the Earth*

"Anderson's masterful synthesis in *New Theory of the Earth* builds upon his classic 1989 text, weaving an extraordinary breadth of new perspectives and insights into a cogent, provocative and nuanced vision of our planet's history and inner workings. This is a must-read for all scientists seeking to understand the Earth."

Thorne Lay, *Professor of Earth and Planetary Sciences, University of California, Santa Cruz*

"*New Theory of the Earth* can be highly recommended for the book shelf of any serious student of geodynamics. The book contains a wealth of data on a wide variety of subjects in petrology, geochemistry, and geophysics. It is well written and reads smoothly. . . . Many challenging and stimulating views are presented."

Donald L. Turcotte, *Distinguished Professor, Department of Geology, University of California at Davis*

"Don Anderson is the only Earth scientist with the breadth of knowledge and insight necessary to write this book – a fascinating combination of basic data, explanation of concepts, speculation, and philosophy. Now, almost half a century after the realization of plate tectonics, there are rumblings of dissatisfaction over long-held concepts of plumes and mantle convection that are thought to drive plate tectonics, and Don Anderson is leading the charge. This makes *New Theory of the Earth* an especially provocative and exciting reference for all of us scrambling to understand how the Earth works."

Dean C. Presnall, *Department of Geosciences, University of Texas at Dallas and Geophysical Laboratory, Carnegie Institute of Washington*

"This remarkable book by a master geophysicist should be studied by everyone, from junior graduate student to senior researcher, interested in geodynamics, tectonics, petrology, and geochemistry. Here are all the factors omitted from widely accepted models, to their detriment: truly multidisciplinary physics, geophysics, mineral physics, phase petrology, statistics, and much, much more."

Warren B. Hamilton, *Distinguished Senior Scientist, Department of Geophysics, Colorado School Mines*

"An old adage says that there are no true students of the earth because we dig our small holes and sit in them. This book is a striking counter example that synthesizes a broad range of topics dealing with the planet's structure, evolution, and dynamics. Even readers who disagree with some of the arguments will find them insightful and stimulating."

Seth Stein, *William Deering Professor of Geological Sciences, Northwestern University*

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It was a long time before man came to understand that any true theory of the earth must rest upon evidence furnished by the globe itself and that no such theory could properly be framed until a large body of evidence had been gathered together.

Sir Archibald Geike, 1905

We now know that science cannot grow out of empiricism alone, that in the constructions of science we need to use free invention which only a posteriori can be confronted with experience as to its usefulness . . . the more primitive the status of science is, the more readily can the scientist live under the illusion that he is a pure empiricist.

Albert Einstein

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Preface and Philosophy

A mind is a fire to be kindled, not a vessel to be filled.

Plutarch

Go not where the path leads; go where there is no path and leave a trail.

Ralph Waldo Emerson

Science progresses by interchanging the roles of prejudice, paradox and paradigm. Yesterday's prejudice leads to today's paradox and tomorrow's 'truth.' An accumulation of paradoxes, enigmas and coincidences means that it is time to step back and start anew. Plate tectonics, mantle convection, isotope geochemistry and seismic tomography are now mature sciences, but they share an uncomfortable coexistence. They are all part of what may be described as the not-yet-unified standard model of mantle dynamics. Evidence for this disunification is the number of times that the words *paradox, enigma, surprise, unexpected, counter-intuitive* and *inconsistent* appear in the current literature of mantle geochemistry and tomography, and the number of meetings dedicated to solving 'long standing paradoxes' between geophysics and geochemistry. In the jargon of the day, present models of geodynamics are not *robust*.

The maturing of the Earth sciences has led to a fragmentation into subdisciplines that speak imperfectly to one another. Some of these subdisciplines are field geology, petrology, mineralogy, geochemistry, geodesy and seismology, and these in turn are split into even finer units. The science has also expanded to include the planets and even the cosmos. The practitioners in each of these fields tend to view Earth in completely different ways. Discoveries in one field diffuse only slowly into the consciousness of a specialist in another. In spite of the fact that there is only one Earth, there are more Theories of the Earth than there are of astronomy, particle physics or cell biology where there are uncountable samples of each object. Even where there is cross-talk among disciplines, it is usually in code and mixed with white noise. Too often, one discipline's unproven assumptions or dogmas are treated as firm boundary conditions for a theoretician in a slightly overlapping area. The data of each subdiscipline are usually consistent with a range of hypotheses. More often, the data are completely consistent with none of the standard models. The possibilities can be narrowed considerably as more and more diverse data and ways of thinking are brought to bear on a particular problem. The questions of origin, composition and evolution of the Earth require input from astronomy, cosmochemistry, meteoritics, planetology, geology, petrology, mineralogy, crystallography, fluid dynamics, materials science and seismology, at a minimum. To a student of the Earth, these are artificial divisions, however necessary they are to make progress on a given front. New ways of looking at things, new sciences, keep things lively. Advances in materials science, statistics, chaos theory, far-from-equilibrium thermodynamics, geochemistry and tomography make this an appropriate time to update our theory of the Earth.

The timing is also appropriate in that there is a widespread feeling of crisis and frustration amongst workers in mantle dynamics and geochemistry.

The paradigm of layered mantle convection was established nearly 20 years ago, mostly based on geochemical mass balance and heat budget arguments. It is now stumbling over the difficulty imposed by convection models to maintain a sharp interface in the mantle at mid-depth and by overwhelming tomographic evidence that at least some of the subducting lithospheric plates are currently reaching the core-mantle boundary. The present situation, however, remains frustrating because the reasons why the layered convection model was defended in the first place are still there and do not find a proper answer with the model of homogeneous mantle convection.

(www.theconference.com/JConfAbs/6/Albarede.html)

Recent discoveries in a variety of fields are converging on a simple model of geodynamics and geochemistry that is inconsistent with current widely held views. These developments include noble-gas measurements, mantle tomography, convection simulations, statistics, quantum-mechanical equations of state, age dating, paleomagnetism, petrology and techniques to infer temperatures and small-scale heterogeneity of the mantle. Recognition that density variations as small as 1%, which are unavoidable in the accretion and differentiation of the Earth, can irreversibly stratify the mantle is one such development.

Multidisciplinarity is more essential than ever. But we must also honor the venerable rules of logic and scientific inference. Fallacies and paradoxes are waiting to surprise and annoy us, but they tell us that we are making bad assumptions or that we are living in the wrong paradigm.

A seismologist struggling with the meaning of seismic velocity anomalies beneath various tectonic provinces, or in the vicinity of a deeply subducting slab, is apt to interpret seismic results in terms of temperature variations in a homogeneous, isotropic half-space or relative to a standard model. However, the petrological aspects – variations in mineralogy, crystal orientation or partial melt content – are much more important than temperature. These, in turn, require knowledge of phase equilibria, mineralogy, anisotropy and material properties.

An isotope geochemist, upon finding evidence for several components in the rocks and being generally aware of the geophysical evidence for a crust and a 650 km discontinuity, will tend to interpret the chemical data in terms of ancient isolated reservoirs, a 'normal' mantle source and a lower mantle source. The 'standard' petrological model is a homogeneous peridotite mantle containing about 20% basalt, available as needed, to fuel the midocean ridges with uniform magmas. Exotic basalts are assumed to be from the core–mantle boundary. The crust and shallow mantle may be inhomogeneous, but the rest of the mantle is viewed as well homogenized by convection. Numerous paradoxes occur in the standard 'box' models of mantle geochemistry.

The convection theoretician, for 'simplicity', treats the mantle as a homogeneous fluid or as a two-layered system, with constant physical properties, driven by temperature-induced buoyancy, ignoring melting and phase changes and even pressure. Thermodynamic self-consistency and realistic boundary conditions – such as the inclusion of continents – can completely change the outcome of a convection simulation.

In *New Theory of the Earth* I attempt to assemble the bits and pieces from a variety of disciplines, including new disciplines, which are relevant to an understanding of the Earth. Rocks and magmas are our most direct source of information about the interior, but they are biased toward the properties of the crust and shallow mantle. Seismology is our best source of information about the deep interior; however, the interpretation of seismic data for purposes other than purely structural requires input from solid-state physics and experimental petrology. One cannot look at a few selected color cross-sections of the mantle, dramatic as they are, and infer temperature, or composition or the style of mantle convection. There is not a simple scaling between seismic velocity and temperature.

The new theory of the Earth developed here differs in many respects from conventional views. Petrologist's models for the Earth's interior usually focus on the composition of mantle samples contained in basalts and kimberlites from the shallow mantle. The 'simplest' hypothesis based on these samples is that the observed basalts and peridotites bear a complementary relation to one another, that peridotites are the source of basalts or the residue after their removal, and that the whole mantle is identical in composition to the inferred chemistry of the upper mantle and the basalt source region. The mantle is therefore homogeneous in composition, and thus all parts of the mantle eventually rise to the surface to provide basalts. Subducted slabs experience no barrier in falling through the mantle to the core–mantle boundary.

Geochemists have defined a variety of distinct reservoirs, or source regions, based on imperfect understanding of seismic results and of statistics, particularly of the central limit theorem. Midocean ridge basalts are viewed as a unique component of the mantle, rather than as an average composition of a heterogeneous population. In some models the mantle is still grossly homogeneous but contains blobs of isotopically distinct materials so that it resembles a marble cake. Most of the mantle is generally considered to be accessible, undegassed and nearly primordial in composition.

Seismologists recognize large lateral heterogeneity in the upper mantle and several major seismic discontinuities. The discontinuities represent equilibrium phase changes rather than reservoir boundaries and major changes in mantle chemistry. High-resolution seismic techniques have identified about 10 other discontinuities and numerous small-scale scatterers in the mantle. These could be due to changes in chemistry or rock type. The oceanic and continental lithospheres represent material that is colder, stronger *and* chemically different from the underlying mantle. Recent discoveries include megastructures in the lower mantle – unfortunately called 'megaplumes' – which are not due to temperature variations. Simple physical scaling arguments suggest that these are ancient features; they are not buoyant plumes.

Current Earth paradigms are full of paradoxes and logical fallacies. It is widely believed that the results of seismology and geochemistry for mantle structure are discordant, with the former favoring whole-mantle convection and the later favoring layered convection. However, a different view arises from recognizing effects usually ignored in the construction of these models. Self-compression and expansion affect material properties that are important in all aspects of mantle geochemistry and dynamics, including the interpretation of tomographic images. Pressure compresses a solid and changes physical properties that depend on volume and does so in a highly non-linear way. Intrinsic, anelastic, compositional and crystal structure effects also affect seismic velocities; temperature is not the only parameter. Deep-mantle features may be convectively isolated from upper-mantle processes. Major chemical boundaries may occur near 1000 and 2000 km depths. In contrast to standard geochemical models the deeper layers may not be accessible to surface volcanoes.

Tomographic images are often interpreted in terms of an assumed velocity–density–temperature correlation, e.g. high shear velocities (blue regions) are attributed to cold dense slabs, and low shear velocity (red regions) are interpreted as hot rising blobs. There are many factors controlling shear velocity and some do not involve temperature or density. Cold, dense regions of the mantle, such as eclogite sinkers, can have low shear velocities. Likewise, large igneous provinces and hotspots are usually viewed as results of particularly hot mantle. But the locations and magnitudes of melting anomalies depend on fertility of the mantle and the stress state of the lithosphere, perhaps more so than on temperature.

From their inception, the standard models of petrology and geochemistry, involving a uniform pyrolite mantle, or a layered primordial mantle, have had paradoxes; lead isotopes in general and the lead paradoxes in particular, the helium paradoxes and various heat-flow paradoxes. Paradoxes have, in fact, multiplied since the first edition of *Theory of the Earth* (TOE). New isotopic systems have been brought on line – Os, Hf, W and other short-lived isotopes – and they show that the Earth accreted and differentiated and formed a core in the first tens of millions of years of its existence; the cold undegassed geochemical model does not make sense. Paradoxes are a result of paradigms and assumptions; sometimes we can make progress by dropping assumptions, even cherished ones, and abandoning the paradigm. Sometimes new embellishments and complications to the standard model are made simply to overcome problems, or paradoxes, created by the original unphysical assumptions.

A theme running throughout the first edition of TOE was that the energy of accretion of the Earth was so great, and the melting temperatures and densities of the products so different, that early and extensive – and irreversible – chemical stratification of the Earth is the logical outcome. Basalts and the incompatible elements – including K, U and Th – are expected to be concentrated toward the surface, and dense refractory – and depleted – crystals are expected to settle toward the interior. Although mantle homogeneity may be the simplest hypothesis for mantle geochemists and convection modelers, any scenario that results in a cold origin, primordial reservoirs, or a homogeneous mantle is incredibly complex and contrived. In addition to geology, chemistry and physics, one must understand Occam's Razor and the difference between cause and effect. Another theme was that seismic velocities depend on many things; tomographic images are not temperature maps. The framework was established for interpreting seismic velocities. A heterogeneous mantle, involving eclogite and isotopically enriched domains, was another theme.

The title of this book was not picked casually. The year of the first edition was the two-hundredth anniversary of the publication of *Theory of the Earth; or an Investigation of the Laws Observable in the Composition, Dissolution, and Restoration of Land Upon the Globe* by James Hutton, the founder of modern geology. It was not until much progress had been made in all the physical and natural sciences that geology could possess any solid foundations or real scientific status. Hutton's knowledge of chemistry and mineralogy was considerable, and his powers of observation and generalization were remarkable, but the infancy of the other basic sciences made his *Theory of the Earth* understandably incomplete. In the last century the incorporation of physics, chemistry and biology into geology and the application of new tools of geophysics and geochemistry has made geology a science that would be unrecognizable to the Founder, although the goals are the same. Hutton's uniformitarian principle demanded an enormous time period for the processes he described to shape the surface of the Earth, and Hutton could see that the different kinds of rocks had been formed by diverse processes. These are still valid concepts, although we now recognize catastrophic and extraterrestrial events as well. Hutton's views prevailed over the *precipitation theory*, which held that all rocks were formed by mineral deposits from the oceans. Ironically, a currently emerging view is that crystallization of rocks from a gigantic magma ocean was an important process in times that predate the visible geological record. Uniformitarianism, as an idea, can be carried too far. Episodic and non-steady-state processes, and *evolving self-organized systems*, are the keys to understanding mantle evolution and the onset of plate tectonics.

The new sciences of chaos, far-from-equilibrium thermodynamics, self-organization and *ab initio* equations of state have been applied to deep-Earth problems. Sampling theory and other branches of statistics are starting to threaten some of the cherished dogmas about reservoirs, mantle homogeneity, convection and volcanism. These are new topics in this edition.

The word *theory* is used in two ways. A theory is the collection of facts, principles and assumptions that guide workers in a given field. Well-established theories from physics, chemistry, biology and astrophysics, as well as from geology, are woven into the Earth sciences. Students of the Earth must understand solid-state physics, crystallography, thermodynamics, quantum mechanics, Hooke's Law, optics and, above all, the principles of logical inference. Yet these collections of theories do not provide a theory of the Earth. They provide the tools for unraveling the secrets of Earth and for providing the basic facts which in turn are only clues to how the Earth operates. By assembling these clues we hope to gain a better understanding of the origin, structure, composition and evolution of our planet. This better understanding is all that we can hope for in developing a new theory of the Earth.

NOTE ON REFERENCES

The Web has completely changed the way researchers and students do research, teach and learn. Search engines can be used to supplement textbooks and monographs. Conventional references are included in this book, but occasionally a `Googlet` is inserted with key search words for a given topic. These `Googlets` when used with a search engine can find pertinent recent references, color pictures, movies and further background on the subject of interest. For example, if one wants to investigate the relationship between the Deccan traps and Reunion one can insert [`Reunion Deccan mantleplumes`] into Google. If one wants to know more about shear-wave splitting or the Love Rayleigh discrepancy one just types into Google [shear-wave splitting] or [Love Rayleigh discrepancy]. Often the author and a keyword can replace a list of references e.g. [Anderson tomography]. These convenient Googlets will be sprinkled throughout the text. The use of these is optional and the book can be used without interrogating the Web. But if this resource is available, if used, it can cut down the time required to find references and supplementary material. For the ordinary reader, these Googlets should be no more distracting than *italics* or **boldface** and much less distracting that the usual form of referencing and footnoting. They can be treated as keywords, useful but not essential. The key phrases have been designed so that, when used in a search, the top hits will contain relevant information. There may be, of course, some un-useful and redundant hits in the top five. Supplementary and current material can be found with keywords Don L Anderson and mantleplumes.

NOTE ON THIS EDITION

At the time of writing of the First Edition, there were some assumptions that were holding up progress in the study of the Earth's interior. Seismologists were mainly assuming that the Earth was isotropic and that seismic waves did not depend on frequency or direction. Tomography was a brand-new science. Seismic velocities were assumed to depend mainly on temperature. In Theory of the Earth (TOE) (this is the first Googlet in the book) there were therefore extensive chapters on anisotropy, anelasticity, anharmonicity and asphericity. These are now mainstream sciences and there are monographs on each, so these chapters have been trimmed back. Mantle convection is a branch of thermodynamics but there are textbooks on this venerable science so the chapters on thermo have been trimmed. We are still awaiting a fully thermodynamic self-consistent treatment of mantle convection but a recent mantle convection monograph on mantle convection fills the need for a background on this. One can even find mantle convection movies on the Web. But new topics have moved in to take their place. Scaling relations, top-down convection, self-organization, pressure effects on convection, the eclogite engine, lower crustal delamination, seismic scattering, chemical stratification and variably fertile mantle are issues that are receiving more attention. The perception of mantle plumes and hotspots is currently undergoing a dramatic paradigm shift. *Plate tectonics itself is a more powerful concept than generally believed.* Sampling theory and the roles of reservoirs versus components, and sampling vs. stirring are receiving more attention. The various noble gas paradoxes have forced a rethinking of geochemical models and the assumptions they are based on. These topics are almost completely ignored in current texts, monographs and reviews and therefore receive more emphasis in *New Theory of the Earth*.

I thank my colleagues and students for stimulating discussions over the years and for their numerous contributions to the ideas and materials in this book. I especially appreciate the wisdom of Hiroo Kanamori, Don Helmberger and Adam Dziewonski, but the names of those who contributed in one way or another to my general world view are too numerous to list. Most recently, I have received considerable support and wise council from Jim Natland, Gillian Foulger, Anders Meibom, Jerry Winterer, Seth Stein, Bruce Julian and Dean Presnall. The more direct products of these collaborations can be seen on www.mantleplumes.org, and in Plates, Plumes and Paradigms, which provide much supplementary material to this book. I again acknowledge my debts to Nancy and my family for their patience and understanding.

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Abbreviations and acronyms (also see Appendix)

ABM	absorption-band model
AOB	alkali olivine basalts
BAB	backarc basins
BABB	BAB basalts
BSE	bulk silicate Earth
C	common component
C	a Bullen region; the TZ; 400- to 1000-km depth
CC	continental crust
CFB	continental flood basalts
CMB	core–mantle boundary
D	a Bullen region; the lower mantle, starting at 1000-km depth
D′	a Bullen subregion; between 1000-km depth and D″; mesosphere
D″	a Bullen subregion; the lowermost mantle
DM	depleted mantle
DMORB	depleted MORB
DUM	depleted upper mantle; BSE-CC
DUPAL	a geochemical component, possible delaminated lower CC
EH	high iron enstatite chondrites
EM	enriched mantle; EM+DM+CC=BSE
EM1	a geochemical component in basalts; possibly sediments
EM2	a geochemical component; possibly continental in origin
EMORB	enriched MORB
FOZO	FOcal ZOne; a common endmember component of basalts; possibly melted peridotite (see C, PHEM, UMR)
G	gravitational constant
GA	billion years ago
HFSE	high field strength elements
HIMU	a geochemical component of basalts based on Pb isotopes
HREE	heavy rare-earth elements
IAB	island-arc basalts
IAV	island-arc volcanics
IC	inner core
IDP	interplanetary dust particles
KIMB	kimberlite; sometimes the Q component
KREEP	K, REE, and P-rich lunar material
LIL	large ion lithophile
LIP	large igneous province
LM	lower mantle; Bullen's region D; between 1000-km depth and the CMB
LONU	low 3He/(U,Th) ratio; yields low $^{3}He/^{4}He$ ratio basalts
LREE	light rare-earth elements
LVZ	low-velocity zone
m	mass
Ma	million years ago
MORB	midocean-ridge basalts
MREE	middle rare-earth elements
NMORB	normal MORB
OC	oceanic crust
OIB	ocean-island basalts
OPB	oceanic-plateau basalts
P	primary seismic wave; 'compressional' wave
PHEM	primary helium mantle component
PKJKP	a seismic wave that traverses the IC as a shear wave
PLUME	primary layer of upper mantle enrichment
PM	primitive mantle
PMORB	plume-type MORB
PN	the P wave that refracts along the top of the mantle
PREM	preliminary reference Earth model
PREMA	prevalent mantle component (see C, FOZO); probably a peridotite
PUM	primitive upper mantle, prior to differentiation
P′P′	a seismic wave that goes through the core and reflects off of the opposite side of the Earth
Q	seismic quality factor; also quintessence or the fifth essential component, and heat flow
QCT	qualitative chromotomography; visual or intuitive interpretations
REE	rare-earth elements
SCLM	subcontinental lithospheric mantle

SH	shear wave, horizontal polarization
SOFFE	self-organized, far-from-equilibrium
SV	shear wave, vertical polarization
SUMA	statistical upper-mantle assemblage
SUMA	sampling upon melting and averaging
TMORB	transitional MORB
TPW	true polar wander
TZ	transition zone; 410- to 650-km
TR	transition region; 410- to 1000-km depth
UDS	undepleted source
UM	upper mantle
UMR	ultramafic rock; a geochemical component