CONTINENTAL CRUST

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Contents

Summary

This article summarizes the structure, composition, and evolution of continental crust. The major characteristic of continental crust is its thickness, which can vary from less than 20 km to more than 70 km. Seismic velocities in the crust increase with depth, and at the base of the crust (the Moho) there is usually a pronounced jump to the upper mantle velocities. In some regions, high-velocity rocks underneath the seismic Moho may have originally been part of the crust; thus, the idea of the petrologic Moho is introduced.

Continental crust is highly heterogeneous in three dimensions. However, it is useful to divide it into several layers, differing by seismic velocities and composition. The three-layer model, distinguishing the upper, middle, and the lower crust, is the most common. The P-wave velocities in the layers are in the ranges 5.7–6.4 km s^{-1}, 6.4–6.8 km s$^{-1,}$ and 6.8–7.6 km s^{-1}, respectively. The upper crust has felsic composition (granite/granodiorite), the middle crust, intermediate-to-felsic, while the lower crust of stable continents is mafic with composition close to basalts. Bimodal distribution of seismic velocities and strong seismic reflectivity, observed in the lower crust in many regions, suggests that it can be formed by a layered sequence of felsic and mafic rocks.

Continental crust may be subdivided into crustal types, that is, segments of the crust with similar geophysical and geologic characteristics. Such subdivision provides a useful tool for generalized models of the velocity structure and composition of the highly heterogeneous crust of the continents. The primary types of continental crust include shields, platforms, orogens, extended crust, and continental margins.

Continental crust is formed primarily at the continental magmatic arcs and oceanic island arcs, both of which are associated with subduction zones. The uneven age distribution of the juvenile continental crust is related to the secular changes in the mantle convection.

1. Introduction

The Earth's crust is the outermost part of the lithosphere, with thickness ranging from less than 10 km in the oceans to more than 70 km in continental regions. Three crustal types are recognized: continental, oceanic (see *Oceanic Crust*), and transitional (the latter includes primarily continental margins). Continental crust includes the major continents, their margins, and several submerged microcontinents. It constitutes only 0.4 % of Earth's mass, but covers about 41 % of Earth's surface and comprises 79 % of the total crustal volume.

The crust differs from the underlying mantle in seismic velocity and density, reflecting their different composition. The base of continental crust is defined as the *Mohorovičić* (or *Moho* for short) seismic discontinuity, named after the Croatian seismologist who discovered it in 1909. At the Moho, seismic velocities abruptly increase from 6–7 km s^{-1} in the crust to about 8 km s^{-1} in the upper mantle. Density and seismic velocities are closely related, and the base of the crust is also associated with a density increase. Thus, the existence of this boundary provides striking evidence for the differentiation of the earth.

Continental crust provides the most complete record of Earth's geological history. Its mean age is about 2.5 Ga, while its oldest fragments, found in the central parts of the continents, are more than 4.0 Ga old. In contrast, the oldest oceanic crust is only about 160 Ma old because of the rapid recycling of oceanic lithosphere at subduction zones. Thus, studies of continental crust provide a unique opportunity to understand the geologic and geodynamic evolution of Earth.

Although continental crust is accessible for geological, geophysical, and geochemical studies, its structure is still much less known than the structure of the oceanic crust, due to its greater degree of heterogeneity. Most of the knowledge of the nature and composition of continental crust is based on seismic and heat flow studies, complemented by gravity and electromagnetic studies, geologic mapping, stress measurements, geochemical studies, continental drilling, and age determinations.

2. Methods of Continental Crust Studies

2.1 Seismic Studies

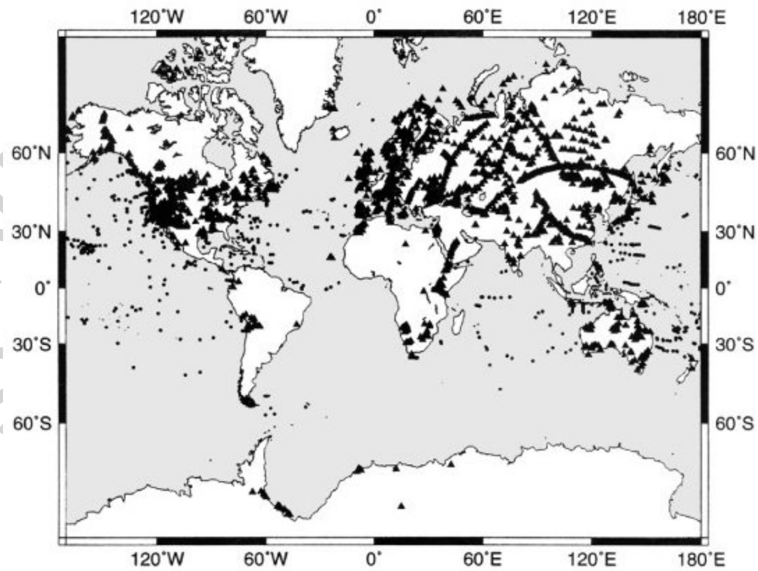

Figure 1. Location of seismic refraction profiles within continents (triangles) and oceans (circles) (from Mooney et al., 1998)

The most detailed information regarding the structure and composition of the crust is based on seismic refraction and reflection methods. Indeed, the discovery of the base of the crust came from seismological studies that identified the Moho as a sharp seismic boundary, which was defined as the base of the crust. Globally, seismic methods provide high-resolution images of continental crust (Figure 1). In crustal studies, two seismic methods play a leading role: reflection and refraction surveys, which are mainly based on the use of artificial energy sources (for example, explosions or air guns), supplemented by natural events (earthquakes).

The first *refraction seismic experiment* was done in the 1860s. Since the 1920s, the refraction seismic method has been routinely used in oil exploration, and since the early 1940s it provides the basis for determining the velocity structure of the entire crust. The accuracy of the interpreted seismic velocities is 3 % or better. Most modern analyses of refraction data include calculations of both seismic travel-times and amplitudes supplemented by calculations of synthetic (theoretical) seismograms. Wide-angle refraction surveys are broadly used nowadays for studies of the continental (especially lower) crust, and provide depth estimates of crustal layers and crustal thickness with an accuracy better than 10 %.

Seismic reflection methods provide the most detailed, high-resolution information on the structure of the continental crust. The vertical resolution of this method is some tens of meters for the typical crustal velocities and frequencies used in normal-incidence reflection seismology. However, reflection methods generally do not resolve seismic velocities within the deep crust. Thus, the reflection profiles can be interpreted in terms of the crustal composition only if additional information on seismic velocities is available.

2.2 Geologic Mapping

Geologic studies of basement outcrops provide a firm basis for models of the composition of continental crust. In some continental regions, deep crustal rocks, that were originally at a depth of 20 km to 30 km or more are exposed at the surface as a result of tectonic processes. Such locations permit direct studies of the deep parts of continental crust, their properties, and composition.

2.3 Petrologic Studies

Xenolith studies also provide important information on the composition of continental crust, especially its deep parts, which rarely are available for study at Earth's surface.

2.4 Heat Flow Studies

(See *Terrestrial Heat Flow*.) Geothermal modeling permits discrimination between models of the depth distribution of heat producing (radioactive) elements in continental crust and, when combined with laboratory measurements of heat production in different rock types, verification of the composition of the crust derived from seismic experiments. Regional heat flow provinces are typically well correlated with tectonic provinces, as based on distinct crustal structure.

2.5 Electromagnetic Studies

(See *Electric Field of the Earth*.) The conductivity structure of the crust is related to its composition and to the presence of pore fluids. The depth to the Curie isotherm, based on magnetic investigations, provides additional control for geothermal constraints. The conductivity contributes auxiliary information on the crustal composition and, in particular, on the depth distribution of crustal fluids.

2.6 Gravity Studies

(See *Applications of Gravimetry and Methods of Survey*.) Rock density and seismic velocity are closely related, and thus combined gravity and seismic data can provide the basis for assessing density distribution in continental crust. Gravity studies can help in discriminating between competing seismic models, and can distinguish density inhomogeneities in the deep crust that may not be evident in seismic data.

2.7 Laboratory Ultrasonic Measurements

The laboratory measurements of V_P and V_S velocities in different rock types provide the basis for models of the crustal composition derived from seismic velocities. Usually these experiments are made at high pressures and temperatures to simulate the *in situ* conditions in the continental crust. Additional parameters derived from laboratory measurements, such as Poisson's ratio and seismic anisotropy, are important for discrimination between competing models of the crustal composition.

2.8 Continental Drilling

Drilling of continental crust is an extremely technically complicated and expensive enterprise. However, it provides a unique opportunity for the direct study of the structure and properties of continental crust. The first deep drilling project started in the early 1970s in northwestern Russia and continues to this day. At present, the Kola Superdeep Borehole is the deepest drilled borehole with a depth of about 13 km. Other deep drilling projects on the continents include the KTB (Continental Deep Borehole) in Germany and the deep borehole in the Urals (Russia).

2.9 Geochronology

Age dating of the crustal rocks is important for understanding the timing and the thermal (for example, magmatism and metamorphism) and tectonic (for example, extension and thrusting) processes by which continental crust is formed and modified (see *Tectonic Processes*). In most cases, these processes are coupled and are usually referred to as tectonothermal events.

3. Average Seismic Structure of Continental Crust

3.1 Crustal Thickness and Seismic Velocities

Seismically, the crust is defined as the outer layer with compressional (or primary, P-) wave velocities (V_P) less than 7.6–7.8 km s^{-1} (with an average velocity of 6.45 km s^{-1}) and shear (or secondary, S-) wave velocities (V_S) less than 4.3 km s^{-1} (with an average velocity of 3.65 km s^{-1}). The average V_P crustal velocities range from 5.6 to 7.4 km s^{-1}; however in 85 % of continental crust $6.1 \leq V_P \leq 6.7$ km s^{-1}. Typically, seismic velocities in continental crust increase with depth (Table 1).

Depth km	5	10	15	20	25	30	35	40	45	50
V_P km s^{-1}	5.95 ± 0.32	6.10 ± 0.25	6.30 ± 0.30	6.45 ± 0.30	6.65 ± 0.30	6.78 ± 0.35	6.92 ± 0.30	7.02 ± 0.32	7.10 ± 0.38	7.15 ± 0.40

Table 1. Average crustal velocities weighted at 5 km intervals (after Christensen and Mooney, 1995)

Total thickness is a basic parameter characterizing continental crust (Figure 2). On the continents, it varies from 16 km in the Afar Triangle (Ethiopia) to 72 km in Tibet (China) (with an accuracy of about 10 %). About 95 % of all seismic measurements indicate continental crust 22 km to 57 km thick, with the most typical values of about 35–45 km. The mean thickness of continental crust is 39.2 km ± 8.5 km. The average (weighted by area) crustal thickness on the continents was recently estimated to be 41 km.

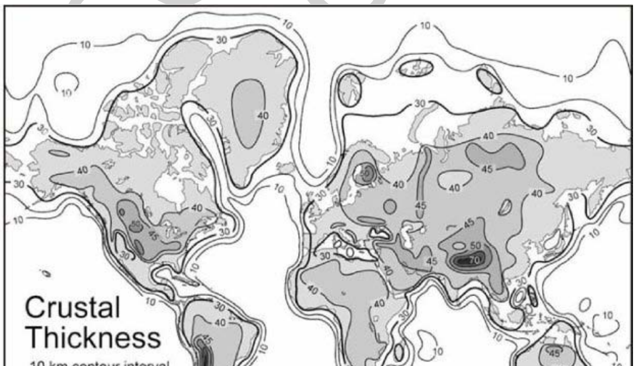

Figure 2: Mercator projection of crustal thickness based on seismic refraction profiles shown in Figure 1 (from Mooney et al., 1998)

Continental crust is very variable and does not have a standard structure. Two- or three-layer models of the crystalline continental crust based on seismic data are most common, although one-layer models, or models with more than three layers, were proposed for some regions. For example, some shield areas may be characterized by a one-layer crust formed by high-grade metamorphic rocks with V_P = 6.5–6.6 km s^{-1}.

The sedimentary cover forms an additional uppermost layer of the crust. Its thickness can vary from zero on the shields to more than 20 km in deep sedimentary basins (for example, the Caspian Basin). On continents, compressional wave velocity is 1.5–3.5 km s^{-1} in *unconsolidated (soft) sediments,* and 3.5–5.8 km s^{-1} in the *consolidated (hard) sediments*. As the rocks of the sedimentary cover are often metamorphosed and become seismically indistinguishable from the crystalline rocks of the basement, the upper part of the crystalline crust is not always well defined, at least in the regions with thick sediments. Usually its top is assumed to have compressional wave velocities V_P > 5.3–5.8 km s^{-1}. In many regions, metamorphosed Paleozoic sediments are included as part of the upper crystalline crust.

The upper continental crust, constituted chiefly by gneisses, granites, and granodiorites, has 5.6–5.8 < V_P < ~6.4 km s^{-1} and a typical thickness of 10-25 km. In the deeper crust an increase in both mafic content and metamorphic grade raise seismic velocities. In the *middle crust* (usually 5–15 km thick), which is usually composed of rocks in amphibolite facies, velocities are ~6.4 < V_P < ~6.8 km s^{-1}. P-wave seismic velocities in *the lower crust*, which is formed by metamorphic rocks in granulite facies (chiefly diorites, gabbros, amphibolites, and granulites), range from ~6.8 km s^{-1} to ~7.2 km s^{-1}. In Precambrian shield and platform areas, *the lowermost crust* may have very high P-wave velocities (~7.2 < V_P < ~7.6 km s^{-1}).

In some continental regions, a small boundary at mid-crustal levels (usually between 15 km and 25 km depth), referred to as the *Conrad discontinuity*, is recognized. This is a gradational boundary, separating the upper "granitic" and the middle (or in some cases lower "mafic") continental crust, and was first identified by Conrad in 1925 as the discontinuity where P-wave velocities become higher than 6.5 km s^{-1}. In some regions, a low velocity zone is found at the base of the upper crust, enhancing the sharpness of the Conrad discontinuity. The Conrad discontinuity varies in depth and character from region to region, suggesting it is not a global feature as was previously believed, and its origin can be diverse. However, in some regions this boundary is significant, and most likely reflects the result of the differentiation of crustal material into light sialic rocks (granites) in the upper crust and heavier mafic rocks of the deeper crust.

The compressional (P-) wave velocity at the top of the ("normal") peridotitic upper mantle is often referred to as the *Pn* velocity. *Pn* velocities usually are in the range from 7.6 km s^{-1} to 8.8 km s^{-1}; however values less than 7.8 km s^{-1} and exceeding 8.4 km s^{-1} are not common. The global average for *Pn* velocity in the continents is 8.07 km s^{-1} ± 0.21 km s^{-1}.

3.2 Crustal Reflectivity

High-resolution seismic reflection studies provide detailed information on the structure of continental crust. Crustal reflectivity typically appears within continental crust as reflecting fault zones in the commonly seismically transparent upper crust, and as subhorizontal laminated strong reflections in the "mafic" lower continental crust.

Seismic reflection programs in North America (COCORP) and Europe (BIRPS, ECORS, DEKORP) show that the reflections from the upper continental crust are chiefly produced by single faults or fault zones. Examples can be found in many tectonically young regions, as for example at the North Variscan Deformation Front. In several cases, the origin of the upper crustal reflectivity was determined by drilling or by field-mapping studies of outcrops (an example is the Sijian meteorite impact structure in Sweden, where strong reflections are from horizontal dolerite intrusions within the granitic host rock).

The origin of the lower crustal reflectivity is still a subject for speculation. Usually four origins of the layered reflectivity of continental crust are considered:

(a) Igneous (compositional) layering caused by mafic intrusions into the crust (for example magma chambers) or by lenses of partial melt of the lower crust; the Basin and Range Province in western USA is an example.
(b) Metamorphic layering caused by regional metamorphism. Ductile flow in the warm crust during a thermal event can produce subhorizontal layering of melting products. The examples of such lamellae reflectivity are known in the southern Appalachians (USA) and in the Archean granulite terrains.
(c) Dynamic layering in the crust caused by partial melting or mylonitization within shear zones and fault zones.
(d) Pore pressure layering associated with suture zones or fluid-filled cracks.

The large diversity in the seismic velocities observed in the lower crust suggests that the composition of the lower crust can vary within a wide range, and therefore the lower crustal reflectivity may be due to different mechanisms in various geologic environments. The reflectivity pattern is very consistent within similar tectonic provinces, which implies that they have undergone common processes of tectonic evolution. The general character of the crustal reflectivity correlates with the thermotectonic age. Usually the reflectivity is high in tectonically young and warm Phanerozoic areas, such as continental rift zones and regions with extended crust (for example, in the western part of the USA). In these regions, the zone of high reflectivity usually extends from near the Conrad discontinuity down to the Moho discontinuity, where it abruptly disappears. Typically, the crustal reflectivity in ancient tectonic provinces (the Precambrian continental shields and platforms) is very weak, especially in their lower crust. In these regions, the reflection Moho cannot be reliably determined.

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Biographical Sketch

Irina M. Artemieva, was born in Moscow, Russia, and graduated from the Physics Department of Lomonosov Moscow State University in 1984 with a Ms. Sci. degree. She completed. her Ph.D. in 1987 in the Institute of Physics of the Earth, Moscow (IPE), Russian Academy of Sciences (with a thesis entitled "Non-steady state thermal conduction models of tectonically active regions"). Since 1988, Irina Artemieva has been a research scientist at the same institute, working on theoretical calculations of effective permeability and thermal conductivity of heterogeneous rocks under different stress-temperature-fluid pressure conditions. During the past several years, her major field of research has been the thermal regime of the stable continental lithosphere and numerical modeling of the lithospheric thermal thickness. Since 1999 Dr. Artemieva has been a research scientist at the Department of Earth Sciences, Uppsala University, Sweden. The author was a visiting scientist at the Technical University, Clausthal-Zellerfeld, Germany (1993), Institut de Physique du Globe, Paris (1998), University of Quebec at Montreal (1998), and the U.S. Geological Survey, Menlo Park, USA (1995–2000). Since 1999, she has been the science coordinator of the European Science Foundation’s multidisciplinary EUROPROBE research program, which involves several hundred geoscientists from 25 European countries. Irina Artemieva is an editor of the Journal of Geodynamics, member of the American Geophysical Union, and fellow of the Royal Astronomical Society, London. She has published about 20 papers, including one monograph and presented more than 50 talks at international meetings