1.11 Crust and Lithospheric Structure – Global Crustal Structure

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1.11.1 Introduction, Purpose, and Scope

The crust preserves a record of the Earth's evolution that extends back more than 3.4 Gy. The crust also provides our natural resources, and presents social challenges in the form of natural hazards, such as earthquakes and volcanoes. Despite its importance, the clear recognition of a ubiquitous crust encircling the Earth dates back to less than 100 years (Mohorovicic, 1910). In fact, as recently as the 1960s it was hypothesized that the ocean floor was composed of serpentinized peridotite (hydratated ultramafic mantle rocks; Hess, 1962), a view that would have restricted true crustal material (i.e., silica-rich rocks) to the continents and its margins. Today it is well established that silicic material extracted from the mantle forms an outer crust in most regions of the Earth.

The Earth's crust has profound implications for all aspects of the planet's physical state and evolution. The process of crustal formation led to the complementary formation of an underlying mantle lithosphere, classically referred to by seismologists as 'the mantle lid' due to its finite thickness (*c.* 50–200 km) (Gutenberg, 1959; Oliver *et al.*, 1959). The physical properties of the crust plus mantle lithosphere modulate the rate at which heat is released to the Earth's surface, regulates mantle convection, determines the location of earthquakes and volcanoes, and more generally defines the rules for plate tectonic processes.

The foundations of seismic studies of the crust and upper mantle were laid in the period 1909–69 when the results of many pioneering studies provided a global view of the structure of the Earth's crust (**Table 1**). However, most of these early studies of the crust were hindered by technical limitations, and yielded field observations that presented an aliased image of the

Table 1 Classical references concerning the Earth's crust and uppermost mantle: the first 60 years: 1909–69

Year	Authors	Areas covered	J/A/B
1910	Mohorovicic	Europe	B
1925	Conrad	Europe	J
1926	Byerly	N-America	J
1932	Byerly and Dyk	N-America	J
1932	Gutenberg	N-America	J
1932	Gutenberg *et al.*	World	J
1935	DeGolyer	World	J
1935	Heiland	World	J
1935	Jeffreys and Bullen	World	J
1936	Leet	Europe	J
1937	Ewing *et al.*	Atlantic	J
1938	Slichter	World	J
1940	Jakosky	World	B
1940	Jeffreys	World	J
1940	Jeffreys	World	B
1943	Woollard	N-America	J
1949	Mintrop	World	J
1951	Junger	N-America	J
1951	Tuve	World	
1951	Slichter	N-America	J
1952	Birch	World	J
1952	Hersey *et al.*		J
1953	Tatel *et al.*	World	J
1953	Hodgson	N-America	J
1953	Tuve	World	J
1954	Ewing and Press	World	J
1954	Tuve *et al.*	World	J
1954	Katz	N-America	J
1955	Ewing *et al.*	N-America	A
1953	Tatel *et al.*	World	J
1955	Tatel and Tuve	World	A
1956	Press	World	B
1957	Oliver and Ewing	World	J
1958	Officer	World	B
1958	Oliver and Ewing	World	J
1959	Gutenberg	World	B
1959	Woollard	World	J
1959	Oliver *et al.*	World	J
1959	Richards and Walker	N-America	J
1960	Birch	World	J
1960	Willmore, Bancroft	World	J

(*Continued*)

Table 1 (Continued)

Year	Authors	Areas covered	J/A/B
1960	Brune *et al*.	World	J
1961	Anderson	World	J
1961	Birch	World	J
1961	Closs and Behnke	Australia	J
1961	Cram	N-America	J
1961	Jensen	World	J
1961	Steinhart and Meyer	World	B
1962	Oliver	World	J
1962	Alexander	N-America	J
1962	Hess	World	A
1963	Hill	Oceans	A
1963	Pakiser	N-America	J
1963	Brune and Dorman	N-America	J
1963	Jackson *et al*.	N-America	J
1963	Wilson	World	J
1963	Raitt	World	A
1964	Anderson and Archambeau	World	J
1964	Simmons	World	J
1964	McEvilly	World	J
1964	Pakiser and Steinhart	World	A
1964	Press	World	J
1964	Crampin	World	J
1964	Kovach and Anderson	World	J
1965	Christensen	World	J
1965	Dix	World	J
1965	Kanasewich and Cumming		J
1965	Jackson and Pakiser	N-America	J
1965	Roller	N-America	J
1965	Willden	N-America	J
1965	Wilson	World	J
1966	Bath and Stefánsson	World	J
1966	Berry and West	N-America	J
1966a, 1966b	Christensen	World	J
1966	Ewing *et al*.	N-America	J
1966	James and Steinhart	World	A
1966	Smith *et al*.	World	J
1966	Crampin	Eurasia	J
1966	Woollard	N-America	J
1967	Anderson	World	J
1967	Steinhart	World	A
1967	Meissner	World	J
1967	Shor		J
1968	Press	Europe	J
1969	Hart	World	B
1969	Zietz	N-America	J
1969	Brune	World	J
1969	Herrin	N-America	J
1957	Baranov	World	J
1967	Bateman and Eaton	N-America	J

N-America, North America.

crust. It is not surprising that, with some notable exceptions (Meissner, 1967; Mueller, 1977), these data were commonly interpreted in terms of two or more homogeneous layers, the upper layer (compressional wave velocity, $V_p = 6.0\ \mathrm{km\ s^{-1}}$) assigned a granitic composition, the lower layer ($V_p = 6.5\ \mathrm{km\ s^{-1}}$) a basaltic composition (Birch, 1952; Pakiser and Steinhart, 1964). Advances in technology have resulted in higher-resolution data revealing a much richer and more complex picture of the crust, as well as generating many new questions. Among the outstanding questions are the age and physical properties of the Moho and mid-crustal seismic discontinuities, the possible presence of deep crustal fluids, the geometry of crustal faults at depth, crustal modification by lateral crustal flow, and the possible existence of pervasive crustal seismic anisotropy.

Our understanding of the seismic structure of the crust began to change radically with the advent of deep seismic reflection profiling (Meissner, 1973; Oliver *et al.*, 1976) and the development of numerous stand-alone, portable seismographs used for seismic refraction/wide-angle reflection profiling (Healy *et al.*, 1982). These data provided an unbiased view of the crust to frequencies of 20 Hz and higher (corresponding to 300 m and higher resolution within the crust). These data demonstrated that the crust is highly heterogeneous, both vertically and laterally, in composition and physical properties (Mueller, 1977, 1978; Fountain, 1986; Holbrook *et al.*, 1992).

By the 1970s a large body of deep seismic data had been collected throughout the world, and the first regional crustal thickness models were created (Warren and Healy, 1973; Giese, 1976; Beloussov and Pavlenkova, 1984; Prodehl, 1984). Compilations of crustal seismic data into global models can be traced to the global Moho map of Soller *et al.* (1982). This map, while highly informative, did not easily lend itself to use in numerical calculations that make quantitative corrections for the crust. A major step forward was the publication of the global 2° × 2° 3SMAC model (Nataf and Ricard, 1996) that for the first time permitted the calculation of crustal corrections to seismological and other geophysical observations. In the past decade, a tremendous number of new seismic field observations have been made, thereby making it possible to improve the accuracy of previous global crustal models (Mooney *et al.* 1998; Pasyanos *et al.*, 2004). In this chapter we document these advances and summarize the current status of global crustal models.

1.11.2 Geology, Tectonics, and Earth History

The Earth's lithosphere is qualitatively defined as the cold, upper layer of the Earth and is divided into large blocks called tectonic plates (**Figure 1**). The lithosphere is on the order of 100 km thick, being the thinnest (20–100 km) in oceanic regions and the thickest (50–250+ km) in continental regions. The base of the lithosphere is defined by a thermal boundary layer (Jordan, 1975, 1979, 1988; Artemieva and Mooney, 2001). The base of the crust is a petrologic boundary between silicic and ultramafic rocks, and may be discerned seismically as the depth within the lithosphere where V_p increases from about 6.57.3 km s^{-1} (in the lower crust) to greater than 7.6 km s^{-1} (the uppermost mantle) (James and Steinhart, 1966). This boundary between the lower crust and upper mantle is called the Mohorovicic discontinuity (Mohorovicic, 1910; Jarchow and Thompson, 1989) and is usually at a depth (below sea level) of 10–14 km for oceanic crust, and 30–50 km for continental crust. The Earth's crust, which was originally extracted from the mantle, constitutes only about 0.7% of the total mass of the crust–mantle system (Taylor and Mclennan, 1985). Further seismic discontinuities below the crust divide the interior of the Earth into the upper mantle, transition region, lower mantle, outer core, and inner core. These other discontinuities are discussed in other chapters of this volume.

As a consequence of plate tectonics (**Figure 2**), oceanic crust and continental crust vary systematically in their principal physical properties, including density, thickness, age, and composition. Continental crust has an average thickness of 39 km, density of 2.84 g cm^{-3}, and an average age of 1500 My, while the oceanic crust has an average thickness of about 6 km, density of 3 g cm^{-3} and is everywhere younger than 200 My. Oceanic crust is largely made up of theoleiitic basalt, which has a dark, fine-grain texture that forms from quickly cooling magma. In contrast, continental crust has a more felsic composition than oceanic crust and ranges in thickness from 16 to 20 km in the Afar Triangle, northeast Africa, to 75+ km in the southern Tibetan Plateau. Ninety-five percent (by area) of the continental crust, however, is between 22 and 56 km thick.

This chapter presents a holistic view of the Earth's crustal structure, and summarizes the types of velocity and density models that characterize the crust on a global scale. In recent years, a wide variety of seismological techniques have been used to explore the crust. These include seismic refraction/wide-angle reflection profiles, near-vertical incidence reflection profiles, receiver functions, and local earthquake tomographic inversions. Some of these survey techniques have been in use for more than a half-century, and the results are reported in thousands of publications. These results make it possible to provide a comprehensive crustal model for the whole Earth, as well as higher-resolution regional models.

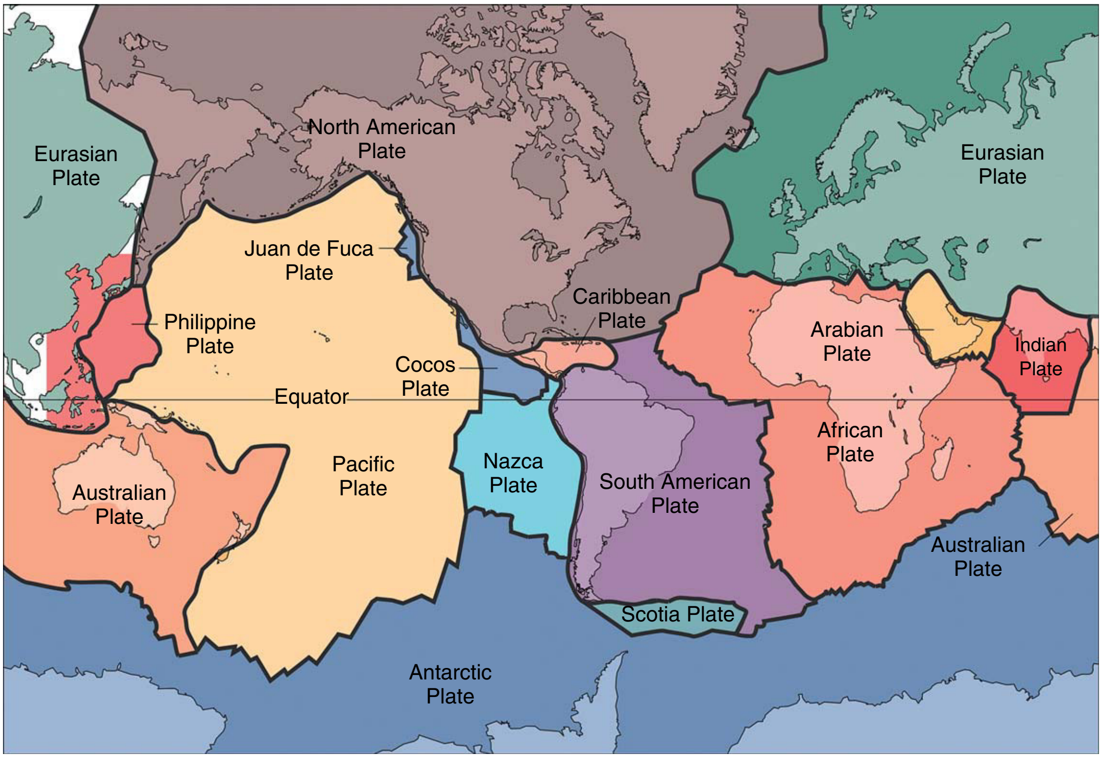


Figure 1 The 15 major tectonic plates on Earth, and the boundaries between these plates (Simkin *et al*., 2006). New oceanic lithosphere is constantly being produced at mid-ocean ridges (a divergent plate boundary) and later subducted back into the mantle at an oceanic subduction zone (a convergent plate boundary) (**Figure 2**). Plate motions led to the recycling of oceanic crust, arc volcanism, and compression at convergent boundaries. This chapter describes the complex and laterally variable deep seismic structure of the Earth's crust.

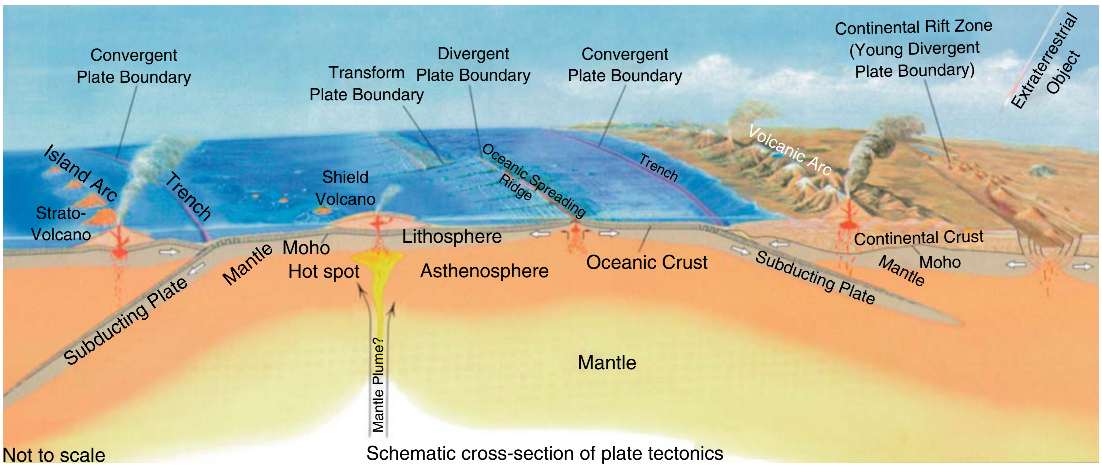


Figure 2 A cross section of the Earth's surface, indicating divergent (oceanic spreading ridge) and convergent (subducting plate) plate boundaries (Simkin *et al*., 2006). Active magmatic arcs at convergent boundaries increase the volume of continental crust and continental rift zones lead to crustal thinning. We summarize the deep structure of these and other features of the Earth's crust.

1.11.3 Seismic Techniques for Determining the Structure of the Crust and Uppermost Mantle

Seismic techniques provide the highest-resolution geophysical measurements of the structure of the crust and uppermost mantle. These techniques may be divided into those using active sources versus passive sources. Active sources are man-made seismic sources such as vibrators, air guns, and borehole explosions. Passive sources are derived from naturally occurring seismicity. Both active and passive sources generate P and S body waves, Love and Rayleigh waves, and diffracted and scattered waves. We discuss active and passive seismic techniques in turn.

1.11.3.1 Active-Source Data

Active-source seismic measurements of the structure of the crust have been conducted on a worldwide basis (Soller *et al.*, 1982; Meissner, 1986; Mooney *et al.*, 2002; **Table 2a**). Seismic studies of the deep

Table 2a Selected papers on data analysis methods in crustal seismology: Active sources

References	Year
Aki	1982
Aki and Lee	1976
Aki *et al*.	1977
Ansorge *et al*.	1982
Berry and West	1966
Bessonova *et al*.	1976
Boore	1972
Bouchon	1982
Braile and Chiang	1986
Braile *et al*.	1995
Chapman and Orcutt	1985
Červený	1972
Červený *et al*.	1977
Červený and Pšeničník	1984
Chapman	1978
Claerbout	1976, 1985
Closs and Behnke	1961
Deichmann and Ansorge	1983
Dix	1965
Dobrin	1976
Dohr	1970
Ewing *et al*.	1957
Finlayson and Ansorge	1984
Fuchs and Mueller	1971
Gajewski and Pšeničník	1987
Giese	1976
Giese *et al*.	1976
Haberland *et al*.	2003
Hajnal	1986
Hale and Thompson	1982
Heacock	1971, 1977
Hole	1992
Hole and Zelt	1995
Hole *et al*.	1992
Hwang and Mooney	1986
Kelley *et al*.	1976
Kennett	1974, 1983
Kind	1978
Klemperer and Luetgert	1987
Klemperer and Oliver	1983
Levander and Holliger	1992
Ludwig *et al*.	1970
Lutter *et al*.	1990
Mair and Lyons	1976
Makovsky *et al*.	1996a, 1996b
McEchan and Mooney	1980
Menke	1989
Milkereit *et al*.	1985
Mooney	1989
Mooney and Brocher	1987
Mooney and Meissner	1992
Mooney *et al*.	2002
Müller	1985
Nelson *et al*.	1996
Sandmeier and Wenzel	1986, 1990
Sheriff and Geldart	1982, 1983
Schilt *et al*.	1979
Telford *et al*.	1976
Willmore and Bancroft	1960
Zandt and Owens	1986
Zelt	1999
Zelt and Barton	1998
Zelt and Smith	1992
Zelt *et al*.	2003
Zelt *et al*.	1999

Table 2b Selected papers on data analysis methods in crustal seismology: Passive sources

References	Year
Aki and Richards	1980
Ammon *et al*.	1990
Barmin *et al*.	2001
Bath and Stefánsson	1966
Bessonova *et al*.	1974
Bijwaard *et al*.	1998
Boore	1972
Boschi *et al*.	2004
Bostock *et al*.	2002
Bouchon	1982
Brune	1969
Brune and Dorman	1963
Brune *et al*.	1960
Bruneton *et al*.	2004
Burdick and Langston	1977
Cassidy	1992

(*Continued*)

Table 2b (Continued)

References	Year
Chapman	1978
Chen *et al*.	2005
Chimera *et al*.	2003
Crosson	1976
Curtis and Woodhouse	1997
Debayle and Lévêque	1997
Dziewonski	1989
Dziewonski and Anderson	1981
Eberhart-Phillips	1986
Ekström *et al*.	1997
Ewing and Press	1954
Grand *et al*.	1997
Hearn and Clayton	1986
Hearn and Ni	1994
Hearn *et al*.	1991, 2004
Hofsetter and Bock	2004
Hole *et al*.	2000
Huang *et al*.	2004
Humphreys and Clayton	1988
Humphreys *et al*.	1984
Iyer and Hirahara	1993
Jordan and Frazer	1975
Karagianni *et al*.	2005
Kennett and Engdahl	1991
Kind	1978
Knopoff	1972
Kovach	1978
Langston	1977
Langston *et al*.	2002
Lebedev and Nolet	2003
Lei and Zhao	2005
Levshin *et al*.	2005
Li and Romanowicz	1996
Liang *et al*.	2004
Liu *et al*.	2005
Maggi and Priestley	2005
Mahadeven	1994
Mandal *et al*.	2004
McEvilly	1964
Mitchell and Herrmann	1979
Mooney	1989
Nakamura *et al*.	2003
Nolet	1987b, 1990
Okabe *et al*.	2004
Owens and Zandt	1985
Pasyanos	2000
Pilidou *et al*.	2005
Priestly and Brune	1978
Ritzwoller and Lavely	1995
Ritzwoller *et al*.	2002a, 2002b
Savage	1999
Shapiro and Ritzwoller	2002
Su *et al*.	1994
Sun *et al*.	2004a, 2004b
Thurber	1983, 1993
Thurber and Aki	1987
Tilmann *et al*.	2003
Vinnik *et al*.	2004
Wang *et al*.	2003
Woodhouse and Dziewonski	1984
Worthington	1984
Yanovskaya and Kozhevnikov	2003
Yliniemi *et al*.	2004
Zandt and Owens	1986
Zhang and Lay	1996
Kennett	1983
Kind *et al*.	1995, 2002
Kissling	1998
Kissling *et al*.	2001
Langston	1994
Lees and Crosson	1989
Leveque *et al*.	1993
Levshin *et al*.	1989
Ma *et al*.	1996
Masters *et al*.	1996
Menke	1989
Nolet	1978, 1987a, 1987b
Owens *et al*.	1984
Rapine *et al*.	2001
Ritzwoller *et al*.	2002
Roecker *et al*.	2004
Tarantola and Nercessian	1984
Van Heijst and Woodhouse	1999
Vidale	1988, 1990
Vinnik	1977
Zhang and Thurber	2003
Zhao *et al*.	1992
Zhou *et al*.	2004, 2005

continental crust that utilize man-made sources are classified into two basic categories, seismic refraction profiles and seismic reflection profiles, depending on their field acquisition parameters. Seismic refraction profiles provide reliable information regarding the distribution of seismic velocities within the crust, and are very effective in mapping crustal thickness (**Figure 3**). In contrast, seismic reflection data provide an image of the crust at a finer scale (50 m in the vertical and horizontal dimensions), but with weak constraints on deep crustal velocities. As a result, seismic reflection and refraction data have complementary strengths: reflection data provide a detailed structural image of the crust, whereas refraction data provide an estimate of the seismic velocity distribution in the crust.

The most common sources used in land profiles are chemical explosions and mechanical vibrators (vibroseis). Chemical explosions are generally composed of ammonium nitrate compounds that are detonated in a borehole at a depth of 20–50 m in the ground. In contrast, a vibrator truck weighs several tons and has a heavy steel plate that is pressed against the ground

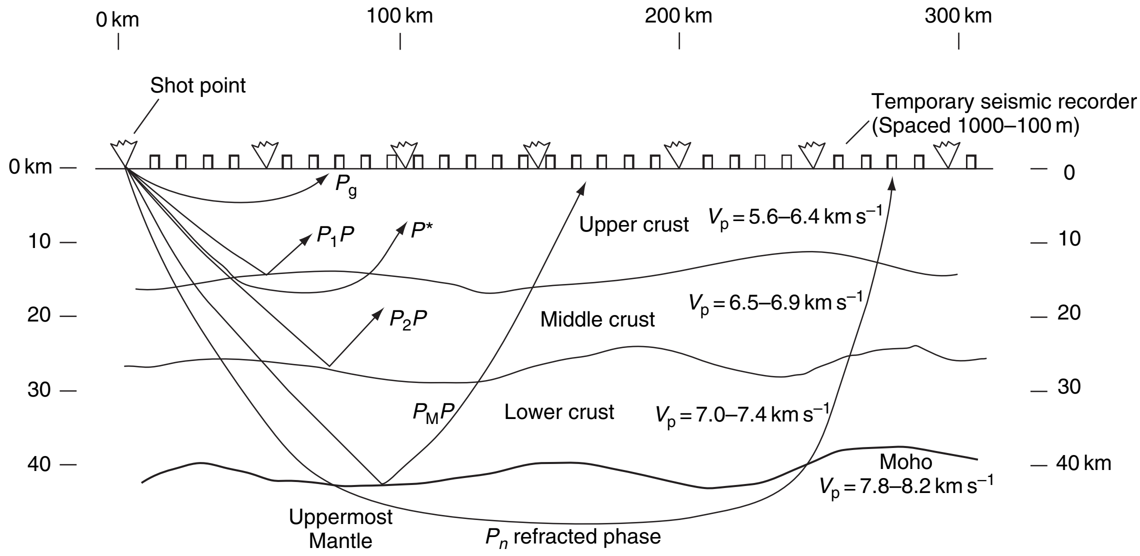


Figure 3 Ray paths for a continental seismic refraction/wide-angle reflection profile for crust with a typical seismic velocity structure found beneath a stable craton. The crust–mantle boundary (Moho) is a continuous feature, but intracrustal boundaries may be discontinuous laterally and several kilometers wide vertically. Commonly, shot points are spaced 50 km apart (or closer for higher resolution); temporary seismic recorders are spaced 1000–100 m apart.

that vibrates at increasing frequencies (5–60 Hz) for up to 30 s. The vibroseis method requires cross-correlation of the recordings with the source signal in the data-processing stage. The most common sources in marine profiles are the air gun, in which a bubble of very high-pressure air is released into water, and, prior to modern environmental concerns for marine life, explosive charges. Long-range seismic refraction data has also been recorded from nuclear sources, particularly in the former Soviet Union (Egorkin *et al.*, 1987; Pavlenkova, 1996). Due to the strength of these nuclear explosions, such long-range profiles probed not only the crust but the entire upper mantle to a depth of 660 km (Mechie *et al.*, 1993; Ryberg *et al.*, 1995, 1996; Morozov *et al.*, 1998; Morozova *et al.*, 1999).

1.11.3.1.1 Seismic refraction/wide-angle reflection profiles

Seismic refraction/wide-angle reflection profiles are recorded with relatively widely spaced (100–5000 m) geophones (typically with vertical-component seismometers) and long off-sets (100–500+ km) between sources and receivers (**Figure 3**). The data from these seismic profiles commonly contain strong wide-angle reflection phases (**Figure 4**) and provide excellent constraints on seismic velocity within the lithosphere.

Profiles with sources all to one side of the receivers are refered to as unreversed refraction profiles. Unreversed refraction profiles record only apparent velocities and are interpreted as if the crust was composed of flat-laying, uniformly thick layers. Split refraction profiles, with the source in the center of the receivers, are in some ways similar to simple reversed refraction lines, and are commonly used for studies of the oceanic crust. Reversed refraction profiles generally have multiple shot points that provide overlapping coverage and provide the most reliable results (**Figure 5**). The most effective way to determine a velocity structure from seismic refraction data is to compute detailed 2-D ray-theoretical traveltimes (**Figure 5(b)**) and synthetic (theoretical) seismograms and compare these with the observed data (Braile and Smith, 1974; Mooney, 1989; Braile *et al.*, 1995; Chulick, 1997; Zelt and Smith, 1992; and Zelt, 1999). This modeling must take into account (1) the source time-function, which could be from an explosion, earthquake, air gun, or vibrator, (2) the effects of transmission through the crust, and (3) the response of the detection systems, which may be seismometers, amplifiers, and filters. For trial-and-error forward modeling, an initial velocity model is constructed, and is adjusted until the synthetic seismograms match the recorded seismograms to the desired degree. For inverse methods (e.g., Zelt and Smith, 1992), seismic traveltimes are used to obtain a best-fitting model, starting from the near-surface and moving down through the crust.

Seismic velocities in the crust are primarily determined by five factors: mineralogical composition,

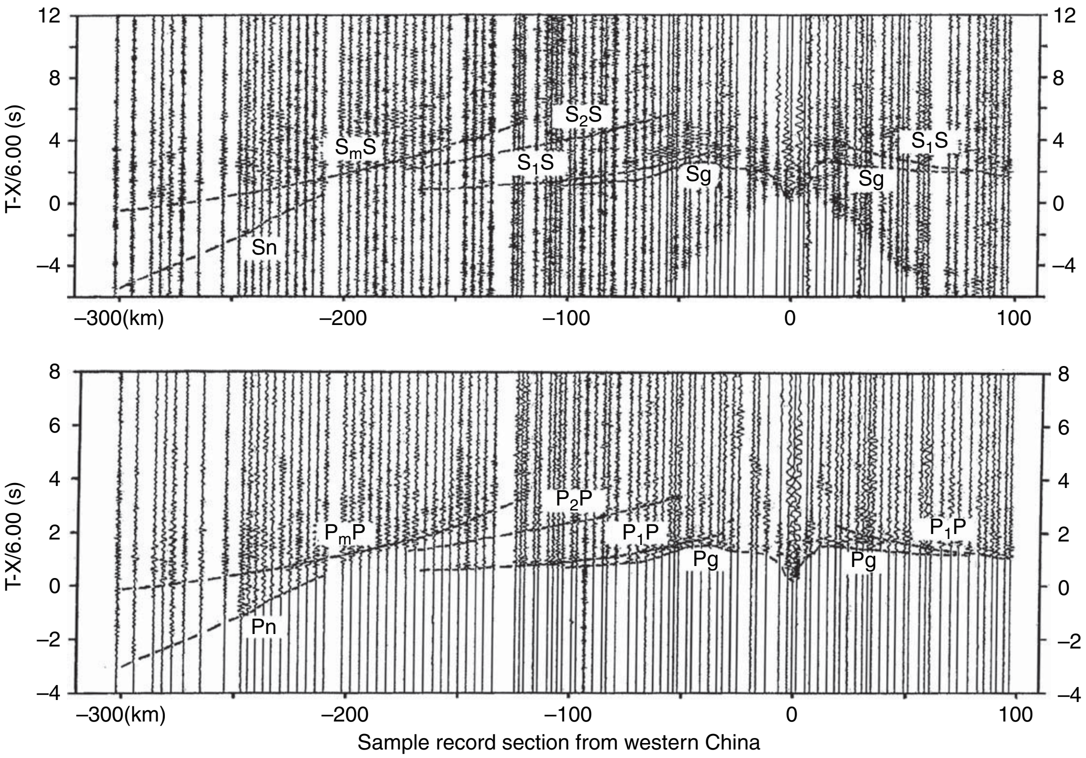


Figure 4 Sample seismic record section from western China. *Top*: Shear (S) wave record section with a reduction velocity of 3.46 km s^{-1}. This is a split-spread profile, with the shot point at 0 km; seismic phases as defined in **Figure 3**; Sg, direct arrival; S_1S, reflection from boundary between upper and middle crust; S_2S, reflection from middle and lower crust; S_mS, reflection from Moho; S_n, refraction from uppermost mantle. *Bottom*: Compressional (P) wave record section with a reduction velocity of 6.0 km s^{-1}; seismic phases as defined for S waves above (Wang *et al*. 2003).

confining pressure, temperature, anisotropy, and pore-fluid pressure. In order to draw inferences about the mineralogical composition of the deep crust, however, one must first estimate the contribution of the other four properties. Confining pressure is easily calculated from depth of burial, and temperature can be estimated from the surface heat flow. The quantitative effect on measured seismic velocities due to seismic anisotropy (Rabbel and Mooney, 1996) and pore-fluid pressure (Hyndman, 1988) are more difficult to estimate.

1.11.3.1.2 Seismic reflection profiles

Reflection seismology provides a more detailed image of crustal structure. Data are recorded with closely spaced (5–100 m) geophones and sources that yield a high-resolution image of the crust, but such data generally do not constrain seismic velocities in the deeper (middle and lower) crust. P waves from an energy source, such as a vibrator, buried explosive, or air gun, are reflected by intracrustal interfaces and recorded by geophones located close (0.1–10 km) to the source. In the data-processing stage, the effects of the source and receiver are removed from the recorded seismograms through a process called deconvolution, allowing for higher-resolution images of the structure. The seismic reflection data are commonly migrated, a processing step that shifts the reflectors into their correct spatial locations.

The seismic properties that are most readily obtained from reflection data are reflectivity patterns, and these correlate with distinct geologic settings. For example, the area around the United Kingdom and Ireland has undergone Mesozoic extension that is evident in deep seismic reflection data as tilted horst-and-grabens, a shallow (30 km) distinct Moho, and a dipping shear zone (Flannan reflections) within the upper mantle (**Figure 6**). When reflectivity patterns are interpreted with complementary seismic velocity and nonseismic crustal parameters (discussed below), inferences regarding the composition and evolution of the crust can be made (Clowes *et al*., 1987).

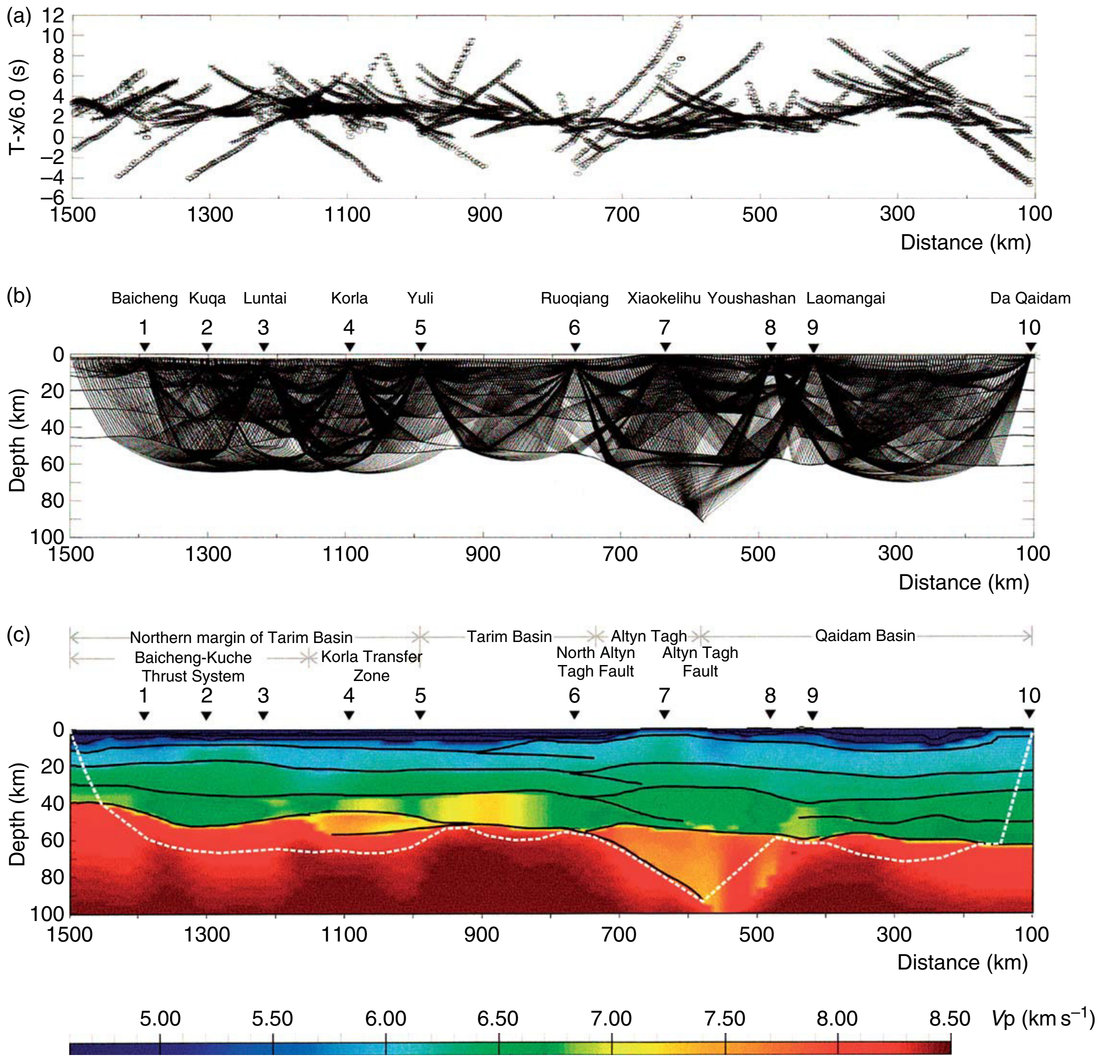


Figure 5 Modeling results along the seismic refraction/wide-angle reflection profile at the northern margin of the Tibetan Plateau. (a) Overlapping and reversing traveltime curves; (b) ray tracing through the crustal model showing dense subsurface ray coverage that provides excellent constraints on seismic velocities; (c) crustal and uppermost mantle seismic velocity (V_p) model. Both V_p and V_s can be estimated for the crust from these data. P_n velocity ranges from 7.8 to 8.2 km s^{-1}. After Zhao JM, Mooney WD, Zhang X, Li Z, Jin Z, and Okaya N (2006) Crustal structure across the Altyn Tagh Range at the northern margin of the Tibetan Plateau and tectonic implications. *Earth and Planetary Science Letters* 241: 804–814.

The widespread observation of crustal reflectivity suggests that common processes account for its existence. The primary cause of crustal reflectivity is compositional and metamorphic layering within the crust. Regional and global plate stresses act to enhance crustal reflectivity by inducing lower crustal ductile flow that produces subhorizontal lamination. This ductile flow requires elevated temperatures, and is therefore more common in the middle and lower crust (e.g., **Figure 6**). A list of key references of active-source seismology studies can be found in **Table 2a**.

1.11.3.2 Passive-Source Data

Techniques to investigate the seismic structure of the crust and uppermost mantle using passive seismic data have seen rapid development in the past two decades (**Table 2b**). These developments can be attributed to the increased availability of higher-quality, broadband data from permanent seismic networks and temporary deployments, as well as increased computer power. Passive seismic techniques began with surface-wave studies (Ewing and Press, 1954; Brune and Dorman, 1963) and progressed to seismic tomography

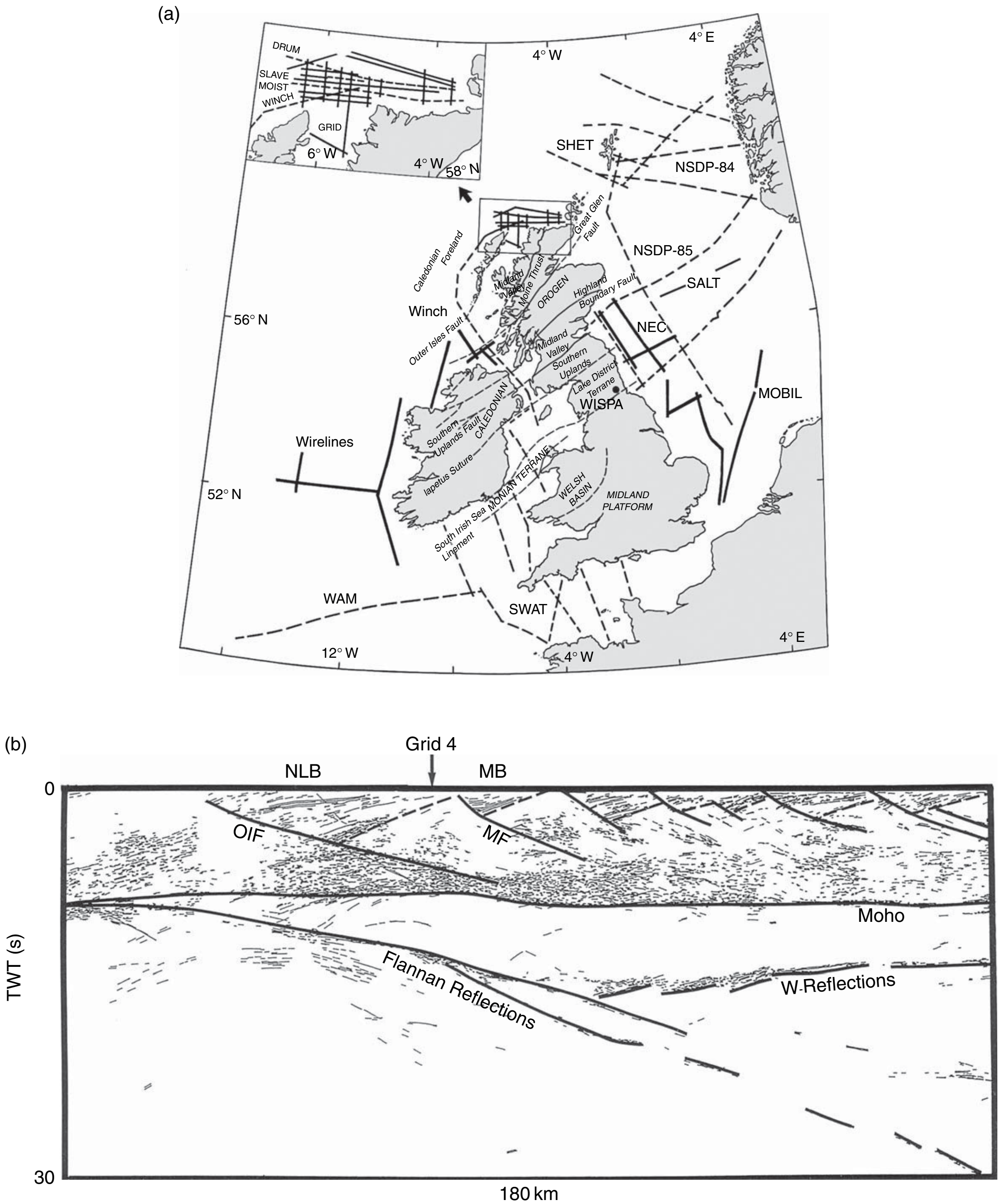


Figure 6 Deep seismic reflection imaging of crustal and upper-mantle fault zones. (a) Location map for the British Isles with marine seismic reflection profile lines indicated. (b) Seismic profile DRUM located off the north coast of Scotland (see inset in panel (a)). This profile shows brittle normal faults within the upper crust that merge into a zone of diffuse ductile deformation in the lower crust. The Moho is labeled at a two-way-time of 10 s (30 km depth). The uppermost mantle shows two zones of reflections, labeled Flannan and W. The Flannan reflections are interpreted as a Caledonian suture that was reactivated as an lithospheric extensional fault (Flack and Warner, 1990). (a) Modified from Matthews DH and BIRPS Core Group (1990) Progress in BIRPS deep seismic reflection profiling around the British Isles. *Tectonophysics* 173: 387–396.

(Aki *et al.*, 1977; Aki and Lee, 1976) and seismic receiver functions (Phinney, 1964; Vinnik, 1977; Langston, 1977). We discuss each of these in turn.

1.11.3.2.1 Surface waves

An earthquake near the Earth's surface will generate both Rayleigh and Love seismic surface waves. The amplitude of motion for these waves decreases exponentially with depth in the earth, with longer-wavelength waves sampling the velocity structure to greater depth than shorter-wavelength waves. This wavelength-depth dependence, combined with the increase of velocity with depth in the Earth gives rise to the dispersion of surface waves. This makes surface waves a valuable tool for the study of the velocity structure of the crust and mantle lithosphere (Oliver and Ewing, 1957, 1958; Oliver, 1962; Aki and Richards, 1980; Nolet, 1987a, 1987b; 1990; Lay and Wallace, 1995). The analysis of seismic surface waves for crustal and upper-mantle structure has been applied on a global basis and is particularly effective in determining 2-D and 3-D shear-wave structure (Debayle and Leveque, 1997; van der Lee and Nolet, 1997; Ritzwoller *et al.*, 2002a, 2002b; Shapiro and Ritzwoller, 2002; Langston *et al.*, 2002; Lebedev and Nolet, 2003; Chimera *et al.*, 2003; Panza *et al.*, 2003; Friederich, 2003; Okabe *et al.*, 2004; Boschi *et al.*, 2004; Bruneton *et al.*, 2004; Yoshizawa and Kennet, 2004; Pilidou *et al.*, 2004, 2005; Karagianni *et al.*, 2005; Levshin *et al.*, 2005; Maggi and Priestley, 2005). Thus, seismic surface waves provide complementary information to seismic refraction data that often provide information only on the compressional-wave structure of the crust. In addition, surface waves can be used to investigate regions that are aseismic (e.g., much of Africa and eastern South America). Such aseismic regions cannot be studied using other passive seismic methods. Surface-wave data can also be used to measure seismic anisotropy within the uppermost mantle (Huang *et al.*, 2004).

1.11.3.2.2 Seismic tomography

Local and distant (teleseismic) earthquake data can be used to determine crustal structure. Local seismic tomography uses earthquake arrivals at a network of seismic stations to determine crustal and upper-mantle structure by examining the arrival times of many crisscrossing paths between the earthquakes and seismometers. This technique, which is similar to medical tomography, has the potential to provide a 3-D picture of the crust and uppermost mantle. Local studies mainly provide information about the upper and middle crust (Thurber, 1993; Mandal *et al.*, 2004; Lei and Zhao, 2005; Salah and Zhao, 2003; **Table 2b**), whereas regional studies have better resolution within the uppermost mantle, especially for P_n velocity (Bannister *et al.*, 1991; Hearn and Ni, 1994; McNamara *et al.*, 1997; Parolai *et al.*, 1997; Mele, 1998; Calvert *et al.*, 2000; Sandoval *et al.*, 2004; Ritzwoller *et al.*, 2002a; Chen *et al.*, 2003; Al-Lazki *et al.*, 2003; 2004; Sandoval *et al.*, 2004; Hearn *et al.*, 2004; Liang *et al.*, 2004). A second technique uses teleseismic data and generally provides an image that extends to greater depth (100+ km), but lacks high resolution of structure within the crust (Petit *et al.*, 1998; Bijwaard *et al.*, 1998; Allen *et al.*, 2002; Benoit *et al.*, 2003; Lippitsch *et al.*, 2003; Liu *et al.*, 2005). Tomographic studies are also effective at determining upper-mantle seismic attenuation (Gung and Romanowicz, 2004).

1.11.3.3 Receiver Functions

Estimating seismic structure from teleseismic receiver functions is a highly effective method of exploring the crust and upper mantle since it requires only a single broadband seismic station. Crustal layering is determined by signal processing of a three-component station using teleseismic P-wave arrivals. The incident P wave will undergo multiple conversions to S waves at seismic boundaries within the uppermost mantle and crust. The analysis of these converted waves yields the shear-wave velocity structure beneath the station (Phinney, 1964; Vinnik, 1977; Burdick and Langston; 1977; Langston, 1977; Owens *et al.*, 1988). The method works best with nearly horizontal layers, although forward modeling may be applied in regions with 3-D structure. An informative discussion of the method is given by Cassidy (1992). While the method is highly effective at determining seismic discontinuities in the crust and uppermost mantle, it cannot, by itself, determine absolute seismic velocities. One approach is to perform a joint inversion of receiver functions and surface-wave dispersion observations (Julia *et al.*, 2000). Numerous local and regional studies have been reported (e.g., Owens and Zandt, 1985; Ramesh *et al.*, 2002), including studies of the crust of North Africa (Sandvol *et al.*, 1998), Spain (Julia and Mejia, 2004), Turkey (Angus *et al.*, 2006), the western USA (Zhu and Kanamori, 2000), and various studies of the upper mantle (Kind and Vinnik, 1988; Yuan *et al.*, 1997; Kind *et al.*, 2002).

Recently, the receiver function method has been extended to consider converted, precursory P waves that arrive just prior to the direct S wave (Li *et al.*, 2004; Angus *et al.*, 2006). This is known as the S-wave receiver function method. S-wave receiver functions have a lower resolution than P-wave receiver functions, but are effective at identifying the base of the lithosphere (Li *et al.*, 2004).

1.11.3.4 Laboratory Studies

1.11.3.4.1 Velocity–density relations

Seismic-wave velocities and density are fundamental properties of Earth materials. Thousands of field and laboratory measurements have been made for V_p, but fewer measurements have been made of rock densities at depth, since these require a borehole. Compressional-wave velocity and density correlations are important because they allow estimates of crustal density for surface-wave inversions and gravity studies, and conversely, rock densities can be used to estimate seismic velocities (Christensen and Mooney, 1995). Classic studies of velocity–density relations include the Nafe–Drake curve (Nafe and Drake, 1957); Birch (1961) law relating velocity, density, and mean atomic weight; and linear regression solutions for oceanic crust (Christensen and Salisbury, 1975). **Figure 7** presents average velocities for 29 rock categories at a depth of 20 km and a temperature of 309°C, corresponding to an average continental geotherm, versus rock density (Christensen and Mooney, 1995). Two curves are drawn in **Figure 7**, a linear curve (solid line) and a nonlinear curve representing V_p–density correlations for continental crust. The appropriate coefficients for both linear and nonlinear solutions are presented by Christensen and Mooney (1995).

1.11.3.4.2 V_p–V_s relations and poisson's ratio

Seismic measurements of crustal structure more commonly report only V_p rather than V_p and V_s. There are several reasons for this. First, explosive or air gun sources generate primarily compressional-wave energy. Second, many field observations record on the vertical component of ground velocity. Third, shear-wave arrivals are often either weak or obscured by scattered seismic energy (coda). In the absence of

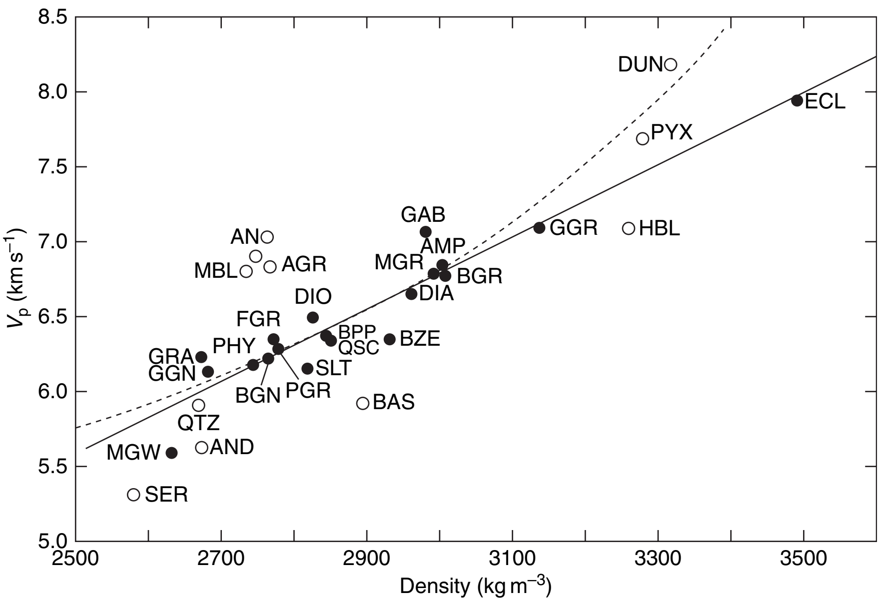


Figure 7 Average velocity versus average density for a variety of rock types at a pressure equivalent to 20 km depth and 309°C. Rock abbreviations are as follows. AGR, anorthositic granulite; AMP, amphibolite; AND, andesite; BAS, basalt; BGN, biotite (tondite) gneiss; BGR, greenschist facies basalt; BPP, prehnite–pumpelliyite facies basalt; BZE, Zeolite facies basalt; DIA, diabase; DIO, dionite; DUN, Dunite; ECL, mafic eclogite; FGR, felsic granulite; GAB, gabbro–norite–troctolite; GGN, granite gneiss; GGR, mafic garnet granulite; GRA, granite–granodiorite; HBL, hornblendite; MBL, calcite marble; MGR, mafic granulite; MGW, metagraywacke; PGR, paragranulite; PHY, phyllite; PYX, Pyroxenite; QCC, mica quartz schist; QTZ, quartzite; SER, serpentinite; SLT, slate. After Christensen NI and Mooney WD (1995) Seismic velocity structure and the composition of the continental crust: A global view. *Journal of Geophysical Research* 100: 9761–9788.

measured shear-wave speeds it is necessary to estimate its value from V_p. A direct relation between V_s and V_p, therefore, is highly desirable for many studies. This is accomplished by using empirically derived V_p–V_s relations that are based on field borehole and seismic profiling data, together with laboratory measurements.

A recent study (Brocher, 2005) presents empirical relations between V_p, V_s, and Poisson's ratio that can be used to estimate the ratio V_p/V_s, or equivalently, Poisson's ratio from a knowledge of V_p and rock type (i.e., sedimentary vs crystalline rocks). The empirical and regressional fits are defined for V_p between 1.5 and 8.5 km s^{-1} and fit the data remarkably well (**Figure 8**).

Conversely, the mineralogy of the crust can be estimated when both compressional (V_p) and shear-wave (V_s) velocities are measured (**Figure 9**). The ratio V_p/V_s is commonly expressed in terms of Poisson's ratio, which varies from 0.23 to 0.32 for most minerals, but quartz has a value of only 0.08 at room conditions (Christensen, 1996). Thus, the measurement of Poisson's ratio offers the means of distinguishing between felsic (quartz-rich) and mafic (quartz-poor) rocks.

1.11.3.4.3 Seismic anisotropy and the uppermost mantle

Many minerals exhibit birefringence, which is a directional dependence of the speed of light through the mineral. This phenomenon is used by petrologists to identify minerals in a thin section ($\leq$1 mm), where a sample illuminated by polarized light is rotated under a microscope to reveal its birefringence. Likewise, elastic waves show a directional dependence in wave speed in many minerals. Perhaps the most prominent example is the mineral olivine which is a major constituent of the upper mantle. The discrepancy between Rayleigh and Love wave speeds was measured in the early 1960s (Anderson, 1961) and led to the recognition of seismic anisotropy in the mantle lid. At about the same time, laboratory measurements of metamorphic rocks demonstrated significant shear-wave anisotropy in the crust (Christensen, 1966b). These measurements demonstrated that seismic anisotropy is not confined to the upper mantle, but also plays a prominent role in the crust (**Figure 10**). **Table 3** lists several key papers on the seismic properties, including anisotropy, of the uppermost mantle. References for laboratory studies of the properties of crustal rocks can be found in **Tables 4a** and **4b**.

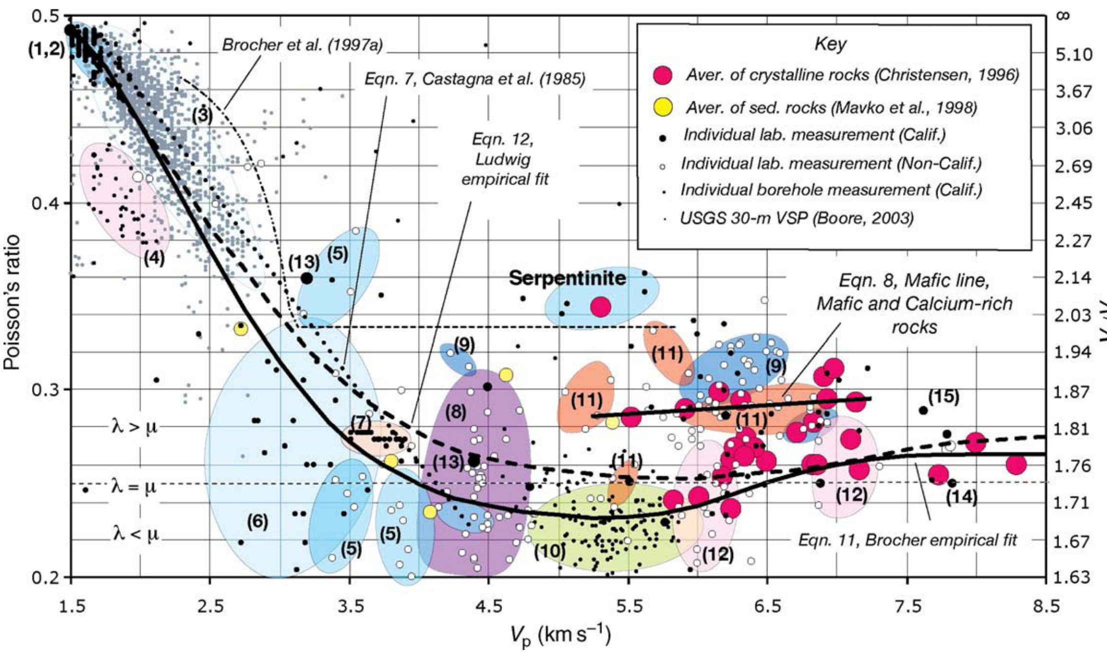


Figure 8 Poisson's ratio as a function of V_p for common lithologies. Colored ellipses highlight measurements reported by a single reference: bold numbers in parentheses link ellipses to results of similar studies. The thin horizontal dashed line shows Poisson's ratio of 0.25 (V_p/V_s = 1.73) commonly assumed for the crust when the first Lame constant, λ, equals the shear modulus, μ. After Brocher TM (2005) Empirical relations between elastic wavespeeds and density in the earth's crust. *Bulletin of the Seismological Society of America* 95(6): 2081–2092.

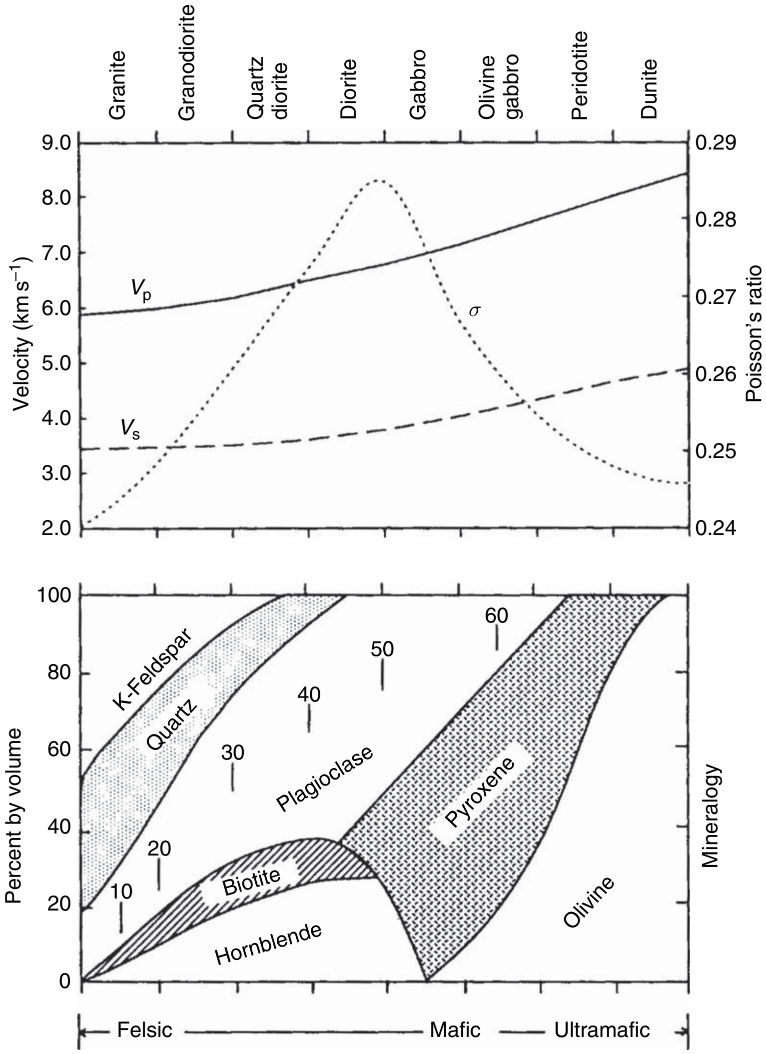


Figure 9 Variations in compressional wave velocity (V_p), shear wave velocity (V_s), and Poisson's ratio (σ) with mineral composition (Berry and Mason, 1959) for common igneous rock types. Percent anorthite content of plagioclase feldspar is shown within the plagioclase field. After Christensen NI (1996) Poisson's ratio and crustal seismology. *Journal of Geophysical Research* 100: 3139–3156.

1.11.4 Nonseismic Constraints on Crustal Structure

All rock types have a variety of distinct, albeit nonunique, physical properties that include density, magnetic susceptibility, and conductivity. Geophysical surveying techniques to measure these properties are highly developed, and it is possible to make detailed maps of lateral changes in rock magnetic properties, conductivity, and to estimate density variations. Advanced digital processing of such data enhances the reliability of interpretations, although resolution typically decreases with depth. Such nonseismic geophysical studies are widely used and have the capability to distinguish between competing geologic models of the structure of the crust.

1.11.4.1 Gravity Anomalies

Gravity anomalies reveal rock density variations, with the amplitude of the anomaly proportional to the density contrast and thickness of the anomalous body. Short-wavelength (<250 km) gravity anomalies are usually correlated with crustal structures, while

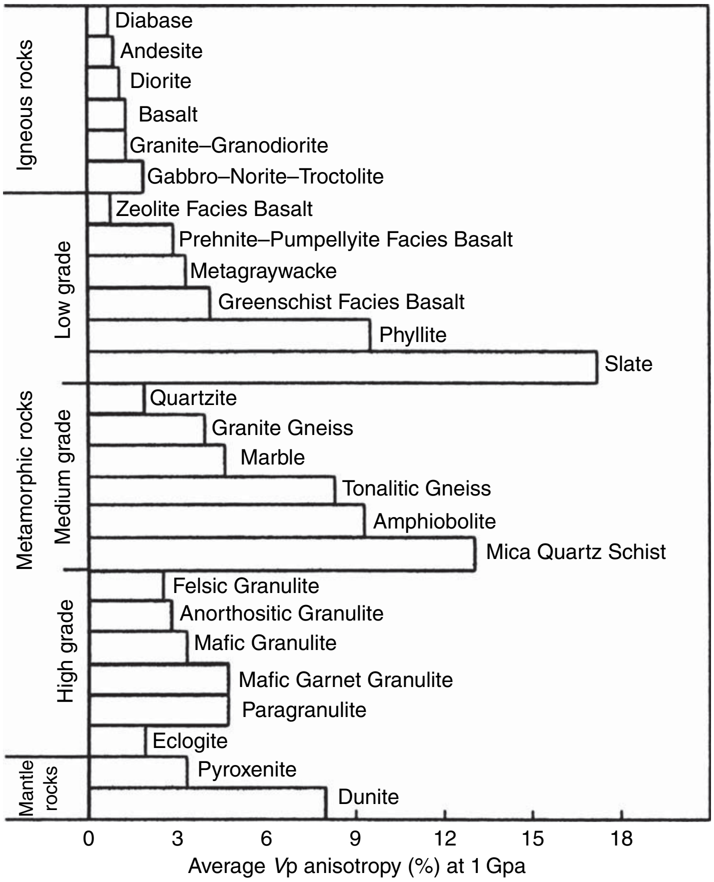


Figure 10 Average anisotropies for typical crustal and upper-mantle rock types, expressed in percent from the relation: 100 ($V_{max}-V_{min}$)/V_{avg}, at pressures corresponding to 35 km depth. After Christensen NI and Mooney WD (1995) Seismic velocity structure and the composition of the continental crust: A global view. *Journal of Geophysical Research* 100: 9761–9788.

long wavelength (<1000 km) gravity anomalies are correlated with lateral variations of mantle densities. Kane and Godson (1989) demonstrate that long-wavelength gravity highs are correlated with high mantle seismic velocities, and gravity lows with low mantle velocities. Kaban and Mooney (2001) and Kaben *et al.* (2003) show that upper-mantle density variations contribute long-wavelength gravity anomalies ranging from −250 MGal to +150 mGal. The largest of these positive anomalies over the continents were associated with the Andes, the East European Platform, the Alpin-Mediterranean fold belt, and the central south-eastern part of North America. The largest negative anomalies, indicating a thin lithosphere, are associated with vast Cenozoic regions of plume–lithosphere interaction: the East African Rift and the Basin and Range Province of western North America.

New satellite measurements of Earth's gravity field were begun in April 2002. The data from the *Gravity Recovery and Climate Experiment (GRACE)* satellites yield a complete measurement of the gravity field to harmonic degree 160 (300 km spatial resolution at the Earth's surface) every 30 days. These observations have improved the precision of the global gravity field by two orders of magnitude (Tapley *et al.*, 2005) For additional references on gravity studies of the crust see **Table 5a**.

1.11.4.2 Aeromagnetics

High-resolution aeromagnetic surveys can be used to define major regions of coherent structure in the Earth's crust (Kane and Godsen, 1989). Since rocks commonly retain magnetism that originates from the time of their formation, magnetic-anomaly data provide a unique opportunity to infer geological processes not readily observed through other geophysical quantities. One common example of this is

Table 3 Selected papers on the seismic properties of the uppermost mantle

References	Year
Al-Lazki *et al*.	2003, 2004
Allen *et al*.	2002
Anderson	1967
Anderson and Archambeau	1964
Artemieva and Mooney	2001
Bamford	1977
Bannister *et al*.	1991
Baraganzi and Ni	1982
Benoit *et al*.	2003
Bibee and Shor	1976
Bijwaard *et al*.	1998
Brocher *et al*.	2003
Bruneton *et al*.	2004
Calvert *et al*.	2000
Canales *et al*.	2000
Chen *et al*.	2003
DeShon and Schwartz	2004
Egorkin	2004
Egorkin *et al*.	1987
Enderle *et al*.	1996
Feng *et al*.	2004
Friedrich	2003
Fromm *et al*.	2004
Gilbert *et al*.	2005
Grand and Helmberger	1984
Grand *et al*.	1997
Gung and Romanowitz	2004
Hearn	1984, 1999
Hearn	1996
Hearn and Ni	1994
Hearn *et al*.	1991, 2004
Herrin	1969
Huang *et al*.	2004
Humphreys *et al*.	1984
Iyer nad Hitchcock	1989
Jordan	1975, 1979, 1988
Jordan and Frazer	1975
Kennett and Engdahl	1991
Kennett *et al*.	1995
Kind *et al*.	2002
Lei and Zhao	2005
Li and Romanowicz	1996
Liang *et al*.	2004
Lippitsch *et al*.	2003
Liu *et al*.	2005
Maggi and Priestly	2005
Matzel and Grand	2004
McNamara *et al*.	1997
Meissner *et al*.	2002
Mele	1998
Meyers *et al*.	1998
Montagner and Tanimoto	1990
Nolet	1977
Oliver	1962
Orcutt	1987
Panza *et al*.	2003
Pavlenkova	1996
Pilidou *et al*.	2004, 2005
Prodehl	1984
Rau and Wu	1995
Ringwood	1975
Ritzwoller and Levshin	1998
Ritzwoller *et al*.	2002a, 2002b
Romanowicz	1991, 1995
Sandoval *et al*.	2004
Sandvol *et al*.	2001
Savage	1999
Shapiro and Ritzwoller	2002
Shapiro *et al*.	2004
Silver	1996
Silver and Chan	1988
Sleep	2003
Song *et al*.	2004
Spakman *et al*.	1993
Trampert and Woodhouse	1995
van der Hilst *et al*.	1997
Van Heijst and Woodhouse	1999
Vinnik *et al*.	1992
Wang *et al*.	2002
Wortel and Spakman	2000
Yuan *et al*.	1997, 2000
Zhang and Lay	1996
Zhang and Tanimoto	1991
Zhang *et al*.	2004
Zhao and Xie	1993
Zhao *et al*.	1992

Table 4a Selected laboratory studies of seismic properties of rocks

References	Year
Bass	1995
Berckhemer *et al.*	1997
Birch	1960, 1961
Birch	1943, 1972, 1975
Carmichael	1982
Christensen	1965, 1966a, 1966b, 1971,1979, 1982, 1996
Christensen and Fountain	1975
Christensen and Mooney	1995
Christensen and Salisbury	1975
Christensen and Salisbury	1982
Clark	1966
Hamilton	1978
Jones and Nur	1983
Kern	1978
Kern *et al.*	1996, 2001
Nafe and Drake	1968
Simmons	1964
Usher	1962
Wepfer and Christensen	1991

Table 4b Selected laboratory studies of nonseismic properties of rocks

References	Year
Berckhemer *et al*.	1997
Carmichael	1982
Christensen and Salisbury	1979
Clark	1966
Duba	1972
Johnson and Olhoeft	1984

Table 5a Selected papers on crustal structure from gravity data

References	Year
Arvidson *et al*.	1984
Banks *et al*.	1977
Barton	1986
Bateman and Eaton	1967
Blakely	1995
Clowes *et al*.	1997
Couch and Woodcock	1981
Dehlinger	1978
Grant and West	1965
Hammer	1983
Hayford and Bowie	1912
Heiskanen and Moritz	1967
Heiskanen and Vening-Meinesz	1958
Hildenbrand *et al*.	1982
Hinze	1985
Kimbell *et al*.	2004
Lachenbruch *et al*.	1985
McNutt	1980
Parker	1973
Paterson and Reeves	1985
Plouff	1976
Roecker *et al*.	2004
Sandwell and Smith	1997
Simpson *et al*.	1987
Talwani and Ewing	1960
Tiberi *et al*.	2003
Turcotte and Schubert	2002
U.S. Department of Commerce	2001
Unsworth *et al*.	2000
Venisti *et al*.	2004
Watts	2001
Woollard	1943, 1959
Zoback and Mooney	2003

seafloor spreading, indicated by a series of magnetic stripes, originating from the mid-ocean ridge.

Magnetization is commonly associated with igneous rocks, but it is controlled more generally by the thermal history of the rock. The remnant magnetization of a mineral is fixed in the direction of the Earth's magnetic field when the mineral is cooled below the Curie temperature; the remnant

Table 5b Selected papers on crustal structure from aeromagnetic data

References	Year
Alvares *et al*.	1978
Baranov	1957
Blakely	1995
Blakely and Grauch	1983
Bond and Zietz	1987
Frost and Shive	1986
Grant and West	1965
Hahn *et al*.	1984
Hall	1974
Hemant and Maus	2005
Hinze	1985
Hinze and Zeitz	1985
Hood *et al*.	1985
Huestis and Parker	1977
Langel	1985
Langel *et al*.	1982
Mayhew and LaBrecque	1987
Mayhew *et al*.	1985
McEnroe *et al*.	2004
Parker	1971
Paterson and Reeves	1985
Plouff	1976
Purucker *et al*.	2002
Redford	1980
Reid	1980
Schouten	1971
Schouten and McCamy	1972
Sexton *et al*.	1982
Talwani	1965
USGS and Society of Exploration Geophysics	1982
Vacquier *et al*.	1951
Vogt *et al*.	1979
Von Freese *et al*.	1986
Williams *et al*.	1985
Zietz	1969, 1982

Table 5c Selected papers on the electrical properties of the crust

References	Year
Banks	1972
Berdichevskiy and Zhadanov	1984
Booker *et al*.	2004
Cagniard	1953
Feldman	1976
Gough	1974
Grant and West	1965
Hyndman	1988
Korja *et al*.	2002
Jones	1992
Jones *et al*.	2001
Li *et al*.	2003
Wannamaker *et al*.	1989

Table 5d Selected papers on crustal heat flow

References	Year
Cermak	1993
Chapman	1986
Jaupart and Mareschal	1999
McKenzie *et al*.	2005
Parson and Sclater	1977
Pollack and Chapman	1977
Pollack *et al*.	1993
Scalter *et al*.	1980
Stein and Stein	1992
Turcotte and Schubert	2002
Zang *et al*.	2002

magnetization is removed when heated above this temperature. Metamorphism can also change the magnetization of a rock, but the magnitude of the effect is usually small. So, in contrast to density, rock magnetization can range through several orders of magnitude (Kane and Godson, 1989).

Long-wavelength gravity and magnetic data are available from space-based observations (Purucker *et al*., 2002; McEnroe *et al*., 2004). The *CHAMP* (*CHAllenging Minisatellite Payload*) mission, is a German satellite designed for geoscientific and atmospheric research and applications. *CHAMP* is presently collecting precise gravity and magnetic measurements of the Earth (Hemant and Maus, 2005). For additional references on magnetic studies of the crust see **Table 5b**.

1.11.4.3 Geoelectrical Measurements

In general, the conductivity of the Earth is correlated with salinity, composition, and temperature (Keller, 1989; Jones, 1992). At the surface, electrical conductivity depends on the amount of salinity of the groundwater in a rock. At intermediate depths, conductivity depends on water content and composition (particularly graphite and sulfide content). At great depths, where temperatures rise to at least 500°C, conductivity is mainly a function of electron and ion mobility (Keller, 1989).

Most studies of the Earth's crust are based on magnetotelluric (MT) data (Keller, 1989). This method relies on measurements of five separate components of the time-varying electromagnetic field at the surface of the Earth. The analysis of these time series yields 1-D and 2-D models of the subsurface conductivity structure. When measurements are made for long periods (10 000 s and longer), estimates of the conductivity of the crust and upper mantle to a depth of 200 km and greater are possible (Jones, 1999). The source for electrically conductive material may be seen as high-density blocks within the crust.

Electrical conductivity profiles of the crust may be divided into marine and continental studies. Major marine studies include the RAMESSES marine experiment over the Reykjanes Ridge (Sinha *et al*., 1997; MacGregor *et al*., 1998), the Pressure, Electromagnetic, Gravity, Active Source Underwater Survey (PEGASUS) experiment in the north-east Pacific Ocean (Constable and Cox, 1996), and electromagnetic studies of the axial zone of the northern East Pacific Rise (Evans *et al*., 1999). On continents, electrical conductivity structure of stable regions, sutures and paleosubduction zones, regions of lithospheric extension, and orogens have all been investigated (Wannamaker *et al*., 1989; Jones, 1992; Jones *et al*., 2001). In most cases, these studies have been conducted in conjunction with active- and passive-source seismic profiles. Noteable results include the correlation between low shear-wave velocity and high electrical conductivity beneath the southern Tibetan Plateau. This correlation has been attributed to the presence of either partial melts or aqueous fluids in the middle crust (Nelson *et al*., 1996; Li *et al*., 2003). Thus, electrical studies provide an important additional constraint on the composition and physical state of the crust and upper mantle. For additional references on geoelectrical studies of the crust see **Table 5c.**

1.11.4.4 Heat Flow Data

Surface heat-flow data provide valuable information on temperatures within the crust. The highest heat-flow values are found at mid-ocean ridges and within geothermal zones and active volcanoes. Heat flow has been measured on a global basis with ocean, continents and their margins (Pollack *et al*., 1993). Surfical heat flow is the product of radiogenic heat production in the crust and heat transferred from the convecting mantle. In order for a lithospheric geotherm to be reliably calculated, crustal heat production and thermal conductivity must be estimated from laboratory measurements on typical crust rocks (Pollack and Chapman, 1977; Chapman, 1986; Cermak, 1993; Jaupart and Mareschal, 1999; Artemieva and Mooney, 2001). Crustal geotherms can be subdivided into hot, normal, and cold geotherms.

Within continental crust these three geotherms predict temperatures at a depth of 40 km (Moho) of about 500°C, 700°C, and 900°C, respectively. Thermal studies of the crust have provided valuable constraints on crustal composition and evolution (Rudnick and Fountain, 1995; Mareschal *et al.*, 1999; Artemieva and Mooney, 2001; Rudnick and Gao, 2003). For additional references on heat flow studies of the crust, see **Table 5d**.

1.11.4.5 Borehole Data

Deep scientific boreholes provide exceptional data regarding the physical properties of the upper crust. The deepest boreholes are the 12-km Kola Superdeep Borehole (KSDB) in Russia (Kozlovsky, 1987), the 9.1-km Kontinentales Tiefbohrprogramm (KTB) in Germany (Emmermann and Lauterjung, 1997), and the 6.8-km and 6.5-km Gravberg–Stenberg boreholes in Sweden (Juhlin, 1988; Papasikas and Juhlin, 1997). In addition, there are numerous scientific boreholes to depths of 3–5 km. These boreholes provide direct sampling of the composition of the upper crust, as well as measurements of *in situ* seismic velocities, density, temperature, state of stress, rock porosity, and the fluid pressure (Smithson *et al.*, 2000; Kern *et al.*, 2001). Evidence has also been obtained for crustal shear zones containing electrically conductive graphite and sulfides. An unexpected result is the presence of free fluid throughout the entire depth range of the KSDB and KTB boreholes.

1.11.4.6 Surface Geology, Exposed Deep Crustal Sections, and Xenolith Data

Surface geology, exposed deep crustal sections, and xenolith samples provide direct observations of the composition and physical properties of the crust. The composition of the upper continental crust is, by definition, evident in global geologic maps which are dominated by felsic intrusive rocks and low-grade metamorphic rcoks, particularly shales and sandstones (Clarke, 1889; Clarke and Washinton, 1924). The recognition that mountain belts provided exposures of the deep crust can be traced to the work of Elie de Beaumont (1847) who studied the Pyreenes. It was, however, many years later that these observations were systematically analyzed in terms of cross-sections of the entire crust (Fountain and Salisbury, 1981; Salisbury and Fountain, 1990; Percival *et al.*, 1992). Xenoliths are samples from the deep crust (and mantle lithosphere) that have been carried to the surface by volcanic activity (Kay and Kay, 1981). These samples provide excellent constraints on lower crustal composition (Fountain *et al.*, 1992; Rudnick and Gao, 2003).

1.11.5 Structure of Oceanic Crust and Passive Margins

Several thousand measurements of the deep seismic structure of the Earth's crust have been made. However, the geographic distribution of seismic measurements is uneven (**Figure 11**), with more

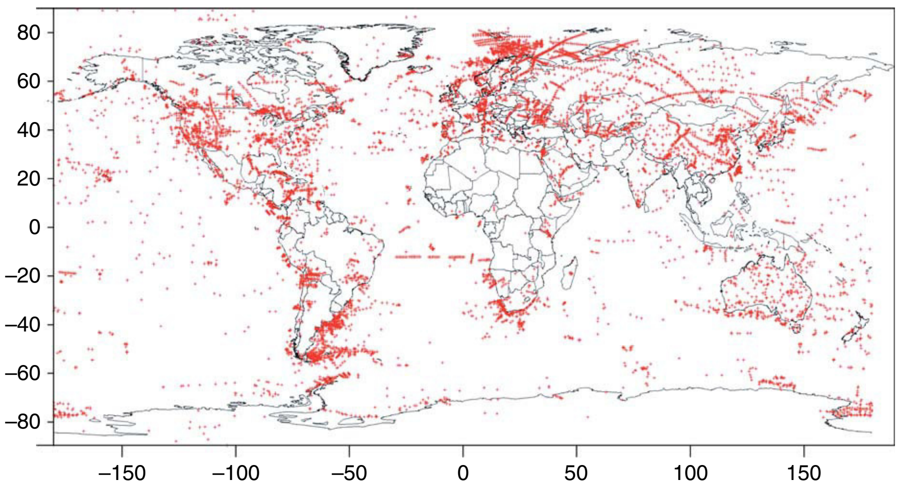


Figure 11 Locations (solid triangles) of individual seismic velocity–depth measurements made within the Earth's crust, 1920–present. Up to 1980, the majority of these measurements were made using the seismic refraction/wide-angle reflection technique. Since 1980 a great many determinations have been made using receiver function analysis of teleseismic arrivals and local earthquake tomography (see text).

results available for the Northern Hemisphere, and a concentration of data in North America, western Europe, and Eurasia. In the Southern Hemisphere, Australia and New Zealand have abundant data. Oceanic data are widely available for all oceans. Here we summarize the principle results obtained by these seismic data, and then present a global model for the Earth's crust.

1.11.5.1 Typical Oceanic Crust

The seismic velocity structure of oceanic crust was established in the 1950s, prior to the acceptance of plate tectonics and seafloor spreading. Oceanic crust was found to be uniformly thinner than continental crust. Much of the knowledge of the structure of ocean crust has come from seismic refraction/wide-angle reflection profiles. These seismic profiles use air gun or explosive sources that are recorded by either hydrophones or ocean-bottom seismometers. Passive seismology has limited application since most receivers are on continents or islands. However, a few tomographic studies of crustal structure at mid-ocean ridges have been completed (Wolfe *et al.*, 1995).

In their pioneering studies, Hill (1957) and Raitt (1963) divided 'normal' oceanic crust into separate, uniform seismic layers, known as 'Raitt–Hill layering.' The basic construction is (1) 0.5 km of soft sediments (layer 1) with a P-wave velocity of 2.0 km s^{-1}; (2) a 2–3-km-thick upper layer (layer 2) with a velocity of 2.5–6.4 km s^{-1}, and (3) a 4–5-km-thick lower crustal layer (layer 3), with a velocity of 6.5–7.3 km s^{-1}. The total thickness of ocean crust is 6–8 km. Layer 2, consists largely of pillow lavas and dykes, while layer 3 consists of a 'sheeted' dyke complex composed of diorites and gabbros (**Figure 12**). More details regarding the structure of the crust have been obtained using modern analysis methods. The application of synthetic seismogram modeling to marine seismic refraction/wide-angle reflection data indicates that the boundary between layer 1 and layer 2 is often transitional, while the boundary between layer 2 to layer 3 is relatively sharp (Spudich and Orcutt, 1980).

In the late 1970s, it was proposed that layer 2 could be further subdivided into three layers: 2A, 2B, and 2C. According to Ewing and Houtz (1979), two distinct layers with seismic velocities of about 3.5 km s^{-1} (layer 2A) and 5.2 km s^{-1} (layer 2B) were consistently identified. Below layer 2B, but above layer 3, a third layer with a seismic velocity of 6.0–6.2 km s^{-1} (layer 2C) was detected. Orcutt *et al.* (1976) and White *et al.* (1992) review previous work and provide a modern synthesis of the seismic structure of typical oceanic crust. Layer 1 lies beneath an average 4.5 km of sea water and is composed of sediments (pelagic sediments, silts, muds, and sand) and is approximately 0.5 km thick, with a seismic velocity of 1.5–2.0 km s^{-1}, increasing with depth as the sediments consolidate. Layers 2A–C, the volcanic layer, is 2.11 ± 0.55 km

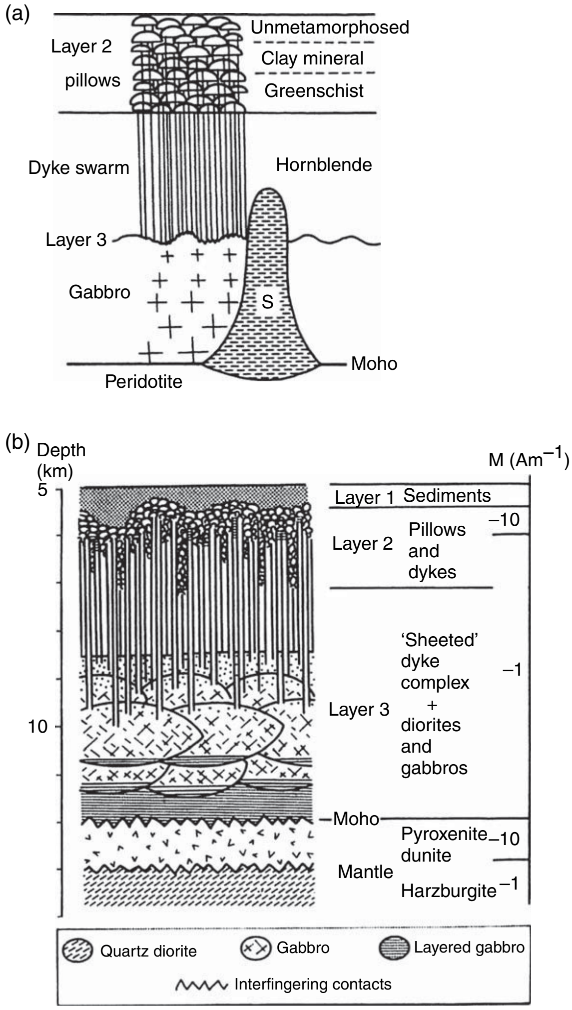


Figure 12 Compositional models of the oceanic crust derived from seismic measurements and exposed crustal sections: (a) crust model of Cann (1970); S refers to serpentine; (b) crustal model of Vine and Moores (1972). Traditionally, the oceanic crust is described as being composed of three layers, termed seismic layers 1–3. According to model (b), layer 1 is sediments; layer 2 is made up of basaltic pillow lavas and their feeder dikes, unmetamorphosed in their upper parts; layer 3 is composed of sheeted dykes underlain by massive plutonic diorites and gabbros. Seismic velocities within these layers are shown in **Figure 13(b)**.

thick, with a seismic velocity of 2.5–6.6 km s^{-1}. Layer 3, sometimes called the oceanic layer, is 4.97 ± 0.90 km thick, with a seismic velocity of 6.6–7.6 km s^{-1}. The upper mantle has an average seismic velocity of 7.9–8.1 km s^{-1}. See Table 6a for additional references on oceanic crust studies. Table 7a lists selected papers on the composition of oceanic crust.

Table 6a Selected papers on the seismic structure of oceanic crust

References	Year
Au and Clowes	1984
Barclay *et al*.	1998
Begnaud *et al*.	1997
Bibee and Shor	1976
Bown and White	1994
Butler	1986
Canales *et al*.	2000
Cann	1974
Cannat	1996
Caress *et al*.	1995
Carlson *et al*.	1980
Chapman and Orcutt	1985
Charvis *et al*.	1995
Chen	1992
Christensen	1972
Christeson *et al*.	1997
Clowes *et al*.	1999
Coffin and Eldholm	1994
Collier and Singh	1997, 1998
Darbyshire *et al*.	2000
Detrick *et al*.	1987, 1990, 1993
El Shazly	1982
Ewing *et al*.	1955
Ewing and Nafe	1982
Foulger *et al*.	2003
Hess	1962
Hill	1963
Hyndman	1979
Jackson and Oakey	1986
Kempner and Gettrust	1982
Laske and Masters	1997
Lindwall	1988
Mair and Forsyth	1982
Maxwell	1970a, 1970b
McKenzie and Bickle	1988
Müller *et al*.	1997
Mutter and Karson	1992
Mutter and Mutter	1993
Nur and Ben-Avraham	1982
Operto and Charvis	1996
Orcutt *et al*.	1976
Oxburg and Parmetier	1977
Peirce and Barton	1991
Purdy and Detrick	1986
Rabinowitz *et al*.	1988
Raitt	1963
Richardson *et al*.	1998
Ritzwoller and Levshin	2002
Shearer and Orcutt	1986
Shor	1967
Sinha *et al*.	1981
Sinha and Louden	1983
Sleep	1990
Smith and Sandwell	1997
Spudich and Orcutt	1980
Stein and Stein	1992
Su *et al*.	1992
Thinon *et al*.	2003
Toomey *et al*.	1990
Tucholke	1986
Tucholke and Uchupi	1989
Vera *et al*.	1990
Walck	1984
White *et al*.	1992
White *et al*.	1984
White and Clowes	1990
Whitmarsh *et al*.	1982
Whitmarsh and Calvert	1986
Wilcock *et al*.	1995

Table 6b Selected papers on the seismic structure of continental margins

References	Year
BABEL working group	1993
Barazangi and Brown	1986a, 1986b
Barton and White	1997
Blundell and Raynaud	1986
Brocher	1995
Chian *et al*.	1995, 1999
Clegg and England	2003
Clowes *et al*.	1999
Clowes *et al*.	1987
Clowes, and Hyndman	2002
Davis and Kusznir	2004
Dean *et al*.	2000
DeShon and Schwartz	2004
El Shazly	1982
Eldholm and Grue	1994
Eldholm *et al*.	2002
England	2000
Ewing *et al*.	1937
Ewing *et al*.	1966
Fernandes *et al*.	2004
Fowler *et al*.	1989
Heacock	1977
Hemant and Maus	2005
Holbrook and Keleman	1993
Horsefield *et al*.	1993
Jensen	1961
Klemperer and Hobbs	1991
Klemperer and Mooney	1998a, 1998b
Matthews	1986

(Continued)

Table 6b (Continued)

References	Year
Matthews and Cheadle	1986
Matthews and the BIRPS group	1987
McKenzie and Bickle	1988
O'Reilly *et al*.	1998
Roberts *et al*.	1988
Tréhu *et al*.	1994
Todd *et al*.	1988
White and McKenzie	1989
White *et al*.	1987a, 1987b

Table 6c Selected papers on the seismic structure of continental crust

References	Year
Barazangi and Brown	1986a, 1986b
Bartelson *et al*.	1982
Barton	1992
Behrendt *et al*.	1988
Beloussov and Pavlenkova	1984
Beloussov *et al*.	1991
Beloussov *et al*.	1988
Blundell *et al*.	1992
Bonini and Bonini	1979
Bourjot and Romanowicz	1992
Brown *et al*.	1986
Clitheroe *et al*.	2000
Clowes *et al*.	1999
Clowes *et al*.	1997, 1987, 1995
Curtis and Woodhouse	1997
Dahl-Jensen *et al*.	2003
Das and Nolet	1998
DESERT group	2004
Drewry and Mooney	1983
Fliedner and Klemperer	1999
Fountain *et al*.	1984
Fromm *et al*.	2004
Giese *et al*.	1976
Guterch *et al*.	1999
Guterch *et al*.	2003
Hale and Thompson	1982
Hamilton	1976
Hart	1969
Heacock	1971, 1977
Hofsetter and Bock	2004
Holbrook *et al*.	1992
Hole *et al*.	2000
James	1971
James and Steinhart	1966
Jarchow and Thompson	1989
Julià and Mejía	2004
Kimbell *et al*.	2004
Kinck *et al*.	1993
Kind *et al*.	1995
Klemperer and Mooney	1998a, 1998b
Langston *et al*.	2002
Laske and Masters	1997
Levshin *et al*.	2005
Li and Mooney	1998
Ludwig and Houtz	1979
Makovsky *et al*.	1996a, 1996b
Makris	1978
Mechie *et al*.	2004
Meissner	1973, 1986
Meissner and Bortfeld	1990
Meissner *et al*.	1987, 1991
Minshull	1993
Mitchell and Herrmann	1979
Mooney and Brocher	1987
Mooney and Meissner	1992
Mooney *et al*.	2002
Mueller	1973, 1977, 1978
Nakamura *et al*.	2003
Nelson *et al*.	1996
O'Reilly *et al*.	1996
Oliver *et al*.	1976, 1983
Olsen	1995
Orcutt	1987
Owens and Zandt	1985
Owens *et al*.	1984
Pakiser	1963
Pakiser and Mooney	1989
Pakiser and Steinhart	1964
Pavlenkova	1996
Petit *et al*.	1998
Pfiffner *et al*.	1997
Prodehl	1970, 1979, 1984
Rai *et al*.	2003
Rao *et al*.	1999
Rapine *et al*.	2001
Reddy and Vijaya Rao	2000
Reddy *et al*.	1999
Regnier *et al*.	1992
Roecker *et al*.	1993
Salah and Zhao	2003
Sandvol *et al*.	1998
Shapiro *et al*.	2004
Snyder *et al*.	1990
Steinhart	1967
Steinhart and Meyer	1961
Stern and McBride	1998
Swenson *et al*.	2000
Thybo *et al*.	2003
Tilmann *et al*.	2003
Wang *et al*.	2003
Woollard	1966
Xu *et al*.	2002
Yliniemi *et al*.	2004
Zandt *et al*.	1995
Zelt and Forsyth	1994
Zhao *et al*.	2001
Zhu and Kanamori	2000
Zorin *et al*.	2003

Table 7a Selected papers on oceanic crustal composition

References	Year
Christensen	1972, 1996
Bown and White	1994
Cann	1974
Charvis *et al*.	1995
Christensen and Salisbury	1982
Condie	1989
Hess	1962
Hyndman	1979
Kempner and Gettrust	1982
Lindwall	1988
Nur and Ben-Avraham	1982
Operto and Charvis	1996
White *et al*.	1992

Table 7b Selected papers on continental crustal composition

References	Year
Beloussov and Pavlenkova	1984
Blundell *et al*.	1992
Christensen	1996
Christensen and Fountain	1975
Christensen and Mooney	1995
Christensen and Salisbury	1975
Condie	1989
Downes	1993
Durrheim and Mooney	1994
Fliedner and Klemperer	1999
Fountain	1986
Fountain *et al*.	1984
Fountain and Salisbury	1981
Goodwin	1991, 1996
Halliday *et al*.	1993
Holbrook *et al*.	1992
Jordan	1979
Julià and Mejía	2004
Kozlovsky	1987
Kusznir and Matthews	1988
Meissner *et al*.	2002
Meissner and Mooney	1998
Mooney and Meissner	1991
Nur and Ben-Avraham	1982
Ringwood	1975
Rudnick and Fountain	1995
Sandmeier and Wenzel	1990
Shapiro *et al*.	2004
Silver and Chan	1988
Sleep	2003, 2005
Smithson *et al*.	1987
Taylor and McLennan	1985
Upton *et al*.	2001
Zandt and Ammon	1995
Ziegler	1990

1.11.5.2 Mid-Ocean Ridges

The concept of seafloor spreading from mid-ocean ridges (**Figure 2**) was first proposed in the early 1960s by several workers, including most prominently the American geologist Harry H. Hess (Hess, 1965). Its major tenets gave great support to the theory of continental drift and provided a conceptual base for the development of plate tectonics.

Mid-Ocean ridges can be separated into three categories: fast spreading, intermediate spreading, and slow spreading. Fast-spreading ridges have a spreading rate of 8–16 cm yr^{-1}; intermediate- spreading ridges have a spreading rate of 4–8 cm yr^{-1}; and slow-spreading ridges have a spreading rate of 1–4 cm yr^{-1} (Perfit and Chadwick, 1998).

The seismic structure of a fast-spreading ridge shows that the intrusive zone is only 2–3 km wide, and normal oceanic crust is found 5–6 km away from the ridge axis (**Figure 13**). Directly beneath the ridge axis, an upper crustal low-velocity zone exists that corresponds to a zone of partial melting. This seismic structure is in contrast to the earlier hypothesis that anomalous oceanic crust extends for tens of kilometers away from the axis of a mid-ocean ridge.

1.11.5.3 Oceanic Plateaux and Volcanic Provinces

Oceanic plateaux are one type of the Large Igneous Provinces (LIPs) that cover portions of the oceans and continents (i.e., flood basalt provinces; Eldholm *et al.* (2002), Coffin and Eldholm (1994), Ernst and Buchan (2003)). While continental flood basalt provinces were recognized in the early twentieth century (Holmes, 1918), regions of unusually thick oceanic crust were not identified until the 1970s. Edgar *et al.* (1971) originally discovered an overthickened region within the Caribbean Plate, and when a number of similar features were documented, they were called 'oceanic flood basalt provinces' (Donnelly, 1973). The term 'ocean plateau' was suggested by Kroenke (1974) when the Ontong Java Plateau in the western Pacific was explored using seismic refraction/wide-angle reflection profiles. More than 12 oceanic plateaux have been identified (**Figure 14**), and these have anomalous crustal structure in comparison with normal oceanic crust.

The crustal structure of several ocean plateaux have been resolved using seismic and gravity data, including recent studies on the Kerguelen and Ontong Java Plateaux. Farnetani *et al.* (1996) and

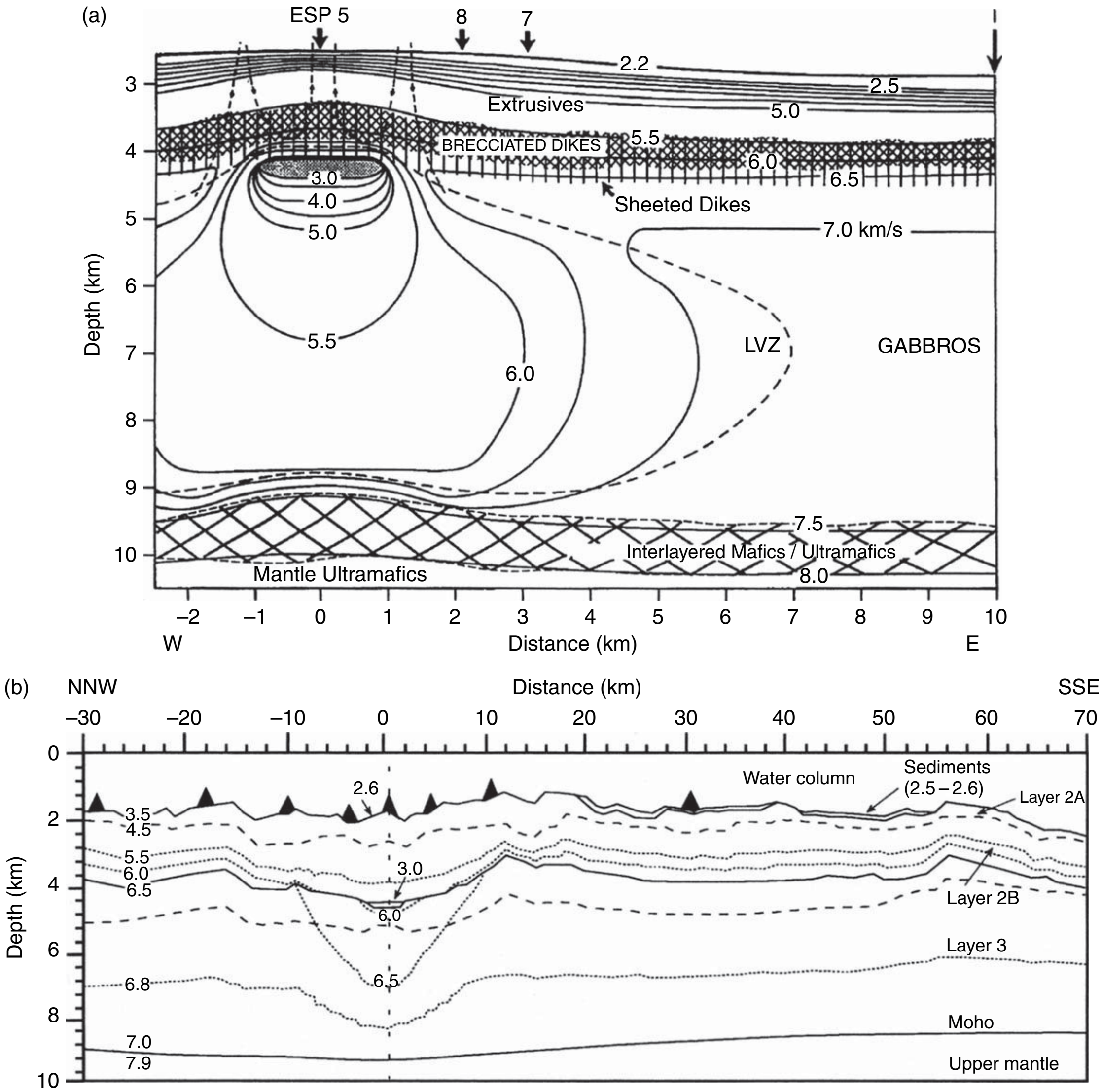
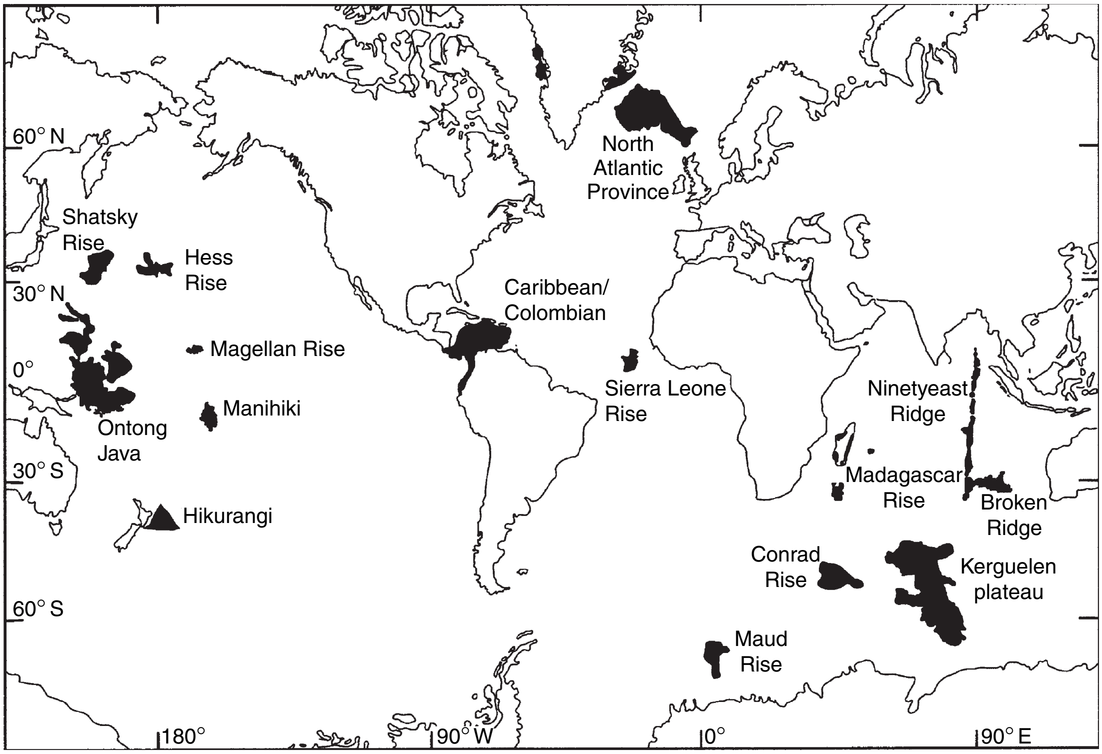


Figure 13 (a) P-wave velocity model and interpretation, based on expanding spread profile and multichannel reflection data, of the fast-spreading East Pacific Rise axis at 9° N. Arrows mark ESP locations. (b) P-wave velocity model and interpretation, based on OBS and seismic reflection data, of the slow-spreading Reykjanes Ridge axis at 57°45′ N. Triangles mark OBS locations and dashed lines mark changes in velocity gradient. (a) Redrawn from Vera EE, Mutter JC, Buhl P, *et al*. (1990) The structure of 0- to 0.2-m.y.-old oceanic crust at 9°N on the East Pacific Rise from expanded spread profiles. *Journal of Geophysical Research* 95: 15529–15556. (b) Redrawn from Navin D, Peirce C, and Sinha MC (1998) The RAMESSES experiment– II. Evidence for accumulated melt beneath a slow spreading ridge from wide–angle refraction and multichannel reflection seismic profiles. *Geophysical Journal International* 135: 746–772 and Minshull TA (2002) Seismic structure of the oceanic crust and rifted continental margins. In: Lee WHK, Kanamori H, and Jennings PC (eds.) *International Geophysics Series 81A: International Handbook of Earthquake and Engineering Seismology*, pp. 911–924. San Diego, CA: Academic Press.

Gladczenko *et al.* (1997) present models for the Ontong Java Plateau that show high seismic velocities (7.1 km s^{-1}) throughout most of the crust. These high velocities are likely due to the presence of basalt and olivine–pyroxene cumulates, with high-velocity garnet granulite in the lower crust. Gladczenko *et al.* (1997) suggested that these garnets may have formed from the deformation and hydrothermal alteration of lower crustal cumulates.

More recently, measurements of upper-mantle shear-wave splitting and shear-wave velocity have suggested the presence of a 300 km thick, long-lived,

(a)



(b)

Oceanic plateau	**Mean age (Ma)**	**Area (10^6 km^2)**	**Thickness range (km)**	**Volume (10^6 km^3)**
Hikurangi	early-mid Cretaceous	0.7	10–15	2.7
Shatsky Rise	147	0.2	10–28	2.5
Magellan Rise	145	0.5	10	1.8
Manihiki	123	0.8	>20	8.8
Ontong Java	121(90)	1.9	15–32	44.4
Hess Rise	99	0.8	>15	9.1
Caribbean	88	1.1	8–20	4.4
South Kerguelen	110	1.0	~22	6.0
Central Kerguelen/Broken Ridge	86	1.0	19–21	9.1
Sierra Leone Rise	~73	0.9	>10	2.5
Maud Rise	~>73	0.2	>10	1.2

Figure 14 (a, b) Map showing all major oceanic plateaux, and other large igneous provinces discussed in the text (after Saunders *et al*. 1999; Eldholm and Coffin, 2000). These plateaux have measured crustal thicknesses of 10–32 km, and an average thickness (22 km) that is three times that of typical oceanic crust.

rheologically strong, and chemically depleted root beneath the Ontong Java Plateau (Klosko *et al.* 2001). Klosko *et al.* (2001) further propose that this chemically depleted root originated from mantle melting processes, which would contribute lower-density material to the base of the plateau, increasing the overall buoyancy of the Ontong Java Plateau.

At the present time, the process of ocean plateau formation is not well understood. There are a number of models for how large volumes of mafic magmas are generated and emplaced by processes unrelated to 'normal' seafloor spreading and subduction (Loper, 1983; McKenzie and Bickle, 1988; Campbell *et al.*, 1989; Griffiths and Campbell, 1990; Farnetani and Richards, 1995), but it is not understood why these eruptions occur in such a rapid, concentrated period of time. Most ocean plateaus were formed in a short time, less than 2–3 My (Coffin and Eldholm, 1994, 2004), which may raise important questions about mantle processes and source regions (Hart *et al.*, 1992; Stein and Hoffman, 1994). During the most recent phase of LIP formation, in the mid-Cretaceous, the Ontong Java, Manihiki, Hess Rise, and Caribbean–Columbian plateaus were formed in the Pacific, while the Kerguelen Plateau formed in the Indian Ocean (Kerr, 2003).

If the plateaus are accreted adjacent to continental margins or island arcs, they may eventually significantly contribute to the growth of existing and new continents (Abbott and Mooney, 1995; Abbott, 1996; Albarede, 1998). Due to their increased thickness relative to normal oceanic crust, plateaus are especially buoyant, preventing them from completely subducting at active margins (Ben-Avraham *et al.*, 1981; Cloos, 1993; Kimura and Ludden, 1995), and potentially allowing the top layers to peel off and -merge with the continental crust (Kimura and Ludden, 1995).

Ideas about the origin and deep mantle roots of hot spots and mantle plumes have been debated for some 40 years (Wilson, 1963), and the deep seismic structure of these features remains controversial (Ritsema and Allen, 2003; Montelli *et al.*, 2004). Currently, there are two different models for the crust and upper mantle beneath Iceland, one of the two most prominent hot spots on the planet (the other being the Big Island of Hawaii). The 'thin-crust model' is based on MT data, heat flow from shallow wells, petrogenetic models, and seismic data. It suggests a ~10–15 km thick crust under the main rifting axis of Iceland, with a 25 km thick, older crust in eastern, western, and north–central regions of the island. There is also a thin, highly conductive, molten basaltic layer. The 'thick-crust' model is based entirely on seismic data, and suggests a Moho depth of 20–40 km. **Figure 15** is a schematic cross-section across the center of Iceland compiling all available seismic, MT, heatflow, and viscosity data (Bjornsson *et al.*, 2005). A unique and prominent feature beneath this hot spot is the continuous good conductor above the underlying asthenosphere. Bjornsson *et al.* (2005) suggest that the 20–40 km deep discontinuous reflector does not necessarily represent the Moho, and thus supports the 'thin-crust' model. Further data are need to resolve this controversy.

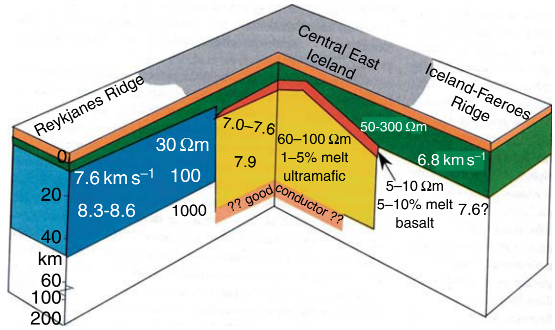


Figure 15 Simplified cross-section showing the main structural features of the Icelandic crust and mantle. The left part of the figure shows a cross-section east and parallel to the Reykjanes ridge along the seismic profile collected during the Reykjanes Ridge Iceland Seismic Experiment. The right part of the figure shows a profile running from central Iceland into the Iceland-Faeroe ridge. Numbers are P-wave velocities (normal type font) and resistivities (italic font). After Björnsson A, Eysteinsson H, and Beblo M (2005) Crustal formation and magma genesis beneath Iceland: Magnetotelluric constraints. In: Foulger GR, Natland JH, Presnall DC, Anderson DL (eds.) *Geological Society of America*, *Special Paper 388 Plates*, *Plumes*, *and Paradigms* pp. 665–686. Boulder, CO: Geological society of America.

1.11.5.4 Ocean Trenches and Subduction Zones

Geophysical studies of oceanic trenches can be traced to gravity measurements made by Vening-Meinesz (1887–1966) in the Indonesian Archipelago in the 1930s. These negative gravity anomalies were interpreted by Vening-Meinesz (1948) as being due to pronounced downbuckling of the oceanic crust. The detailed structure of oceanic trenches was clarified from marine seismic profiles that were made 30 years after Vening Meinesz's pioneering gravity measurements. One of the best-studied trenches is the Nankai Trough, eastern Japan. Two crustal models derived from seismic refraction/wide-angle reflection and gravity data collected across the Nankai Trough (**Figure 16**) show the geometry of the subducting oceanic crust as it descends beneath the Japan volcanic arc (**Figure 16**). These models define the geometry of the thick sedimentary basins that are located between the Nankai Trough and continental Japan. These results are typical of many subduction zones, including the Cascades region of western North America. Due to the pronounced lateral variations across oceanic trenches and subduction zones, studies that combine multiple seismic and nonseismic data have been the most successful at determining the deep structure (Wannamaker *et al.*, 1989).

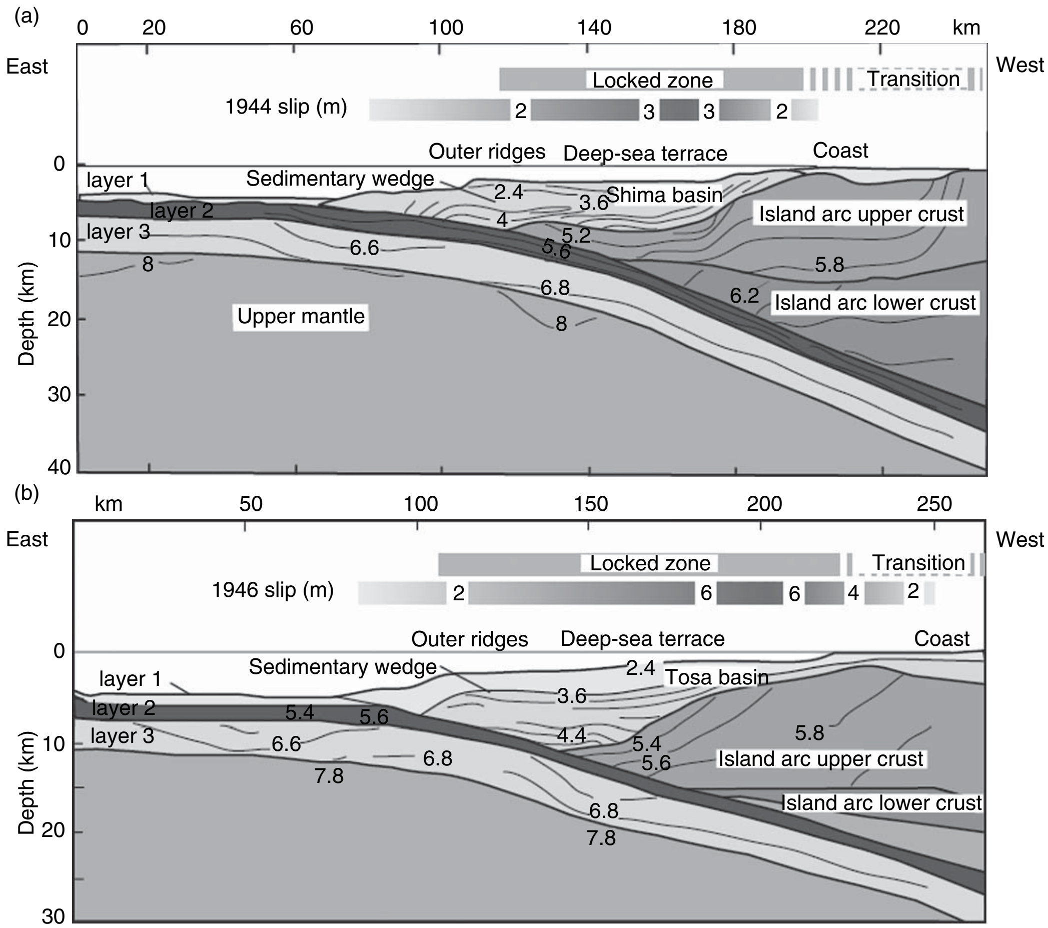


Figure 16 Seismic velocity structure of (a) the Tonanki subduction zone, site of the 1944 earthquake, and (b) the Nankai subduction zone, site of the 1946 earthquake. The relationship between the crustal structure and the locked zone is indicated (Hyndman *et al*., 1995; Sagiya and Thatcher 1999; Kodaira *et al*, 2000; Nakanishi *et al*. 2002). The crustal structure is typical of many subduction-zone complexes and includes a prominent low-seismic-velocity sedimentary wedge and the higher-velocity igneous crust of the island arc. After Wells RE, Blakely RJ, Sugiyama Y, Scholl DW and Dinterman PA (2003) Basin-centered asperities in great subduction zone earthquakes: A link between slip, subsidence, and subduction erosion? *Journal of Geophysical Research* 108(B10): 2507 (doi:10.1029/2002JB002072).

1.11.5.5 Passive Continental Margins

As the name implies, passive continental margins are boundaries between oceanic and continental regions where neither collisional deformation nor subduction is taking place. Despite their present-day tectonic quiescence, the crustal structure of passive continental margins is diverse and complex since they are formed by continental rifting that accompanies the breakup of a supercontinent, such as Pangea (200 Ma) or Rodinia (750 Ma). Prominent examples include the eastern seaboard of North America, the Gulf Coast, the Atlantic coasts of Europe, the coasts of Antarctica, and the east, west, and south coasts of Africa. Tectonic activity is minimal and erosional or weathering processes dominate, forming low-relief geography and increased sedimentary debris. These sedimentary basins are economically and scientifically valuable due to their large reservoirs of hydrocarbon and their recorded history of the rifting between two continents.

Passive margins are may be divided into two primary types: volcanic margins and nonvolcanic margins (White and McKenzie, 1989; Holbrook and Keleman, 1993: Eldholm *et al*., 2002). The North Atlantic margin, formed during early Tertiary lithospheric extension between Europe and Greenland, is one of the world's largest volcanic margins (Eldholm and Grue, 1994), as is the US Atlantic margin (Holbrook and Keleman, 1993).

The extensive volcanic rocks of this margin were formed by excess melting associated within a wide, hot zone of asthenospheric upwelling present during rifting (McKenzie and Bickle, 1988). In many cases a high-seismic velocity (7.3 km s^{-1}) lower crust is also present. Nonvolcanic passive margins are formed where asthenospheric temperatures remain lower during rifting. An example is the nonvolcanic margin of the Laborador Sea of northeastern Canada.

The passive margin between continental and oceanic lithosphere is sometimes characterized by a sharp drop in elevation and 20–30 km of crustal thinning over horizontal distances less than ~30 km. The abrupt lateral change in structure is indicated by several interpretations of wide-angle seismic and gravity data (Delhinger *et al.*, 1970; Jones and Mgbatogu, 1982; Todd *et al.*, 1988; Faleide *et al.*, 1990). A velocity profile of the passive margin off the Ghana coast is shown in **Figure 17**. This African ocean–continent transition indicates the absence of underplating beneath the continental basement, due to the lack of high velocities in the lower crust. See **Table 6b** for additional references on continental margins.

1.11.6 Structure of Continental Crust

1.11.6.1 General Features

Continental crust above sea level comprises 29% of the Earth's crust by area, but when submerged continental crust is taken into account, continental crust amounts to 41% of the total crust by area. Since some 75% of continental crust is covered either by sediments or water, geophysical measurements are a very important source of information about the properties of the continental crust. **Figure 18** shows the age of the basement of the crust, that is the age of the crystalline crust beneath the supracrustal sediments. It is evident in **Figure 18** that many continents are predominentaly composed of Pre-Cambrian shield and platforms. The deep structure of the continental crust has been investigated for nearly 100 years, beginning with the landmark study of Mohorovicic (1910) that defined the crust–mantle boundary. The locations of most of the presently available seismic refraction/wide-angle reflection profiles on continental crust are shown in **Figure 11**, and amounts to several thousand profiles. **Table 6c** lists many key papers regarding continental crust studies and **Table 7b** lists selected papers on the composition of continental crust.

Studies of the continental crust using active (explosive sources) began in earnest in the 1950s and 1960s (Tuve, 1951; 1953; Tuve *et al.*, 1954; Steinhart and Meyer, 1961; James and Steinhart, 1966; see also Pavlenkova, 1973; **Table 1**). These early studies provided the first clear evidence that the seismic structure of the crust varied in a systematic way with geologic setting. They also showed that the crust can be described as consisting of several layers that are separated by either sharp or transitional boundaries. The existence of crustal layers, which have a heterogeneous fine structure, can be viewed as the product of igneous differentiation of the crust, whereby silicic melts rise into the upper and middle crust, leaving behind a mafic lower crust. Igneous differentiation thus leads to a heterogeneously stratified crust, with granitic to dioritic plutons forming the upper layer.

The evidence for distinct layers within the continental crust depends almost exclusively on the interpretation of second-arriving phases (wide-angle reflections). Whereas some regions display clear secondary phases, in other regions the seismic velocity may increase gradually with depth, producing no distinct wide-angle intracrustal reflections (Levander and Holliger, 1992).

1.11.6.2 Principal Crustal Types

Seismic measurements of continental structure are best described in terms of the local geologic setting. The primary crust types are illustrated in **Figure 19**. In stable regions the continental crust has an average thickness close to 40 km, and there are typical crustal velocities within the upper, middle and lower crust (**Figure 19**). Compressional-wave seismic velocities in the upper crust are 5.6–6.3 km s^{-1}, corresponding to granitic and meta-sedimentary rocks. At a depth of 10–15 km the seismic velocity commonly increases to 6.4–6.7 km s^{-1} (the middle crust), corresponding to intermediate-composition plutonic rocks and amphibolite-grade metamorphic rocks. When the velocity increase is abrupt, this discontinuity is traditionally referred to as the 'Conrad discontinuity' (Conrad, 1925; **Table 1**), a term that is now out of date, as it came into use at a time when the crust was believed to consist of only two layers, an upper granitic layer and a lower basaltic layer. We now know from direct observation of exposed crustal sections and numerous seismic measurements that the crust is much more complex than this term implies. The lowermost crust of stable continental regions commonly has a

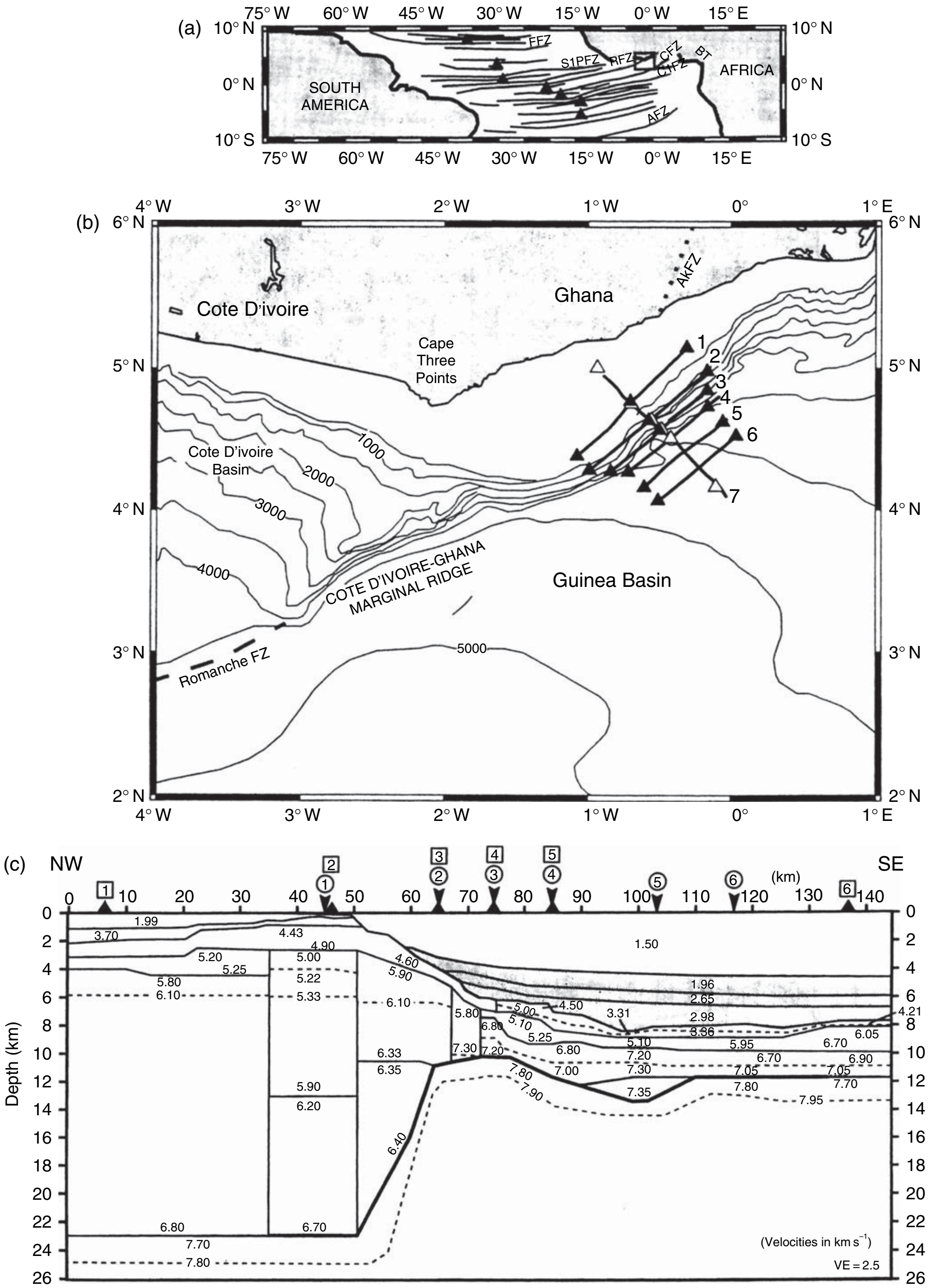


Figure 17 Example of an oceanic–continent transition zone from Ghana, West Africa. (a) Regional setting with Atlantic fracture zones. (b) Locations of wide-angle seismic profiles used to derive the crustal model. (c) Detailed seismic velocity model of the Ghana passive continental margin. The 23 km thick crust of the continental shelf thins to 10-12 km over a remarkably short distance. The igneous oceanic crust is covered by 3–4 km of low density, low-seismic-velocity sediments. From Edwards RA, Whitmarsh RB, and Scrutton RA (1997) The crustal structure across the transform continental margin of Ghana, eastern Equatorial Atlantic. *Journal of Geophysical Research* 102: 747–772.

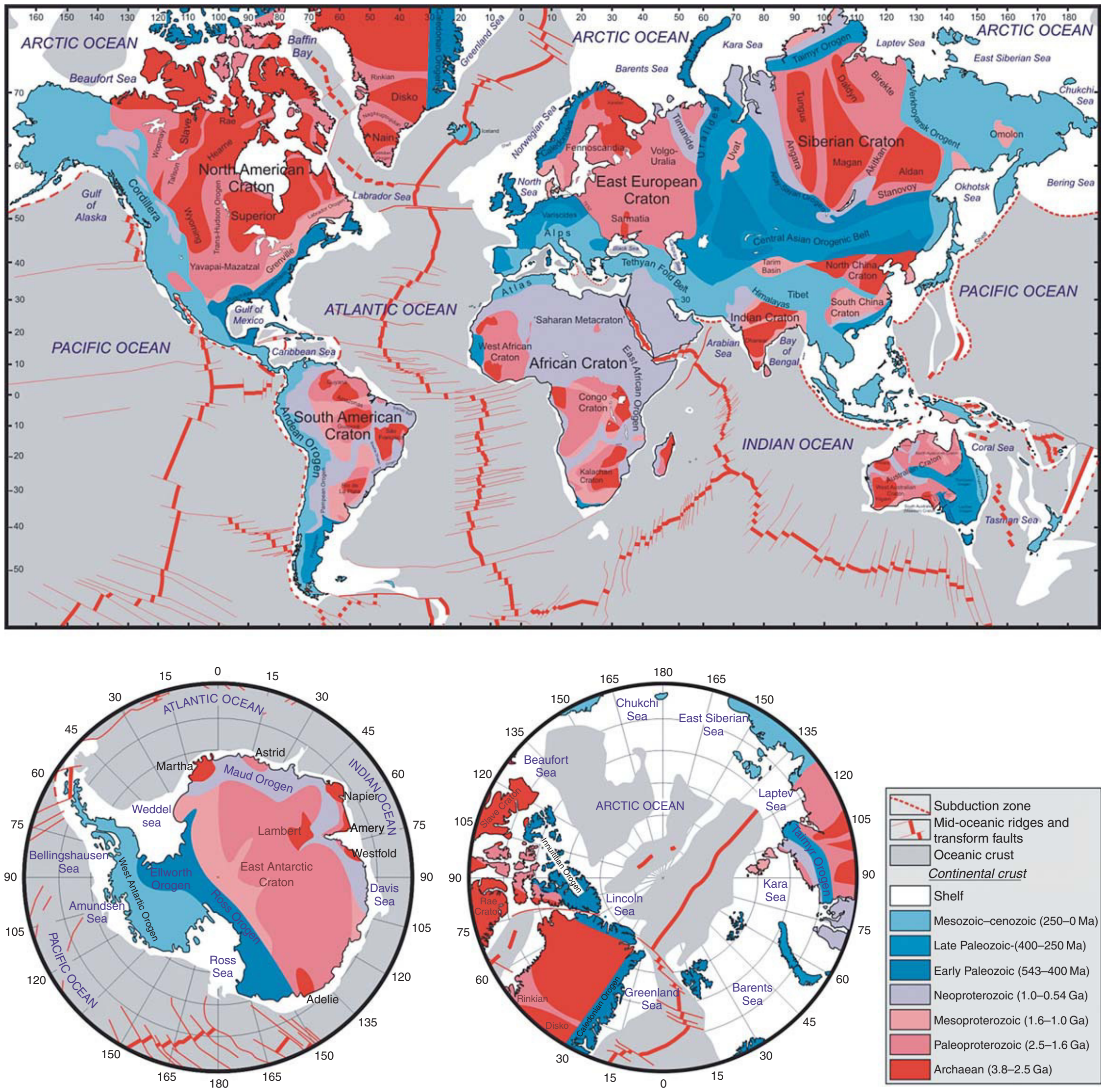


Figure 18 Basement age of the continental crust, distribution of mid-ocean ridges, oceanic crust, and continental shelf. The crust is subdivided by age. Pre-Cambrian shields and platforms comprise 69% of the continental crust by area. Seismic measurements cover much of the Earth's crust, but gap in coverage still exist (cf. **Figure 11**). Statistical averages and their standard deviations for crust of a specific age and tectonic setting make it possible to estimate crustal thickness and velocity structure in unmeasured regions, as is required to make complete global crust models (Mooney *et al*., 1998).

seismic velocity of 6.8–7.3 km s^{-1}. The seismic head wave (or diving wave) that travels within the uppermost mantle just below the Moho is known as the P_n phase, for 'P-wave normal phase' (Mohorovicic, 1910). This phase has a seismic velocity of 8.1 ± 0.2 km s^{-1} in stable continental regions. A wide-angle reflected phase from the Moho, known as P_mP, is generally clearly observed in active-source seismic profiles due to the large seismic-velocity increase (0.6–1.5 km s^{-1}) at this boundary.

Seismic measurements do not have a uniform global distribution (**Figure 11**) which affects attempts to calculate average crustal properties. The proportion of continental crustal types, by area, are 69% shield and platform (cratons), 15% old and young orogens, 9% extended crust, 6% magmatic arc, and 1% rift (Christensen and Mooney, 1995). Using these statistics, we calculate a weighted average for crustal thickness and average crustal velocity. This procedure corrects for the overrepresentation of

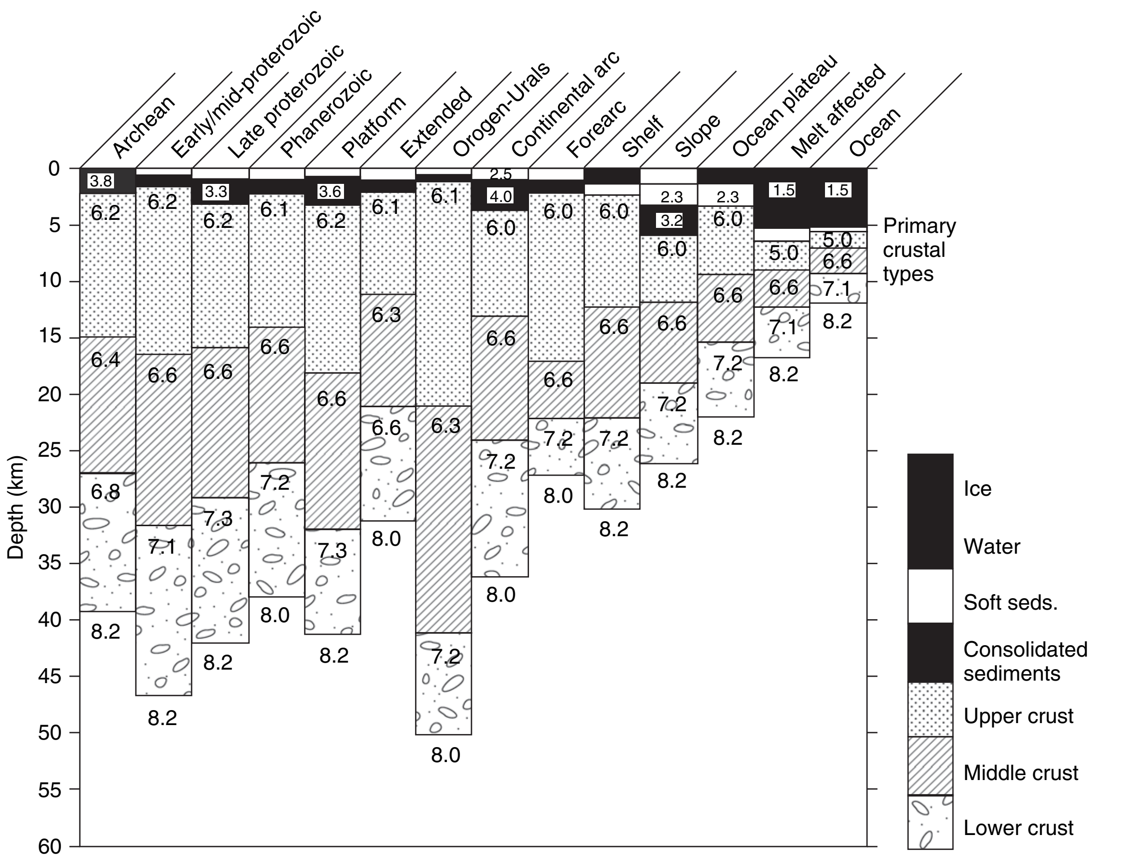


Figure 19 Fourteen primary continental and oceanic crustal types (Mooney *et al*. 1998). Typical P-wave velocities are indicated for the individual crustal layers and the uppermost mantle. Velocities refer to the top of each layer, and there commonly is a velocity gradient of 0.01–0.02 km s^{-1} per km within each layer. The crust thins from an average value of 40 km in continental interiors to 12 km beneath oceans.

crustal measurements in regions of extended crust, such as western Europe and the Basin and Range Province of western North America, and the scarcity of measurements from Africa, South America, Greenland, and Antarctica. The weighted mean crustal thickness and average crustal velocity are 41 km (SD 6.2 km) and 6.45 km s^{-1} (SD 0.21 km s^{-1}), respectively, as compared with the simple arithmetic average of 39.2 km (SD 8.5 km) and 6.45 km s^{-1} (SD 0.23 km s^{-1}; Christensen and Mooney, 1995). The weighted average is more representative of the average continental crust.

Seismic measurements of the deep crust from around the world provide a firm basis for defining the characteristics of primary crustal types associated with specific geologic settings (**Figure 19**). The thickest continental crust (70+ km) is found beneath the Tibetan Plateau and the South American Andes, both of which are young orogens. Continental crust with an elevation above sea level has an (unweighted) average thickness of 39 km, with a standard deviation of 8.5 km. Thus, 95% (two standard deviations) of the crust has a thickness of between 22 and 56 km. The higher value of this range (56 km) is well below the 70–75 km thickness of some orogens, which indicates that crustal thickness may not follow a strictly normal distribution. The thickest crust is usually young (Late Cenozoic) crust, and undergoes rapid uplift and erosion which results in crustal thinning.

Continental crust thinner than 30 km is generally limited to rifts and highly extended crust, including continental margins. The process of crustal extension rarely results in uniform stretching of the crust. Instead, the brittle upper crust fractures and rotates along normal faults and the middle and lower crust undergo pure shear extension. Nonuniform crustal extension over a large region gives rise to Moho undulations, which in turn drive lateral lower crustal flow (creep). Thus, tectonic processes can give rise to significant changes in the distribution of crustal materials. Lower crustal flow is not limited to extending crust; the gravitational forces associated with the high (4–5 km) topography of young orogens also drives crustal flow. A prominent example is the hypothesized southeast crustal flow of the northern and central Tibetan Plateau into the adjacent continental crust (Molnar and Tapponnier, 1975).

The deep structure of orogenic crust has been studied in nearly all the mountain belts of the world, including the South American Andes, Tibetan Plateau, Western Cordillera of North America, Urals, and the European Alps (**Figure 20**). Orogenic crust is commonly characterized by a highly thickened, low-density, low seismic-velocity upper crust combined with strong folding and thrusting (**Figure 20**). In some cases it appears that the lower crust is being subducted into the mantle, possibly aided by a phase transformation of the mafic lower crust to the dense eclogite facies (Rudnick and Gao, 2003). Due to the

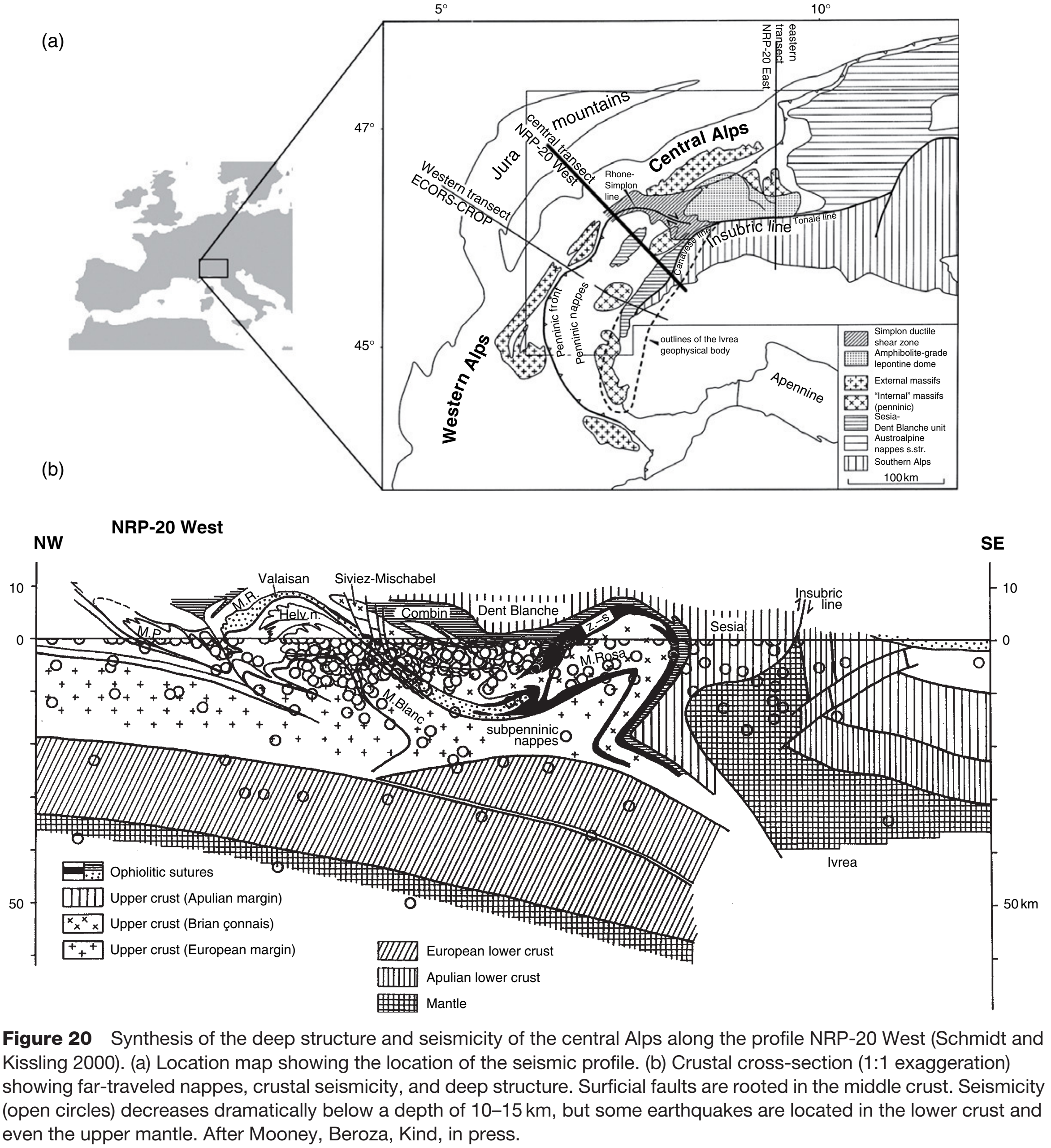


Figure 20 Synthesis of the deep structure and seismicity of the central Alps along the profile NRP-20 West (Schmidt and Kissling 2000). (a) Location map showing the location of the seismic profile. (b) Crustal cross-section (1:1 exaggeration) showing far-traveled nappes, crustal seismicity, and deep structure. Surficial faults are rooted in the middle crust. Seismicity (open circles) decreases dramatically below a depth of 10–15 km, but some earthquakes are located in the lower crust and even the upper mantle. After Mooney, Beroza, Kind, in press.

complexity of the crustal and upper-mantle structure, multiple seismic and nonseismic techniques are needed to reliably determine the deep structure of orogens.

1.11.6.3 Correlation of Crustal Structure with Tectonic Provinces

Shields and platform occupy by far the largest area (69%) of continental crust (**Figure 18**). These regions have an average crustal thickness of 41.5 km, very close to the weighted global average continental crustal thickness of 41 km. Orogens, young and old, show a wide range of thicknesses, from 30 to 75 km. Extended crust, as the name implies, has been thinned and shows an average thickness of 30.5 km. Rifts, both active and inactive, show a broad range, from 18 to 46 km. Tectonic provinces commonly have a complex crustal structure. For example, the Tibetan Plateau ranges in thickness from 55 to 75 km, and the Kenya rift from 20 to 36 km. Thus, significant variations sometimes occur within a single tectonic province. A second important observation is that there are numerous regions with anomalous crustal thickness. For example, southern Finland consists of a Proterozoic shield that is nearly at sea level. Global statistics would predict a crustal thickness of 41.5 ± 6.2 km. In fact, in southern Finland the crust reaches a maximum thickness of 65 km due to the persistence of an ancient crust root at a Pre-Cambrian suture zone. This example attests to the considerable variability of continental crustal properties.

1.11.7 Global Crustal Models

The studies of the Earth's crust that have been summarized in the previous sections are sufficient to form the basis for a global model of the Earth's crust. One simple representation is a contour map of global crustal thickness (**Figure 21**). This map shows several interesting features. Continental interiors generally have a crustal thickness of 35–45 km, with the thickest values beneath the high topography of the Tibetan Plateau and South American Andes (80 km). Most continental margins have a thickness of close to 30 km, and the vast oceanic basin are underlain by approximately 6–8 km-thick crust, plus the 4–5 km thick water layer. Such a contour map, while presenting the main variations in crustal thickness, lacks information regarding lateral variations in compressional and shear-wave velocity, and density. These physical properties vary strongly within the uppermost mantle as well. For this reason, it has proved valuable to create global crustal models that quantify not only crustal thickness, but seismic velocities and density for the entire crust and uppermost mantle.

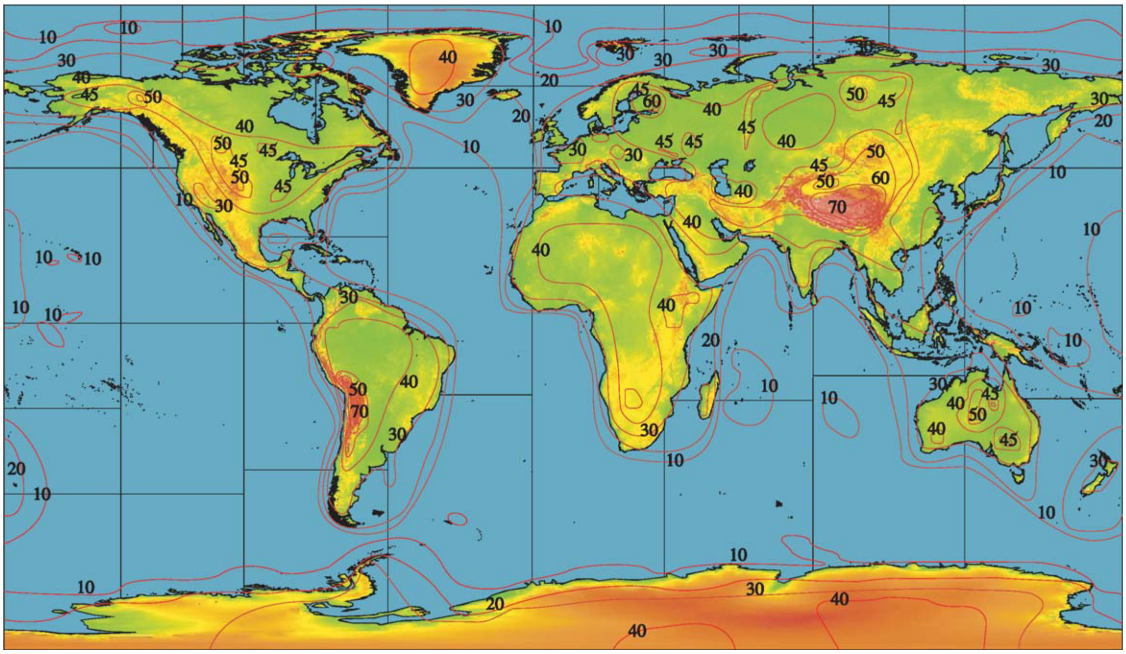


Figure 21 Global contour map of crustal thickness. Red lines indicate 10 km contour intervals.

Global models of the seismic velocity and density structure of the crust have numerous applications in geophysics. Such models provide regional traveltimes to determine accurate earthquake locations, and provide crustal corrections to improve mantle seismic tomographic models. Furthermore, lateral variations in mantle density may be inferred from long-wavelength gravity data if the density structure and thickness of the overlying crust is known. In addition, the crustal contribution to lithospheric stress and crustal isostasy can be calculated from crustal thickness, density, and topography (Mooney *et al.*, 1998).

The earliest 3-D seismic velocity model of the Earth's crust dates back approximately 20 years to Soller *et al.* (1982) who assembled one of the first compilations of global Moho and upper-mantle velocity. A $2° \times 2°$ cell model called 3SMAC followed more than a decade later (Nataf and Ricard, 1996). The 3SMAC model was derived using both seismological data and nonseismological constraints such as chemical composition, heat flow, and hot spot distribution, from which estimates of seismic velocities and the density in each layer were made. Two years later, CRUST 5.1 was introduced (Mooney *et al.*, 1998) incorporating twice the amount of active-source seismic data as 3SMAC. Statistical averages were calculated for the different tectonic regions (**Figure 22**) and these average models were used in regions with no direct seismic measurements. However, the $5° \times 5°$ resolution was still too coarse for regional studies. In 2000, CRUST 2.0 updated the ice and sediment thickness information of CRUST 5.1 at $1° \times 1°$ resolution, and presented crustal thickness data onto a $2° \times 2°$ grid (**Figure 23**). In addition, several high-resolution regional compilations of depth-to-Moho values have been developed for Europe (Meissner *et al.*, 1987; Geiss, 1987; Dèzes and Ziegler, 2001; Ritzmann *et al.*, 2007) and the Middle East and North Africa (Seber *et al.*, 2001).

Other published crustal models include WINPAK3D (Johnson and Vincent, 2002) and WENA 1.0 (Pasyanos *et al.*, 2004), which provide an estimate of the velocity and density structure of the upper lithosphere (i.e., whole crust and uppermost mantle, P_n and S_n velocity) for specifically defined geophysical regions. These models are based on independent compilations of sediment, crust, and mantle models and data previously constructed or collected within these regions. Pasyanos *et al.* (2006) describe a probabilistic inverse technique that allows for the use of multiple data sets in regional or global model building. Complete crustal models can be used to compare a variety of empirical observations over large geographic areas, to test the propagation of seismic waves, and to serve as starting models for tomographic inversion techniques. **Tables 8a and 8b** list select references on global and regional crustal models, respectively.

1.11.7.1 The Sedimentary Cover

The sedimentary cover plays an important role in global crustal models because these materials have low seismic velocities and low densities. Thus, the sedimentary cover can have a large influence on traveltimes of seismic body and surface waves, as well as on the global gravity field.

Although sedimentary rocks cover most of the ocean floor and nearly three-quarters of continental surfaces, they are estimated to constitute only 5% of the upper 16 km of the crust by volume (Rudnick and Gao, 2003). This volumetric estimate is based on a variety of sources: (1) direct calculation from exposed stratigraphic sections or boreholes, (2) seismic reflection and refraction surveys, and (3) geochemical analyses including dissolved sodium or potassium in seawater than can be traced to total sediment-sedimentary rock volume. Taylor and McLennan (1985) and Rudnick and Gao (2003) use geologic data to estimate the abundances of common sedimentary rocks. The average abundances from these authors are 75% shales, 12% carbonates (limestone and dolomite), 10% sandstones, and 3% evaporates. Sedimentary rocks, especially fine-grained shales or mudstones, are subject to postdepositional processes such as diagenesis, metamorphism, and alteration by oceanic water (Rudnick and Gao, 2003). These processes increase rock density and seismic velocity.

1.11.7.2 The Crystalline Crust and Uppermost Mantle

A complete global P- and S-wave crustal (and upper lithospheric) model is based on three types of information: (1) synthesizing existing models, such as WENA 1.0, the Barents Sea model (Ritzmann *et al.*, 2007), and WINPAK; (2) seismic tomography data, and (3) an ongoing compilation of published seismic models for the crust, based on active- and passive-source seismology (**Figure 11**). Thus, in addition to results from controlled sources, the model also incorporates results from receiver function analysis, surface-wave dispersion analysis, and seismic tomography.

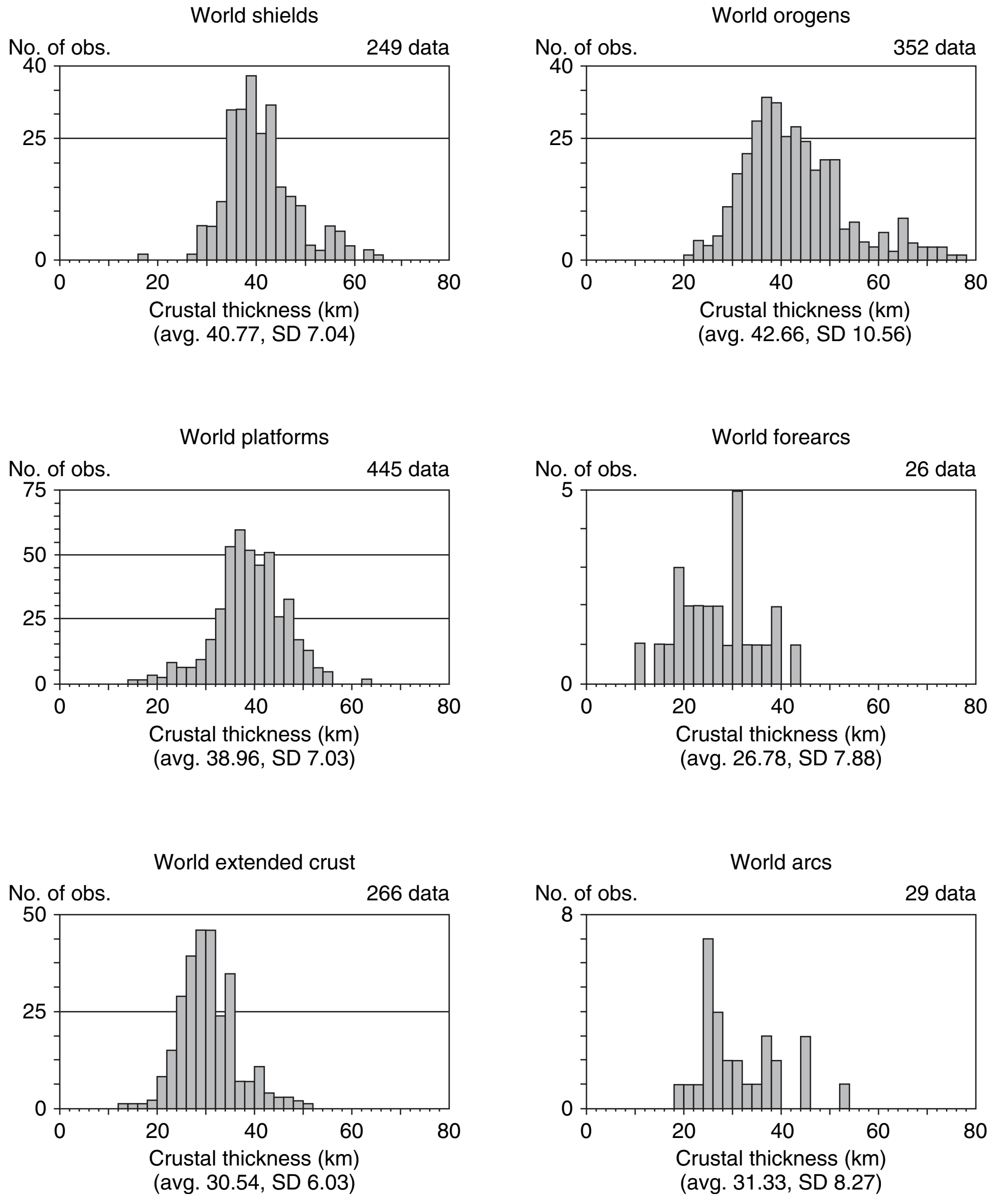


Figure 22 Histograms of crustal thickness for six continental tectonic provinces calculated from the individual point measurements (**Figure 11**). Average and standard deviations are indicated. These histograms indicate systematic differences among tectonic provinces, and provide a basis for extrapolating crustal thickness into unmeasured regions.

After compiling all of the existing regional models, the models are then compared and evaluated based on their technique and data quality. Separate databases are constructed for each technique, for example (1) active-source models, (2) surface-wave models, (3) seismic tomography models, and (4) receiver function models. Integration of such varied models requires some discrimination of data and model quality, and a suite of models emerges from which a 'best fit' composite model is developed. Discrepancies between input models are resolved based on the best available data, which must occasionally be decided subjectively.

In the $2° \times 2°$ mode CRUST 2.0 (**Figure 23**), the Earth's crust is divided into eight layers: (1) ice, (2) water, (3) soft sediments, (4) hard sediments, (5) crystalline upper, (6) middle, and (7) lower crust, and (8) uppermost mantle. Both P- and S-wave velocities and estimated density are specified in each layer.

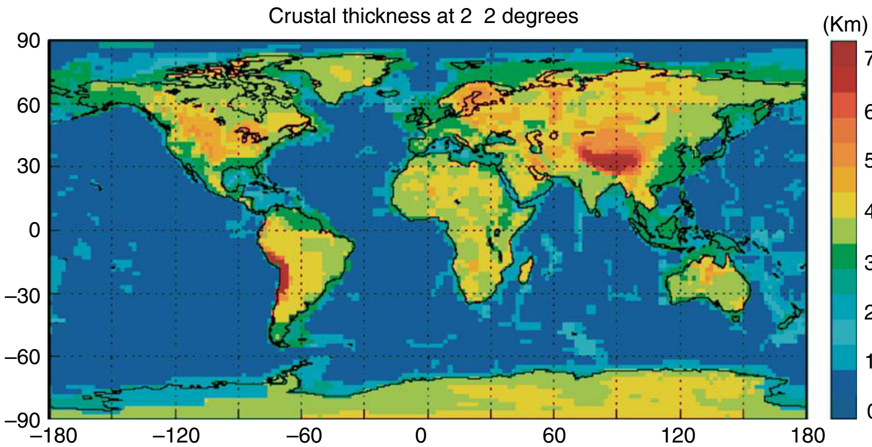


Figure 23 Crustal thickness provided by the 2° × 2° CRUST2.0 model (Bassin *et al*. 2000). The locations of seismic profiles used to make this model are shown in **Figure 11**. Typical crustal velocity models are summarized in **Figure 19**. The crustal structure is estimated in regions with no seismic measurements using the statistic averages illustrated in **Figure 22**. This crustal model is useful to make crustal velocity (P- and S-wave) or density corrections in many types of geophysical models.

Layers 1 and 2 are the easiest to determine. Ice is only found near the poles, and in high regions such as the Himalayas. Efforts to determine its thickness are straightforward and relatively expeditious. Water depth is also relatively easy to interpret at 2° × 2° using the ETOPO 2 model of the National Geophysical Data Center (2004). Both soft and hard (unconsolidated and consolidated, respectively) sediments are determined as these represent two distinct layers (3 and 4) in the model.

Layers 5–8 are determined from the compiled global crustal structure database and regional models. At present, the largest global crustal structure database of active-and passive-source measurements of the structure of the upper lithosphere includes more than 9200 data sets (almost 10 times the number available for CRUST 5.1). This is more than sufficient to build a 2° × 2° crustal block model.

Using the criteria set forth in the construction of CRUST 5.1 and other similar models, one of a series of primary crustal 'types' is assigned to each cell. There are approximately 400 different crustal model 'types' used in the 2° × 2° global model. Once the global crustal structure model has been compiled, the model must be evaluated. Model testing is generally based on a comparison of P_g (S_g), and P_n (S_n) traveltime predictions, with some empirical observations. Another useful test is a comparison with high-frequency Love wave phase velocities. **Tables 8a and 8b** lists the currently available global and regional crustal models. Updates to these models appear on a regular basis.

Table 8a Global crustal models

References	Year
Bassin *et al*.	2000
Laske and Masters	1997
Mooney *et al*.	1998
Nataf and Ricard	1996
National Geophysical Data Center	2004
Soller *et al*.	1982
Tanimoto	1995

Table 8b Regional crustal models

References	Year
Bungum *et al*.	2005
Mooney and Braile	1989
Pasyanos *et al*.	2004
Ritzmann *et al*.	2007
Van der Lee and Nolet	1997
Walter *et al*.	2000
Warren and Healy	1973

1.11.8 Discussion and Conclusions

Seismological studies of the crust and uppermost mantle began in the first decade of the twentieth century (Mohorovicic, 1910). Over the next 60 years a wide range of studies (**Table 1**) defined the gross properties of the crust. The past 35 years have seen a pronounced increase in lithospheric studies, with the development of such techniques as seismic reflection studies of the deep crystalline crust, receiver function analysis, and earthquake tomography and high-resolution surface-wave inversions. These advances have been matched by extensive laboratory studies of rock velocities and densities, and nonseismic geophysical studies using gravity, magnetic, and geoelectrical methods. Geophysical studies of the crust and subcrustal lithosphere have become so numerous that it is difficult for any individual or research group to keep abreast of all recent results. This highlights the need for a searchable databank of geophysical results, whereby it would be possible to sort by technique, location, depth of penetration, crustal age, or geologic and tectonic setting.

The process of synthesizing global studies of crustal structure is more than 20 years old (Soller *et al.*, 1982) and numerous regional and global models have become available (**Tables 8a** and **8b**). Until recently these models have been largely based on seismic measurements of compressional-wave velocity (V_p), with the shear-wave velocity (V_s) and density estimated using empirical relations. Future models should be able to rely more heavily on measured shear-wave velocities. Estimating deep crustal density will continue to be a challenge, but is greatly aided by borehole and laboratory measurements. The use of multiple seismic data sets in constructing regional and global crustal models will be aided by the use of inverse techniques (Pasyanos *et al.*, 2006).

As high-resolution surface-wave models become available, it will be possible to directly compare regional models derived from body-wave studies with models derived from surface waves. Likewise, nonseismic methods are rapidly developing, including satellite observations of long-wavelength gravity and magnetic fields. The synthesis of all of these methods promises to provide ever-increasing resolution on the global structure of the Earth's crust and subcrustal lithosphere.

References

Abbott DH (1996) Plumes and hotspots as sources of greenstone belts. *Lithos* 37: 113–127.

Abbott DH and Mooney WD (1995) The structural and geochemical evolution of the continental crust: Support for the oceanic plateau model of continental growth. *Reviews of Geophysics* 99: 231–242 (supplement).

Aki K (1982) Three-dimensional seismic inhomogeneities in the lithosphere and asthenosphere. *Reviews of Geophysics and Space Physics* 20: 161–170.

Aki K, Christoffersson A, and Husebye ES (1976) three-dimensional seismic structure of the lithosphere under Montana LASA. *Bulletin of the Seismological Society of America* 66: 501–524.

Aki K, Christoffersson A, and Husebye ES (1977) Determination of the three-dimensional seismic structure of the lithosphere. *Journal of Geophysical Research* 82: 277–296.

Aki K and Lee WHK (1976) Determination of three-dimensional velocity anomalies under a seismic array using first *P*-arrival time from local earthquakes. Part 1: A homogeneous initial model. *Journal of Geophysical Research* 81: 4381–4399.

Aki K and Richards P (1980) *Quantitative Seismology. Theory and Methods*. San Francisco, CA: Freeman.

Alexander SS (1962) A study of the normal modes of surface waves across the Western United States. *Journal of Geophysical Research* 67: 3537–3538.

Albarede F (1998) The growth of continental crust. *Tectonophysics* 296: 1–14.

Al-Lazki AI, Sandvol E, Seber D, Barazangi M, Turkelli N, and Mohammad R (2004) Pn tomographic imaging of mantle lid velocity and anisotropy at the junction of the Arabian, Eurasian and African plates. *Geophysical Journal International* 158: 1024–1040.

Al-Lazki AI, Seber D, Sandvol E, Turkelli N, Mohamad R, and Barazangi M (2003) Tomographic Pn velocity and anisotropy structure beneath the Anatolian plateau (eastern Turkey) and the surrounding regions; the Turkey seismic experiment; the study of a young continent-continent collision. *Geophysical Research Letters* 30: (doi:10.1029/2003GL017391).

Allen RM, Nolet G, Morgan WJ, *et al.* (2002) Imaging the mantle beneath Iceland using integrated seismological techniques. *Journal of Geophysical Research* 107: (doi: 10.1029/2001JB000595).

Alvares R, Reynoso JP, Alvarez LJ, and Martinez ML (1978) Electrical conductivity of igneous rocks; composition and temperature relations. *Bulletin Volcanologique* 41: 317–327.

Ammon C, Randall G, and Zandt G (1990) On the nonuniqueness of receiver function inversions. *Journal of Geophysical Research* 95: 15303–15328.

Anderson DL (1961) Elastic wave propagation in layered anisotropic media. *Journal of Geophysical Research* 66: 2953–2963.

Anderson DL (1967) The anelasticity of the mantle. *Geophysical Journal of the Royal Astronomical Society* 14: 135–164.

Anderson DL and Archambeau CB (1964) The anelasticity of the Earth. *Journal of Geophysical Research* 69: 2071–2084.

Angus DA, Wilson DC, Sandvol E, and Ni JF (2006) Lithospheric structure of the Arabian and Eurasian collision zone in eastern Turkey from *S*-wave receiver functions. *Geophysical Journal* 166: 1335–1346.

Ansorge J, Prohedel C, and Bamford D (1982) Comparative interpretation of explosion seismic data. *Journal of Geophysics* 51: 69–84.

Artemieva IM and Mooney WD (2001) Thermal thickness of Precambrian lithosphere: A global study. *Journal of Geophysical Research* 106: 16 387–16 414.

Arvidson RE, Bindschadler D, Bowring S, Eddy M, Guinness E, and Leff C (1984) Bouguer images of the North American craton and its structural evolution. *Nature* 311: 241–243.

Au D and Clowes RM (1984) Shear-wave velocity structure of the oceanic lithosphere from ocean bottom seismometer studies. *Geophysical Journal of the Royal Astronomical Society* 77: 105–123.

BABEL Working Group (1993) Deep seismic reflection/refraction interpretation of crustal structure along BABEL

profiles A and B in the southern Baltic Sea. *Geophysical Journal International* 112: 325–343.
Banks RJ (1972) The overall conductivity distribution in the earth. *Journal of Geomagnetism and Geoelectricity* 24: 337–351.
Banks RJ, Parker RL, and Huestis SP (1977) Isostatic compensation on a continental scale: Local versus regional mechanisms. *Geophysical Journal of the Royal Astronomical Society* 51: 431–452.
Bannister SC, Ruud BO, and Husebye ES (1991) Tomographic estimates of sub–Moho seismic velocities in Fennoscandia and structural implications; imaging and understanding the lithosphere of Scandinavia and Iceland. *Tectonophysics* 189: 37–53.
Bamford D (1977) *Pn* velocity anisotropy in a continental upper mantle. *Geophysical Journal of the Royal Astronomical Society* 49: 29–48.
Baranov V (1957) A new method for interpretation of aeromagnetic maps: Pseudogravimetric anomalies. *Geophysics* 22: 359–383.
Barazangi M and Ni J (1982) Velocities and propagation characteristics of *Pn* and *Sn* waves beneath the Himalayan arc and Tibetan plateau: Possible evidence for underthrusting of Indian continental lithosphere beneath Tibet. *Geology* 10: 175–185.
Barazangi M and Brown L (eds.) (1986a) *Geodynamics series 13: Reflection seismology:* A Global Perspective. Washington, DC: American Geophysical Union.
Barazangi M and Brown L (eds.) (1986b) *Geodynamics series 14: Reflection Seismology: The Continental Crust*. Washington, DC: American Geophysical Union.
Barclay AH, Toomey DR, and Solomon SC (1998) Seismic structure and crustal magmatism at the Mid-Atlantic Ridge, 35°N. *Journal of Geophysical Research* 102: 3109–3129.
Barmin MP, Levshin AL, and Ritzwoller MH (2001) A fast and reliable method for surface wave tomography. *Pure and applied Geophysics* 158: 1351–1375.
Bartelson H, Lueschen E, Krey Th, Meissner R, Scholl H, and Walter Ch (1982) The combined seismic reflection-refraction investigation of the Urach geothermal anomaly. In: Haemel R (ed.) *The Urach Geothermal Project*, pp. 247–262. Stuttgart: Schweizerbart'sche Verlagsbuchhandlung.
Barton AJ and White RS (1997) Crustal structure of the Edoras Bank continental margin and mantle thermal anomalies beneath the North Atlantic. *Journal of Geophysical Research* 102: 3109–3129.
Barton PJ (1986) The relationship between seismic velocity and density in the continental crust. *Geophysical Journal of the Royal Astronomical Society* 87: 195–208.
Barton PJ (1992) LISPB revisited: A new look under the Caledonides of northern Britain. *Geophysical Journal International* 110: 371–391.
Bass JD (1995) Elasticity of minerals, glasses, and melts. In: Athrens TJ (ed.) *Mineral Physics and Crystallography: A Handbook of Physical Constants*, pp. 45–63. Washington, DC: American Geophysical Union Reference Shelf.
Bassin C, Laske G, and Masters GNY (2000) The current limits of resolution for surface tomography in North America. *EOS* 81: F897.
Bateman PC and Eaton JP (1967) Sierra Nevada Batholith. *Science* 158: 1407–1417.
Bath M and Stefánsson R (1966) *S–P* conversion at the base of the crust. *Annali di Geofisica* 19: 119–130.
Begnaud ML, McClain JS, Barth GA, Orcutt JA, and Harding AJ (1997) Preliminary velocity structure from forward modeling of the eastern ridge-transform intersection area of the Clipperton Fracture Zone, East Pacific Rise. *Journal of Geophysical Research* 102: 7803–7820.
Behrendt JC, Green AG, Cannon WF, *et al.* (1988) Crustal structure of the Midcontinent rift system; results from GLMPCE deep seismic reflection studies. *Geology* 16: 81–85.
Beloussov VV, Kunin NY, Mazur VB, Ostisty BK and Ostrovsky MI (1988) *Map of the relief of the basement surface of Eurasia*, scale 1:15,000,000.
Beloussov VV and Pavlenkova NI (1984) The types of the Earth's crust. *Journal of Geodynamics* 1: 167–183.
Beloussov VV, Pavlenkova NI, and Egorkin AV (eds.) (1991) *Geophysical Models of the Teritory of the USSR*, 224. Moscow: Nauka.
Ben-Avraham Z, Nur A, Jones D, and Cox A (1981) Continental accretion: from oceanic plateaus to allochthonous terranes. *Science* 213: 47–54.
Benoit MH, Nyblade AA, VanDecar JC, and Gurrola H (2003) Upper mantle P wave velocity structure and transition zone thickness beneath the Arabian shield. *Geophysical Research Letters* 30: (doi:10.1029/2002GL016436).
Berckhemer H, Rauen A, Winter H, *et al.* (1997) Petrophysical properties of 9-km-deep crustal section at KTB. *Journal of Geophysical Research* 102: 18337–18362.
Berdichevskiy MN and Zhdanov MS (1984) *Advanced Theory of Deep Electromagnetic Sounding*. Amsterdam: Elsevier.
Berry LG and Mason BH (1959) *Mineralogy: Concepts Description Determinations*, 444 pp. New York: W.H. Freeman.
Berry MJ and West GF (1966) An interpretation of the first-arrival data of the Lake Superior experiment by the time-term method. *Bulletin of the Seismological Society of America* 56: 141–171.
Bessonova EN, Fishmen VM, Ryaboy VZ, and Sitnikova GA (1974) The tau method for inversion of travel times. I. Deep seismic sounding data. *Geophysical Journal of the Royal Astronomical Society* 36: 377–398.
Bessonova EN, Fishmen VM, Shirman MG, Strikova GA, and Johnson LR (1976) The tau method of inversion of travel times. II. Earthquake data. *Geophysical Journal of the Royal Astronomical Society* 46: 87–108.
Bibee LD and Shor GG (1976) Compressional wave anisotropy in the crust and upper mantle. *Geophysical Research Letters* 3: 639–642.
Bijwaard H, Spakman W, and Engdahl ER (1998) Closing the gap between regional and global travel time tomography. *Journal of Geophysical Research* 103: 30055–30078.
Birch F (1943) Elasticity of igneous rocks at high temperatures and pressures. *Bulletin of the Geological Society of America* 54: 263–286.
Birch F (1952) Elasticity and constitution of the Earth's interior. *Journal of Geophysical Research* 57: 227–286.
Birch F (1960) The velocity of compressional waves in rocks to 10 kilobars. Part 1: *Journal of Geophysical Research* 5: 1083–1102.
Birch F (1961) The velocity of compressional waves in rocks to 10 kilobars. Part 2: *Journal of Geophysical Research* 66: 2199–2224.
Birch F (1972) Numerical experiments on the velocities in aggregates of olivine. *Journal of Geophysical Research* 77: 6385–6391.
Birch F (1975) Velocity and attenuation from resonant vibrations of spheres of rock, glass, and steel. *Journal of Geophysical Research* 80: 756–764.
Björnsson A, Eysteinsson H, and Beblo M (2005) Crustal formation and magma genesis beneath Iceland: Magnetotelluric constraints. In: Foulger GR, Natland JH, Presnall DC, and Anderson DL (eds.) *Geological Society of America, Special Paper 388 Plates, Plumes, and Paradigms* pp. 665–686. Boulder, CO: Geological society of America.

Blakely RG (1995) *Potential Theory in Gravity and Magnetic Applications*. New York: Cambridge University Press.
Blakely RJ and Grauch VJS (1983) Magnetic models of crystalling terrane: Accounting for the effect of topography. *Geophysics* 48: 1551–1557.
Blundell D, Freeman R, and Mueller S (eds.) (1992) *A Continent Revealed – the European Geotraverse*. New York: Cambridge University Press.
Blundell DJ and Raynaud B (1986) Modeling lower observed on BIRPS profiles. In: Barazangi M and Brown L (eds.) *American Geophysical Union Geodynamics Series 13: Reflection Seismology; A global Perspective*, pp. 287–295. Washington, DC: American Geophysical Union.
Bond KR and Zietz I (1987) Composite Magnetic Anomaly Map of the Conterminous United States west of the 96° longitude. U.S. Geological Survey Geophysical Investigations Map GP-977, scale 1:2,500,000.
Bonini WE and Bonini RR (1979) Andrija Mohorovîĉić: Seventy years ago an earthquake shook Zagreb. *EOS, Transactions, American Geophysical Union* 60: 699–701.
Booker J, Favetto A, and Pomposiello MC (2004) Low electrical resistivity associated with plunging of the Nazca flat slab beneath Argentina. *Nature* 429: 399–403.
Boore DM (1972) Finite difference methods for seismic wave propagation in heterogeneous materials. In: Bolt BA (ed.) *Seismology; Surface Waves and Earth Oscillations; Methods in Computational Physics*, Vol. 11, pp. 1–37. New York: Academic Press.
Boschi L, Ekstroem G, and Kustowski B (2004) Multiple resolution surface wave tomography; the Mediterranean basin. *Geophysical Journal International* 157: 293–304.
Bostock M, Hyndman R, Rondenay S, and Peacock S (2002) An inverted continental Moho and serpentinization of the forearc mantle. *Nature* 417: 536–538.
Bouchon M (1982) The complete synthesis of seismic crustal phases at regional distances. *Journal of Geophysical Research* 87: 1735–1741.
Bourjot L and Romanowicz B (1992) Crust and upper mantle tomography in Tibet using surface waves. *Geophysical Research Letters* 19: 881–884.
Bown JW and White RS (1994) Variation with spreading rate of oceanic crustal thickness and geochemistry. *Earth and Planetary Science Letters* 121: 435–449.
Braile L and Smith RB (1974) Guide to the interpretation of crustal refraction profiles. *Geophysical Journal of the Royal Astronomical Society* 40: 145–176.
Braile LW and Chiang CS (1986) The continental Mohorovičić discontinuity; results from near-vertical and wide-angle seismic refraction studies. In: Barazangi M and Brown L (eds.) *American Geophysical Union Geodynamics Series 13: Reflection Seismology; A Global Perspective*, pp. 257–272. Washington, DC: American Geophysical Union.
Braile LW, Keller GR, Mueller S, and Prodehl C (1995) Seismic techniques. In: Olsen KH (ed.) *Continental Rifts: Evolution, Structure, Tectonics*, pp. 61–92. Amsterdam: Elsevier.
Brocher TM (1995) Deep-crustal seismology of continental margins, U.S. Natl. Rep. Int. Union Geod. Geophys. 1991–1994. *Review of Geophysics* 33: 309–314.
Brocher TM (2005) Empirical relations between elastic wavespeeds and density in the earth's crust. *Bulletin of the Seismological Society of America* 95(6): 2081–2092.
Brocher TM, Parsons T, Tréhu AM, Snelson CM, and Fisher MA (2003) Seismic evidence for widerspread serpentinized forearc upper mantle along the Cascadia margin. *Geology* 31: 267–1307.
Brown L, Barazangi M, Kaufman S, and Oliver J (1986) The first decade of COCORP; 1974–1984. In: Barazangi M and Brown LD (eds.) *American Geophysical Union Geodynamics Series 13: Reflection Seismology; A Global Perspective*, pp. 107–120. Washington, DC: American Geophysical Union.
Brune J and Dorman J (1963) Seismic waves and earth structure in the Canadian shield. *Bulletin of the Seismological Society of America* 53: 167–210.
Brune JN (1969) Surface waves and crustal structure. In: Hart PJ (ed.) *American Geophysical Union Geophysical Monograph Series 13: The Earth's Crust and Upper Mantle*, pp. 230–242. Washington, DC: American Geophysical Union.
Brune JN, Nafe J, and Oliver J (1960) A simplified method for the analysis and synthesis of dispersed wave trains. *Journal of Geophysical Research* 65: 287–304.
Bruneton M, Pedersen HA, Farra V, *et al.* (2004) Complex lithospheric structure under the central Baltic Shield from surface wave tomography. *Journal of Geophysical Research* 109: (doi:10.1029/2003JB002947).
Bungum H, Ritzmann O, Maercklin N, Faleide J-I, Mooney WD, and Detweiler ST (2005) Three-dimensional model for the crust and upper mantle in the Barents Sea Region. *EOS, Transactions, American Geophysical Union* 86(16): 160–161.
Butler R (1986) Regional seismic observations of the Ongtong Java Plateau and East Marina Basin. *Marine Geophysical Researches* 8: 27–38.
Burdick LJ and Langston CA (1977) Modeling crust-structure through the use of converted phases in teleseismic body-wave-forms. *Bulletin of the Seismological Society of America* 67: 677–691.
Byerly P (1926) The Montana earthquake of June 28, 1925. *Bulletin of the Seismological Society of America* 16: 209–265.
Byerly P and Dyk K (1932) Richmond quarry blast of September 12, 1931, and the surface layering of the earth in the region of Berkeley. *Bulletin of the Seismological Society of America* 22: 50–55.
Cagniard L (1953) Basic theory of magnetotelluric method of geophysical prospecting. *Geophysics* 18(3): 605–635.
Calvert A, Sandvol E, Seber D, *et al.* (2000) Propagation of regional seismic phases (Lg and Sn) and Pn velocity structure along the Africa–Iberia plate boundary zone; tectonic implications. *Geophysical Journal International* 142: 384–408.
Campbell IH, Griffiths RW, and Hill R (1989) Melting in an Archaean mantle plume: Heads it's basalts, tails it's komatiites. *Nature* 339: 697–699.
Canales JP, Detrick RS, Lin J, Collins JA, and Toomey DR (2000) Crustal and upper mantle seismic structure beneath the rift mountains and across a nontransform offset at the Mid-Atlantic Ridge (35°N). *Journal of Geophysical Research* 105: 2699–2719.
Cann JR (1970) New model for the structure of the oceanic crust. *Nature* 226: 928–930.
Cann JR (1974) A model for oceanic crustal structure developed. *Geophysical Journal of the Royal Astronomical Society* 39: 169–187.
Cannat M (1996) How thick is the magmatic crust at slow spreading oceanic ridges? *Journal of Geophysical Research* 101: 2847–2857.
Caress DW, McNutt MK, Detrick RS, and Mutter JC (1995) Seismic imaging of hotspot-related crustal underplating beneath the Marquesas Islands. *Nature* 373: 600–603.
Carlson RL, Christensen NI, and Moore RP (1980) Anomalous crustal structure in ocean basins: Continental fragments and oceanic plateaus. *Earth and Planetary Science Letters* 51: 171–180.
Carmichael RS (1982) *Handbook of Physical Properties of Rocks*. Boca Raton, FL: CRC Press.

Cassidy JF (1992) Numerical experiments in broadband receiver function analysis. *Bulletin of the Seismological Society of America* 82: 1453–1474.

Cermak V (1993) Lithospheric thermal regimes in Europe. *Physics of the Earth and Planetary Interiors* 79: 179–193.

Červený V (1972) Seismic rays and ray intensities in inhomogeneous anisotropic media. *Geophysical Journal of the Royal Astronomical Society* 72: 755–766.

Červený V, Molotkov IA, and Pšeničník I (1977) *Ray Method in Seismology*. Prague, Czechoslovakia: University of Karlova (Charles).

Červený V and Pšeničník I (1984) SEIS83 – Numerical modeling of seismic wave fields in 2 – D laterally varying layered structures by the ray method. In: Engdal ER (ed.) *Documentation of Earthquake Algorithms*. World Data Center A for Solid Earth Geophys, Rep. SE-35, pp. 36–40. Boulder, CO.

CGMW (Commission for the Geological Map of the World) (2002) *Geological Map of the World*. Paris: UNESCO.

Chapman CH (1978) A new method for computing synthetic seismograms. *Geophysical Journal of the Royal Astronomical Society* 54: 481–518.

Chapman CH and Orcutt JA (1985) Least-squares fitting of marine seismic refraction data. *Geophysical Journal of the Royal Astronomical Society* 82: 339–374.

Chapman DS (1986) Thermal gradients in the continental crust. In: Dawson JB (ed.) *Geological Society Special Publication. The Nature of the Lower Continental Crust*, vol. 24, pp. 63–70. Oxford: Blackwell scientific publications.

Charvis P, Recq M, Operto S, and Brefort D (1995) Deep structure of the northern Kerguelen Plateau and hotspot-related activity. *Geophysical Journal International* 122: 899–924.

Chen C, Chen Y, Yen H, and Yu G (2003) Lateral variations of P (sub n) velocity and anisotropy in Taiwan from travel-time tomography. *Earth, Planets and Space* 55: 223–230.

Chen H, Chiu JM, Pujol J, *et al.* (2005) A simple algorithm for local earthquake location using 3-dimensional Vp and Vs Models- test examples in the central USA and Taiwan regions. *Bulletin of the Seismological Society of America* 96: 288–305.

Chen YJ (1992) Oceanic crustal thickness versus spreading rate. *Geophysical Research Letters* 19: 753–756.

Chian D, Louden KE, Minshull TA, and Whitmarsh RB (1999) Deep structure of the ocean continent transition in the southern Iberia Abyssal Plain from seismic refraction profiles. Part 1: ocean drilling program (Legs 149 and 173) transect. *Journal of Geophysical Research* 104: 7443–7462.

Chian D, Louden KE, and Reid I (1995) Crustal structure of the Labrador sea conjugate margin and implications for the formation of nonvolcanic continental margins. *Journal of Geophysical Research* 100: 24239–24253.

Chimera G, Aoudia A, Sarao A, and Panza GF (2003) Active tectonics in central Italy; constraints from surface wave tomography and source moment tensor inversion. *Physics of the Earth and Planetary Interiors* 138: 241–262.

Christensen NI (1965) Compressional wave velocities in metamorphic rocks at pressures to 10 kilobars. *Journal of Geophysical Research* 70: 6147–6164.

Christensen NI (1966a) Elasticity of ultrabasic rocks. *Journal of Geophysical Research* 71: 5921–5931.

Christensen NI (1966b) Shear wave velocities in metamorphic rocks at pressures to 10 kilobars. *Journal of Geophysical Research* 71: 3549–3556.

Christensen NI (1971) Shear wave propagation in rocks. *Nature* 229: 549–550.

Christensen NI (1972) The abundance of serpentinities in the oceanic crust. *Journal of Geology* 80: 709–719.

Christensen NI (1979) Compressional wave velocities in rocks at high temperatures and pressures, critical thermal gradients, and crustal low-velocity zones. *Journal of Geophysical Research* 84: 6849–6857.

Christensen NI (1982) Sieismic velocities. In: Carmichael RS (ed.) *Handbook of Physical Properties of Rocks*, vol. II, pp. 1–228. Boca Raton, FL: CRC Press.

Christensen NI (1996) Poisson's ratio and crustal seismology. *Journal of Geophysical Research* 100: 3139–3156.

Christensen NI and Fountain DM (1975) Constitution of the lower contineIatal crust based on experimental studies of seismic velocities in granulite. *Bulletin of the Geological Society of America* 86: 277–236.

Christensen NI and Salisbury MH (1975) Structure and constitution of the lower oceanic crust. *Reviews of Geophysics and Space Physics* 13: 57–86.

Christensen NI and Salisbury MH (1979) Seismic anisotropy in the upper mantle: Evidence from the Bay of Islands ophiolite complex. *Journal of Geophysical Research* 84: 4601–4610.

Christensen NI and Salisbury MH (1982) Lateral heterogeneity in the seismic structure of the oceanic crust inferred from velocity studies in the Bay of Islands ophiolite, Newfoundland. *Geophysical Journal of the Royal Astronomical Society* 68: 675–688.

Christensen NI and Mooney WD (1995) Seismic velocity structure and the composition of the continental crust: A global view. *Journal of Geophysical Research* 100: 9761–9788.

Christeson GL, Shaw PR, and Garmany JD (1997) Shear and compressional wave structure of the East Pacific Rise, 9°–10°N. *Journal of Geophysical Research* 102: 7821–7835.

Chulick GS (1997) Comprehensive seismic survey database for developing three-dimensional models of the earth's crust. *Seismological Research Letters* 68: 734–742.

Chulick GS and Monney WD (2002) Seismic structure of the crust and upper most mantle of North America and adjacent oceanic basins: A synthesis. *Bulletin of the Seismological Society of America* 92: 2478–2492.

Claerbout JF (1976) *Fundamentals of Geophysical Data Processing*. Palo Alto, CA: Blackwell Scientific Publications.

Claerbout JF (1985) *Imaging the Earth's Interior*. Palo Alto, CA: Blackwell Scientific Publications.

Clarke FW (1889) The relative abundance of the chemical elements. *Phil Soc Washington Bull* XI: 131–142.

Clarke FW and Washington HS (1924) The composition of the Earth's crust. US Geological Survey Professional Paper 127: 117 pp.

Clark SP (1966) *Geological Society of America Memoir 97: Handbook of Physical Constants*. Boulder,CO: Geological Society of America.

Clegg B and England R (2003) Velocity structure of the UK continental shelf from a compilation of wide-angle and refraction data. *Geological Magazine* 140: 453–467.

Clitheroe GM, Gudmundsson U, and Kennett BLN (2000) The crustal thickness of Australia. *Journal of Geophysical Research* 105: 13697–13713.

Cloos M (1993) Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts. *Geophysical Society of America Bulletin* 105: 715–737.

Closs H and Behnke C (1961) Fortschritte der Anwendung seismischer Methoden in der Erforschung der Erdkruste. *Geologische Rundschau* 51: 315.

Clowes R, Cook F, Hajnal Z, *et al.* (1999) Canada's LITHOPROBE Project (Collaborative, multidisciplinary

geoscience research leads to new understanding of continental evolution). *Episodes* 22: 3–20.
Clowes RM, Baird DJ, and Dehler SA (1997) Crustal structure of the northern Cascadia subduction zone, southwestern British Columbia, from potential field and seismic studies. *Canadian Journal of Earth Sciences* 34: 317–335.
Clowes RM, Brandon MT, Green AG, *et al.* (1987) LITHOPROBE – southern Vancouver Island: Cenozoic subduction complex imaged by deep seismic reflections. *Canadian Journal of Earth Sciences* 24: 31–51.
Clowes RM and Hyndman RD (2002) Geophysical studies of the northern Cascadia subduction zone off western Canada and their implications for great earthquake seismotectonics: A review. In: Fujinawa Y and Yoshida A (eds.) *Seismotectonics in Convergent Plate Boundary*, pp. 1–23. Tokyo, Japan: Terra Scientific Publishing.
Clowes RM, Kanasewich ER, and Cumming GL (1968) Deep crustal seismic reflections at near vertical incidence. *Geophysics* 33: 441–451.
Clowes RM, Zelt CA, Amor JR, and Ellis RM (1995) Lithospheric structure in the southern Canadian Codillera from a network of seismic refraction lines. *Canadian Journal of Earth Sciences* 32: 1485–1513.
Coffin MA and Eldholm O (1994) Large igneous provinces: Crustal structure, dimensions and external consequences. *Reviews of Geophysics* 32: 1–36.
Collier JS and Singh SC (1997) Detailed structure of the top of the melt body beneath the East pacific Rise at 9°40′N from waveform inversion of seismic reflection data. *Journal of Geophysical Research* 103: 20287–20304.
Collier JS and Singh SC (1998) Poisson's ratio structure of young oceanic crust. *Journal of Geophysical Research* 103: 20981–20996.
Condie KC (1989) *Plate Tectonics and Crustal Evolution*, pp. 244–282. New York: Elsevier.
Conrad V (1925) Laufzeitkurven des Taueren vom 28. November 1923. *Akademische Wissenschaft* 59: Mitteiler Erdbeban Kommission Wien, 1–23.
Constable SC and Cox CS (1996) Marine controlled-source electromagnetic soundry. Part 2: The PEGASUS experiment. *Journal of Geophysical Research* 101: 5519–5530.
Couch R and Woodcock S (1981) Gravity and structure of the continental margins of southwestern Mexico and northwestern Guatemala. *Journal of Geophysical Research* 86: 1829–1840.
Cram IH, Jr. (1961) Crustal structure refraction survey in south Texas. *Geophysics* 26: 560–573.
Crampin S (1964) Higher modes of seismic surface waves: Preliminary observations. *Geophysical Journal of the Royal Astronomical Society* 9: 35–37.
Crampin S (1966) Higher modes of seismic surface waves: Propagation in Eurasia. *Bulletin of the Seismological Society of America* 56: 1227–1239.
Crosson RS (1976) Crustal structure modeling of earthquake data; 1, Simultaneous least squares estimation of hypocenter and velocity parameters. *Journal of Geophysical Research* 81: 3036–3046.
Curtis A and Woodhouse JH (1997) Crust and upper mantle structure beneath the Tibetan plateau and surrounding regions from interevent surface wave inversion. *Journal of Geophysical Research* 102: 11789–11813.
Dahl-Jensen T, Larsen TB, Woelbern I, *et al.* (2003) Depth to Moho in Greenland. *Earth and Planetary Science Letters* 205: 379–393.
Darbyshire FA, White RS, and Priestley KF (2000) Structure of the crust and uppermost mantle of Iceland from a combined seismic and gravity study. *Earth and Planetary Science Letters* 181: 409–428.
Das T and Nolet G (1998) Crustal thickness map of the western United States by portioned waveform inversion. *Journal of Geophysical Research* 103: 30 021–30 038.
Davis M and Kusznir N (2004) Depth-dependent lithospheric stretching at rifted continental margins. In: Karner GD, Taylor B, Discoll NW, and Kohlsted DL (eds.) *Rheology and deformation of the Lithosphere at Continental Margins*, pp. 92–136. New York: Columbia University Press.
Dean SM, Minshull TA, Whitmarsh RB, and Louden KE (2000) Deep structure of the ocean-continent transition in the southern Iberia Abyssal Plain from seismic refraction profiles: II. The IAM-9 transect at 40°20′N. *Journal of Geophysical Research* 105: 5859–5886.
Debayle E and Lévêque J (1997) Upper mantle heterogeneities in the Indian Ocean from waveform inversions. *Geophysical Research Letters* 24: 245–248.
Deichmann N and Ansorge J (1983) Evidence for lamination in the lower continental crust beneath the Black Forest (Southwestern Germany). *Journal of Geophysics* 52: 109–118.
DeGolyer E (1935) Notes on the early history of applied geophysics in the petroleum industry. *Society Petroleum Geophysics Journal* 30: 1–10.
Dehlinger P (1978) *Marine Gravity*. Amsterdam: Elsevier Scientific Publishing Co.
Delhinger P, Couch RW, McManus DA, and Gemperle M (1970) Northeast Pacific structure. In: Maxwell AE (ed.) *The Sea*, vol. 4, (Part 2) pp. 133–189. New York: Wiley-Interscience.
DESERT Group (2004) The crustal structure of the Dead Sea transform. *Geophysical Journal International* 156: 655–681.
DeShon HR and Schwartz SY (2004) Evidence for serpentinization of the forearc mantle wedge along Nicoya Peninsula, Costa Rica. *Geophysical Research Letters* 31: L21611 (doi:10.1029/1004GL021179).
Detrick RS, Buhl P, Vera E, *et al.* (1987) Multichannel seismic imaging of a crustal magma chamber along the East Pacific rise. *Nature* 326: 35–41.
Detrick RS, Harding AJ, Kent GM, Orcutt JA, Mutter JC, and Buhl P (1993) Seismic structure of the southern East Pacific Rise. *Science* 259: 499–503.
Detrick RS, Mutter J, Buhl P, and Kim II (1990) No evidence from multichannel reflection data for a crustal magma chamber in the MARK area of the Mid-Atlantic ridge. *Nature* 347: 61–64.
Dèzes P and Ziegler PA (2001) *European Map of the Mohorovicic Discontinuity*, version 1.3. world wide web access: http://comp1.geol.unibas.ch.
Dix CH (1965) Reflection seismic crustal studies. *Geophysics* 30: 1068–1084.
Dobrin MB (1976) *Introduction to Geophysical Prospecting*, 3rd edn. New York: McGraw-Hill.
Dohr G (1970) Reflexionsseimische Messungen im Oberrheingraben mit digitaler Aufzeichnungstechnik und Bearbeitung. In: Mueller JH and Illies S (eds.) *Graben Problems*, pp. 207–218. Stuttgart: Schweizerbart Verlag.
Donnelly TW (1973) Late Cretaceous basalts from the Caribbean, a possible flood basalt province of vast size. *EOS* 54: 1004.
Downes H (1993) The nature of the lower continental crust of Europe: Petrological and geochemical evidence from xenoliths. *Physics of the Earth and Planetary Interiors* 79: 195–218.
Drewry DJ and Mooney WD (1983) *Antarctica: Glaciological and Geophysical Folio*. Cambridge, England: Polar Research Institute.
Duba AS (1972) Electrical conductivity of olivine. *Journal of Geophysical Research* 77: 2483–2495.
Durrheim RJ and Mooney WD (1994) Evolution of the Precambrian lithosphere: Seismological and geochemical

constraints. *Journal of Geophysical Research* 99: 15 359–15 374.
Dziewonski AM (1989) Earth structure, global. In: James DE (ed.) *The Encyclopedia of Solid Earth Geophysics*, pp. 331–359. New York: Van Nostrand-Reinhold.
Dziewonski AM and Anderson DL (1981) Preliminary Reference Earth Model (PREM). *Physics of the Earth and Planetary Interiors* 25: 297–356.
Eberhart-Phillips D (1986) Three-dimensional velocity structure in northern California Coast Ranges from inversion of local earthquake arrival times. *Bulletin of the Seismological Society of America* 76: 1025–1052.
Edgar NT, Ewing JI, and Hennion J (1971) Seismic refraction and reflection in the Caribbean Sea. *American Association of Petroleum Geologists* 55: 833–870.
Edwards RA, Whitmarsh RB, and Scrutton RA (1997) The crustal structure across the transform continental margin of Ghana, eastern Equatorial Atlantic. *Journal of Geophysical Research* 102: 747–772.
Egorkin AV (2004) Mantle structure of the Siberian platform: Izvestiya. *Physics of the Solid Earth* 40: 385–394.
Egorkin AV, Zuganov SK, Pavlenkova NA, and Chernyshev NM (1987) Results of lithosphere studies from long-range profiles in Siberia. *Tectonophysics* 140: 29–47.
Ekström G, Tromp J, and Larson EWF (1997) Measurement and global models of surface wave propagation. *Journal of Geophysical Research* 102: 8137–8157.
El Shazly EM (1982) The Red Sea region. In: Nairs AEM and Stehli FG (eds.) *The Oceans Basins Margins, The Indian Ocean*, vol. 6, pp. 205–252. New York: Plenum.
Eldholm O and Coffin MF (2000) *Large igneous provinces and plate tectonics.* America Geophysical Union, Monograph 121: 309–326.
Eldholm O and Grue K (1994) North Atlantic volcanic margins: Dimensions and production rates. *Journal of Geophysical Research* 99: 2955–2968.
Eldholm O, Tsikalas F, and Faleide JI (2002) The continental margin off Norway 62–75 °N: Palaeogene tectono-magmatic segmentation and sedimentation. In: Jolley DW and Bell BR (eds.) *Geological Society London Special Publication 197: The North Atlantic Igneous Province: Stratigraphy, Tectonics, Volcanic and Magmatic Processes*, pp. 39–68. Bath, UK: Geological Society of London.
Elie de Beaumont E (1847) Note sur les systemes de montagnes les plus anciens de l'Europe, Extr. Du Bulletin de la Societe geologique de France 2e serie t. IV 864 pp.
Emmermann R and Lauterjung J (1997) The German Continental Deep Drilling Program KTB: Overview and major results. *Journal of Geophysical Research* 102: 18179–18201.
Enderle U, Mechie J, Sobolev S, and Fuchs K (1996) Seismic anisotropy within the uppermost mantle of southern Germany. *Geophysical Journal International* 125: 747–767.
England RW (2000) Deep structure of north west Europe from deep seismic profiling: The link between basement tectonics and basin development. In: Mohriak W and Talwani M (eds.) *American Geophysical Union Geophysics Monograph 111: Atlantic Rifts and Continental Margins*, 115, pp. 57–83. Washington, DC: American Geophysical Union.
Ernst RE and Buchan KL (2003) Recognizing mantle plumes in the geologic record. *Annual Review of Earth and Planetary Sciences* 31: 469–523.
Evans RL, Tanits P, Chave AD, *et al.* (1999) Asymetric electrical structure in the mantle beneath the east Pacific Rise at 17° S. *Science* 286: 752–756.
Ewing J and Houtz R (1979) Acoustic stratigraphy and structure of the oceanic crust. In: Talwani M, Harrison CG, and Hayes DE (eds.) *Deep Drilling Results in the Atlantic Ocean*, pp. 1–14. Washington, DC: American Geophysical Union.
Ewing WM, Carry AP, and Rutherford HM (1937) Geophysical investigations in the emerged and submerged Atlantic Coastal Plain. Part 1: *Bulletin of the Geological Society of America* 48: 753–802.
Ewing WM, Dainty AM, Blanchard JE, and Keen JJ (1966) Seismic studies on the eastern seaboard of Canada: The Appalachian system I. *Canadian Journal of Earth Sciences* 3: 89–109.
Ewing WM, Jadetzky WS, and Press F (1957) *Elastic waves in Layered Media*. New York: McGraw-Hill Book Co.
Ewing WM and Nafe JE (1982) The unconsolidated sediments. In: Hill MN (ed.) *The Sea,* vol. 3, *The Earth Beneath the Sea*, pp. 73–84. New York: Wiley-Interscience.
Ewing WM and Press F (1954) An investigation of mantle Rayleigh waves. *Bulletin of the Seismological Society of America* 44: 127–148.
Ewing WM, Worzel JL, Ericson DB, and Heezen BC (1955) Geophysical and geological investigations in the Gulf of Mexico. Part 1: *Geophysics* 20: 1–18.
Faleide JI, Gudlaugsson ST, Eldholm O, Myhre AM, and Jackson HR (1990) Deep seismic transects across the sheared Western Barents Sea-Svalbard continental margin. *Tectonophysics* 189: 73–89.
Farnetani CG and Richards MA (1995) Thermal entrainment and melting in mantle plumes. *Earth and Planetary Science Letters* 136: 251–267.
Farnetani CG, Richards MA, and Ghiorso MS (1996) Petrologic models of magma evolution and deep crustal structure beneath hotspots and flood basalts. *Earth and Planetary Science Letters* 143: 81–84.
Feldman IS (1976) On the nature of conductive layers in the Earth's crust and upper mantle. In: Adam A (ed.) *Geoelectic and Geothermal Studies*, pp. 721–730. Budapest: Akademiai Kiado.
Fernandez M, Torne M, Garcia-Castellanos D, Verges J, Wheeler W, and Karpuz R (2004) Deep structure of the Voring Margin: The transition from a continental shield to a young oceanic lithosphere. *Earth and Planetary Science Letters* 221: 131–144.
Finlayson DM and Ansorge J (1984) Workshop proceedings; interpretation of seismic wave propagation in laterally heterogeneous structures. *Bureau of Mineral Resources*, *Geology*, *and Geophysics Report* 258. Canberra, Australia.
Feng M, Assumpção M, and van der Lee S (2004) Group-velocity tomography and lithospheric S-velocity structure of the South American continent. *Physics of the Earth and Planetary Interior* 147(4): 315–331.
Flack C and Warner M (1990) Three-dimensional mapping of seismic reflections from the crust and upper mantle northwest of Scotland. *Tectonophysics* 173: 469–481.
Fliedner MM and Klemperer SL (1999) Structure of an island arc: Wide-angle seismic studies in the eastern Aleutian Islands, Alaska. *Journal of Geophysical Research* 104: 10 667–10 694.
Foulger GR, Du Z, and Julian BR (2003) Icelandic-type crust. *Geophysical Journal International* 155: 567–590.
Fountain DM (1986) Implications of deep crustal evolution for seismic reflection interpretation. In: Barazangi M and Brown L (eds.) *American Geophysical Union Geodymanics Series 14: Reflection Seismology; The Continental Crust*, pp. 1–7. Washington, DC: American Geophysical Union.
Fountain DM, Arculus R, and Kay RW (1992) *Continental Lower Crust*, 485pp. Amsterdam: Elsevier.
Fountain DM, Hurich CA, and Smithson SB (1984) Seismic reflectivity of mylonite zones in the crust. *Geology* 12: 195–198.
Fountain DM and Salisbury MH (1981) Exposed crustal-sections through the continental crust: Implication for crustal

structure, petrology and evolution. *Earth and Planetary Science Letters* 56: 263–302.

Fowler CMR (1976) Crustal structure of the Mid-Atlantic Ridge crest at 37°N. *Geophysical Journal of the Royal Astronomical Society* 47: 459–491.

Fowler S, White RS, Spence GD, and Westbrook GK (1989) The Hatton Bank continental margin-II. deep structure from two-ship expanding spread profiles. *Geophysics Journal* 96: 295–309.

Friederich W (2003) The S-velocity structure of the east Asian mantle from inversion of shear and surface waveforms. *Geophysical Journal International* 153: 88–102.

Fromm R, Zandt G, and Beck SL (2004) Crustal thickness beneath the Andes and Sierras Pampeanas at 30° S inferred from Pn apparent phase velocities. *Geophysical Research Letters* 31: L006625 (doi:10.1029/2003GL019231).

Frost BR and Shive PN (1986) Magnetic mineralogy of the lower continental crust. *Journal of Geophysical Research* 91: 6513–6522.

Fuchs K and Müller G (1971) Computation of synthetic seismograms with the reflectivity method and comparison with observations. *Geophysical Journal of the Royal Astronomical Society* 23: 417–433.

Gajewski D and Pšenčík I (1987) *Ray Method in Seismology*. Prague: University of Karlova.

Geiss E (1987) A new compilation of crustal thickness data for Mediterranean area. *Annals of Geophysics* 5: 623–630.

Giese P (1976) Results of the generalized interpretation of the deep-seismic sounding data. In: Giese P, Prodehl C, and Stein A (eds.) *Explosion Seismology in Central Europe*, pp. 201–214. New York: Springer.

Giese P, Prodehl C, and Stein A (eds.) (1976) *Explosion Seismology in Central Europe – Data and Results*. Berlin-Heidelberg-New York: Springer.

Gilbert H, Beck S, and Zandt G (2005) Lithosperic and upper mantle structure of Central Chile and Argentina. *Geophysical Journal International* 165: 383–398.

Gladczenko TP, Coffin MF, and Eldholdm O (1997) Crustal structure of the Ontong Java Plateau: Modeling of new gravity and existing seismic data. *Journal of Geophysical Research* 102: 22711–22729.

Goodwin AM (1991) *Precambrian Geology: The Dynamic Evolution of the Continental Crust*. San Diego, CA: Academic Press.

Goodwin AM (1996) *Principles of Precambrian Geology*. San Diego, CA: Academic Press.

Gough DE (1974) Electrical conductivity under western North America in realtion to heat flow, seismology, and structure. *Journal of Geomagnetism and Geoelectricity* 26: 105–123.

Grad M, Gryn D, Guterch A, *et al.* (2003) ''DOBREfraction'99''; velocity model of the crust and upper mantle beneath the Donbas foldbelt (east Ukraine). *Tectonophysics* 371: 81–110.

Grad M, Janik T, Yliniemi J, *et al.* (1999) Crustal structure of the Mid-Polish Trough beaneath the Teisseyre-Tornquist Zone seismic profile. *Tectonophysics* 314: 145–160.

Grand SP and Helmberger DV (1984) Upper mantle shear structure of North America. *Geophysical Journal of the Royal Astronomical Society* 76: 399–438.

Grand SP, van der Hilst RD, and Widiyantoro S (1997) Global seismic tomography: A snapshot of convection in the Earth. *GSA Today* 7: 1–7.

Grant FS and West GS (1965) *Interpretation Theory in Applied Geophysics*. New York: McGraw-Hill.

Griffiths RW and Campbell IH (1990) Stirring and structure in mantle starting plumes. *Earth and Planetary Science Letters* 99: 66–78.

Gung Y and Romanowicz B (2004) Q tomography of the upper mantle using three-component long-period waveforms. *Geophysical Journal International* 157: 813–830.

Gutenberg B (1932) Traveltime curves at small distances and wave velocities in southern California. *Beiträge zur Geophysik* 35: 6–45.

Gutenberg B (1959) *Physics of the Earth's Interior*. New York: Academic Press.

Gutenberg B, Wood H, and Buwalda J (1932) Experiments testing seismographic methods for determining crustal structure. *Bulletin of the Seismological Society of America* 22: 185–246.

Guterch A, Grad M, Thybo H, Keller GR, and POLONAISE Working Group (1999) POLONAISE '97 – An international seismic experiment between Precambrian and Variscan Europe in Poland. *Tectonophysics* 314: 101–121.

Guterch A, Grad M, Keller GK, *et al.* (2003) CELEBRATION 2000 Seismic Experiment. *Stud. Geophysics and Geodesy* 47: 659–670.

Haberland C, Agnon A, El-Kelani R, *et al.* (2003) Modelling of seismic guided waves at the Dead Sea Transform. *Journal of Geophysical Research* 108(B7): 2342 (doi:10.1029/2002JB002309).

Hahn A, Ahrendt H, Jeyer J, and Hufen J-H (1984) A model of magnetic sources within the Earth's crust compatible with the field measured by the satellite Magsat. *Geologisches Jahrbuch Reihe A* 75: 125–156.

Hajnal Z (1986) Crustal reflection and refraction velocities. In: Barazangi M and Brown LD (eds.) *American Geophysical Union Geodynamics Series 13: Reflection Seismology; A Global Persective* pp. 247–256. Washington, DC: American Geophysical Union.

Hale LD and Thompson GA (1982) The seismic reflection character of the continental Mohorovičić discontinuity. *Journal of Geophysical Research* 87: 4625–4635.

Hall DH (1974) Long-wavelength aeromagnetic anomalies and deep crustal magnetisation in Manitoba and northwestern Ontario, Canada. *Journal of Geophysical Research* 40: 403–430.

Halliday AN, Dickin AP, Hunter RH, *et al.* (1993) Formation and composition of the lower continental crust: Evidence from Scottish xenolith suites. *Journal of Geophysical Research* 98(B1): 581–607.

Hamilton EL (1976) Shear-wave velocity versus depth in marine sediments: A review. *Geophysics* 41: 985–996.

Hamilton EL (1978) Sound velocity–density relations in sea-floor sediments and rocks. *Journal of the Acoustical Society of America* 63: 366–377.

Hammer S (1983) Airborne Gravity is here! *Geophysics* 48: 213–223.

Hart PJ (1969) *American Geophysical Union Geophysical Monograph 13:* The earth's crust and upper mantle. Washington, DC: American Geophysical Union.

Hart SR, Hauri EH, Oschmann LA, and Whitehead JA (1992) Mantle plumes and entrainment: Isotopic evidence. *Science* 256: 1673–1707.

Hayford JF, Bowie W (1912) The effect of topography and isostatic compensation upon the intensity of gravity. *U.S. Coast and geodetic Survey Special publication* 10.

Heacock JG (1971) *American Geophysical Union Geophysical Monograph 14:* The structure and physical properties of the earth's crust. Washington, DC: American Geophysical Union.

Heacock JG (1977) *American Geophysical Union Geophysical Monograph The earth's crust – its nature and properties 20*. Washington, DC: American Geophysical Union.

Healy JH, Mooney WD, Blank HR, *et al.* (1982) Saudi Arabian seismic deep-refraction profile, Final project report. *Saudi Arabian Deputy Ministry of Mineral Resources*, 429 p. Open-file report, USGS-OF-02-37.

Hearn TM (1984) Pn travel times in southern California. *Journal of Geophysical Research* 89: 1843–1855.
Hearn TM (1996) Anisotropic *Pn* tomography in the western United States. *Journal of Geophysical Research* 101: 8403–8414.
Hearn TM (1999) Uppermost mantle velocities and anisotropy beneath Europe. *Journal of Geophysical Research* 104: 15123–15139.
Hearn TM, Beghoul N, and Barazangi M (1991) Tomography of the western United States from regional arrival times. *Journal of Geophysical Research* 96: 16369–16381.
Hearn TM and Clayton RW (1986) Lateral velocity variations in southern California: 1, Results for the upper crust from P-waves. *Bulletin of the Seismological Society of America* 76: 495–509.
Hearn TM and Ni JF (1994) Pn velocities beneath continental collision zones; the Turkish-Iranian plateau. *Geophysical Journal International* 117: 273–283.
Hearn TM, Ni JF, Wang S, Xu Z, Yu Y, and Zhang X (2004) Uppermost mantle velocities beneath China and surrounding regions. *Journal of Geophysical Research* 109: (doi:10.1029/2003JB002874).
Heiskanen WA and Moritz H (1967) *Physical Geodesy*. San Francisco: W.H. Freeman.
Heiskanen WA and Vening-Meinez FA (1958) *The Earth and its Gravity Field*. New York: McGraw Hill.
Heiland CA (1935) Geophysical mapping from the air: It's possibilities and advantages. *Engineering and Mining Journal* 136: 609–610.
Hemant K and Maus S (2005) Why no anomaly is visible over most of the continent-ocean boundary in the global crustal magnetic field. *Physics of the Earth and Planetary Interiors* 149: 321–333.
Herrin E (1969) Regional variations of P–wave velocity in the upper mantle beneath North America. In: Hart PJ (ed.) *American Geophysical Union Monograph 13:* The Earth's Crust and Upper Mantle, pp. 242–246. Washington, DC: American Geophysical Union.
Hersey J, Officer C, Johnson H, and Bergstrom S (1952) Seismic refraction observations north of the Brownson Deep. *Bulletin of the Seismological Society of America* 42: 291–306.
Hess HH (1962) History of the ocean basins. In: Engel AE, James HL, and Leonard B (eds.) *Petrologic Studies, Burlington Volume*, pp. 599–620. Boulder, CO: Geological Society of America.
Hess HH (1965) Mid-oceanic ridges and tectonics of the sea-floor; submarine geology and geophysics. *17th Colston Research Society Symposium*, 1–10.
Hildenbrand TG, Simpson RW, Godson RH and Kane MF (1982) Digital colored residual and regional Bouguer gravity maps of the conterminous United States with cut-off wavelengths of 250 km and 1,000 km. U.S. Geological Survey Geophysical Investigations Map GP-953-A, scale 1:7,500,000.
Hill MN (1957) Recent geophysical exploration of the ocean floor. *Physics and Chemistry of the Earth* 2: 129–163.
Hill MN (ed.) (1963) *The Sea Volume 3. The Earth beneath the Sea, History*. New York: Interscience Publishers.
Hinze WJ (ed.) (1985) *The Utility of Regional Gravity and Magnetic Anomaly Maps.* Society of Exploration of Geophysicists.
Hinze WJ and Zeitz I (1985) The compromise magnetic–anomaly map of the conterminous United Satates. In: Hinze WJ (ed.) *The Utility of Regional Gravity and Magnetic Anomaly Maps*, pp. 1–24. Tulsa, OK: Society of Exploration Geophysicists.
Hirn A, Sachpazi M, Siliqi R, *et al.* (1996) A traverse of the Ionian islands front with coincident normal incidence with wide-angle seismology. *Tectonophysics* 264: 35–49.
Hodgson JH (1953) A seismic survey of the Canadian Shield: 1, Refraction studies based on rock bursts at Kirkland Lake, Ontario. *Dominion Observatory Publication* 16: pp. 111–163. Ottawa, Ontario.
Hofsetter R and Bock G (2004) Shear-wave velocity structure of the Sinai sub-plate from receiver function analysis. *Geophysical Journal International* 158: 67–84.
Holbrook WS and Keleman PB (1993) Large igneous province on the U.S. Atlantic margin and implications during continental breakup. *Nature* 364: 433–436.
Holbrook WS, Mooney WD, and Christensen NI (1992) The seismic velocity structure of the deep continental crust. In: Fountain DM, Arculus R, and Kay RW (eds.) *Continental Lower Crust. Development in Geotectonics*, vol. 23, pp. 1–43. Amsterdam: Elsevier.
Hole JA (1992) Non-linear high-resolution three-dimensional seismic travel time tomography. *Journal of Geophysical Research* 97: 6553–6562.
Hole JA, Brocher TM, Klemperer SL, Parsons TE, Benz HM, and Furlong KP (2000) Three-dimensional seismic velocity structure of the San Francisco Bay area. *Journal of Geophysical Research* 105: 13859–13874.
Hole JA, Clowes RM, and Ellis RM (1992) Interface inversion using broadside seismic refraction data and three-dimensional travel time calculations. *Journal of Geophysical Research* 97: 3417–3429.
Hole JA and Zelt BC (1995) Three-dimensional finite-difference reflection travel times. *Geophysical Journal International* 121: 427–434.
Holmes A (1918) The basaltic rocks of the Arctic region. *Mineralogical Magazine* 18: 180–223.
Hood PJ, McGrath PH, and Teskey DJ (1985) Evolution of Geological Survey of Canada magnetic anomaly maps: A Canadian perspective. In: Hinze WJ (ed.) *The Utility of Regional Gravity and Magnetic Anomaly Maps*, pp. 62–68. Tulsa, OK: Society of Exploration of Geophysicists.
Horsefield SJ, Whitmarsh RB, White RS, and Sibuet J-C (1993) Crustal structure of Goban Spur rifted continental margin, NE Atlantic. *Geophysical Journal International* 119: 1–19.
Huang Z, Peng Y, Luo Y, Zheng Y, and Su W (2004) Azimuthal anisotropy of Rayleigh waves in East Asia. *Geophysical Research Letters* 31: L15617 (doi:10.1029/2004GL020399).
Huestis SP and Parker RL (1977) Bounding thickness of the oceanic magnetized layer. *Journal of Geophysical Research* 82: 5293–5303.
Humphreys E and Clayton RW (1988) Adaption of back projection tomography to seismic travel time problems. *Journal of Geophysical Research* 93: 1073–1085.
Humphreys E, Clayton RW, and Hager BH (1984) A tomographic image of mantle structure beneath southern California. *Geophysical Research Letters* 11: 625–627.
Hwang L and Mooney WD (1986) Velocity and Q structure of the Great Valley, California, based on synthetic seismogram modeling of seismic refraction data. *Bulletin of the Seismological Society of America* 76: 1053–1067.
Hyndman RD (1979) Poisson's ratio in the oceanic crust: A review. *Tectonophysics* 59: 321–333.
Hyndman RD (1988) Dipping seismic reflectors, electrically conductive zones, and trapped water in the crust over a subducting plate. *Journal of Geophysical Research* 93: 13133–13405.
Hyndman RD, Wang K, and Yamano M (1995) Thermal constraints on the seismogenic portion of the south western Japan subductim Thrust. *Journal of Geophysical Research* 100: 15373–15392.
Iyer HM and Hitchcock T (1989) Upper-mantle velocity structure in the continental U.S. and Canada. In: Pakiser LC and

Mooney WD (eds.) *Geological Society of America Memoir 172: Geophysical framework of the Continental United States*, pp. 681–710. Boulder,CO: Geological Society of America.

Iyer HM and Hirahara K (1993) *Seismic Tomography Theory and Practice*. London: Chapman and Hall.

Jackson WH and Oakey GN (1986) Sedimentary thickness map of the Arctic Ocean. In: Grantz A, Johnson L, and Sweeney JF (eds.) *The Geology of North America*. Boulder, CO: Geological Society of America: Plate 5.

Jackson WH and Pakiser LC (1965) Seismic study of crustal structure in the southern Rocky Mountains. *U.S. Geological Survey Professional Paper* 525-D: p. D-85-D-92.

Jackson WH, Stewart SW, and Paksier LC (1963) Crustal structure in eastern Colorado from seismic-refraction measurements. *Journal of Geophysical Research* 68: 5767–5776.

Jakosky JJ (1940) *Exploration Geophysics*. Los Angeles: Trija Publishing Co.

James DE (1971) Andean crustal and upper mantle structure. *Journal of Geophysical Research* 76: 3246–3271.

James DE and Steinhart JS (1966) Structure beneath continents, a critical review of explosion seismic studies 1960–1965. In: Steinhart JS and Smith TJ (eds.) *American geophysical Union Geophysical Monograph 10: The Earth Beneath the Continents*, pp. 293–333. Washington, DC: American Geophysical Union.

Jarchow CM and Thompson GA (1989) The nature of the Mohorovicic discontinuity. *Annual Review Earth and Planetary Sciences* 17: 475–506.

Jaupart C and Mareschal JC (1999) The thermal structure and thickness of continental roots. *Lithos* 48: 93–114.

Jeffreys H (1940) *Seismological Tables*. British Association for the Advancement of science. London, Gray Milne Trust.

Jensen H (1961) The airborne magnetometer. *Scientific American* 204: 151–162.

Jeffreys H and Bullen KE (1935) Times of transmission of earthquake waves. *Bureau of Central Séismologique International*, Series A, Fasc. II.

Johnson GR and Olhoeft GR (1984) Density of rocks and minerals. In: Charmichael RS (ed.) *Handbook of Physical Properties of rocks*, vol. 3, pp. 1–38. Boca Raton, FL: CRC Press.

Johnson M and Vincent C (2002) Development and testing of a 3D velocity model for improved event location: A case study for the India-Pakistan region. *Bulletin of the Seismological Society of America* 92: 2893–2910.

Jones AG (1992) Electrical conductivity structure of the continental lower crust. In: Fountain DM, Arculus RJ, and Kay RW (eds.) *Continental Lower Crust*, pp. 81–143. Amsterdam: Elsevier.

Jones AG, Ferguson IJ, Chave AD, Evans RL, and McNeice GW (2001) The electrical lithosphere of the Slave Province *Geology* 29: 423–426.

Jones EJW (1999) *Marine Geophysics*. Chichester, England: John Wiley & Sons.

Jones EJW and Mgbatogu CCS (1982) The structure and evolution of the West African continental margin off Guine Bissau Guinee and Sierra Leone. In: Scrutton RA, Talwani M, and Chichester JW (eds.) *The Ocean Floor*, pp. 165–202. New York: Wiley.

Jones T and Nur A (1983) Velocity and attenuation in sandstone at elevated temperatures and pressures. *Geophysical Research Letters* 10: 140–143.

Jordan TH (1975) The continental tectosphere. *Geophysics and Space Physics* 13: 1–12.

Jordan TH (1979) Mineralogies, densities and seismic velocities of garnet lherzolites and their geophysical implications. In: Boyd FR and Meyer HOA (eds.) *The Mantle Sample: Inclusions in Kimberlites and Other Volcanics*, vol. 2, pp. 2–14. Washington, DC: American Geophysical Union.

Jordan TH (1988) Special Lithosphere Issue: *Structure and Formation of the Continental Tectosphere*. *Journal of Petrology* 29: 11–37.

Jordan TH and Frazer LN (1975) Crustal and upper mantle structure from *Sp* phases. *Journal of Geophysical Research* 80: 1504–1518.

Juhlin C (1988) Interpretation of the seismic reflectors in the Gravberg-I well. In: Boden A and Erickson KG (eds.) *Deep Drilling in Crystalline Bedrock*, 364 pp. Berlin: Springer.

Julia J, Ammon CJ, Herrmann RB, and Correig AM (2000) Joint inversion of receiver function and surface wave dispersion observations. *Geophysical Journal International* 143: 99.

Julià J and Mejía J (2004) Thickness and vp/vs ratio variation in the Iberian crust. *Geophysical Journal International* 156: 59–72.

Junger A (1951) Deep refractions in Big Horn County, Montana. *Geophysics* 16: 499–505.

Kaban MK and Mooney WD (2001) Density structure of the lithosphere in the southwestern United States and its tectonic significance. *Journal of Geophysical Research* 106: B1.

Kaban MK, Schwintza P, Artemieva IM, and Mooney WD (2003) Density of the continental roots: Compositional and thermal contributions. *Earth and Planetary Science Letters* 209: 53–69.

Kanasewich ER and Cumming GL (1965) Near vertical-incidence seismic reflections from the ''Conrad'' discontinuity. *Journal of Geophysical Research* 70: 3441–3446.

Kane MF and Godson RH (1989) A crust/mantle structural framework of the continuous United States based on gravity and magnetic data. In: Pakiser LC and Mooney WD (eds.) *Geological Society America Memoir 172: Geophysical Framework of the Continental United States*, pp. 383–404. Boulder, CO: Geological Society of America.

Karagianni EE, Papazachos CB, Panagiotopoulos DG, Suhadolc P, Vuan A, and Panza GF (2005) Shear velocity structure in the Aegean area obtained by inversion of Rayleigh waves. *Geophysical Journal International* 160: 127–143.

Katz S (1954) Seismic study of crustal structure in Pennsylvania and New York. *Bulletin of the Seismological Society of America* 44: 303–325.

Kay RW and Kay SM (1981) The nature of the lower continental crust: Inferences from geophysics, surface geology, and crustal xenoliths. *Reviews of Geophysics and Space Physics* 19: 271–297.

Keller G (1989) Conductivity of the crust. In: Pakiser LC and Mooney WD (eds.) *Geological Society of America Memoir 172: Geophysical Framework of the continental United States*, pp. 425–446. Boulder, CO: Geological Society of America.

Kelley KR, Ward RW, Treitel S, and Alford RM (1976) Synthetic seismograms: A finite approach. *Geophysics* 41: 2–27.

Kempner WC and Gettrust JF (1982) Ophiolithes, synthetic seismograms, and oceanic crustal structure, 1: Comparsion of ocean bottom seismometer data and synthetic seismograms from the Bay of Islands ophiolite. *Journal of Geophysical Research* 87: 8462–8476.

Kennett BLN (1974) Reflections, rays, and reverberations. *Bulletin of the Seismological Society of America* 64: 1685–1696.

Kennett BLN (1983) *Seismic Wave Propagation in Stratified Media*. Cambridge: Cambridge University Press.

Kennett BLN and Engdahl ER (1991) Traveltimes for global earthquake location and phase identification. *Geophysical Journal International* 105: 429–465.
Kennett BLN, Engdahl ER, and Buland R (1995) Constraints on seismic velocities in the Earth from traveltimes. *Geophysical Journal International* 122: 108–124.
Kern H (1978) The effect of high temperature and high confining pressure on compressional wave velocities in quartz-bearing and quartz-free igneous and metamorphic rocks. *Tectonophysics* 44: 185–203.
Kern H, Gao S, and Liu QS (1996) Seismic properties and densities of middle and lower crustal rocks exposed along the North China Geoscience Transect. *Earth and Planetary Science Letters* 139(3–4): 439–455.
Kern H, Popp T, Gorbatsevich, Zharikov A, Lobanov KV, and Smirnov Yu P (2001) Pressure and temperature dependence of Vp and Vs in rocks from the superdeep well and from surface analgues at Kola and the nature of velocity anisotropy. *Tectonophysics* 338: 113–143.
Kerr AC (2003) Oceanic plateaus. In: Holland HC and Turekian K (eds.) *Treatise on Geochemistry*, Vol. 3, pp. 537–565. Amsterdam: Elsevier.
Kimbell GS, Gatli RW, Ritchie JD, Walker ASD, and Williamson JP (2004) Regional Three-dimensional gravity modeling of the NE Atlantic margin. *Basin Research* 16: 259–278.
Kimura G and Ludden J (1995) Peeling oceanic crust in subduction zones. *Geology* 23: 217–220.
Kinck JJ, Husebye ES, and Larsson FR (1993) The Moho depth distribution in Fennoscandia and regional tectonic evolution from Archean to Permian times. *Precambrian Research* 64: 23–51.
Kind R (1978) The reflectivity method for a buried source. *Journal of Geophysics* 44: 603–612.
Kind R, Kosarev GL, and Petersen NV (1995) Receiver functions at the stations of the German Regional Seismic Network (GRSN). *Geophysical Journal International* 121: 191–202.
Kind R and Vinnik LP (1988) The upper mantle discontinuities underneath the GRF array from P-to-S converted phases. *Journal of Geophsics* 62: 138–147.
Kind R, Yuan X, Saul J, *et al.* (2002) Seismic images of crust and upper mantle beneath Tibet: Evidence for Eurasian plate subduction. *Science* 298: 1219–1221.
Kissling E (1998) Geotomography with local earthquake data. *Reviews of Geophysics* 26: 659–698.
Kissling E, Husen S, and Haslinger F (2001) Model parameterization in seismic tomography: A choice of consequence for the solution quality. *Physics of the Earth and Planetary Interiors* 123: 89–101.
Klemperer SL and Hobbs R (1991) *The BIRPS Atlas: Deep Seismic Reflection Profiles Around the British Isles*. Cambrige: Cambridge University Press.
Klemperer SL and Luetgert JH (1987) A comparison of reflection and refraction processing and interpretation methods applied to conventional refraction data from costal maine. *Bulletin of the Seismological Society of America* 77: 614–630.
Klemperer SL and Mooney WD, (eds.) (1998a) Deep seismic profiling of the Continents, Part 1: General results and new methods. *Tectonophysics* 286: 1–298.
Klemperer SL and Mooney WD, (eds.) (1998b) Deep seismic profiling of the continents, Part 2: A global survey. *Tectonophysics* 288: 1–292.
Klemperer SL and Oliver JE (1983) *The Advantage of Length in Deep Crustal Reflection Profiles*. First Break, 20–27. April.
Klosko ER, Russo RM, Okal EA, and Richardson WP (2001) Evidence for a rheologically strong chemical mantle root beneath the Ontong-Java Plateau. *Earth and Planetary Science Letters* 186: 347–361.
Knopoff L (1972) Observation and inversion of surface-wave dispersion. *Tectonophysics* 13: 497–519.
Kodaira S, Takahashi N, Park JO, Mochbaki K, Shinohana M, and Kimma S (2000) Wester Nankai Trough seismogenic: Results from a wide-angle ocean bottom seismic survey. *Journal of Geophysical Research* 105: 5882–5906 (doi:10.1029/1999 JB 900394).
Korja T, Engels M, Zhamaletdinov AA, *et al.* (2002) Crustal conductivity in Fennoscandia-a compilation of a database on crustal conductance in the Fennosacnadian Shield. *Earth Planet Space* 54: 535–558.
Kovach RL (1978) Seismic surface waves and crystal and upper mantle structure. *Reviews of the Geophysics and Space Physics* 16: 1–13.
Kovach RL and Anderson DL (1964) Higher mode surface waves and their bearing on the structure of the earth's mantle. *Bulletin of the Seismological Society of America* 54: 161–182.
Kozlovsky YA (ed.) (1987) *The Superdeep Well of the Kola Peninsula (Exploration of the Deep Continental Crust)*, 558 pp. Berlin: Springer-Verlag.
Kroenke LW (1974) Origin of continents through development and coalescence of oceanic flood basalt plateaus. *EOS* 55: 443.
Kusznir NJ and Matthews DH (1988) *Special Lithosphere Issue: Deep Seismic Reflection and Deformational Mechanisms of the Continental Lithosphere*. *Journal of Petrology* 63–87.
Lachenbruch AH, Sass JH, and Galanis SP, Jr. (1985) Heat flow in southernmost California and the origin of the Salton trough. *Journal of Geophysical Research* 90: 6709–6736.
Langel RA (1985) Introduction to the special issue: A perspective on MAGSAT results. *Journal of Geophysical Research* 90: 2441–2444.
Langel RA, Ousley G, and Berbert J (1982) The Magsat Mission. *Geophysical Research Letters* 9: 243–245.
Langston CA (1977) Corvallis, Oregon, crustal and upper mantle receiver structure from teleseismic P and S waves. *Bulletin of the Seismological Society of America* 67: 713–725.
Langston CA (1994) An integrated study of crustal structure and regional wave propagation for southeastern Missouri. *Bulletin of the Seismological Society of America* 84: 105–118.
Langston CA, Nyblade AA, and Owens TJ (2002) Regional wave propagation in Tanzania, East Africa. *Journal of Geophysical Research* 107: (doi:10.1029/2001JB000167).
Laske G and Masters G (1997) A global digital map of sediment thickness (abstract). *EOS*, *Transactions*, *American Geophysical Union* 78, vol. 46, Fall meeting supplement: F483.
Lay T and Wallace TC (1995) *Modern Global Seismology*, 521 pp. San Diego, CA, USA: Academic Press.
Lebedev S and Nolet G (2003) Upper mantle beneath southeast Asia from S velocity tomography. *Journal of Geophysical Research* 108: 26.
Lees JM and Crosson RS (1989) Tomographic inversion for three-dimensional velocity structure at Mount St. Helens using earthquake data. *Journal of Geophysical Research* 94: 5716–5728.
Leet LD (1936) Seismological data on surface layers in New England. *Bulletin of the Seismological Society of America* 26: 129–145.
Lei J and Zhao D (2005) P-wave tomography and origin of the Changbai intraplate volcano in northeast Asia. *Tectonophysics* 397: 281–295.
Levander AR and Holliger K (1992) Small scale heterogeneity and large-scale velocity structure of the continental crust. *Journal of Geophysical Research* 97: 8797–8804.

Leveque J, Rivera L, and Wittlinger G (1993) On the use of the checker-board test to access the resolution of tomographic inversions. *Geophysical Journal International* 115: 313–318.
Levshin AL, Yanovskaya TB, Lander AV, *et al.* (1989) Recording, identification, and measurement of surface wave parameters. In: Keilis-Borok VI (ed.) *Seismic Surface Waves in a Laterally Inhomogeneous Earth*. London: Kluwer Publication House.
Levshin AL, Ritzwoller MH, and Shapiro NM (2005) The use of crustal higher modes to constrain crustal structure across central Asia. *Geophysical Journal International* 160: 961–972.
Li S, Unsworth MJ, Booker JR, *et al.* (2003) Partial melt or aqueous fluid in the mid-crust of southern Tibet? Constraints from INDEPTH magnetotelluric data. *Geophysical Journal International* 153: 289–304.
Li SL and Mooney WD (1998) Crustal structure of China from deep seismic sounding profiles. *Tectonophysics* 288: 105–113.
Li X, Kind R, Yuan X, Woelbern I, and Hanka W (2004) Rejuvenation of the lithosphere by the Hawaiian plume. *Nature* 427: 827–829.
Li XD and Romanowicz B (1996) Global mantle shear velocity model developed using nonlinear asymptotic coupling theory. *Journal of Geophysical Research* 101: 22245–22272.
Liang C, Song X, and Huang J (2004) Tomographic inversion of Pn travel times in China. *Journal of Geophysical Research* 109: B11304 (doi:10.1029/2003JB002789).
Lindwall DA (1988) A two-dimensional seismic investigation of crustal structure under the Hawaiian islands near Oahu and Kauai. *Journal of Geophysical Research* 93: 12107–12122.
Lippitsch R, Kissling E, and Ansorge J (2003) Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography. *Journal of Geophysical Research* 108: 15.
Liu Y, Xu C, He J, Liu F, and Sun H (2005) Three-dimensional velocity images of the crust and upper mantle beneath the North-South Zone in China. *Bulletin of the Seismological Society of America* 95: 916–925.
Loper DE (1983) The dynamical and thermal structure of deep mantle plumes. *Physics of the Earth and Planetary Interiors* 33: 304–317.
Ludwig WJ and Houtz RE (1979) *Isopack Map of Sediments in the Pacific Ocean Basin and Marginal Sea Basins*. Tulsa, Oklahoma: American Association of Petroleum Geologists.
Ludwig WJ, Nafe JE, and Drake LE (1970) Seismic refraction. In: Maxwell AE (ed.) *The Sea. New Concepts of Sea Floor Evolution*, pp. 53–84. New York: Wiley-Interscience.
Luosto U (1997) Structure of Earth's crust in Fennoscandia as revealed from refraction and wide-angle reflections studies. *Geophysica* 33: 3–16.
Lutter WJ, Nowack RL, and Braile LW (1990) Seismic imaging of upper crustal structure using traveltimes from the PASSCAL Ouachita experiment. *Journal of Geophysical Research* 95: 4621–4631.
Ma KF, Wang JH, and Zhao D (1996) Three-dimensional seismic velocity structure of the crust and uppermost mantle beneath Taiwan. *Journal of Physics of the Earth* 44: 85–105.
MacGregor LM, Constable S, and Sinha MC (1998) The RAMESSES experiment-III controlled- source electromagnetic sounding of the ReyKjanes Ridge AT 57° 45′ N. *Geophysical Journal International* 135: 773–789.
Maggi A and Priestley K (2005) Surface waveform tomography of the Turkish-Iranian plateau. *Geophysical Journal International* 160: 1068–1080.
Mahadevan TM (1994) Deep Continental Structure of India: A Review. *Geological Society of India Memoir* 28, Bangalore.
Mahoney JJ and Coffin MF (1997) *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. Washington, DC: American Geophysical Union.
Mair JA and Forsyth DA (1982) Crustal structure of Canada Basin near Alaska, the Lomonosov Ridge, and adjoining basins near the North Pole. *Tectonophysics* 89: 239–254.
Mair JA and Lyons JA (1976) Seismic reflection techniques for crustal structure studies. *Geophysics* 41: 1272–1290.
Makovsky Y, Klemperer SL, Huang LY, Lu DY, and Project INDEPTH Team (1996a) Structural elements of the southern Tethyan Himalaya crust from wide-angle seismic data. *Tectonics* 15: 997–1005.
Makovsky Y, Klemperer SL, Ratschbacher L, *et al.* (1996b) INDEPTH wide-angle reflection observations of P-wave-to-S-wave conversions from crustal bright spots in Tibet. *Science* 274: 1690–1691.
Makris J (1978) The crust and upper mantle of the Aegean region from deep seismic soundings. *Tectonophysics* 46: 269–284.
Mandal P, Rastogi BK, Satyanarayana HVS, and Kousalya M (2004) Results from local earthquake velocity tomography: Implications toward the source process involved in generating the 2001 Bhuj earthquake in the lower crust beneath Kachchh (India). *Bulletin of the Seismological Society of America* 94: 633–649.
Mareschal J-C, Jaupart C, Cheng LZ, *et al.* (1999) Heat flow in the Trans-Hudson Orogen of the Canadian Shield: Implications for Proterozoic continental growth. *Journal of Geophysical Research* 104: 29007–29024.
Masters G, Johnson S, Laske G, and Bolton H (1996) A shear-velocity model of the mantle. *Philosophical Transactions of the Royal Society of London A* 354: 1285–1411.
Matthews DH (1986) Seismic reflections from the lower crust around Britain. In: Dawson J, Carswell D, Hall J, and Wedepohl K (eds.) *Geological Society of London Special Publication: Nature of the Lower Continental Crust*, vol. 24, pp. 11–21. Bath, UK: Geological Society of London.
Matthews DH, and BIRPS group (1987) Some unsolved BIRP problems. *Geophysical Journal of the Royal Astronomical Society* 89: 209–216.
Matthews DH and BIRPS Core Group (1990) Progress in BIRPS deep seismic reflection profiling around the British Isles. *Tectonophysics* 173: 387–396.
Matthews DH and Cheadle MJ (1986) *Geodynamics Series 13: Deep Reflections from the Caledonides and the Variscides of Britain and comparison with the Himalayas*, pp. 5–19. Washington, DC: American Geophysical Union.
Matzel E and Grand SP (2004) The anisotropic seismic structure of the East European platform. *Journal of Geophysical Research* 109: (doi:10.1029/2001JB000623).
Maxwell AE (ed.) (1970a)*I The Sea. New Concepts of Sea Floor Evolution*, vol. 4., New York: Wiley-Interscience.
Maxwell AE (ed.) (1970b)*II., The Sea. New Concepts of Sea Floor Evolution*, vol. 4., New York: Wiley-Interscience.
Mayhew MA, Johnson BD, and Wasilewski PJ (1985) A review of problems and progress in studies of satellite magnetic anomalies. *Journal of Geophysical Research* 90: 2511–2522.
Mayhew MA and LaBrecque JL (1987) Crustal geologic studies with Magsat and the surface magnetic data. *Reviews of Geophysics and Space Physics* 25: 971–981.
Mayne H (1962) Common reflection point horizontal data stacking techniques. *Geophysics* 27: 927–938.
Mayne H (1967) Practical considerations in the use of common reflection point techniques. *Geophysics* 32: 225–229.
McCaughey M, Barton PJ, and Singh SC (2000) Joint inversion of wide-angle seismic data and a deep reflection profile from the central North Sea. *Geophysical Journal International* 141: 100–114.
McEvilly TV (1964) Central U.S. crust-upper mantle structure from Love and Raleigh wave phase velocity inversion.

Bulletin of the Seismological Society of America 54: 1997–2016.
McEchan GA and Mooney WD (1980) Asymptotic ray theory and synthetic seismograms for laterally varying structure: theory and application to the Imperial Valley, California. *Bulletin of the Seismological Society of America* 70: 2021–2035.
McEnroe SA, Langenhorst F, Robinson P, Bromiley GD, and Shaw CSJ (2004) What is magnetic in the lower crust? *Earth and Planetary Science Letters* 22: 175–192.
McKenzie D and Bickle MJ (1988) The volume and composition of melt generated by extention of the lithosphere. *Journal of Petrology* 29: 625–679.
McKenzie D, Jackson J, and Priestley K (2005) Thermal structure of oceanic and continental lithosphere. *Earth and Planetary Science Letters* 233: 337–349.
McNamara DE, Walter WR, Owens TJ, and Ammon CJ (1997) Upper mantle velocity structure beneath the Tibetan plateau from Pn travel time tomography. *Journal of Geophysical Research* 102: 493–505.
McNutt MK (1980) Implications of regional gracity for state of stress in the Earth's crust and upper mantle. *Journal of Geophysical Research* 85: 6377–6396.
Mechie J, Abu-Ayyash K, Ben-Avraham Z, *et al.* (2004) Crustal shear velocity structure across the Dead Sea Transform from 2-D modeling of project DESERT explosion seismic data. *Geophysical Journal International* 160: 910–924.
Mechie J, Egorkin AV, Fuchs K, *et al.* (1993) P-wave mantle velocity structure beneath northern Eurasia from long-range recordings along the profile. *Physics of the Earth and Planetary Interiors* 79: 469–486.
Meissner R (1967) Exploring the deep interfaces by seismic wide angle measurements. *Geophysical Prospecting* 15: 598–617.
Meissner R (1973) The ''Moho'' as a transition zone. *Geophysical Survey* 1: 195–216.
Meissner R (1986) *The Continental Crust: A Geophysical Approach*. London: Academic Press.
Meissner R and Bortfeld RK (eds.) (1990) *DEKORP – Atlas: Results of Deutsches Kontinentales Reflexionsseismisches Programm*. Berlin: Springer-Verlag.
Meissner R, Brown L, Dürbaum H-J, Franke W, Fuchs K, and Siefert F (eds.) (1991) *Geodynamics Series 22: Continental lithosphere: Deep Seismic Reflections*. Washington, DC: American Geophysical Union.
Meissner R and Mooney WD (1998) Weakness ot the lower continental crust: A condition for delamination, uplift, and escape. *Tectonophysics* 296: 47–60.
Meissner R, Mooney WD, and Artemieva IM (2002) Seismic anisotropy and mantle creep in young orogens. *Geophysical Journal International* 149: 1–14.
Meissner R, Wever T, and Fluh ER (1987) The Moho in Europe – implications for crustal development. *Annales Geophysicae* 5: 357–364.
Mele G (1998) Pn anisotropy in the northern Apennine chain (Italy); geodynamics of lithosphere and earth's mantle; seismic anisotropy as a record of the past and present dynamic processes. *PAGEOPH* 151: 495–502.
Menke W (1989) *Geophysical Data Analysis: Discrete Inverse Theory, rev. edn*. New York: Springer.
Meyers SC, Beck S, Zandt G, and Wallace T (1998) Lithospheric-scale structure across the Bolivian Andes from tomographic images of velocity and attenuation for P and S waves. *Journal of Geophysical Research* 103: 21 233–21 252.
Milkereit B, Mooney WD, and Kohler WM (1985) Inversion of seismic refraction data in planar dipping structure. *Geophysical Journal of the Royal Astronomical Society* 82: 81–103.
Minshull TA (1993) Wide-angle imaging of reflectors in Mesozoik oceanic crust. *Geophysical Research Letters* 20: 1619–1622.
Minshull TA (2002) Seismic structure of the oceanic crust and rifted continental margins. In: Lee WHK, Kanamori H, and Jennings PC (eds.) *International Geophysics Series 81A. International Handbook of Earthquake and Engineering Seismology*, pp. 911–924. San Diego, CA: Academic Press.
Mintrop L (1949) On the stratification of the earth's crust according to seismic studies of a large explosion and earthquakes. *Geophysics* 14: 321–336.
Mitchell BJ and Herrmann RB (1979) Shear velocity structure in the eastern United States from the inversion of surface-wave group and phase velocities. *Bulletin of the Seismological Society of America* 69: 113–1148.
Mitra S, Priestley K, Bhattacharyya AK, and Gaur VK (2005) Crustal structure and earthquake focal depths beneath northeastern India and southern Tibet. *Geophysical Journal International* 160: 277.
Molnar P and Tapponnier P (1975) Cenozoic tectonics of Asia: Effects of a continental collision. *Science* 189: 415–426.
Montagner J-P and Tanimoto T (1990) Global anisotropy in the upper mantle inferred from the regionalization of phase velocities. *Journal of Geophysical Research* 95: 4797–4819.
Montelli R, Nolet G, Dahlen FA, Masters G, Engdahl ER, and Hung S (2004) Finite-frequency tomography reveals a variety of plumes in the mantle. *Journal of Science* 303: 338–343.
Mohorovicic A (1910) Das Beben vom 8.x.1909. *Jahrb. meteorol. Obs. Zagreb für 1909* IX, IV.Teil, Abschn. 1, Zagreb, 1–63.
Mooney WD (1989) Seismic methods for the determining earthquake source parameters and lithospheric structure. In: Pakiser LC and Mooney WD (eds.) *Geophysical framework of the Continental United States*, pp. 11–34. Geological Society of America Memoir 172. Boulder, CO: Geological Society of America.
Mooney WD, Beroza G, and Kind R (2007) Fault zones from top to bottom: A geophysical perspective. In: Handy M, Hirth G, and Hovius N (eds.) *Tectonic Faults: Agents of Change on a Dynamic Earth*, pp. 9–46. Cambridge, MA: MIT Press.
Mooney WD and Braile LW (1989) The seismic structure of the continental crust and upper mantle of North America. In: Bally AW and Palmer AR (eds.) *The geology of North America – An Overview*, pp. 39–52. Boulder, CO: Geological Society of America.
Mooney WD and Brocher TM (1987) Coincident seismic reflection/refraction studies of the continental lithosphere: A global review. *Reviews of Geophysics* 25: 723–742.
Mooney WD and Meissner R (1991) Continental crustal evolution observations. *Eos, Transactions, American Geophysical Union* 72(48,537): 540–541.
Mooney WD and Meissner R (1992) Multi-genetic origin of crustal reflectivity: A review of seismic reflection profiling of the continental lower crust and Moho. In: Fountain DM, Arculus R, and Kay RW (eds.) *Continental Lower Crust. Development in Geotectonics*, vol. 23, pp. 45–79. Amsterdam: Elsevier.
Mooney WD, Laske G, and Masters TG (1998) CRUST 5.1: A global crustal model at $5^\circ \times 5^\circ$. *Journal of Geophysical Research* 103: 727–747.
Mooney WD, Prodehl C, and Pavlenkova NI (2002) Seismic velocity structure of the continental lithosphere from controlled source data. In: Lee WHK, Kanamori H, Jennings PC, and Kisslinger C (eds.) *International Handbook of Earthquake and Engineering Seismology*, vol. 81A, pp. 887–908. The International Association of Seismology and Physics of the Earth's Interior.
Morozov IB, Morozova EA, Smithson SB, and Solodilov LN (1998) On the nature of teleseismic P_n phase observed on the ultralong–range profile ''Quartz'' Russia. *Bulletin of the Seismological Society of America* 1: 62–73.

Morozova EA, Morozov IB, Smithson SB, and Solodilov LN (1999) Heterogeniety of the uppermost mantle beneath Russian Eurasia from the ultra-long-range profile QUARTZ. *Journal of Geophysical Research* 104: 20329–20348.

Müller G (1985) The reflectivity method: A tutorial. *Journal of Geophysics* 58: 153–174.

Müller RD, Roest WR, Royer J, Gahagan LM, and Sclater JG (1997) Digital isochrons of the world's ocean floor. *Journal of Geophysical Research* 102(B2): 3211–3214.

Mueller S, (ed.) (1973) The structure of the earth's crust based on seismic data. *Tectonophysics* 20: 1–391.

Mueller S (1977) A new model of the continental crust. In: Heacock JG (ed.) *Geophysical Monograph 20: The Earth's Crust - Its Nature and Properties*, pp. 289–317. Washington, DC: American Geophysical Union.

Mueller S (1978) Evolution of the Earth's crust. In: Ramberg I and Neumann E (eds.) *Tectonics and Geophysics of Continental Rifts*, vol. 2, pp. 11–28. Dordrecht: Reidel.

Mutter CZ and Mutter JC (1993) Variations in thickness of layer 3 dominante oceanic crustal structure. *Earth and Planetary Science Letters* 117: 295–317.

Mutter JC and Karson JA (1992) Structural processes at slow spreading ridges. *Science* 257: 627–634.

Nafe JE and Drake CL (1957) Variation with depth in shallow and deep water marine sediments of porosity, density and velocity of compressional and shear waves. *Geophysics* 22: 523–552.

Nafe JE and Drake CL (1968) Physical properties of rocks of basaltic composition. In: Hess HH and Poldevaart A (eds.) *The Poldevaart treatise on Rocks of Basaltic Composition*, vol 2, pp. 483–502. New York: Wiley-Interscience.

Nakamura M, Yoshida Y, Zhao D, Katao H, and Nishimura S (2003) Three-dimensional P- and S-wave velocity structures beneath the Ryukyu arc. *Tectonophysics* 369: 121–143.

Nataf H-C and Ricard Y (1996) 3SMAC: An *a priori* tomographic model of the upper mantle based on geophysical modeling. *Physics of the Earth and Planetary Interiors* 95: 101–122.

National Geophysical Data Center (1988) ETOPO-5, bathymetry/topography data. *Data Announcement 88-MGG-02*, National Oceanic and Atmospheric Administration, U.S. Dep. of Commerce, Washington, DC.

National Geophysical Data Center (2004) Total Sediment Thickness of the World's Oceans and Marginal Seas. http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html

Navin D, Peirce C, and Sinha MC (1998) The RAMESSES experiment- II. Evidence for accumulated melt beneath a slow spreading ridge from wide-angle refraction and multichannel reflection seismic profiles. *Geophysical Journal International* 135: 746–772.

Nelson KD, Zhao W, Brown JK, *et al.* (1996) Partially molten middle crust beneath southern Tibet: Synthesis of project INDEPTH results. *Science* 274: 1684–1688.

Nkanish AT, Narumi K, Mivra S, *et al.* (2002) Crustal structure across the coseismic Neptune zone of the 1944 tonakai earthquake, The central Nakai trough seismic zone. *Journal of Geophysical Research* 107: pp. EPM-2-1 (doi: 10.1029/2001JB0000424).

Nolet G (1977) The upper mantle under Western Europe inferred from the dispersion of Rayleigh modes. *Journal of Geophysics* 43: 265–285.

Nolet G (1978) Simultaneous inversion of seismic data. *Geophysical Journal of the Royal Astronomical Society* 55: 679–691.

Nolet G (ed.) (1987a) *Seismic Tomography with Applications in Global Seismology and Exploration Geophysics*. Dordrecht: D. Reidel Publ. Co.

Nolet G (1987b) Waveform tomography. In: Nolet G (ed.) *Seismic Tomography*, pp. 301–322. Dordrecht: Reidel.

Nolet G (1990) Partitioned waveform inversion and two-dimensional structure under the network of autonomously recording seismographs. *Journal of Geophysical Research* 95(6): 8499–8512.

Nur A and Ben-Avraham Z (1982) Oceanic plateaus, the fragmentation of continents, and mountain building. *Journal of Geophysical Research* 87: 3644–3661.

Okabe A, Kaneshima S, Kanjo K, Ohtaki T, and Purwana I (2004) Surface wave tomography for southeastern Asia using IRIS–FARM and JISNET data; plumes and superplumes. *Physics of the Earth and Planetary Interiors* 146: 101–112.

Officer CB (1958) *Introduction to the Theory of Sound Transmission*. New York: McGraw-Hill Co.

Oliver J (1962) A summary of observed surface wave dispersion. *Bulletin of the Seismological Society of America* 52: 81–86.

Oliver J, Cook F, and Brown L (1983) COCORP and the continental crust. *Journal of Geophysical Research* 88: 3329–3347.

Oliver JE, Dorbin M, Kaufman S, Meyer R, and Phinney R (1976) Continuous seismic reflection profiling of the deep basement. *Bulletin of the Geological Society of America* 87: 1537–1546.

Oliver J, Dorman J, and Sutton G (1959) The second shear mode of continental Rayleigh waves. *Bulletin of the Seismological Society of America* 49: 379–389.

Oliver J and Ewing M (1957) Higher modes of continental Rayleigh waves. *Bulletin of the Seismological Society of America* 47: 187–204.

Oliver J and Ewing M (1958) Normal modes of continental Rayleigh waves. *Bulletin of the Seismological Society of America* 48: 33–49.

Olsen KH (ed.) (1995) *Continental Rifts Evolution, Structure, Tectonics*. Amsterdam: Elsevier.

Operto S and Charvis P (1996) Deep structure of the southern Kerguelen Plateau (southern Indian Ocean) from ocean bottom seismometer wide-angle seismic data. *Journal of Geophysical Research* 101: 25077–25103.

Orcutt JA (1987) Structure of the Earth: Oceanic crust and uppermost mantle. *Reviews of Geophysics* 25: 1177–1196.

Orcutt JA, Kennett BLN, and Dorman LM (1976) Structure of the East Pacific Rise from an ocean bottom seismometer survey. *Geophysical Journal of the Royal Astronomical Society* 45: 305–320.

O'Reilly BM, Hauser F, Jacob AWB, and Shannon PM (1996) The lithosphere below the Rockall Trough: Wide-angle seismic evidence for extensive serpentinisation. *Tectonophysics* 255: 1–23.

O'Reilly BM, Readman PW, and Hauser F (1998) Lithospheric structure across the western Eurasian plate from a wide-angle seismic and gravity study: Evidence for a regional thermal anomaly. *Earth and Planetary Science Letters* 156: 275–280.

Owens TJ, Crosson RS, and Hendrickson MA (1988) Constraints on the subduction geometery beaneath western Washington from broadband teleseismic waveform modeling. *Bulletin of the Seismological Society of America* 78: 1319–1334.

Owens TJ and Zandt G (1985) The response of the continental crust–mantle boundary observed on broadband teleseismic receiver functions. *Geophysical Research Letters* 12: 705–708.

Owens TJ, Zandt G, and Taylor SR (1984) Seismic evidence for an ancient rift beneath the Comberland Plateau, Tennessee: A detailed analysis of broadband teleseismic P waveform. *Journal of Geophysical Research* 89: 7783–7795.

Oxburgh ER and Parmentier EM (1977) Compositional and density stratification in oceanic lithosphere - causes and consequences. *Journal of the Geological Society of London* 133: 343–355.
Pakiser LC (1963) Structure of the crust and upper mantle in the western United States. *Journal of Geophysical Research* 68: 5747–5756.
Pakiser LC and Steinhart JS (1964) Explosion seismology in the western hemisphere. In: Odishaw J (ed.) *Research in Geophysics, 2, Solid earth and interface phenomena*, pp. 123–147. Cambridge, MA: Massachusetts Institute of Technology Press.
Pakiser LC and Mooney WD (eds.) (1989) *Geological Society America Memoir* 172. Boulder, CO: Geological Society of America, Geophysical framework of the continental United States.
Panza GF, Pontevivo A, Chimera G, Raykova R, and Aoudia A (2003) The lithosphere–asthenosphere; Italy and surroundings; Geology of Italy. *Episodes* 26: 169–174.
Papasikas N and Juhlin C (1997) Interpretation of reflections from the central part of the Siljan Ring impact structure based on results from the Stenberg–1 borehole. *Tectonophysics* 269: 237–245.
Parker RL (1971) The determination of seamount magnetism. *Geophysical Journal of the Royal Astronomical Society* 24: 321–324.
Parker RL (1973) The rapid calculations of potential anomalies. *Geophysical Journal of the Royal Astronomical Society* 31: 447–455.
Parsons B and Sclater JG (1977) An analysis of the variation of ocean floor bathymetry and heat flow with age. *Journal of Geophysical Research* 82: 803–825.
Parolai S, Spallarossa D, and Eva C (1997) Bootstrap inversion for P_n wave velocity in northwestern Italy. *Annali di Geotisica* XL: 133–150.
Parsons T, Trehu AM, Luetgert JH, *et al.* (1998) A new view into the Cascadia subduction zone and volcanic arc: Implications for earthquake hazards along the Washington margin. *Geology* 26: 199–202.
Pasyanos M (2000) Predicting geophysical measurements: Testing a combined empirical and model–based approach using surface waves. *Bulletin of the Seismological Society of America* 90: 790–798.
Pasyanos ME, Franz GA, and Ramirez AL (2006) Reconciling a geophysical model to data using a Markov chain Monte Carlo algorithm: An application to the Yellow sea-Korean peninsula region. *Journal of Geophysical Research* 111(B3): (doi: 10.1029/2005JB003851).
Pasyanos ME, Walter WR, Flanagan MP, Goldstein P, and Bhattacharyya J (2004) Building and Testing an a priori Geophysical Model for Western Eurasia and North Africa. *PAGEOPH* 161: 235–281.
Pasyanos ME, Walter WR, and Hazler SE (2001) A surface wave dispersion study of the Middle East and North Africa for monitoring the comprehensive nuclear–test–ban treaty. *Journal of Pure and Applied Geophysical* 158: 1445–1474.
Paterson NR and Reeves CV (1985) Applications of gravity and magnetic surveys: The state-of-the-art in 1985. *Geophysics* 50: 2558–2594.
Pavlenkova NI (1973) Ware Fields and crustal models of the continental type. Naukova Durnka Kiev (in Russian).
Pavlenkova NI (1996) Crustal and upper mantle structure in northern Eurasia from seismic data. *Advances in Geophysics* 37: 1–133.
Patro BPK, Harinarayana T, Sastry RS, *et al.* (2005) Electrical imaging of Narmada-Son Lineament Zone, Central India from magnetotellurics. *Physics of the Earth and Planetary Interiors* 148: 215–232.
Peirce C and Barton PJ (1991) Crustal structure of the Madeira–Tore Rise, eastern North Atlantic – results of a DOBS wide-angle and normal incidence seismic experiment in the Josephine Seamount region. *Geophysical Journal International* 106: 357–378.
Percival JA, Fountain DM, and Salisburg MH (1992) Exposed crustal cross sections as windows on the lower crust. In: Fountain DM, Arculus R, and Kay RW (eds.) *Continental Lower Crust*, pp. 317–362. Amsterdam: Elsevier.
Perfit MR and Chadwick WW, Jr. (1998) Magmatism at mid-ocean ridges: Constraints from volcanological and geochemical investigations. In: Buck WR, Delaney P, and Karson JA (eds.) *Geophys Monograph 92: Faulting and Magmatism at Mid-Ocean Ridges*. Washington, DC: American Geophysical Union.
Petit C, Koulakov I, and Deverchere J (1998) Velocity structure around the Baikal rift zone from teleseismic and local earthquake traveltimes and geodynamic implications; continents and their mantle roots. *Tectonophysics* 296: 125–144.
Pfiffner OA, Lehner P, Heitzmann P, Mueller S, and Steck A (eds.) (1997) *Deep Structure of the Swiss Alps: results of NRP 20*. Basel-Boston-Berlin: Birkhäuser.
Phinney RA (1964) Structure of the Earth's crust from spectral behavior of long–period body waves. *Journal of Geophysical Research* 69: 2997–3017.
Pilidou S, Priestley K, Debayle E, and Gudmundsson O (2005) Rayleigh wave tomography in the north Atlantic; high resolution images of the Iceland, Azores and Eifel mantle plumes; mantle plumes; physical processes, chemical signatures, biological effects. *Lithos* 79: 453–474.
Pilidou S, Priestley K, Gudmundsson O, and Debayle E (2004) Upper mantle S–wave speed heterogeneity and anisotropy beneath the North Atlantic from regional surface wave tomography; the Iceland and Azores plumes. *Geophysical Journal International* 159: 1057–1076.
Plouff D (1976) Gravity and magnetic fields of polygonal prisms and application to magnetic terrain corrections. *Geophysics* 41: 727–741.
Pollack HN and Chapman DS (1977) On the regional variation of heat flow, geotherms, and lithospheric thickness. *Tectonophysics* 38: 279–296.
Pollack HN, Hurter SJ, and Johnson JR (1993) Heat flow form the Earth's interior: Analysis of the global data set. *Reviews of Geophysics* 31(3): 267–280.
Press F (1956) Determinantion of crustal structure from phase velocity of Rayleigh waves: 1, Southern California. *Bulletin of the Geological Society of America* 67: 1647–1658.
Press F (1964) Seismic wave attenuation in the crust. *Journal of Geophysical Research* 69: 4417–4418.
Press F (1968) Earth models obtained by the Monte Carlo inversion. *Journal of Geophysical Research* 73: 5223–5234.
Priestly K and Brune J (1978) Surface waves and the structure of the Great Basin of Nevada and western Utah. *Journal of Geophysical Research* 83: 2265–2272.
Prodehl C (1970) Seismic refraction study of crustal structure of the Great Basin of Nevada and western Utah. *Journal of Geophysical Research* 83: 2629–2645.
Prodehl C (1979) Crustal structure of the western United States. *U.S. Geological Survey*, *Professional Paper* 1034.
Prodehl C (1984) Structure of the Earth's crust and upper mantle. In: Hellwege KH (editor in chief) *Landolt Börnstein New Series: Numerical Data and Functional Relationships in Science and Technology* Group V. Fuchs Kand Soffel H (eds.) *Physical Properties of the Interior of the Earth, the moon and the Planets*, vol 2a, pp. 97–206. Berlin-Heidelberg: Springer.
Purdy GM and Detric R (1986) Crustal structure of the Mid–Atlantic Ridge at 23°N from seismic refraction studies. *Journal of Geophysical Research* 91: 3739–3762.

Purucker MB, Langlais B, Olsen N, Hulot G, and Mandea M (2002) The southern edge of crationic North America: Evidence from new satellite magnetometer observations. *Geophysical Research Letters* 29(15): 8000 (doi:10.1029/2001GL013645).

Rabbel W and Mooney WD (1996) Seismic anistotropy of the crystalline crust: What does it tell us? *Terra Nova* 8: 16–21.

Rabinowitz PD, Dipiazza N, and Matthias PK (1988) Sediment thickness map of the Indian Ocean. *American Association of Petrolieum Geologists*. Tulsa: Okla.

Rai S, Priestley K, Suryaprakasm K, Srinagesh D, Gaur V, and Du Z (2003) Crustal shear velocity structure of the south Indian shield. *Journal of Geophysical Research* 108(B2): (doi:10.1029/2002JB001776).

Raitt RW (1963) The crustal rocks. In: Hill MN (ed.) *The Sea - Ideas and Observations on Progress in the Study of the Seas, The Earth Beneath the Sea*, vol. 3, pp. 85–102. New York: Wiley-Interscience.

Ramesh DS, Kind R, and Yuan X (2002) Receiver function analysis of the North American crust upper mantle. *Geophysical Journal International* 150: 91–108.

Rapine R, Tilmann F, West M, Ni J, and Rodgers A (2001) Crustal structure of northern and southern Tibet from surface wave dispersion analysis. *Journal of Geophysical Research* 108: 2120 (doi:10.1029/2001JB000445).

Rao IBP, Murty PRK, Koteswara Rao P, Murty ASN, Madhava Rao N, and Kaila KL (1999) Structure of the lower crust revealed by one- and two-dimensional modeling of wide-angle reflections-west Bengal basin, India. *Pure and Applied Geophysics* 156: 701–718.

Rau RJ and Wu FT (1995) Tomographic imaging of lithospheric structures under Taiwan. *Earth and Planetary Science Letters* 133: 517–532.

Reddy PR, Venkateswarlu N, Koteswar Rao P, and Prasad ASSSRS (1999) Crustal structure of Peninsular shield, India, from DSS studies. *Current Science* 77: 1606–1611.

Reddy PR and Vijaya Rao V (2000) Structure and tectonics of the Indian Peninsular shield - Evidence from seismic velocities. *Current Science* 78: 899–906.

Redford MS (1980) Magnetic method. *Geophysics* 45: 1640–1658.

Regnier M, Chatelain JL, Smalley R, Jr., Chiu JM, Isacks B, and Araujo M (1992) Crustal thickness variation in the Andean foreland, Argentina from converted waves. *Bulletin of the Seismological Society of America* 84: 1097–1111.

Reid AB (1980) Aeromagnetic survey design. *Geophysics* 45: 1640–1658.

Richards TC and Walker DJ (1959) Measurement of the thickness of the earth's crust in the Albertan plains of western Canada. *Geophysics* 24: 262–284.

Richardson KR, Smallwood JR, White RS, Snyder DB, and Maguire PKH (1998) Crustal structure beneath the Faroe islands and the Faroe-Iceland Ridge. *Tectonophysics* 300: 159–180.

Ringwood AE (1975) *Composition and Petrology of the Earth's Mantle*. New York: McGraw-Hill.

Ritsema J and Allen RM (2003) The elusive mantle plume. *Earth and Planetary Science Letters* 207: 1–12.

Ritzmann O, Maercklin N, Faleide JI, *et al*. (2007) A 3D geophysical model of the crust in the Barents Sea region: Model construction and basement characterisation, *Geophysical Journal International* 169: 365–425.

Ritzwoller MH, Barmin MP, Villasenor A, Levshin AL, and Engdahl ER (2002a) Pn and Sn tomography across Eurasia to improve regional seismic event locations. *Tectonophysics* 358: 39–55.

Ritzwoller MH and Lavely EM (1995) Three-dimensional seismic models of the earth's mantle. *Reviews of Geophysics* 33: 1–66.

Ritzwoller MH and Levshin AL (1998) Eurasian surface wave tomography: Group Velocities. *Journal of Geophysical Research* 103: 4839–4878.

Ritzwoller MH and Levshin AL (2002) Estimating shallow shear velocities with marine multi–component seismic data. *Geophysics* 67: 1991–2004.

Ritzwoller MH, Shapiro NM, Barmin MP, and Levshin AL (2002b) Global surface wave diffraction tomography. *Journal of Geophysical Research* 107(B12): 2335 (doi:10.1029/2002JB001777).

Roberts DG, Ginzberg A, Nunn K, and McQullin R (1988) The structure of the Rockall Trough from seismic refraction and wide-angle measurements. *Nature* 332: 632–635.

Rodi W and Mackie RL (2001) Nonlinear conjugate gradients algorithm for 2–D magnetotelluric inversion. *Geophysics* 66: 174–187.

Roecker SW (1993) Tomography in zones of collision; practical considerations and examples. In: Iyer HM and Hirahara K (eds.) *Seismic Topography: Theory and Practice*, pp. 584–612. London: Chapman and Hall.

Roecker SW, Sabitova TM, Vinnik LP, *et al.* (1993) Three-dimensional elastic wave velocity structure of the western and central Tien Shan. *Journal of Geophysical Research* 98: 15779–15795.

Roecker SW, Thurber C, and McPhee D (2004) Joint inversion of gravity and arrival time data from Parkfield: New constraints on structure and hypocenter locations near the SAFOD drill site. *Geophysical Research Letters* 31: L12SO4 (doi:10.1029/2003GJ019396).

Romanowicz B (1991) Seismic tomography of the Earth's mantle. *Annual Review of Earth and Planetary Science* 19: 77–99.

Romanowicz B (1995) A global tomographic model of shear attenuation in the upper mantle. *Journal of Geophysical Research* 100: 12375–12394.

Roller JC (1965) Crustal structure in the eastern Colorado Plateau province from seismic–refraction measurements. *Bulletin of the Seismological Society of America* 55: 107–119.

Rudnick R (1992) Xenoliths: Samples of the lower continental crust. In: Fountain DM, Arculus R, and Kay RW (eds.) *Continental Lower Crust*, pp. 269–316. Amsterdam: Elsevier.

Rudnick R and Fountain DM (1995) Nature and composition of the continental crust: a lower crustal perspective. *Reviews of Geophysics* 33: 267–309.

Rudnick RL and Gao S (2003) The composition of the continental crust. In: Holland HD and Turekian KK (eds.) *Encyclopedia of Geochemistry The Crust*, vol. 3, pp. 1–64. Elsevier-Pergamon.

Ryberg T, Fuchs K, Egorkin AV, Solodilov L, and Uchida Y (1995) Observation of high–frequency teleseismic P_n on the long–range Quartz profile across northern Eurasia. *Journal of Geophysical Research* 100: 18151–18164.

Ryberg T, Wenzel F, Mechie J, Egorkin A, Fuchs K, and Solodilov L (1996) Two-dimensional velocity structure beneath northern Eurasia derived from the super long-range seismic profile quartz. *Bulletin of the Seismological Society of America* 86: 857–867.

Sagiya T and Thatcher W (1999) Coseismic Slip Aesolutim along a plate boundary mega thrust: The Nankai trough Southwest Japan. *Journal of Geophysical Research* 104: 1111–1130.

Salisburg MH and Fountain DM (1990) *Exposed Cross-Sections of the Continental Crust*, 662 pp. Dordrecht: Kluwer.

Salah MK and Zhao D (2003) 3-D seismic structure of Kii peninsula in southwest Japan; evidence for slab dehydration in the forearc. *Tectonophysics* 364: 191–213.

Sandmeier K-J and Wenzel F (1986) Synthetic seismograms for a complex crustal model. *Geophysical Research Letters* 13: 22–25.

Sandmeier K-J and Wenzel F (1990) Lower crustal petrology from wide-angle P- and S-wave measurements in the Black Forest. *Tectonophysics* 173: 495–505.
Sandvol E, Al–Damegh K, Calvert A, *et al.* (2001) Tomographic imaging of Lg and Sn propagation in the Middle East; regional wave propagation and crustal structure; monitoring the comprehensive nuclear-test-ban treaty. *PAGEOPH* 158: 1121–1163.
Sandoval S, Kissling E, Ansorge J, and SVEKALAPKO Seismic Tomography Working Group, (CHE) (2004) High-resolution body wave tomography beneath the SVEKALAPKO array – II. Anomalous upper mantle structure beneath the central Baltic shield. *Geophysical Journal International* 157: 200–214.
Sandvol E, Seber D, Calvert A, and Barazangi M (1998) Grid search modeling of receiver functions: implications for crustal structure in the Middle East and North Africa. *Journal of Geophysical Research* 103: 26899–26971.
Sandwell DT and Smith WHF (1997) Marine gravity anomaly from Geosat and ERS 1 satellite altimetry. *Journal of Geophysical Research* 102: 10039–10054.
Saunders AD, Kempton OD, Fitton JG, *et al.* (1999) Sr, Nd, and Pb isotopes and trace element geochemistry of basalts from the Southeast Greenland margin. In: Larsen HC, Duncan RA, Allan JF, and Brooks K (eds.) *Proceedings of Ocean Drilling Program, Scientific results*, vol. 163, pp. 77–93. Ocean Drilling Program.
Saunders AD, Storey M, Kent RW, and Norry MJ (1992) Consequences of plume-lithosphere interactions. In: Storey BC, Alabaster T, and Pankhurst RJ (eds.) *Magmatism and the Causes of Continental Breakup*, vol. 68, pp. 41–60. London: Geological Society of London.
Savage MK (1999) Seismic anisotropy and mantle deformation: What have we learned from shear wave splitting? *Reviews of Geophysics* 37: 65–106.
Scalter JG, Jaupart C, and Galson D (1980) The heat flow through oceanic and continental crust and the heat loss of the Earth. *Reviews of Geophysics* 18: 269–311.
Schilt S, Oliver J, Brown L, *et al.* (1979) The heterogeneity of the continental crust: Results from deep crustal seismic reflection profiling using the VIBROSEIS technique. *Reviews of Geophysics and Space Physics* 17: 354–368.
Schouten H and McCamy K (1972) Filtering marine magnetic anomalies. *Journal of Geophysical Research* 77(35): 7089–7099.
Schouten JA (1971) A fundamental analysis of magnetic anomalies over oceanic ridges. *Marine Geophysical Researches* 1: 111–114.
Schmid S and Kissling E (2000) The arc of the western Alps in the light of geophysical data on deep crustal structure. *Tectonics* 19: 62–85.
Seber D, Sandvol E, Sandvol C, *et al.* (2001) Crustal model for the Middle East and North African region: Implications for the isostatic compensation mechanism. *Geophysical Journal International* 147: 630–638.
Sexton JL, Hinze WJ, von Freese RRB, and Braile L (1982) Long–wavelength aeromagnetic anomaly map of the conterminous United States. *Geology* 10: 364–369.
Shapiro NM and Ritzwoller MH (2002) Monte Carlo inversion for a global shear velocity model of the crust and upper mantle. *Geophysical Journal International* 151: 88–105.
Shapiro NM, Ritzwoller MH, Molnar P, and Levin V (2004) Thinning and flow of Tibetan crust constrained by seismic anisotropy. *Science* 305: 233–236.
Shearer PM (1988) Cracked media, Poisson's ratio, and the structure of the upper oceanic crust. *Geophysical Journal* 92: 357–362.
Shearer PM and Orcutt JA (1986) Compressional and shear wave anisotropy in the oceanic lithosphere – the Ngendei seismic reflection experiment. *Geophysical Journal of the Royal Astronomical Society* 87: 967–1003.
Sheriff RE and Geldart LP (1982) *Exploration seismology: History, Theory, and Data Acquisition*. Cambridge: Cambridge University Press.
Sheriff RE and Geldart LP (1983) *Exploration Seismology: Data processing and Interpretation,* vol. 1. Cambridge: Cambridge University Press.
Shor GG (1967) Seismic refraction profile in Coral Sea Basin. *Science Letters* 92: 234–246.
Silver PG (1996) Seismic anisotropy beneath the continents: Probing the depths of geology. *Annual Review of Earth and Planetary Science* 24: 385–432.
Silver PG and Chan WW (1988) Implications for continental structure and evolution from seismic anisotropy. *Nature* 335: 34–39.
Simkin T, Tilling RI, Vogt PR , Kirby SH, Kimberly P, and Stewart DB (2006) This Dynamic Planet, United States Geological Survey Geological Investigations Map I–2800, one sheet.
Simmons G (1964) Velocity of shear waves in rocks to 10 kilobars. *Journal of Geophysical Research* 69: 1123–1130.
Simpson RW, Hildenbrand TG, Godson RH, and Kane MF (1987) *Digital colored Bouguer gravity, free–air gravity*, *station location*, *and terrain maps for the continental United States*. U.S. Geological Survey Geophysical Investigations Map GP 953-B, scale 1:7,500,000.
Sinha MC, Constable SC, Peirce C, *et al.* (1998) Magnetic processes at slow spreading ridges: Implications of the RAMESSES Experiment at 57° 45′ N on the Mid-Atlantic Ridge. *Geophysical Journal International* 135: 731–745.
Sinha MC, Lounden KE, and Parsons B (1981) The crustal structure of the Madagascar Ridge. *Geophysical Journal of Astronomical Society* 66: 351–377.
Sinha MC and Louden KE (1983) The Oceanographer fracture zone, I. Crustal structure from seismic refractions studies. *Geophysical Journal of the Royal Astronomical Society* 75: 713–736.
Sinha MC, Navin DA, MacGregor LM, *et al.* (1997) Evidence for accumulated melt beneath the slow-spreading Mid-Atlantic ridge. *Philosophical Transactions of the Royal Society of London, Series A* 355: 233–253.
Sleep NH (1990) Hotspots and mantle plumes: Some phenomenology. *Journal of Geophysical Research* 95: 6715–6736.
Sleep NH (2003) Survival of Archean craton lithosphere. *Journal of Geophysical Research* 108: 2302 (doi: 10.1029/2001JB000169).
Sleep NH (2005) Evolution of the continental lithosphere. *Annual Review of the Earth and Planet Science* 33: 369–393.
Slichter LB (1938) Seismological investigations of the earth's crust using quarry blasts [abs.]. *Bulletin of the Geological Society of America* 49: 19–27.
Slichter LB (1951) Crustal structure in the Wisconsin area. *Office of Naval Research Report N9*, NR86200. Arlington, VA.
Smith TJ, Steinhart JS, and Aldrich LT (1966) Lake Superior crustal structure. *Journal of Geophysical Research* 71: 1141–1181.
Smith WHF and Sandwell DT (1997) Global sea floor topography from satellite altimetry and ship depth soundings. *Science* 277: 1956–1962.
Smithson SB, Johnson RA, Hurich CA, Valasek PA, and Branch C (1987) Deep crustal structure and genesis from contrasting reflection patterns: An integrated approach. *Geophysical Journal of the Royal Astronomical Society* 87: 67–72.

Smithson SB, Wenzel F, Ganchin YV, and Morozov IB (2000) Seismic results at Kola and KTB deep scientific boreholes: Velocities, reflections, fluids, and crustal composition. *Tectonophysics* 329: 301–317.

Snavely PD, Jr., Wagner HC, and Lander DL (1980) Geologic cross section of the central Oregon continental margin, Map and Chart Series MC-28J, scale 1:250,000. Boulder, CO: Geological Society of America.

Snyder DB, Ramos VA, and Allmendinger RW (1990) Thick–skinned deformation observed on deep seismic reflection profiles in western Argentina. *Tectonics* 9: 773–788.

Soller DR, Ray RD, and Brown RD (1982) A new global crustal thickness model. *Tectonics* 1: 125–149.

Song LP, Koch M, Koch K, and Schlittenhardt J (2004) 2–D anisotropic Pn-velocity tomography underneath Germany using regional traveltimes. *Geophysical Journal International* 157: 645–663.

Spakman W, van der Lee S, and van der Hilst RD (1993) Travel–time tomography of the European–Mediterranean mantle down to 1400 km. *Physics of the Earth and Planetary Interiors* 79: 3–74.

Spudich P and Orcutt J (1980) A new look at the seismic veolocity structure of the oceanic crust. *Reviews of Geophysic and Space Physics* 18: 627–645.

Stein CA and Stein S (1992) A model for the global gravitation in oceanic depth and heat flow with lithospheric age. *Nature* 359: 123–129.

Stien M and Hoffman AW (1994) Mantle plumes and episodic crustal, growth. *Nature* 372: 63–68.

Steinhart JS (1967) Mohorovicic–discontinuity. In: Runcorn K (ed.) *International Dictionary of Geophysics*, vol. 2, pp. 991–994. Oxford: Pergamon Press.

Steinhart JS and Meyer RP (1961) *Explosion Studies of Continental Structure*. Washington, DC: Carnegie Institute, Publication 622.

Stern TA and McBride JH (1998) Seismic exploration of continental strike-slip zones. In: Klemperer SL and Mooney WD (eds.). Deep Seismic Profiling of the Continents, I, General Results and New Methods. Tectonophysics 286: 63–78.

Su WJ, Woodward RL, and Dziewonski AM (1992) Deep origin of mid-ocean-ridge seismic velocity anomalies. *Nature* 359: 149–152.

Su WJ, Woodward RL, and Dziewonski AM (1994) Degree 12 model of shear wave velocity heterogeneity in the mantle. *Journal of Geophysical Research* 99: 6945–6980.

Sun YS, Li X, Kuleli S, Morgan FD, and Toksoz MN (2004b) Adaptive moving window method for 3D P–velocity tomography and its application in China. *Bulletin of the Seismological Society of America* 94: 740–746.

Sun YS, Morgan D, and Toksoz MN (2004a) 3D P- and S-velocity models for the crust and uppermost mantle of China by Monte-Carlo adaptive moving window inversion. *Seismological Research Letters* 74: 202–203.

Swenson J, Beck S, and Zandt G (2000) Crustal structure of the Altiplano from broadband regional waveform modeling: implications for the composition of thick continental crust. *Journal of Geophysical Research* 105: 607–621.

Talwani M (1965) Computation with the help of a digital computer of magnetic anomalies caused by bodies of arbitrary shape. *Geophysics* 30(5): 797–817.

Talwani M and Ewing M (1960) Rapid computation of gravitational attractions of three-dimensional bodies of arbitrary shape. *Geophysics* 25: 203–225.

Tanimoto T (1995) Crustal structure of the Earth. In: Ahrens TJ (ed.) *Global earth Physics: A handbook of Physical Constants*, pp. 214–224. Washington, DC: AGU.

Tapley B, Ries J, Bettadpurs, *et al.* (2005) An improved Earth gravity field model from GRACE. *Journal of Geodesy* 79(8): 467–478.

Tarantola A and Nercessian A (1984) Three-dimensional inversion without blocks. *Geophysical Journal of the Royal Astronomical Society* 76: 299–306.

Tatel HE, Adams LH, and Tuve MA (1953) Studies of the earth's crust using waves from explosions. *American Philosophy Society Proceedings* 97: 658–669.

Tatel HE and Tuve MA (1955) Seismic exploration of a continental crust. In: Poldervaart A (ed.) *Crust of the Earth*, pp. 35–50. Boulder, CO: Geological Society of America.

Taylor SR and McLennan SM (1985) *The Continental Crust: Its Composition and Evolution*. Maldon, MA: Blackwell Science.

Telford WM, Geldart LP, Sheriff RE, and Keys DA (1976) *Applied Geophysics*. Cambridge: Cambridge University Press.

Thinon I, Matias L, Rehault JP, Hirn A, Fidalgo-Gonzalez L, and Avedik F (2003) Deep structure of the Armorican Basin (Bay of Biscay): A review of Norgasis seismic reflection and refraction data. *Journal of the Geological Society of London* 160: 99–116.

Thumben C and Aki K (1987) Three-dimesional seismic imaging. *Annual Review of Earth and Plantary Sciences* 15: 115–139.

Thurber CH (1983) Earthquake locations and Three-dimensional crustal structure in the Coyote Lake area, central California. *Journal of Geophysical Research* 88: 8226–8236.

Thurber CH (1993) Local earthquake tomography: Velocities and Vp/Vs – theory. In: Iyer H and Hihahara K (eds.) *Seismic Tomography, Theory and Practice*, pp. 563–583. Boca Raton, FL: CRC Press.

Thurber CH and Kissling E (2000) Advances in travel–time calculations for Three-dimensional structures. In: Thurber CH and Rabinowitz N (eds.) *Advances in Seismic Event Location*, pp. 71–79. New York: Springer.

Thybo H, Janik T, Omelchenko VD, *et al.* (2003) Upper lithospheric seismic velocity structure across the Pripyat trough and the Ukrainian shield along the EUROBRIDGE′97 profile. *Tectonophysics* 371: 41–79.

Tiberi C, Diament M, Déverchère J, *et al.* (2003) Deep structure of the Baikal rift zone revealed by joint inversion of gravity and seismology. *Journal of Geophysical Research* 108: (doi:10.1029/2002JB001880).

Tilmann F, Ni J, Hearn T, *et al.* (2003) Seismic imaging of the downwelling Indian lithosphere beneath central Tibet. *Science* 300: 1424–1427.

Todd BJ, Reid I, and Keen CE (1988) Crustal structure across the Southwest Newfoundland Transform Margin. *Canadian Journal of Earth Sciences* 25: 744–759.

Toomey DR, Purdy GM, Solomon SC, and Wilcock WSD (1990) The three–dimensional seismic velocity structure of the East Pacific Rise near latitude 9°30′N. *Nature* 347: 639–645.

Trampert J and Woodhouse JH (1995) Global phase velocity maps of Love and Rayleigh waves between 40 and 150 seconds. *Geophysical Journal International* 122: 675–690.

Tréhu AM, Asudeh I, Brocher TM, *et al.* (1994) Crustal architecture of the Cascadia forearc. *Science* 266: 237–243.

Tucholke BE (1986) Structure of basement and distribution of sediments in the western North Atlantic Ocean. In: Vogt PR and Tucholke BE (eds.) *The Geology of North America, Vol. M, The Western North Atlantic Region*, pp. 331–340. Boulder, CO: Geological Society of America.

Tucholke BE and Uchupi E (1989) Thickness of sedimentary cover. In: Udintsev GB (ed.) *International Geology-Geophysical Atlas of the Atlantic Ocean*. Moscow: Russian Ministry of Geology Russian Acadamy of Science.

Turcotte DL and Schubert G (2002) *Geodynamics* 2nd edn. Cambridge: Cambridge University Press.

Tuve MA (1951) The Earth's crust: Washington DC. *Yearbook of the Carnegie Institution of Washington* 50: 69–73.

Tuve MA (1953) The earth's crust. *Yearbook at the Carnegie Institution of Washington* 52: 103–108.
Tuve MA, Tatel HE, and Hart PJ (1954) Crustal structure from seismic exploration. *Journal of Geophysical Research* 59: 415–422.
Unsworth MJ, Malin PE, Egbert G, and Siripunvaraporn W (2000) Along strike variations in the electrical structure of the San Andreas fault at Parkfield, California. *Geophysical Research Letters* 27: 3021–3024.
Usher MJ (1962) Elastic behavior of rock at low frequencies. *Geophysical Prospecting* 10: 119–127.
Upton BGJ, Aspen P, and Hinton RW (2001) Pyroxenite and granulite xenoliths from beneath the Scottish Northern Highlands Terrane: Evidence for lower-crust/upper-mantle relationships. *Contributions to Mineralogy and Petrology* 142: 178–197.
US Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical data center (2001) 2-minute Gridded Global Relief Data (ETOPO2).
US Geological Survey and Society of Exploration Geophysicists (1982) Composite magnetic anomaly map of the United States: Part A, Conterminous United States. U.S. Geological Survey Geophysical Investigations Map GP-954-A, scale 1:1,250,000, 2 sheets.
Vacquier V, Steenland NC, Henderson RG, and Zietz I (1951) Interpretation of aeromagnetic maps. *Geological Society of American Memoir* 47: 151.
van Heijst HJ and Woodhouse JH (1999) Global high-resolution phase velocity distribution of overtone and fundamental-model surface waves determined by mode branch stripping. *Geophysical Journal International* 137: 601–620.
van der Hilst RD, Widiyantoro S, and Engdahl ER (1997) Evidence for deep mantle circulation from global tomography. *Nature* 386: 578–584.
van der Lee S and Nolet G (1997) Upper mantle *S* velocity structure of North America. *Journal of Geophysical Research* 102: 22815–22838.
Vening-Mieinesz FA (1948) *Gravity expeditions at Sea, 1923–1938, Vol. IV: Complete Results and Isostatic Reduction*. Waltman, Delft, Netherlands: Netherlands Geodetic Commission Publication.
Venisti N, Calcagnile G, Del Gaudio V, and Pierri P (2004) Combined analysis of seismic and gravimetric data in the Adriatic plate. *Physics of the Earth and Planetary Interiors* 142: 89–100.
Vera EE, Mutter JC, Buhl P, *et al.* (1990) The structure of 0- to 0.2-m.y.-old oceanic crust at 9°N on the East Pacific Rise from expanded spread profiles. *Journal of Geophysical Research* 95: 15529–15556.
Vidale JE (1988) Finite-difference calculation of travel times. *Bulletin of the Seismological Society of America* 78: 2062–2076.
Vidale JE (1990) Finite–difference calculation of traveltimes in three dimensions. *Geophysics* 55: 521–526.
Vine FJ and Moores EM (1972) A model for the gross structure, petrology, and magnetic properties of oceanic crust. In: *Studies in Earth and Space Sciences: A Memoir in Honor of Harry Hammond Hess.* Memoir 132, pp. 195–205. Boulder, CO: Geological Society of America.
Vinnik L (1977) Detection of waves converted from P to SV in the mantle. *Physics of the Earth and Planetary Interior* 15: 39–45.
Vinnik LP and Kosarev GL (1981) Determination of crustal parameters from observations of teleseismic body waves. *Proceedings of the Acadamy of Science USSR* 261: 1091–1095 (in Russian).
Vinnik LP, Makeyeva LI, Milev A, and Usenko Y (1992) Global patterns of azimuthal anisotropy and deformation in the continental mantle. *Geophysical Journal International* 111: 433–447.
Vinnik LP, Farra V, and Kind R (2004) Deep structure of the Afro–Arabian hotspot by S receiver functions. *Geophysical Research Letters* 31: L11608 (doi:10.1029/2004GL019574).
Vogt PR, Taylor PT, Kovacs LC, and Johnson GL (1979) Detailed aeromagnetic investigation of the Arctic Basin. *Journal of Geophysical Research* 83: 1071–1089.
Von Freese RRB, Hinze WJ, Olivier R, and Bentley CR (1986) Regional magnetic anomaly constraints on continental breakup. *Geology* 14: 68–71.
Walck M (1984) The *P* wave upper mantle structure beneath an active spreading centre: The Gulf of California. *Geophysical Journal of the Royal Astronomical Society* 76: 697–723.
Walter WR, Pasyanos ME, Bhattacharyya J and O'Boyle J (2000) MENA 1.1 – An Updated Geophysical Regionalization of the Middle East and North Africa. UCRL-ID-138079, LLNL.
Wang CY, Chen W, and Mooney WD (2003) Three-dimensional velocity structure of the crust and upper mantle in southwestern China and its tectonic implications. *Journal of Geophysical Research* 108: 2442 (doi:10.1029/2002JB001973).
Wang S, Hearn T, Xu J, Ni J, Yu Y, and Zhang X (2002) Velocity structure of uppermost mantle beneath China continent from Pn tomography. Science in China. Series D. *Earth Sciences* 45: 143–150.
Wang XY, Mooney WD, and Yuan XC (2003) The crustal structure from the Altai Mountains to the Altyn Tagh fault, northwest China. *Journal of Geophysical Research* 108: 2322 (doi:10.1029/2001JB000552).
Wannamaker PE, Booker JR, Jones AG, *et al.* (1989) Resistivity cross–section through the Juan de Fuca subduction system and its tectonic implications. *Journal of Geophysical Research* 94: 14,127–14,144.
Watts AB (2001) *Isotasy and Flexure of the Lithosphere*. Cambridge: Cambridge University Press.
Warren DH and Healy JH (1973) Structure of the crust in the conterminous United States. *Tectonophysics* 20: 203–213.
Weber M, Abu-Ayyah K, and 42 others (2004) The crustal structure of the Dead Sea transform. *Geophysical Journal International* 156: 655–681 (doi:10.1111/j.1365–246X.2004.02143.x).
Wells RE, Blakely RJ, Sugiyama Y, Scholl DW, and Dinterman PA (2003) Basin–centered asperities in great subduction zone earthquakes: A link between slip, subsidence, and subduction erosion? *Journal of Geophysical Research* 108(B10): 2507 (doi:10.1029/2002JB002072).
Wepfner WW and Christensen NI (1991) Q structure of the oceanic crust. *Marine Geophysical Researches* 13: 227–237.
White DJ and Clowes RM (1990) Shallow crustal structure beneath the Juan de Fuca Ridge from 2D seismic reflaction tomography. *Geophysical Journal International* 100: 349–367.
White RS, Detrick RS, Sinha MC, and Cormier M-H (1984) Anomalous seismic structure of oceanic fractures zones. *Geophysical Journal of the Royal Astronomical Society* 79: 779–798.
White RS, Spence GD, Fowler SR, McKenzie DP, Westbrook GK, and Bowen AN (1987a) Magmatism at rifted continental margins. *Nature* 330: 439–444.
White RS, Westbrook GH, Bowen AN, *et al.* (1987b) Hatton bank (northwest U.K.) continental margin structure. *Geophysical Journal of the Royal Astronomical Society* 89: 265–272.
White RS and McKenzie D (1989) The generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research* 94: 7685–7729.

White RS, McKenzie D, and O'Nions RK (1992) Oceanic crustal thickness from seismic measurements and rare earth element inversions. *Journal of Geophysical Research* 97: 19683–19715.

Whitmarsh RB, Ginzburg A, and Searle RC (1982) The structure and origin of the Azores–Biscay Rise, north-east Atlantic Ocean. *Geophysical Journal of the Royal Astronomical Society* 70: 79–107.

Whitmarsh RB and Calvert AJ (1986) Crustal structure of Atlantic fracture zones- I. The Charlie-Gibbs fracture zone. *Geophysical Journal of the Royal Astronomical Society* 85: 107–138.

Wilcock WSD, Solomon SC, Purdy GM, and Toomey DR (1995) Seismic attenuation structure of the East Pacific Rise near 9°30′N. *Journal of Geophysical Research* 100: 24147–24165.

Willden R (1965) Seismic-refraction measurements of crustal structure beneath American Falls Resevoir, Idaho, and Flaming Gorge Resevoir, Utah. *U.S. Geological Survey Professional paper* 525-C: C-44-C-50.

Williams MC, Shrive PN, Fountain DM, and Frost BR (1985) Magnetic properties of exposed deep crustal rocks from the Superior Province of Manitoba. *Earth Planetary Science Letters* 76: 176–184.

Willmore PL and Bancroft AM (1960) The time term approach to refraction seismology. *Geophysical Journal of the Royal Astronomical Society* 3: 419–432.

Wilson JT (1963) Hypothetis of the Earth's behaviour. *Nature* 198: 925–929.

Wilson JT (1965) A new class of fault and their bearing on continental drift. *Nature* 2: 343–347.

Wolfe CJ, Pundy GM, Toomey DR, and Solomon SC (1995) Microearthquake characteristics and crustal velocity structure at 29° N on the Mid-Atlantic Ridge: The architecture of a slow spreading segment. *Journal of Geophysical Research* 100: 24,449–24,472.

Woodhouse JH and Dziewonski AM (1984) Mapping the upper mantle: Three-dimensional modeling of Earth structure by inversion of seismic waveforms. *Journal of Geophysical Research* 89: 5953–5986.

Woollard GP (1943) Transcontinental gravitational and magnetic profile of North America and its relation to geologic structure. *Bulletin of the Geological Society of America* 44: 747–789.

Woollard GP (1959) Crustal structure from gravity and seismic measurements. *Journal of Geophysical Research* 64: 1521–1544.

Woollard GP (1966) Regional isostatic relations in the united States. In: Tuve M A (ed.) *Geophysical Monograph 10: The Earth Beneath the Continents*, pp. 557–594. Washington, DC: American Geophysical Union.

Wortel MJR and Spakman W (2000) Subduction and slab detachment in the Mediterranean–Carpathian region. *Science* 290: 1910–1917.

Worthington MH (1984) *An Introduction to Geophysical tomography*. First Break, November, pp. 20–26.

Xu Y, Liu FT, Liu JH, and Chen H (2002) Crust and upper mantle structure beneath western China from wave traveltime tomography. *Journal of Geophysical Research* 107: (doi:10.1029/2001JB000402).

Yanovskaya TB and Kozhevnikov VM (2003) 3D S-wave velocity pattern in the upper mantle beneath the continent of Asia from Rayleigh wave data. *Physics of the Earth and Planetary Interiors* 138: 263–278.

Yliniemi J, Kozlovskaya E, Hjelt S, Komminaho K, Ushakov A, and SVEKALAPKO Seismic Tomography Working Group International, (III) (2004) Structure of the crust and uppermost mantle beneath southern Finland revealed by analysis of local events registered by the SVEKALAPKO seismic array. *Tectonophysics* 394: 41–67.

Yoshizawa K and Kennett BLN (2004) Multimode suface wave tomography for the Australian region using a three-stage approach incorporating finite frequency effects. *Journal of Geophysical Research* 109: (doi:10.1029/2002JB002254).

Yuan X, Ni J, Kind R, Mechie J, and Sandvol E (1997) Lithospheric and upper mantle structure of southern Tibet from a seismological passive source experiment. *Journal of Geophysical Research* 102: 27491–27500.

Yuan X, Sobolev SV, Kind R, *et al.* (2000) Subduction and collision processes in the Central Andes constrained by converted seismic phases. *Nature* 408: 958–961.

Zandt G and Ammon CJ (1995) Continental crust composition constrained by measurements of crustal Poisson's ratio. *Nature* 374: 152–154.

Zandt G and Owens TJ (1986) Comparison of crustal velocity profiles determined by seismic refraction and teleseismic methods. *Tectonophysics* 128: 155–161.

Zandt G, Myers SC, and Wallace TC (1995) Crustal and mantle structure across the Basin and Range – Colorado Plateau boundary at 37°N latitude and implications for Cenozoik extensional mechanism. *Journal of Geophysical Research* 100: 10 529–10 548.

Zang SX, Liu YG, and Ning JY (2002) Thermal structure of the lithosphere in North China. *Chinese Journal of Geophysics* 17(1): 56–66.

Zelt CA (1999) Modelling strategies and model assessment for wide-angle seismic traveltime data. *Geophysical Journal International* 139: 183–204 (22).

Zelt CA and Barton PJ (1998) Three-dimensional seismic refraction tomography: A comparison of two methods applied to data from the Faeroes Basin. *Journal of Geophysical Research* 103: 7187–7210.

Zelt CA and Forsyth DA (1994) Modelling wide-angle seismic data for crustal structure: Southeastern Grenville Province. *Journal of Geophysical Research* 99: 11678–11704.

Zelt CA, Hojkoa AM, Flueh ER, and McIntosh KD (1999) 3D simultaneous seismic refraction and reflection tomography of wide-angle data from the central Chilean margin. *Geophysical Research Letters* 26: 2577–2580.

Zelt CA, Sain K, Naumenko JV, and Sawyer DS (2003) Assessment of crustal velocity models using seismic refraction and reflection tomography. *Geophysical Journal International* 153: 609–626.

Zelt CA and Smith RB (1992) Seismic traveltime inversion for 2–D crustal velocity structure. *Geophysical Journal International* 108: 16–34.

Zhang H and Thurber CH (2003) Double-difference tomography: The method and its application to the Hayward fault, California. *Bulletin of the Seismological Society of America* 93: 1875–1889.

Zhang H, Thurber CH, Shelly D, Ide S, Beroza GC, and Hasegawa A (2004) High-resolution subducting-slab structure beneath northern Honshu, Japan, revealed by double–difference tomography. *Geology* 32: 361–364.

Zhang Y-S and Lay T (1996) Global surface wave phase velocity variations. *Journal of Geophysical Research* 101: 8415–8436.

Zhang Y-S and Tanimoto T (1991) Global Love wave phase velocity variation and its significance to plate tectonics. *Physics of the Earth and Planetary Interiors* 66: 160–202.

Zhao D, Hasegawa A, and Horiuchi S (1992) Tomographic imaging of P and S wave velocity structure beneath northeastern Japan. *Journal of Geophysical Research* 97: 19909–19928.

Zhao JM, Mooney WD, Zhang X, Li Z, Jin Z, and Okaya N (2006) Crustal structure across the Altyn Tagh Range at the northern margin of the Tibetan Plateau and tectonic implications. *Earth and Planetary Science Letters* 241: 804–814.

Zhao LS and Xie J (1993) Lateral variations in compressional velocities beneath the Tibetan Plateau from Pn traveltime tomography. *Geophysical Journal International* 115: 1070–1084.

Zhao W, Mechie J, Brown CD, *et al.* (2001) Crustal structure of central Tibet as derived from project INDEPTH wide-angled seismic data. *Geophysical Journal International* 145: 486–498.

Zhou Y, Dahlen FA, and Nolet G (2004) Three-dimensional sensitivity kernels for surface wave observables. *Geophysical Journal International* 158: 142–168.

Zhou Y, Nolet G, and Laske G (2005) Global upper-mantle structure from finite-frequency surface-wave tomography. *Journal of Geophysical Research* 111: B04304.

Zhu H and Kanamori H (2000) Moho depth variation in southern California from teleseismic receiver functions. *Journal of Geophysical Research* 105: 2969–2980.

Ziegler PA (1990) *Geological Atlas of Western Europe 2nd edn, London:* Shell International and the Geological Society.

Zietz I (1969) Aeromagnetic investigations of the earth's crust in the United States. In: Hart PJ (ed.) Geophysical Monograph 13: The Earth's Crust and Upper Mantle, pp. 404–415. Washington, DC: American Geophysical Union.

Zietz I (1982) *Compisite magnetic anomaly map of United States*; Part A. Conterminous United States: U.S. Geological Survey Geophysical Invastigations Map GP–954A, scale 1:2,500,000.

Zoback ML and Mooney WD (2003) Lithospheric buoyancy and continental intraplate stresses. *International Geology Review* 45: 95–118.

Zorin YA, Turutanov EK, Mordvinova VV, Kozhevnikov VM, Yanovskaya TB, and Treussov AV (2003) The Baikal rift zone; the effect of mantle plumes on older structure. *Tectonophysics* 371: 153–173.