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CHAPTER 2 History of Controlled-Source Seismology—A Brief Summary

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Notes

CHAPTER 2

History of Controlled-Source Seismology—A Brief Summary

2.1. INTRODUCTION AND WORLDWIDE REVIEWS

Controlled-source seismology (also called "explosion seismology" or "deep-seismic sounding") is a special method to explore the velocity-depth structure of the Earth's crust and uppermost mantle, approximately to a depth range of about 50–100 km, by the investigation of the propagation of seismic body waves. The particular advantage of controlled-source seismology is that it uses man-made seismic sources, such as quarry blasts, borehole or underwater explosions, vibrators on land and in water (airguns), etc., where time and origin of the seismic source are precisely known. This has the particular advantage that the instruments can be switched on and off at any pre-established time and can be arranged and properly oriented on profiles or fans.

The beginning of controlled-source seismology can be defined in several ways. In 2009, controlled-source seismology could have celebrated its 160th birthday, because in 1849, Robert Mallet used dynamite explosions to measure the speed of elastic waves in surface rocks. In 2006, controlled-source seismology could have celebrated its 100th birthday, because in 1906, Emil Wiechert in Goettingen developed the first mobile seismograph with which profiles could be laid out. In 2008, it was 100 years since Ludger Mintrop made the first experiments to investigate the uppermost sedimentary layers using a weight drop and recording with Wiechert's portable seismographs. The stepwise improvement and development of this method led to applied geophysics and to its first commercial successes in the 1930s, when gravity and seismic prospecting guided geologists to locate oil resources in sedimentary basins.

The scientific exploration of the Earth's crust using controlled-source seismology as we know it today, however, effectively only started after World War II, when simultaneously the systematic use of large explosions and of quarry blasts, the development of proper instrumentation, and theoretical work on wave propagation became a joint and worldwide effort to study the physical properties of the Earth's crust and uppermost mantle. With time, borehole explosions on land and the development of non-explosive sources for oceanic research as well as the development of recording devices, both on land and in water, became determining factors for large-scale experiments, hand in hand with the development of theory and corresponding fast computer programs to handle the steadily increasing amount of data.

Controlled-source seismology involves both seismic-refraction and seismic-reflection investigations. In general, reflections (with much higher frequencies than used in refraction work) deliver completely different information than do refraction-wide angle studies. Often, reflection sections show structures and tectonics directly and with relatively high resolution, while refraction-wide angle studies reveal major interfaces and variations in velocities that are important for petrologic interpretations.

Since the beginning of explosion seismology, text books on seismic theory and interpretation methods (e.g., Nettleton, 1940) as well as reviews on crustal and upper-mantle research, achieved by seismic and seismological methods, were published from time to time, summarizing the results for the whole world. Table 2.1 gives an overview of summary publications on worldwide seismic crustal and uppermost mantle studies, sorted by publication date.

2.2. REVIEWS AT REGIONAL SCALES

Many publications exist in which the results of seismic research projects for particular regions were reviewed. There are, for example, crustal study summaries for individual countries or groups of countries such as Scandinavia, or summaries on larger regions such as the western United States. Other summaries concentrate on tectonic units such as the Alps, or the Afro-Arabian rift system. Furthermore, crustal thickness (depth to the Mohorovičić discontinuity, or Moho) compilations exist for Europe, the former USSR, the United States, and Australia, for example. Those summaries were updated from time to time by the same or by other authors, depending on the state of the art at the time. In Table 2.2, publications were collected which review results on regional scales covering countries, continents and/or large tectonic units, sorted by publication date.

2.3. THE FIRST 100 YEARS (1845–1945)

Since the beginning of the twentieth century, seismic waves have been used to study Earth's interior. Such studies involved both investigations of the whole Earth by distant earthquakes and of the Earth's crust by local natural and artificial events. Thus, the earliest studies of the Earth's crust employed whatever data were available, either earthquake traveltimes or controlled sources. Mohorovičić's classic study that defined the crust was based on earthquake traveltimes rather than on controlled sources. Nevertheless, Mohorovičić is still considered as the father of seismic studies of the Earth's crust. The rapid development of this special branch of seismology would not have been possible without the earlier technical developments of seismographs and sensitive recording devices during the nineteenth century. An early historic review was published by Mintrop as early as 1947, describing the history of the first 100 years of earthquake research and explosion

TABLE 2.1. REVIEWS OF WORLDWIDE SEISMIC CRUSTAL AND UPPERMOST MANTLE STUDIES

Year	Author or editor	Contents	
1947	Mintrop	100 years of explosion seismology	A
1951	Gutenberg	Crustal layers of the continents and oceans	A
1951	Macelwane	Tables of seismic investigations until 1950	A
1954	Reinhardt	Quarry blasts and explosion seismology history	B
1955	Poldervaart	Crust of the Earth	E
1955	Gutenberg	Wave velocities in the Earth's crust	A
1961	Closs and Behnke	Velocity–cross section around the world	A
1961	Steinhart and Meyer	Explosion studies of continental structure	E
1966	James and Steinhart	Critical review of explosion studies 1960–1965	A
1969	Hart	The Earth's crust and upper mantle	E
1971	Heacock	Structure and physical properties of the Earth's crust	E
1973	Mueller	Structure of the Earth's crust based on seismic data	E
1975	Ansorge	Uppermost mantle under Europe and North America	B
1975	Christensen and Salisbury	Structure and constitution of lower oceanic crust	A
1977	Heacock	The Earth's crust—Its nature and properties	E
1978	Klemperer et al.	Seismic probing of continents and their margins	E
1980	Spudich and Orcutt	Seismic velocity structure of the oceanic crust	A
1981	Soller et al.	A global crustal thickness map	B
1984	Prodehl	Tables of Earth's crust and uppermost mantle structure	A
1986	Meissner	The continental crust	A
1986	Barazangi and Brown	Reflection seismology on continents—Global perspective	E
1987	Fuchs et al.	Mantle heterogeneities: High-resolution experiments	A
1987	Matthews and Smith	Seismic reflection profiling of continental lithosphere	E
1987	Mooney and Brocher	Coincident seismic-reflection/refraction studies	A
1987	Orcutt	Oceans	A
1988	Leven et al.	Seismic probing of continents and their margins	E
1991	Meissner et al.	Continental lithosphere: deep seismic reflections	E
1992	Mooney and Meissner	Review of seismic-reflection profiling of lower crust	A
1992	Holbrook et al.	Seismic velocity structure of deep continental crust	A
1992a,b,c	Ziegler	Geodynamics of rifting	E
1994	Clowes and Green	Seismic reflection profiling of continents and margins	E
1995	Christensen and Mooney	Seismic velocity structure and composition of continents	A
1995	Olsen	Continental rifts: Evolution, structure, tectonics	E
1996	White et al.	Seismic reflection profiling of continents and margins	E
1997	Jacob et al.	Lithospheric structure and evolution in continental rifts	E
1998	Mooney et al.	CRUST5.1: A global model at 5° x 5°	A
1998	Klemperer and Mooney	Deep seismic probing of the continents	E
1999	Jones	Oceans	A
2000	Carbonell et al.	Deep seismic profiling of continents and margins	E
2000	Jacob et al.	Active and passive seismic techniques reviewed	E
2002	Mooney	Continental crust	A
2002	Mooney et al.	Seismic velocity structure from controlled-source data	A
2002	Minshull	Seismic structure of the oceanic crust	A
2002	Thybo	Deep seismic probing of continents and margins	E
2004	Davey and Jones	Continental lithosphere	E
2005	Fowler	The solid Earth—Global geophysics	A
2006	Snyder et al.	Seismic probing of continents and their margins	E
2007	Romanowicz and Dziewonski	Seismology and structure of the earth	E
2012	Prodehl and Mooney (this volume)	Controlled-source seismology history and global model	B

Note: A—article in a book or journal, B—single-author book, E—editors of a book with several seismic crustal study articles.

seismology (Mintrop, 1947; see Appendix A3-1). While the average structure of the Earth's crust could be detected by the detailed study of local earthquake records, the accuracy of seismological studies was limited for more refined studies of the Earth's crust because of too many unknown parameters, i.e., the exact time and the exact location of natural earthquakes.

In the middle of the nineteenth century, the first studies with controlled events were started. Explosion seismology was born in 1849 when Robert Mallet used dynamite explosions to measure the speed of elastic waves in surface rocks (Mintrop, 1947; Dewey and Byerly, 1969; Jacob et al., 2000).

The final instrumental progression to record artificial earthquakes was in 1906, when Emil Wiechert in Göttingen constructed a transportable seismograph which amplified the horizontal component of the ground movements by 50,000. In 1908, active seismological experiments started in Goettingen, when Ludger Mintrop used a weight drop as a controlled source and recorded it with Wiechert's portable seismographs. Thus he obtained the first seismograms, which included the fine details of precursor waves, now called P and S body waves (Mintrop, 1947).

For academic crustal structure research, however, it was not until 1923 that "artificial earthquakes" were introduced by the use of large explosions (Angenheister, 1927, 1928; Wiechert, 1923, 1926, 1929). Not only had large explosions been recorded in Germany. For example, in France, large surface explosions in

TABLE 2.2. REVIEWS OF REGIONAL SEISMIC CRUSTAL AND UPPERMOST MANTLE STUDIES

Year	Author or editor	Region	
1963	Closs and Labrouste	Western Alps	A
1964	Pakiser and Steinhart	Western Hemisphere	A
1966	Steinhart and Smith	North America	E
1967	Morelli et al.	Europe	A
1969	Kosminskaya et al.	USSR	A
1969	Healy and Warren	United States	A
1970	Maxwell	Oceans	E
1970	Shor et al.	Pacific basin	A
1971	Vogel	Northern Europe	E
1972	Sollogub et al.	Eastern and southeastern Europe	E
1973	Willmore et al.	British Isles	A
1973	Sellevoll	Northern Europe	A
1973	Belyaevsky et al.	USSR	A
1973	Cleary	Australia	A
1973	Warren and Healy	United States	A
1973	Berry	Canada	A
1973	Massé	North America	A
1973	Furumoto et al.	Hawaii and Central Pacific Basin	A
1975	Woollard	Pacific Ocean	A
1976a	Giese et al.	Central Europe	E
1977	Makris	Eastern Mediterranean and Hellenides	B
1980	Morelli and Nicolich	Western Mediterranean	B
1980	Zverev and Kosminskaya	USSR	B
1980	Brewer and Oliver	USA COCORP	A
1980	Jacoby et al.	Iceland	E
1987	Meissner et al.	Europe	A
1987	Orcutt	Oceans	A
1988	Dooley and Moss, Moss and Dooley	Australia	A
1989	Yan and Mechie	Alps	A
1989	Pakiser and Mooney	United States	E
1989	Braile et al.	North America	A
1989	Smithson and Johnson	Western United States	A
1989	Phinney and Roy-Chowdury	Eastern United States	A
1989	Trehu et al.	Continental margin, North America	A
1989	Mereu et al.	Canada COCRUST	A
1990	Meissner and Bortfeld	Germany DEKORP Atlas	B
1991	Bois and ECORS Scienific Parties	France ECORS review	A
1991	Heitzmann et al.	Swiss Alps	A
1991	Fuis et al.	TACT Southern Alsaska	A
1991	Collins	Australia	A
1991	Drummond	Australia	E
1992	Blundell et al.	Europe EGT	E
1992	Freeman and Mueller	Europe EGT maps	E
1992	Clowes et al.	Canada LITHOPROBE	A
1992	Klemperer and Hobbs	British Isles BIRPS Atlas	B
1993	Mechie et al.	USSR PNE data	A
1994	Mahadevan	India	B
1994	Ludden	Canada LITHOPROBE Abitibi-Grenville I	E
1994	Percival	Canada LITHOPROBE Kapuskasing transect	E
1994	Prodehl et al.	Kenya Rift	E
1995	Prodehl et al.	Central European Rift	A
1995	Ludden	Canada LITHOPROBE Abitibi-Grenville II	E
1995	Cook	Canada LITHPOROBE S Canadian Cordillera	E
1995	Braile et al.	East African Rift	A
1996	Pavlenkova	USSR	A
1997	Fuis et al.	TACT Northern Alaska	A
1997	Fuchs et al.	Afro-Arabian Rift	E
1997	Prodehl et al.	Afro-Arabian Rift	A
1998	Quinlan	Canada LITHOPROBE Newfoundland Appalachians	E
1998	Li and Mooney	China	A
1999	Reutter	Chile: Central Andean Deformation	E
2000a	Ludden and Hynes	Canada LITHOPROBE Abitibi-Grenville III	E
2000	Ross	Canada LITHOPROBE Alberta basement I	E
2000	Clitheroe et al.	Australia	A
2002	Iwasaki et al.	Japan	A
2002	Ross	Canada LITHOPROBE Alberta basement II	E
2002a	Wardle and Hall	LITHOPROBE eastern Canadian Shield on-offshore	E
2002	Chulick and Mooney	North America and adjacent oceans	A

(*continued*)

TABLE 2.2. REVIEWS OF REGIONAL SEISMIC CRUSTAL AND UPPERMOST MANTLE STUDIES (*continued*)

Year	Author or editor	Region	
2003	Collins et al.	Australia	A
2005	Landes et al.	Ireland and Irish seas	A
2005a	Hajnal et al.	Canada LITHOPROBE Trans-Hudson Orogen	E
2005	Cook and Erdmer	Canada LITHOPROBE northwestern Canada	E
2006	Gee and Stephenson	Europe EUROPROBE	E
2006	Percival and Helmstaedt	Canada LITHOPROBE West Superior Province	E
2006	Li et al.	China	A
2006	Gebrande et al.	Alps—TRANSALP	E
2007	Guterch et al.	Central and eastern Europe—long-range profiles	A
2009	Díaz and Gallart	Iberian peninsula	A
2009	Grad et al.	Moho map of European plate	A
2010	Finlayson	Australia deep seismic profiling chronicle	B

Note: A—article in a book or journal; B—single-author book; E—editors of a book or journal with several seismic crustal study articles.

1924 near La Courtine were recorded and reported. In California and in the eastern United States, seismic investigations of quarry blasts had been undertaken, but successful interpretations were not published until 1935. Seismic refraction and reflection investigations in water-covered areas started as early as 1927 (Rosaire and Lester, 1932) and were continued in the 1930s at the Atlantic coastal shelf (e.g., Ewing et al., 1937).

An overview on seismic velocities obtained from explosions and blasts in France, Germany, Italy, Switzerland and California up to 1939 was published by J.B. Macelwane in table 41 of the first edition of Volume VII of *Physics of the Earth* (edited by B. Gutenberg) on the internal constitution of the Earth (see second edition: Macelwane, 1951, table 41, reproduced in Table 3.3-02 in Chapter 3). A historical review of early explosion seismology work until the early 1950s was also summarized by Reinhardt (1954; see Appendix A4-1). Table 2.3 summarizes outstanding historical events on the early development of controlled-source seismology.

2.4. THE 1940s (1940–1950)

Controlled-source seismology investigations of the Earth's crust and the first international cooperation started effectively after 1945. The large explosions on Heligoland in 1947 and in the Black Forest in 1948 (Schulze, 1947; Reich et al., 1948) had the greatest impacts on crustal studies at this time. The explosion on the island of Heligoland is the factual beginning of controlled-source seismology for science in Germany (Schulze, 1974).

Early crustal studies in the 1940s had also been undertaken in other parts of the world, in part during World War II. In 1950, Twaltwadzse reported on a series of very large explosions which had occurred between 1941 and 1945 in the Soviet Republic of Georgia. In 1949 and 1950, underwater explosions in the lakes Issyk-Kul and Kara-Kul served to investigate the crustal structure under the northern Tien-Shan region (Gamburtsev, 1952). In Canada, rock bursts occurring between 1938 and 1945 in the mining area near Kirkland Lake, Ontario, were used for the first time for crustal structure studies (e.g., Hodgson, 1947) and these were continued in 1947–1951. In the United States, a large explosion of ammunition occurred in 1944 near Port Chicago in California (Byerly, 1946). The first nuclear tests were also recorded in North America (Gutenberg and Richter, 1946). In the Appalachian Mountains, large quarry blasts were recorded by optical-mechanical-electrical mobile field stations at distances up to 350 km (Tuve et al., 1948).

At sea during World War II, the techniques of seismic measurement were further developed so that after 1945 the experiments could be extended from shallow coastal waters into the deep ocean basins using hydrophones. The data obtained in the late 1930s were supplemented by new expeditions, in particular in the northwestern Atlantic Ocean in 1948 and 1949 (e.g., Drake et al., 1952; Ewing et al., 1950), but offshore investigations were

TABLE 2.3. MAJOR STEPS TOWARDS CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CONTINENTAL CRUST IN THE BEGINNING OF MODERN SEISMOLOGY

Chapter	Year	Project	Location	Reference
3.3	1849	First controlled-source seismic experiment	Ireland	Mallet (1852)
3.3	1906	Wiechert's first portable seismometer	Germany	Wiechert (1923)
3.3	1908	Mintrop's iron ball experiment	Germany	Mintrop (1947)
3.3	1923	Start of using "artificial earthquakes" (blasts)	Central Europe	Wiechert (1926)
3.3	1926–1929	Quarry blast recording in southern California	California	Wood and Richter (1931)
3.3	1927	Observations at detonations	Germany	Angenheister (1927)
3.3	1927	Coastal lakes Louisiana seismic-refraction tests	United States	Rosaire and Lester (1932)
3.3	1931	Quarry blast recording in southern California	California	Wood and Richter (1933)
3.3	1935	Richmond quarry blasts	California	Byerly and Wilson (1935b)
3.3	1935	Atlantic coastal plain seismic-refraction surveys	Atlantic shelf	Ewing et al. (1937)
3.3	1936–1938	New England quarry blasts	Eastern United States	Leet (1938)
3.3	1938	Bermuda seismic-refraction survey	Atlantic	Woollard and Ewing (1939)
3.3	1939	Shelf east of Britain	North Sea	Bullard et al. (1940)
3.3	1940	Continental slope off Britain	North Atlantic	Bullard and Gaskell (1941)

also undertaken in the eastern Atlantic Ocean in 1949 (Hill and Swallow, 1950) and in the Pacific Ocean off California in 1948 (Raitt, 1949).

An overview of the early seismic projects undertaken in the 1940s is mentioned in Chapter 4 and can be seen in Table 2.4.

By the early 1950s, the overall picture of the crust had been established. Gutenberg (1951b, 1955) summarized worldwide results; his crustal columns (Fig. 2.4-01) provided a rough picture of the seismic structure of the Earth's crust around the world (Gutenberg, 1955). Reinhardt (1954) wrote a fundamental study on the use of quarry blasts. In his review of crustal investigations up to 1954, he plotted the basic scheme (see Fig. 4.1-01) of seismic refraction work, compiled a world map (Fig. 2.4-02) showing the locations of crustal studies around the world which had used explosive sources, and also summarized the results in crustal columns. Beneath a layer of sediments, the Earth was divided into an upper crust of granitic composition and a lower crust consisting of gabbroic rocks, underlain by the Mohorovičić discontinuity and a peridotitic mantle layer (Gutenberg, 1951b, 1955; Reinhardt, 1954).

2.5. THE 1950s (1950–1960)

Since the beginning of the 1950s, commercial quarry blasts have been increasingly used, since they proved to be a powerful and low-cost energy source for a systematic investigation of the detailed structure of the Earth's crust (Reinhardt, 1954). Systematic seismic crustal research started in central Europe in

TABLE 2.4. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1940S

Chapter	Year	Project	Location	Reference
4.1.0	1947	Heligoland	Germany	Reich et al. (1951)
4.1.0	1948	Haslach	Southern Germany	Reich et al. (1948)
4.2.1	1941ff	Large explosions	Central Asia, USSR	Twaltwadze (1950)
4.2.1	1949–1950	Tien-Shan	Central Asia, USSR	Gamburtsev (1952)
4.2.2	1938ff	Rock bursts	Canada	Hodgson (1953)
4.2.2	1945ff	Appalachian quarry blasts	Eastern United States	Tuve et al. (1948)
4.2.2	1945–1946	First nuclear tests	New Mexico, United States; Pacific	Gutenberg (1946)
4.2.2	End of 1940s	Big Horn County, Montana, United States	Western United States	Junger (1951)
4.2.3	1948–1949	Whitwatersrand tremors	South Africa	Willmore et al. (1952)
4.2.4	1948	Gulf of Maine	Northwest Atlantic	Drake et al. (1952)
4.2.4	1948	Pacific off Southern California, United States	Eastern Pacific	Raitt (1949)
4.2.4	1948–1949	North American Basin	Northwest Atlantic	Ewing et al. (1952)
4.2.4	1948–1949	North American Basin	Northwest Atlantic	Hersey et al. (1952)
4.2.4	1949	Gulf of Maine	Northwest Atlantic	Katz et al. (1953)
4.2.4	1949	West of British Isles	Northeast Atlantic	Hill and Swallow (1950)

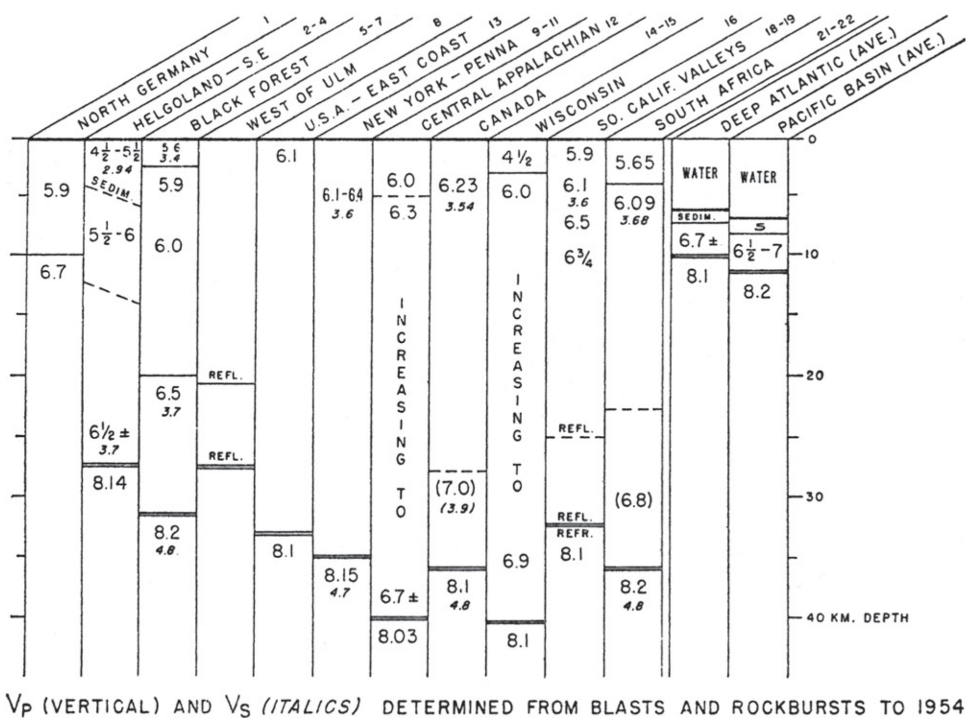

Figure 2.4-01. (See also Fig. 4.4-01.) Average velocities of longitudinal and of transverse waves in the Earth's crust based on explosion records (from Gutenberg, 1955, fig. 1). [Geological Society of America Special Paper 62, p. 19–34. Reproduced by permission of the Geological Society of America.]

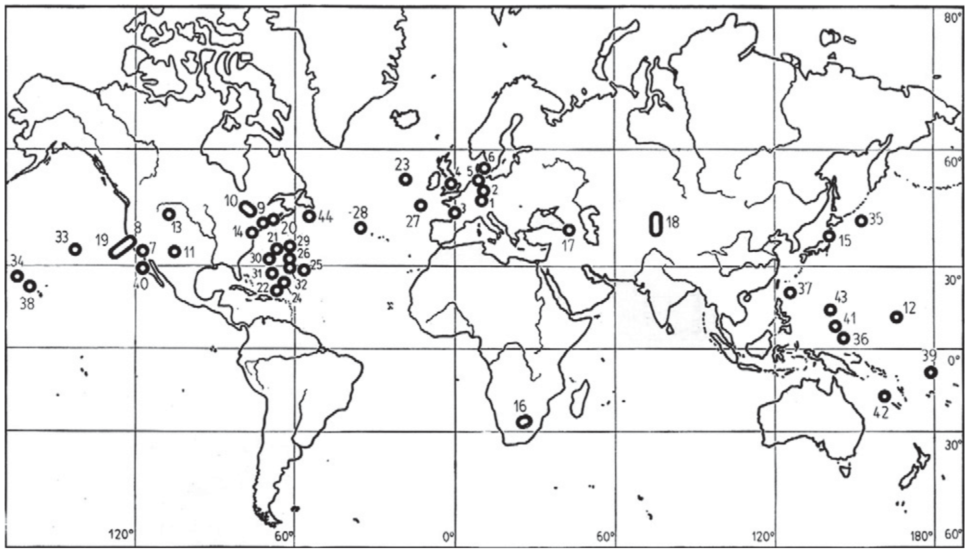

Figure 2.4-02. (See also Fig. 4.4-02.) Location map of large explosion-seismic studies of the Earth's crust (from Reinhardt, 1954, fig. 3). For explanation of numbers, see Table 4.4-02 in Chapter 4. [Freiberger Forschungshefte, C15, p. 9–91. Reproduced by permission of TU Freiberg, Germany.]

1954, when the Alps became a special target of crustal research by the foundation of the Subcommission of Alpine Explosions under the umbrella of the International Union of Geodesy and Geophysics (IUGG), initiating the first major inter-European fieldwork in 1954 (Closs and Labrouste, 1963). In 1957 in Germany, a priority program funded by the German Research Society, "Geophysical Investigation of Crustal Structure in Central Europe," was initiated. This program comprised both reflection and refraction seismic experiments and involved all geophysical university institutes of Germany and geophysical departments of the German state geological surveys. It also prompted cooperation with geophysical institutions in neighboring countries. The priority program included the development of new recording systems (Closs and Behnke, 1961; Closs, 1969; Giese et al., 1976a). It was strongly supported by commercial geophysical exploration companies in Germany which showed particular interest in the scientific deep-seismic sounding programs and helped these efforts by recording up to 12 seconds two-way traveltime (e.g., Dohr, 1959; Liebscher, 1964).

In North America and Canada, the studies of the Earth's crustal structure using blasts and rockbursts were continued more systematically from the late 1940s. Tatel and Tuve (1955) and Katz (1955) carried out seismic-refraction experiments in various geologic provinces and regions of the United States. Steinhart and Meyer (1961) edited a special volume describing the experimental work of several projects in detail, the interpretation method used at this time and a critical review of worldwide results (see Appendix A5-1).

In the USSR, the first period of deep-seismic sounding experiments started at the end of the 1940s. The first deep seismic research was conducted in 1948–1954 under the leadership of G.A. Gamburtzev, E. Galperin, and I.P. Kosminskaya in central Asia and in the southern Caspian area. Since the middle of the 1950s, deep-seismic sounding profiles were recorded on the Russian platform as well as on the Russian part of the Baltic Shield, in central Asia, in the Caucasus, and in the Urals covering thousands of kilometers (results published in Russian, for references see Pavlenkova, 1996). A major project covered the transition zone from the Asian continent to the Pacific Ocean (Galperin and Kosminskaya, 1964).

In Japan, controlled-source seismology started in 1950, when the construction of the Isibuti dam in north-central Honshu required a large explosion of 57 tons "carlit" to be detonated simultaneously. Within the short time span of only ten days, an active working group, the Research Group for Explosion Seismology, was established and became very active in the following years to provide instrumentation and to organize shotpoints for deep-seismic sounding investigations (Research Group for Explosion Seismology, Tokyo, 1951).

On continental Australia, the first definitive measurement of Moho depth was interpreted from recordings of nuclear explosions at Maralinga (South Australia) westwards across the Nullarbor Plain (Bolt et al., 1958; Finlayson, 2010; Appendix 2-2).

At the same time, when the continental crust was studied by the first systematic experiments, the seismic refraction method for work at sea was already well established. The experiments of Ewing and coworkers in the 1950s were concentrated mainly on the Northwestern Pacific, but the Gulf of Mexico and the Caribbean Sea were also investigated in great detail. Worldwide sea expeditions led U.S. and British researchers into the eastern Atlantic, into the Pacific, and into the Mediterranean Sea, and the Indian Ocean became the focus of several seismic refraction investigations. A detailed overview and summary on oceanic crustal structure studies was published by Raitt (1963), based on experiments obtained by the application of the seismic-refraction method in the 1950s.

By the end of the 1950s, a basic knowledge on crustal structure around the Earth had been established, based on a considerable number of seismic refraction investigations recording man-made explosions out to distances of several hundred kilometers, as shown in reviews such as Steinhart and Meyer (1961; see Table 5.7-01) and of Closs and Behnke (1961; Fig. 2.5-01). Steinhart and Meyer (1961; see Appendix A5-1) as well as Ewing (1963a) also gave detailed and critical reviews on the state of the art in the methodology and its limitations, including the present state of instrumentation and major field problems. An overview of the major seismic projects undertaken in the 1950s and mentioned in Chapter 5 can be seen in Table 2.5.

2.6. THE 1960s (1960–1970)

The first experimental phase of the 1950s to develop new types of instruments continued into the 1960s and finally led to the production of powerful instruments for wide-angle seismic profiling in large numbers, in particular in western Europe, North America, and the USSR. With this instrumentation, a major breakthrough in the study of the Earth's crust was achieved. In central Europe, in the western United States, and in the southern part of the USSR, major seismic-refraction fieldwork was undertaken. In central Europe, quarry blasts were the main source for seismic profiling; in the western United States and southwestern USSR, seismic energy was provided mainly by borehole explosions. Thus, at the end of the 1960s, major networks of seismic profiles existed in all three areas.

During the 1960s, experimental reflection profiling surveys were also undertaken in many parts of the world, in particular in Canada (e.g., Kanasewich and Cumming, 1965; Clowes et al., 1968), Germany (e.g., Liebscher, 1964; Dohr and Fuchs, 1967) and Russia (e.g., Beloussov et al., 1962; Kosminskaya and Riznichenko, 1964). They demonstrated that near-vertical profiling methods used in oil and gas exploration could be used to image geological structures within basement rocks and that at long recording times, reflections from the deep crust and the Moho could be obtained. This paved the way for COCORP and subsequent deep reflection programs around the world in the 1970s and 1980s.

In parallel with the fieldwork, the art of interpretation was pushed forward by new developments in the theory of seismic wave propagation and by applying the results using the rapidly developing new computer technology. The known methods were made more efficient, and at the same time new methods were developed to interpret the increasing number of recently observed data. In the 1960s, the interpretations were almost exclusively based on the correlation of waves by travel times, read from picked arrival times, plotted in time-distance graphs, and correlated by straight or curved lines, but gradually seismic phase correlation using record sections became common.

The use of record sections created a major breakthrough in understanding the character of seismic waves and their relation to the structure of the Earth's crust and mantle which would guide the interpretation of seismic refraction observations through the following decades. In an internal report (Prodehl, 1998) a major collection of record sections was compiled which had been produced from observed data and had been published from the early 1960s to the end of the 1990s from major controlled-source seismic projects around the world. The report included an abstract and location map from the most relevant publication of the corresponding project. This report is reproduced in Appendix A2-1 and the data shown there will be referred to in the following chapters. Furthermore, for the Australian continent and its margins a comprehensive chronicle on the history of deep-seismic profiling was prepared showing maps and many data (Finlayson, 2010; Appendix A2-2). Additional data and abstracts can be found in Appendices A3 to A10 accompanying the corresponding decades. A more complete compilation of seismic projects carried out in the 1960s using controlled seismic sources and mentioned in Chapter 6 is compiled in Table 2.6.

While most of the seismic-refraction and -reflection experiments in the 1960s were carried out on a national basis, major international projects were pushed forward also. These efforts were strongly supported by the formulation of major international research programs, which were supported and financed by national research foundations and thus allowed the systematic study of specific tectonic regions of the Earth. In Europe, the European Seismological Commission (ESC) had been founded with meetings every two years, alternatively held in eastern or in

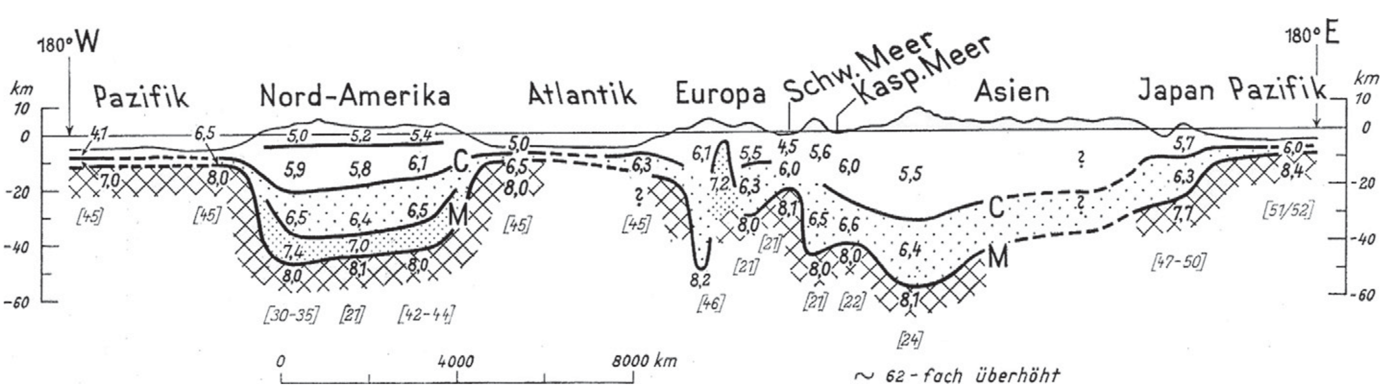

Figure 2.5-01. (See also Fig. 5.7-01.) West-east profile across the Earth at 45°N, compiled after individual results (for detailed references see Closs and Behnke, 1961). [Geologische Rundschau, v. 51, p. 315–330. Reproduced with kind permission of Springer Science+Business Media.]

TABLE 2.5 MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1950S

Chapter	Year	Project	Location	Reference
5.1	1952	Blaubeuren deep reflections	Germany	Reich (1953)
5.1	1955ff	Deep reflection recording	Germany	Dohr (1959)
5.1	1956–1958	Lac Nègre and other lake shots	Western Alps	Closs and Labrouste (1963)
5.1	1957ff	Quarry blast profiling	Germany	Giese et al. (1976)
5.1	1957ff	Seismic reflection work, southern Germany	Southern Germany	Dohr (1959)
5.1	1960	Ivrea zone borehole shot profiles	Western Alps	Closs and Labrouste (1963)
5.2	1950ff	Quarry blast and test explosions profiling	United States	Tatel and Tuve (1955)
5.2	1950–1953	New York–Pennsylvania quarry blasts	Eastern United States	Katz (1955)
5.2	1955	Underwater explosions	Alaska	Tatel and Tuve (1956)
5.2	1956–1959	Nevada Test Site and quarry blast profiles, Nevada-Utah	Western United States	Berg et al. (1960)
5.2	1957	Central Plateau, Mexico	Mexico	Meyer et al. (1961a)
5.2	1958	Arkansas-Missouri	Central United States	Steinhart et al. (1961a)
5.2	1958–1959	Wisconsin–Upper Michigan	Central United States	Steinhart et al. (1961b)
5.2	1959	Rocky Mountains, Montana	Western United States	Meyer et al. (1961b)
5.3	1948–1954	Central Asia, southern Caspian area	USSR	Pavlenkova (1996)
5.3	1955ff	Deep seismic sounding profiling	USSR	Pavlenkova (1996)
5.3	1957–1958	Deep seismic sounding profiling	Sea of Ochotsk	Galperin and Kosminskaya (1964)
5.4	1950	First Japanese profiles on Honshu	Japan	Matuzawa et al. (1959)
5.4	1953–1956	Nuclear explosions	Australia	Bolt et al. (1958)
5.4	1956–1957	Eaglehawk quarry blasts	East Australia	Doyle et al. (1959)
5.4	1959	Prospect blue metal quarry blasts	East Australia	Bolt (1962)
5.5.1	1952	Wellington refraction line	New Zealand	Officer (1955)
5.5.3	1950s	Andes	Peru and Chile	Tatel and Tuve (1958)
5.5.3	1950s–1960s	Arctic interior upper crust	Antarctica	Bentley (1973)
5.5.3	1959–1960	Belgian Antarctic expedition	Antarctica	Dieterle and Peterschmitt (1964)
5.6.1	1950–1967	Seismic reflection profiles, Atlantic and Pacific	Atlantic and Pacific	Ewing and Ewing (1970)
5.6.1	1950	Bermuda area	Northwest Atlantic	Officer et al. (1952)
5.6.1	1950	North Atlantic Ocean	Atlantic	Gaskell and Swallow (1951)
5.6.1	1950+	Continental slope south of Nova Scotia	Northwest Atlantic	Officer and Ewing (1954)
5.6.1	1950+	Grand Banks	Northwest Atlantic	Press and Beckmann (1954)
5.6.1	1950+	Continental slope south of Grand Banks	Northwest Atlantic	Bentley and Worzel (1956)
5.6.1	1950–1951	English Channel	English Channel	Hill and King (1953)
5.6.1	1950–1952	Bermuda—North American shelf	Northwest Atlantic	Katz and Ewing (1956)
5.6.1	1951	North American Basin	Northwest Atlantic	Ewing et al. (1954)
5.6.1	1952	Gulf of Maine	Northwest Atlantic	Drake et al. (1952)
5.6.1	1953	Deep-sea reflection profile (Bermuda)	Northwest Atlantic	Officer (1955a)
5.6.1	1954–1956	US Atlantic continental margin	Northwest Atlantic	Hersey et al. (1959)
5.6.1	1957	Caribbean Sea—Lesser Antilles	Caribbean Sea	Edgar et al. (1971)
5.6.2	1950	Mid Pacific expedition	Central Pacific	Raitt (1956)
5.6.2	1951	North Pacific Ocean	Pacific	Gaskell and Swallow (1952)
5.6.2	1952–1953	Capricorn expedition	Central Pacific	Raitt (1956)
5.6.2	1952	Indian Ocean and Mediterranean Sea	Middle-East	Gaskell and Swallow (1953)
5.6.2	1957	Peru-Chile Trench	South Pacific	Raitt (1964)
5.6.2	1957	East Pacific Rise	South Pacific	Raitt (1964)
5.6.2	1959	First Japanese deep-sea expedition	Japan trench	Ludwig et al. (1966)

western Europe. These meetings served as most effective communication centers between scientists in eastern and western Europe and secured personal contacts of scientists also at times of difficult political situations. A special subcommission of the ESC dealt in particular with experiments and results of explosion seismology investigations. In 1964 under the umbrella of IASPEI (International Association of Seismology and Physics of the Earth's Interior), the Upper Mantle Project was started as an international program of geophysical, geochemical, and geological studies concerning the "upper mantle and its influence on the development of the Earth's crust."

In central and western Europe, national research programs in Germany, Italy, France, and Britain were extended into collaborative investigations and triggered joint studies. The cooperative research in the Western Alps of the 1950s was continued in the 1960s. The Eastern Alps and the Apennines became the focus of international experiments mainly based on the fruitful cooperation of Italian, Austrian and German institutions. The Scandinavian countries undertook major efforts to investigate the Baltic Shield in close cooperation with German and British institutions. The Moho map in Figure 2.6-01, compiled by Morelli et al. (1967), is primarily the result of international cooperation.

The East European countries developed a separate methodology of deep-seismic sounding. They extended their national research projects into a cooperative effort by establishing a network of international profiles, which covered the entire southeast of Europe and included all Eastern Block countries. The resulting network of deep-seismic sounding profiles reached from the East European Craton of the USSR into Poland as well

TABLE 2.6. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1960S

Chapter	Year	Project	Location	Reference
6.2.2	1960ff	Quarry blast profiling	Germany	Giese et al. (1976a)
6.2.2	1964	Common-depth-point Bavarian Molasse Basin	Germany	Meissner (1966)
6.2.2	1968	Common-depth-point profile Rhenish Massif	Germany	Meissner et al. (1976a)
6.2.3	1960	Continental shelf	West of Britain	Bunce et al. (1964)
6.2.3	1962ff	Underwater explosions	British Isles and seas	Bamford (1971)
6.2.3	1965	NORSAR deep seismic sounding profiles	Southern Norway	Sellevoll (1973)
6.2.3	1967	North Sea traverse	Norway–Scotland	Sornes (1968)
6.2.3	1969	Continental margin project	Atlantic off Ireland	Bamford (1971)
6.2.3	1969	Rockall Plateau off Ireland	Atlantic off Ireland	Scrutton (1972)
6.2.3	1969	Trans-Scandinavian deep seismic sounding project	Scandinavia	Vogel and Lund (1971)
6.2.4	1961, 1962	Lago Lagorai profiles	Eastern Alps	Prodehl (1965)
6.2.4	1961–1967	French Massif Central	France	Perrier and Ruegg (1973)
6.2.4	1964	Lago Bianco profiles	Central Alps	Giese and Prodehl (1976)
6.2.4	1965	Alpine quarry and construction blasts	Western Alps	Giese et al. (1967)
6.2.4	1965–1968	Puglia–Sicily	South Italy	Giese et al. (1973)
6.2.4	1966	Lac Negre underwater shots	Alps and Appenines	Röwer et al. (1977)
6.3	1963ff	Deep seismic international profiles	Southeastern and eastern Europe	Sollogub et al. (1972)
6.3.2	1960–1965	Deep seismic sounding profiles	Poland	Guterch et al. (1967)
6.3.2	1965ff	Continuous profiling Tornquist-Teysseire Zone and Sudetes	Poland	Toporkiewicz (1986)
6.3.2	1969	International Profile V and VII	Poland	Uchman (1972)
6.3.2	1969	International Profile V and VI	Czechoslovakia	Beránek et al. (1972)
6.3.2	1969	International Profile VI	E Germany	Knothe and Schröder (1972)
6.3.2	1969	International Profile III, IV and V	Hungary	Mituch and Posgay (1972)
6.3.2	1969	International Profile III	Yugoslavia	Prosen et al. (1972)
6.3.2	1969	International Profile II and X	Bulgaria	Dachev et al. (1972)
6.3.2	1969	International Profile II and XI	Romania	Constantinescu (1972)
6.4	1960ff	Deep seismic sounding profiles	USSR Europe and Asia	Kosminskaya et al. (1969)
6.4	1963ff	Deep seismic sounding profiles	Southwest USSR	Sollogub and Chekunov (1972)
6.5.1	1961	USGS profiles in Colorado	Western United States	Jackson et al. (1963)
6.5.1	1962–1963	USGS California-Nevada profiles	Western United States	Prodehl (1979)
6.5.1	1964	Tonto Forest Array project, Arizona	Southwest United States	Warren (1969)
6.5.1	1965	USGS Rocky Mountain profiles	Western United States	Prodehl and Pakiser (1980)
6.5.1	1965	Kansas refraction line	Central United States	Steeples and Miller (1989)
6.5.1	1966	LASA array deep seismic sounding project, Montana	Northwest United States	Warren et al. (1973)
6.5.1	1967	Coast Ranges deep seismic sounding, California	Western United States	Walter and Mooney (1982)
6.5.1	1969	Wind River reflection, Wyoming	Western United States	Perkins and Phinney (1969)
6.5.2	1962ff	Great Plains borehole shots profiles	Central United States	Healy and Warren (1969)
6.5.2	1963, 1964	Lake Superior shots	Canada and United States	Mansfield and Evernden (1966)
6.5.2	1965	Cumberland Obs, Appalachians	Eastern United States	Prodehl et al. (1984)
6.5.2	1965	East Coast Offshore-Onshore Experiment	Eastern United States	Hales et al. (1968)
6.5.4	1964	Near-vertical incidence seismic reflection studies	Central Canada	Kanasewich and Cumming (1965)
6.5.4	1965	Hudson Bay experiment	Northeast Canada	Hobson (1967)
6.5.4	1966	Yellowknife Seismic Array project	Northwest Canada	Weichert and Whitham (1969)
6.5.4	1966	Bear, Slave, Churchill Precambrian	Northwest Canada	Berry (1973)
6.5.4	1967–1968	Alaska Range—Tanana Basin profile	Central Alaska	Hanson et al. (1968)
6.5.4	1968	Grenville Front seismic experiment	Eastern Canada	Berry and Fuchs (1973)
6.5.4	1969	Yellowknife Seismic Array project	Northwest Canada	Clee et al. (1974)
6.5.5	1965	EARLY RISE Lake Superior 5-t shots	North America	Iyer et al. (1969); Massé (1973)
6.5.5	1969	EDZOE Upper mantle seismic project	Western North America	Berry and Forsyth (1975)
6.6	1963–1964	Deep seismic sounding Kurayoshi-Hanasuba profile	Honshu, southwest Japan	Research Group for Explosion Seismology (1966b)
6.6	1966–1967	Deep seismic sounding Atumi-Noto profile	Honshu, central Japan	Aoki et al. (1972)
6.6	1968–1969	Deep seismic sounding Shakotan-Erimo profile	Hokkaido, northeast Japan	Okada et al. (1973)
6.6	1970	Deep seismic sounding Kurayoshi-Hanasuba profile	Honshu, southwest Japan	Yoshii et al. (1974)
6.7.1	1959–1964	Quarry blasts, SW Western Australia	Australia	Everingham (1965)
6.7.1	1960	Marine shots, Perth Basin	Australia	Hawkins et al. (1965)
6.7.1	1962	Marine shots off Perth	Australia	Hawkins et al. (1965)
6.7.1	1963	Marine shots off Perth	Australia	Hawkins et al. (1965)
6.7.1	1963–1967	Quarry blasts, South Australia	Australia	White (1969)
6.7.1	1960ff	Continuous deep reflection profiles	Australia	Moss and Dooley (1988)

(*continued*)

TABLE 2.6. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1960S (*continued*)

Chapter	Year	Project	Location	Reference
6.7.1	1965	Offshore shots off New South Wales	Eastern Australia	Cleary (1973)
6.7.1	1966	CRUMP Offshore shots	North Australia	Cleary (1973)
6.7.1	1966	WRAMP Inland borehole shots	North Australia	Cleary (1973)
6.7.1	1966	BUMP Bass Street experiment	Southeast Australia	Cleary (1973)
6.7.1	1967	FRUMP Western Australia	Southwest Australia	Finlayson (2010)
6.7.1	1968–1969	Deep reflection experiments	Southwest Australia	Moss and Dooley (1988)
6.7.1	1969	Western Australia Geotraverse	Southwest Australia	Mathur (1974)
6.7.1	1970	ORD RIVER experiment	North Australia	Denham et al. (1972)
6.7.2	1969	First Kenya Rift Seismic Project	Kenya	Griffiths et al. (1971)
6.7.3	1968	Peru-Bolivia Altiplano project	West South America	Ocola and Meyer (1972)
6.7.4	1969	14th Soviet Antarctica Expedition	Antarctica	Bentley (1973)
6.8.2	1950–1967	Seismic reflection profiles, Atlantic and Pacific	Atlantic and Pacific	Ewing and Ewing (1970)
6.8.2	1962	"*Arlis II*" ice island drift Arctic	Arctic Ocean	Kutschale (1966)
6.8.2	1966	"*Meteor* (1964)" expedition M04	Reykjanes Ridge	Sarnthein et al. (2008)
6.8.2	1967	Seamounts "Atlantic Kuppelfahrten"	Northeast Atlantic	Closs et al. (1968)
6.8.2	1968	Mid-Atlantic Ridge at 45°N	Atlantic	Keen and Tramontini (1970)
6.8.2	1969	Gulf of Mexico upper mantle experiment	Gulf of Mexico	Hales (1973)
6.8.2	1969	"*Meteor* (1964)" expedition M17	Mediterranean Sea	Closs et al. (1972)
6.8.2	1969	"*Meteor* (1964)" expedition M17	Arabian Sea	Closs et al. (1969a)
6.8.2	1969	"*Meteor* (1964)" expedition M18	Norwegian Sea	Closs (1972)
6.8.2	1969	Iceland–Faeroe Ridge	North Atlantic	Bott et al. (1971)
6.8.3	1959, 1961	Japanese Deep Sea Expedition	Japan trench	Ludwig et al. (1966)
6.8.3	1960ff	Oceanic seismic refraction lines	Indian and Pacific Ocean	Shor and Raitt (1969)
6.8.3	1963ff	Kuril Islands–South Kamchatka	Western Pacific	Kosminskaya et al. (1973)
6.8.3	1964, 1966	Hawaii Big Island projects	Hawaii	Hill (1969)
6.8.3	1965	Juan de Fuca and Gorda Ridges	Off Oregon-California	Shor et al. (1968)
6.8.3	1965	Cook Islands	Pacific east of Fiji	Hochstein (1968)
6.8.3	1965	Philippine Sea	West Pacific	Murauchi et al. (1968)
6.8.3	1964ff	Upper mantle anisotropy experiment	East Pacific	Raitt et al. (1971)
6.8.3	1966	Northwest Pacific Basin	West Pacific	Den et al. (1969)
6.8.3	1967	Nova expedition Melanesian borderland	West Pacific	Shor et al. (1971)
6.8.3	1967	Coral Sea—Queensland Basin	West Pacific	Ewing et al. (1970)
6.8.3	1967, 1969	Bismarck archipelago project	Northern Melansia	Finlayson et al. (1972)
6.8.4	1962	Central Indian Ridge	Northwest Indian Ocean	Francis and Shor (1966)
6.8.4	1962	Ninetyeast Ridge	Southern Indian Ocean	Francis and Raitt (1967)
6.8.4	1962	Seychelles Bank	Northwest Indian Ocean	Shor and Pollard (1963)
6.8.4	1962	Broken and Naturaliste Plateaus	Southeast Indian Ocean	Francis and Raitt (1967)
6.8.4	1962	Agulhas Bank and Transkei Basin	Southeast Indian Ocean	Green and Hales (1966)
6.8.4	1962	Southeast African continental margin	Southwest Indian Ocean	Ludwig et al. (1968)
6.8.4	1968	Agulhas Bank and Plateau	Southern Indian Ocean	Hales and Nation (1973)

as into the Bohemian Massif, the Carpathians, and the Dinarides (Sollogub et al., 1972).

In the territory of the USSR, not only the southwestern part was intensively investigated by deep-seismic sounding profiles, but many other projects dealt with detailed crustal structure investigations covering also the Asian part of the USSR, which culminated in some 215 crustal sections along deep-seismic sounding profiles of over 50,000 km length (Belyaevsky et al., 1973), the results of which could be compiled into a Moho map covering the whole USSR (Fig. 2.6-02).

In North America a major seismic refraction survey was started by the U.S. Geological Survey (Pakiser, 1963), but also several university projects dealt with seismic crustal research. The main target was the investigation of the crustal structure of the Basin and Range province in the west, which included the adjacent Sierra Nevada and Coast Ranges in the west and the Rocky Mountains and adjacent Great Plains in the east. Some areas in the central and the eastern United States were also investigated. On the basis of the numerous new data, gathered in the 1960s, Warren and Healy (1973) created fence diagrams of crustal cross sections throughout the United States and compiled a Moho map (Fig. 2.6-03).

Another focus became the Lake Superior region (Steinhart and Smith, 1966). The Lake Superior experiments which involved all major North American research institutions did not only comprise detailed crustal studies, but in particular the EARLY RISE project of 1965 opened another dimension by recording man-made events to distances of several thousand kilometers thus demonstrating that parts of the uppermost mantle could be systematically studied with controlled-source seismology. Another large cooperative project, EDZOE, covered much of Canada and aimed to study the structure of the North American Great Plains and the Rocky Mountains.

In Southeast Asia, from 1964 onwards, considerable progress was made in Japan in instrumentation and seismic fieldwork for crustal studies (Research Group for Explosion Seismology, 1966a). Some of the experiments were carried out under the Upper Mantle Project, providing first cross sections of Honshu Island (Aoki et al., 1972; Yoshii and Asano, 1972; Okada et al., 1973; Yoshii et al., 1974). From these data, it could be concluded

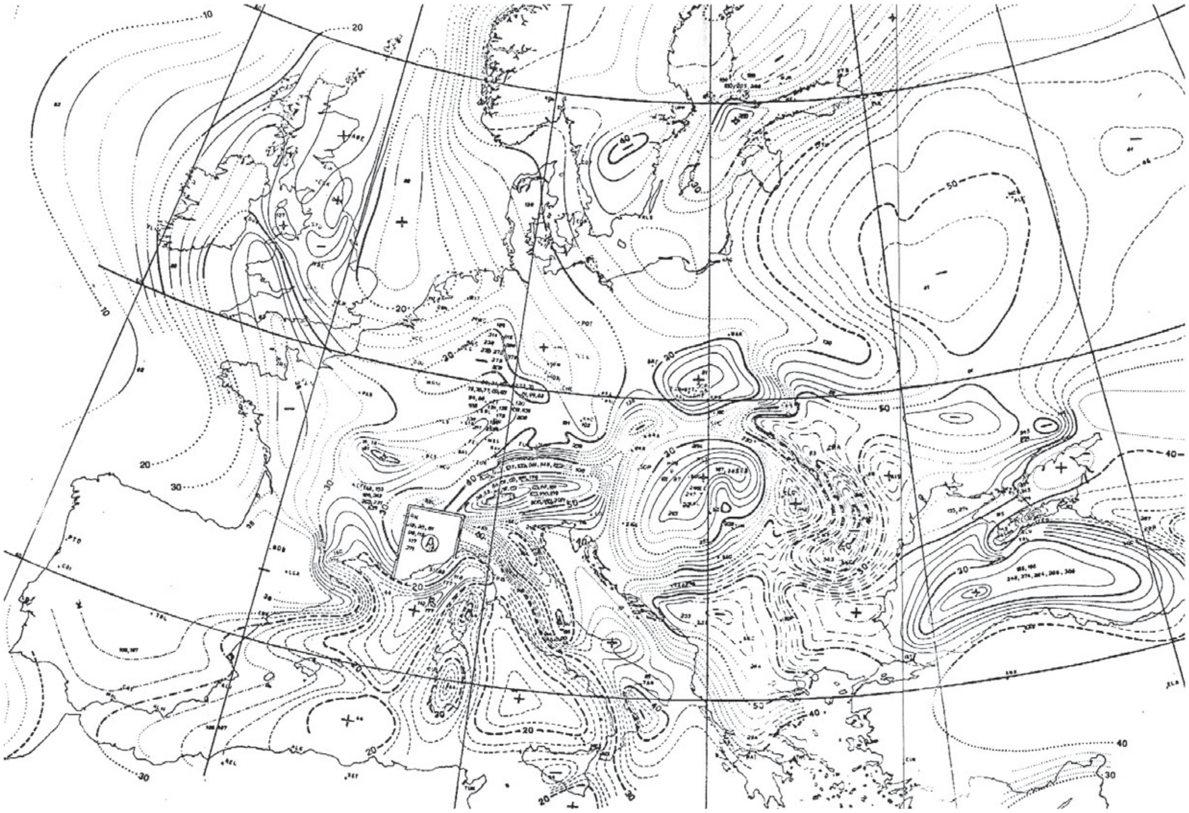

Figure 2.6-01. Moho contour map of Europe (from Morelli et al., 1967, fig. 2). [Bolletino di Geofisica Teorica Applicata, v. 9, p. 142–157. Reproduced by permission of Bolletino di Geofisica, Trieste, Italy]

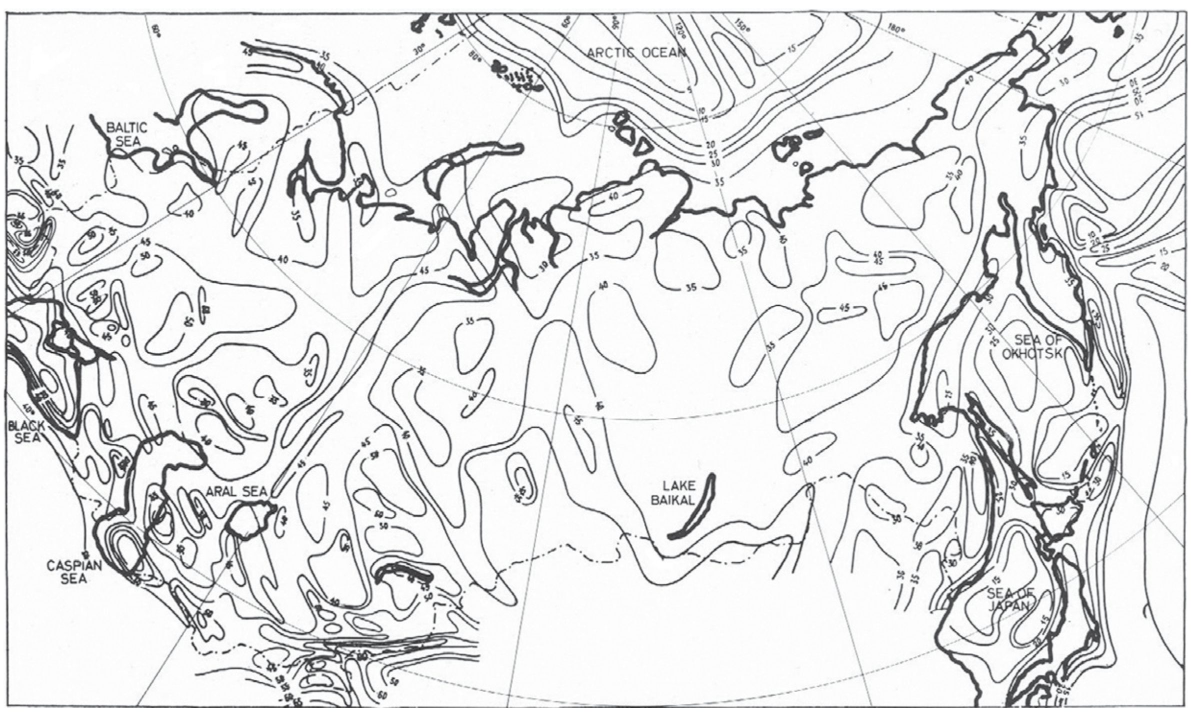

Figure 2.6-02. Moho contour map of the territory of the USSR (from Belyaevsky et al., 1973, fig. 1). [Tectonophysics, v. 20, p. 35–45. Copyright Elsevier.]

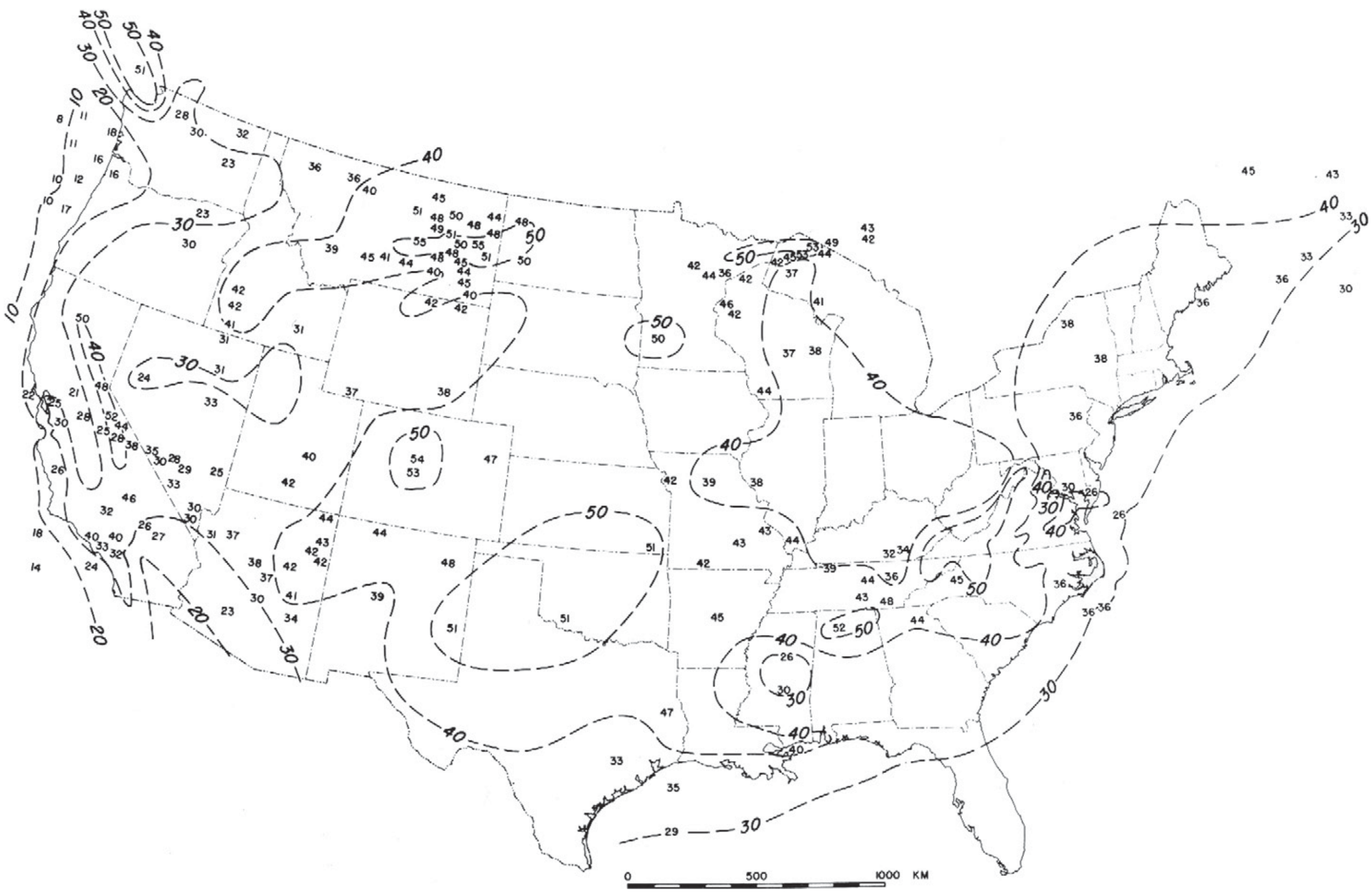

Figure 2.6-03. Moho contour map of the United States of America (from Warren and Healy, 1973, fig. 8). [Tectonophysics, v. 20, p. 203–213. Copyright Elsevier.]

that the northern part of the NE Japan arc is characterized by a low (~7.5 km/s) uppermost mantle velocity (Yoshii and Asano, 1972; Okada et al., 1973).

In Australia, several large-scale experiments provided first results on crustal thickness for southeastern and northern Australia (Denham et al., 1972; Cleary, 1973). Also, reflection profiling in basins in central and southeastern Australia provided strong reflections from the Moho (Dooley and Moss, 1988; Moss and Dooley, 1988; Finlayson, 2010; Appendix 2-2). In Africa, the first seismic investigation of the East African rift system was initiated by British scientists in Kenya (Griffiths et al., 1971). The very first explosion seismic investigation in South America concentrated on the Andes with a reconnaissance survey of the Peru-Bolivia Altiplano involving recording distances of 320–400 km (Ocola and Meyer, 1972).

At sea, all instruments in use in the 1950s and 1960s were essentially echo sounders utilizing pulses of low frequency sonic energy and a graphic recording system that displayed the data in the form of cross sections. The analysis methods, available also during the 1960s (Ewing, 1963a), used least-squares slope-intersect solutions for picked first arrivals, but did not allow for velocity gradients. Techniques and equipment for continuous seismic profiling were developed early in the 1960s, enabling studies of local variations in sediment thickness and details of its stratification. To eventually overcome the work with explosives, continuous research tried to develop efficient non-explosive energy sources (Ewing and Zaunere, 1964). On the basis of many observations in the Atlantic Ocean, a detailed overall picture of the oceanic crust was established but significant deviations from this average were found on the flanks of the Mid-Atlantic Ridge. Numerous new data were also gathered in the Indian and Pacific Ocean (Shor and Raitt, 1969). Detailed surveys involved, for example, the surroundings of the islands of Hawaii and archipelagos to the northeast of Australia (Furumoto et al., 1973). For the first time, the existence of seismic anisotropy of the uppermost mantle was discussed and investigated by a series of special anisotropy experiments in various areas of the Pacific Ocean (e.g., Raitt et al., 1971).

The 1960s accumulated a wealth of data, based on the integration of gradual improvement in seismic-refraction and -reflection techniques, instrumental development and the art of interpretation. In many experiments seismic energy produced by effective explosive sources was recorded out to large distances of several 100 km. Moho contour maps published for Europe (e.g., Morelli et al., 1967; Fig. 2.6-01), the USSR (e.g., Belyaevsky et al., 1973; Fig. 2.6-02) and the United States (Warren and Healy, 1973; Fig. 2.6-03) were based on a large number of published models, available by the end of the 1960s. They not only resulted in a relatively complete picture of the gross velocity-depth structure of the Earth's crust underneath the northern hemisphere around the world, but also detected specific properties of different tectonic areas such as shields, platforms, orogens, basins, rift zones, etc. However, the long-range data had not yet been interpreted in terms of subcrustal fine structure. In order to understand the seismic wave field, various groups had worked on the theoretical background, so that by the end of the 1960s the art of computing synthetic seismograms was ready for application. Other groups had concentrated on the character and basic features of seismic phases so that gradually a fine structure of the hitherto homogeneously layered crust was detected. In particular the character of the crust-mantle boundary was attracting increased interest.

2.7. THE 1970s (1970–1980)

In the 1960s, the personnel situation in the geophysical departments of universities and other research institutions of western Europe had gained by public support of science, leading to an increase of existing facilities as well as to the foundation of new geophysical departments. By the beginning of the 1970s many young scientists had become professors and heads of departments.

With the powerful instrumentation developed in the 1960s and acquired in major numbers in the 1970s, in particular in western Europe, North America, and the USSR, controlled-source seismology approached new frontiers. The 1970s can be characterized by several highlights.

Making use of the rapidly developing new computing facilities, the traveltime routines of the 1960s enabled many different computer programs to be developed. They now allowed a faster interpretation of the large quantity of new data. Furthermore, the consequent application of the reflectivity method published by Fuchs and Müller (1971) enabled the calculation of synthetic seismograms for the full wave field in laterally homogeneous structures. By comparing observational and synthetic data, the models calculated by traveltime routines could now be improved and/or verified by including the amplitude information from the correlated phases. Braile and Smith (1975) published a whole series of synthetic record sections calculated for typical crustal models. The further development and application of the time-term method widely used by British scientists to the data of dense networks of seismic-refraction profiles led unexpectedly to the detection of uppermost mantle velocity anisotropy under continents (Bamford, 1973; Bamford et al., 1979).

Underwater shots in the Lake Superior experiment of 1965 had shown that controlled seismic sources could efficiently be recorded to at least 2000 km distance if the recording conditions were favorable. In particular, it was recognized that the hitherto uniform P_n phase at distances of several hundred kilometers in reality consisted of a number of different phases reflected from various depth levels in the uppermost mantle. This enabled the seismic investigation of hitherto unknown depth ranges below the Moho and led to the detection of fine structures in the lower lithosphere down to 80–100 km depth. A considerable number of long-range profiles was subsequently organized and recorded throughout Europe (Fig. 2.7-01). One-thousand-km-long lines through France (Hirn et al., 1973, 1975), Britain (Faber and Bamford, 1979) and along the axis of the Alps (Alpine Explosion Seismology Group, 1976), and a 2000-km-long line through Scandinavia (Guggisberg and Berthelsen, 1987), for example, became well-known experiments (see also Fuchs et al., 1987). In the USSR, super-long profiles were recorded using nuclear devices as sources (Fig. 2.7-01). However, the data from these profiles did not become generally available until the early 1990s (Pavlenkova, 1996).

Japanese research activities in the 1970s were characterized by two programs. Big offshore shot experiments were carried out in 1974–1976 in the Pacific Ocean and the Sea of Japan and onshore seismic refraction surveys started in 1979 under the framework of the national project of earthquake prediction. The onshore activities were continued up to 2003, providing various scale crustal heterogeneities existing within NE and SW Japan arcs (e.g., Asano et al., 1981; Yoshii, 1994). In Australia, long-term recording devices had been developed (Finlayson, 2010; Appendix 2-2). A long-range seismic profile through the center of Australia recorded earthquakes from South East Asia and studied the upper mantle (Hales et al., 1980). Crustal profiles based mainly on quarry blasts investigated the crustal structure of Precambrian Shield in western Australia (Drummond 1979, 1981) and under the Lachlan Fold Belt in southeastern Australia (Finlayson et al., 1979). In southwest Africa, a large-scale seismic refraction experiment investigated the Damara orogen and the adjacent Kalahari craton, using the German MARS-66 equipment and long-term recording devices developed at the University of Johannesburg (Baier et al., 1983).

In the oceans, long-range profiles were recorded that penetrated well below Moho. In the Pacific Ocean, e.g., a 600-km-long line was laid out in the northeastern Pacific between the Clarion and Molokai fracture zones (Orcutt and Dorman, 1977). In the western Pacific basin, explosions were recorded by ocean-bottom seismometers up to distances of 1300 km during two Longshot experiments in 1973 in the East Mariana basin (Asada and Shimamura, 1976). From 1974 to 1980, intensive long-range experiments were undertaken in the northwestern Pacific, which detected large scale lithospheric structure and anisotropy in the upper-mantle (Asada and Shimamura, 1979; Asada et al., 1983; Shimamura et al., 1983). In the Atlantic Ocean, from 40° to 43°N a long-range profile was recorded near the Azores (Steinmetz et al., 1977), dealing also with the lower lithosphere. Another long-range seismic refraction experiment in 1977 established an 800 km long line along the southeastern flank of the Reykjanes Ridge which aimed to resolve both crust and upper mantle to greater depths than previously possible (RRISP Working Group,

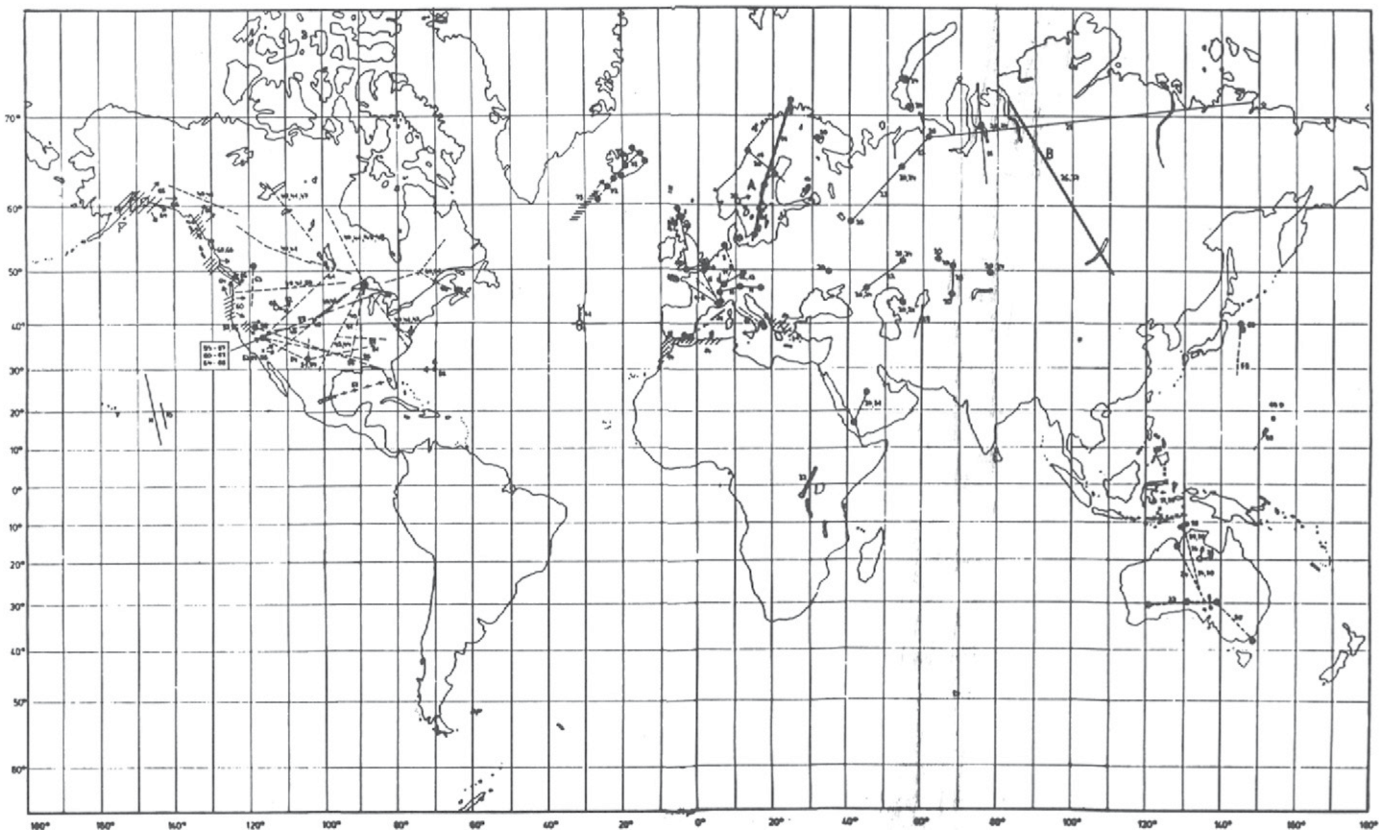

Figure 2.7-01. World map showing long-range profiles until 1980 (from Fuchs et al., 1987, fig. 1). [*In* Fuchs, K., and Froidevaux, C., eds., Composition, structure and dynamics of the lithosphere-asthenosphere system: American Geophysical Union Geodynamics Series, v. 16, p. 137–154. Reproduced by permission of American Geophysical Union.]

1980). Figure 2.7-01 gives an overview, where in the world controlled-source seismic experiments were performed up to 1980 and which penetrated well below Moho (Prodehl, 1984).

Another highlight of the 1970s was an advanced understanding of rifting. Detailed studies were carried out in Europe in the central European Rift System through Germany and France (Prodehl et al., 1995; Fig. 2.7-02), along the Tornquist-Teysseire Zone in Poland (Guterch et al., 1983), in the Afro-Arabian rift system, in the western Jordan–Dead Sea transform, in the Afar triangle of Ethiopia (Ginzburg et al., 1979a; Berckhemer et al., 1975, see Fig. 2.9-02), and in North America in the Mississippi embayment (Mooney et al., 1983), the Rio Grande rift (Olsen et al., 1979) and the Yellowstone–Snake River Plain area, a suggested hot spot (Smith et al., 1982).

In several countries surrounding the Mediterranean, crustal studies were started in the 1970s such as in Portugal, Spain, Morocco, Greece, and Israel. In Italy, both the northern Apennines and adjacent Mediterranean Sea including the island of Corsica and southernmost Italy were the focus of several seismic land and sea investigations (e.g., Morelli et al., 1977).

Seismic near-vertical incidence reflection experiments were organized on a large scale for the first time in the 1970s. They covered distances of 100 km or more which brought new insight into details of crustal structure and composition of the Earth's crust down to Moho. On the continents sedimentary basins and at sea the ocean basins had already been studied in much detail, the former by petroleum seekers since the 1930s and the latter by marine scientists largely during the decades following World War II. For the study of sedimentary basins, the seismic reflection profiling method had been highly developed over the years by the petroleum industry. Consequently, academic researchers now took advantage of the expertise, techniques, and equipment of the industry to study the whole crystalline crust and obtain not only geophysical models with velocity, density and attenuation, but also determine the extent and the configuration of reflecting horizons (Oliver, 1986). So, in the 1970s the first national large-scale seismic-reflection programs were initiated. COCORP in the United States (e.g., Oliver et al., 1976), a purely seismic reflection program, was soon followed by the Canadian equivalent COCRUST (Mereu et al., 1989), which, however, comprised a combination of crustal reflection and refraction studies. Similar large-scale seismic near-vertical incidence reflection profiles, accompanied by wide-angle reflection observations, were recorded in Germany (Bartelsen et al., 1982; Meissner et al., 1980).

Besides special upper-mantle studies, detailed crustal research continued in the oceans. For the Pacific Ocean, for example,

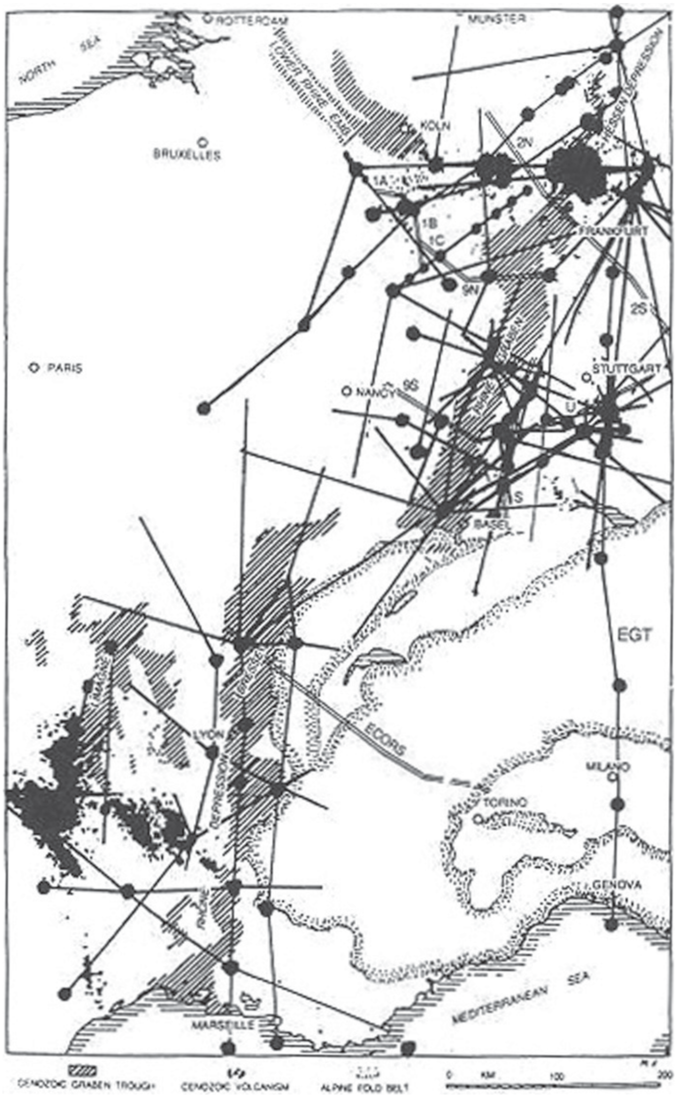

Figure 2.7-02. Location map of explosion seismology surveys in the European Cenozoic rift system (ECRIS) until 1989 (from Prodehl et al., 1995, fig. 1). Double lines—seismic-reflection observations (numbers and letters denote DEKORP and other lines); single lines—seismic-refraction profiles (dots = shotpoints, EGT = European Geotraverse line of 1986). [*In* Olsen, K.H., ed., Continental rifts: evolution, structure, tectonics: Amsterdam, Elsevier, p. 133–212. Copyright Elsevier.]

Woollard (1975) reviewed the available data and published several cross sections with details of crustal structure. In the 1970s, the main interest of oceanic crust and upper mantle research had shifted from the investigation of crustal and upper mantle structure under ocean basins to special structures with anomalous properties such as mid-ocean ridges, hotspots, ocean islands and ocean-continent transition zones. The 1970s were also the decade when ocean-bottom seismometers (OBS) and ocean-bottom hydrophones (OBH) were developed in various institutions and successfully tested in experiments around the world. From the numerous new investigations carried out in the 1970s, using airguns and expendable sonobuoys, a more detailed picture of the crust under the ocean basins was obtained. The application of the reflectivity method to calculate synthetic seismograms for deep-ocean data proved to be most powerful in unraveling details of the basement structure (Spudich and Orcutt, 1980). It was shown that the structure was better represented by velocity gradient zones than by discrete constant-velocity layers. There was also research work going on to determine if seismic anisotropy could be observed in the crust. Bibee and Shor (1976) investigated a large number of standard marine refraction studies and concluded that anisotropy in the crust was insignificant, but that mantle velocities, however, exhibited a high correlation with both age and azimuth, indicating an increase of velocity with age and ~5% anisotropy with the highest velocity in the direction perpendicular to the local magnetic anomalies. In OBS refraction experiments in the 1970s on the northern East Pacific Rise, a fast-spreading ridge, a localized low-velocity zone was detected for the first time (Orcutt et al., 1976; Minshull, 2002) which was interpreted as resulting from the presence of a magma chamber containing partially molten rocks. Other seismic studies in the 1970s were concentrated on the Mid-Atlantic Ridge, a slow-spreading ridge. Here, early OBS refraction experiments found neither a low-velocity zone corresponding to magma chamber nor a strong velocity contrast at Moho depths. Instead, the crust-mantle boundary was defined by a gradual increase in velocities (Fowler, 1976, 1978; Minshull, 2002).

Numerous other crustal studies were performed during the 1970s, leading to a large amount of crustal data available by 1980 (Fig. 2.7-03; for details, see Appendix 7-1). The main features of crustal and uppermost mantle studies available by the end the 1970s were compiled as tables giving details such as thicknesses of the whole crust, upper and lower crust and corresponding average velocities (Prodehl, 1984). An overview of the large number of major seismic projects undertaken in the 1970s around the world and mentioned in Chapter 7 can be seen in Table 2.7.

Fundamental for future decades were new steps undertaken both in theory and instrumental development. During the second half of the 1970s, the ray method was developed (Červený et al., 1977), which led to the development of several ray tracing methods which could handle data in complex tectonic structures and which would become the standard tool for interpreting seismic data in the 1980s and following decades up to the present day. Also other groups were writing synthetic seismogram routines on the basis of ray theory which were widely applied, for example, the program by McMechan and Mooney (1980) in the United States or the program by Spence et al. (1984) in Canada and elsewhere.

At the same time, J.H. Healy started to raise new interest in explosion seismology in the United States by developing a new type of equipment, later called the cassette recorders, which was ready for its first field test in Saudi Arabia in 1978. The Saudi Arabian long-range profile set new standards and laid the foundation for new activities in the following 1980s (Healy et al., 1982). This new system was small, was timed by a sophisticated clock

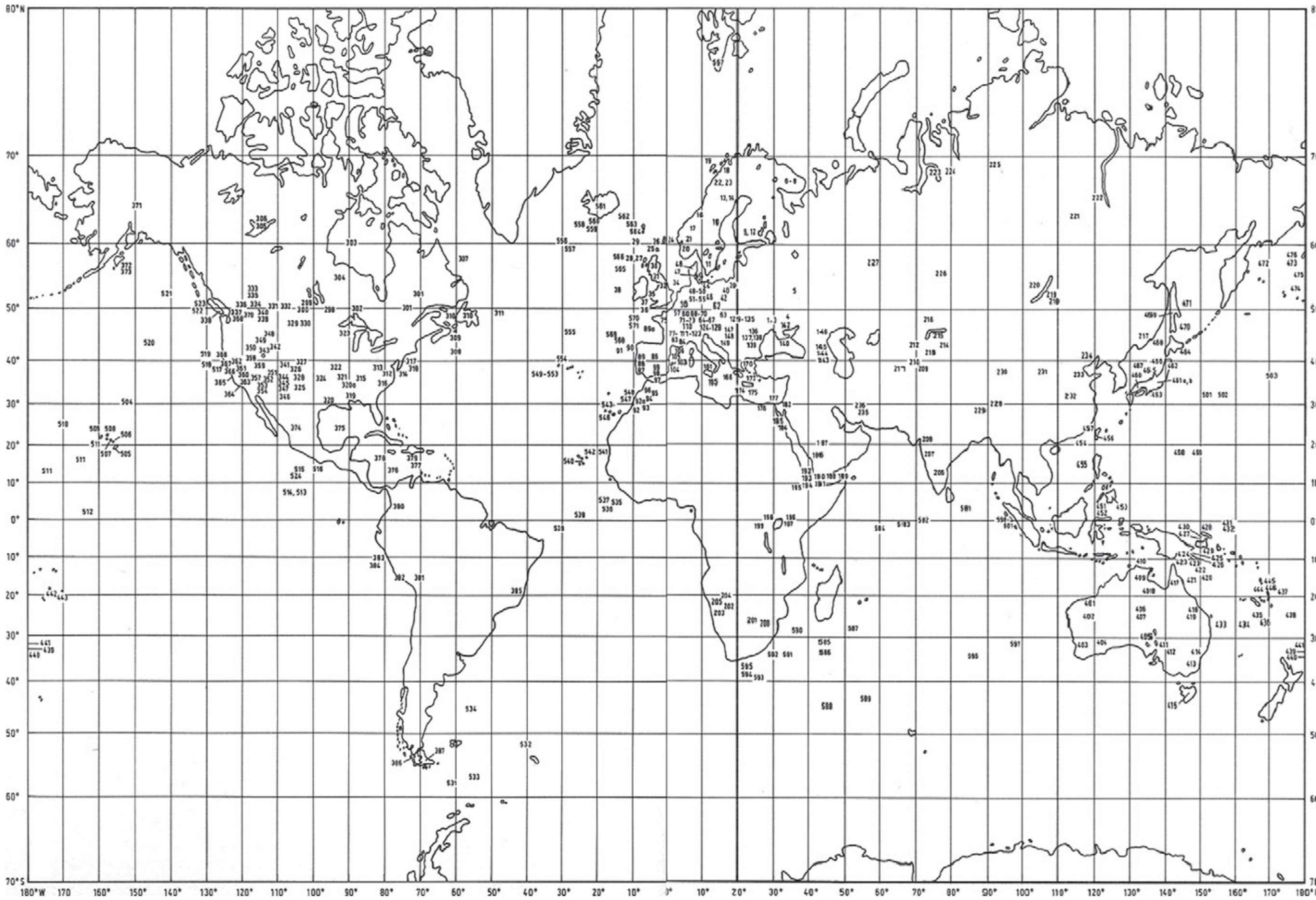

Figure 2.7-03. World map showing points where seismic data on crustal structure were available by 1980–1981 (from Prodehl, 1984, fig. 10). [*In* Hellwege, K.-H., editor in chief, Landolt Börnstein New Series: Numerical data and functional relationships in science and technology. Group V, Volume 2a: Fuchs, K., and Soffel, H., eds., Physical properties of the interior of the earth, the moon and the planets: Berlin-Heidelberg, Springer, p. 97–206. Reproduced with kind permission of Springer Science+Business Media.]

of high accuracy, was built in large quantities, could easily be operated by untrained personnel, and was able to record mostly automatically and run unattended for several days.

2.8. THE 1980s (1980–1990)

In the 1980s, the success of controlled-source seismology continued, but with increased interest into details of the crust. Computer programs for ray tracing, which had been developed in the 1970s and early 1980s, were now ready for applications. In contrast to the reflectivity method, ray theory enabled the interpretation of complicated structures in two or three dimensions, and therefore the interpretation of the fast-growing amount of data in crustal and upper mantle research work was carried out more and more by applying ray theory (Červený et al., 1977).

With these techniques, the requirement to obtain a denser data coverage, particularly in tectonically complicated regions, grew rapidly. The station spacing of 5 km or more for detailed crustal structure studies which had been regarded as sufficient up to the 1970s no longer suited the accuracy aimed for. In continental Europe, the MARS-66 analogue system, of which by the early 1980s ~200 units were available, experienced a late peak of magnetic-tape recording systems. Thus it became possible to decrease the station spacing to 2 km in most seismic-refraction experiments.

In North America, the 1980s saw a transformation in the development of new instrumentation. Here too it had also become clear that a station spacing of 5 km or more for detailed crustal structure studies was no longer sufficient. Smaller shotpoint and station spacings were required to achieve the scientific results needed. The development of the cassette recorders (Healy et al., 1982; Murphy, 1988; Appendix A7-5.6) at the U.S. Geological Survey at the end of the 1970s was the first attempt to fill this gap. This system provided a large number of easily maintained instruments with fast play-back facilities and led to an increasing number of fine-tuned experiments in North America. The increasing demand for more recording equipment sped up the developments of a new generation of recording units. It was in Canada where

TABLE 2.7. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1970S

Chapter	Year	Project	Location	Reference
7.2.1	1971	Crustal project France	France	Sapin and Prodehl (1973)
7.2.1	1971	Lower Lithosphere Project 1971	France	Hirn et al. (1973)
7.2.1	1972	Asthenosphere Project 1972	W-Europe	Steinmetz et al. (1974)
7.2.1	1973	Lower Lithosphere Verification 1971	France	Hirn et al. (1975)
7.2.2	1972	Upper Rhinegraben project	Central Europe	Edel et al. (1975)
7.2.2	1972	Rhônegraben project	South France	Sapin and Hirn (1974)
7.2.3	1970–1973	Southern and Western Portugal	Portugal	Moreira et al. (1977)
7.2.3	1970	ANNA Western Mediterranean project	Mediterranean Sea	Leenhardt et al. (1972)
7.2.3	1971	Southern Italy Puglia and Calabria	Italy	Colombi et al. (1973)
7.2.3	1971	"*Meteor* (1964)" M22 Ionian Sea	Greece	Weigel (1974)
7.2.3	1971	Meteor offshore-onshore Peleponnese	Greece	Weigel (1974)
7.2.3	1973	Island of Crete project	Greece	Makris and Vees (1977)
7.2.3	1973–1974	Central Greece–Aegean Sea	Greece	Makris (1977)
7.2.3	1974	"*Meteor* (1964)" expedition M33	Cretan Sea	Makris et al. (1977)
7.2.3	1974	Northern Appenines to Corsica	Italy-France	Morelli et al. (1977)
7.2.3	1974	Long range project Ligurian Sea	Mediterranean Sea	Hirn et al. (1977)
7.2.3	1974–1975	Betic Cordillera long range	Southern Spain	Banda and Ansorge (1980)
7.2.3	1975	Moroccan Meseta and Atlas	Morocco	Makris et al. (1985)
7.2.3	1976	Balearic islands land-sea project	Spain	Banda et al. (1980)
7.2.3	1976, 1981	Eastern Spain	Spain	Zeyen et al. (1985)
7.2.3	1977, 1979	Canary islands land-sea project	Off North Africa	Banda et al. (1981a)
7.2.3	1977, 1980	Betic Cordillera crust	South Spain	Barranco et al. (1990)
7.2.3	1978	Pyrenees seismic refraction lines	Spain-France	Gallart et al. (1980)
7.2.3	1978	"*Meteor* (1964)" expedition M50	Ionian Sea	Avedik et al. (1981)
7.2.3	1979	Long-range project Thyrrenian Sea	Mediterranean Sea	Steinmetz et al. (1983)
7.2.4	1974	Lithospheric Seismic Profile through Britain, Crustal Seismic Project Britain	British Isles	Bamford et al. (1976, 1978)
7.2.4	1974	Lithospheric Seismic Profile through Britain, Lower Lithosphere Britain	British Isles	Faber and Bamford (1979)
7.2.4	1976	Lewisian Units Seismic Traverse	British Isles	Hall (1978)
7.2.4	1977	South Irish Sea Seismic Experiment Wales	British Isles	Ransome (1979)
7.2.4	1979	Western Isles Seismic Experiment offshore W Scotland	British Isles	Summers et al. (1982)
7.2.4	1975	ALP75Alpine Longitudinal Profile	Alps	Miller et al. (1978)
7.2.4	1977	SÜDALP77	Northern Italy	Ansorge et al. (1979b)
7.2.4	1979	Institute of Geological Sciences, Wiltshire Survey	British Isles	Kenolty et al. (1981)
7.2.5	1973, 1975	Hunsrück seism refl surveys	West Germany	Meissner et al. (1980)
7.2.5	1974	North German Basin hydrocarbon survey	North Germany	Yoon et al. (2008)
7.2.5	1975–1976	North German Plain	North Germany	Reichert (1993)
7.2.5	1976	Northern Rhônegraben	France	Ansorge and Mueller (1979)
7.2.5	1978	Hunsrück-Eifel refraction line	West Germany	Meissner et al. (1983)
7.2.5	1978	Urach refraction seismics	Southwest Germany	Jentsch et al. (1982)
7.2.5	1979	Urach reflection seismics	Southwest Germany	Bartelsen et al. (1982)
7.2.6	1972	Blue Road profile	Norway-Sweden	Hirschleber et al. (1975)
7.2.6	1979	Rhenish Massif long range project	Germany-France	Mechie et al. (1983)
7.2.6	1979	FENNOLORA Scandinavia crust	Scandinavia	Guggisberg et al. (1991)
7.2.6	1979	FENNOLORA Scandinavia asthenosphere	Scandinavia	Guggisberg and Berthelsen (1987)
7.2.7	1970ff	M1-M13 Fore-Sudetic seismics	Poland	Toporkiewicz (1986)
7.2.7	1970ff	LT2-LT5Tornquist-Teisseye Zone	Poland	Guterch (1977)
7.2.7	1970ff	Deep seismic international profiles	Eastern Europe	Guterch et al. (1991)
7.2.7	1970ff	Deep seismic international profiles	Southeastern Europe	Radulescu et al. (1976)
7.3	1970ff	Deep seismic sounding profiles	Southwest USSR	Sollogub et al. (1973)
7.3	1972ff	Deep seismic sounding Voronezh Shield	Southwest USSR	Tarkov and Basula (1983)
7.3	1970ff	Deep seismic sounding crustal profiles USSR	Europe and Asia	Zverev and Kosminskaya (1980)
7.3	1970ff	Peaceful nuclear explosions asthenosphere USSR	Europe and Asia	Egorkin and Pavlenkova (1981)
7.3	1977–1979	Peaceful nuclear explosions athenosphere profiles	USSR	Mechie et al. (1993)
7.4.1	1971–1972	Bingham, Utah–Wasatch Front	Western USA	Braile et al. (1974)
7.4.1	1973	Long Valley Caldera seismics	Western USA	Hill (1976)
7.4.1	1976	DICE THROW Rio Gande Rift	Western USA	Olsen et al. (1979)
7.4.1	1978	Arizona Basin and Range province	Western USA	Sinno et al. (1981)
7.4.1	1978, 1980	Yellowstone–Snake River Plain	Western USA	Smith et al. (1982)
7.4.2	1978–1979	USGS seismic reflection, New Madrid	Eastern USA	Hamilton (1986)
7.4.2	1979	Imperial Valley, California	Western USA	Fuis et al. (1984)
7.4.2	1979–1980	Mississippi embayment reflections survey	Central USA	Mooney et al. (1983)
7.4.3	1975ff	COCORP	USA	Brewer and Oliver (1980)
7.4.3	1975	COCORP Hardeman County	Central USA	Oliver et al. (1976)
7.4.3	1975–1976	COCORP Rio Grande Rift	Western USA	Brown et al. (1979)
7.4.3	1976	COCORP San Andreas Fault project	Western USA	Long et al. (19
7.4.3	1977	COCORP Wind River Mountains	Western USA	Smithson et al. (1979)

(*continued*)

TABLE 2.7. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1970S (*continued*)

Chapter	Year	Project	Location	Reference
7.4.3	1978	COCORP Michigan basin Michigan reflection survey	Central USA	Jensen et al. (1979)
7.4.3	1978–1979	COCORP S Appalachians GAA and GAB	Eastern USA	Cook et al. (1979)
7.4.3	1978–1979	COCORP Charleston–Georgia GAC/CHP	Eastern USA	Cook et al. (1979)
7.4.3	1979	COCORP Wichita Uplift Oklahoma Wichita Mountains reflection survey	Central USA	Brewer and Oliver (1980)
7.4.3	1979	COCORP Minnesota Archean Minnesota reflection survey	Central USA	Gibbs et al. (1984)
7.4.3	1979	USGS Grandfather Mountain Profile	Eastern USA	Harris et al. (1981)
7.4.4	1970	Baffin Bay	Canada	Keen et al. (1972)
7.4.4	1972–1973	Cordillera seismic reflection profiles	Canada	Berry and Mayr (1977)
7.4.4	1977ff	COCRUST Williston Basin	Canada	Green et al. (1986)
7.5.1	1971	Djbouti crustal survey	Djibouti	Ruegg (1975)
7.5.1	1972	Afar crustal survey	Ethiopia	Berckhemer et al. (1975)
7.5.2	1977	Jordan–Dead Sea transform	Israel	Ginzburg et al. (1979)
7.5.2	1978	Cyprus-Israel	Israel	Makris et al. (1983a)
7.5.2	1978	Saudi Arabia lithosphere	Saudi Arabia	Mooney et al. (1985)
7.5.2	1978	Northern Red Sea–Egypt	Egypt	Rihm et al. (1991)
7.5.2	1978	Zagros Belt reconnaissance	Iran	Giese et al. (1984)
7.6.1	1972–1975	Deep seismic sounding S-India, Indian Shield	South India	Kaila et al. (1979)
7.6.1	1972ff	Deep seismic sounding N-India, Kashmir	North India	Kaila et al. (1978)
7.6.1	1970s	Cambay basin	India	Kaila et al. (1981a)
7.6.1	1970s	Koyna Dam	India	Kaila et al. (1981b)
7.6.2	1975–1977	Tibetan plateau	China	Teng (1987)
7.6.2	1978ff	Qaidam basin, Yongping eplosions	China	Teng (1979); Yuan et al. (1986)
7.6.3	1975	Shizuoka district, central Japan	Japan	Ikami (1978)
7.6.3	1976	Western Kanto district	Japan	Kaneda et al. (1979)
7.6.3	1979	Mishima-Shimoda profile, Izu peninsula	Central Japan	Asano et al. (1982)
7.6.3	1979	Seismic intrusion detector onshore line Shikoku Island	Southwest Japan	Ikami et al. (1982)
7.7.1	1970–1971	Deep reflection experiments	Australia	Moss and Dooley (1988)
7.7.1	1972	Trans-Australia seismic survey	Australia	Finlayson et al. (1974)
7.7.1	1973	Bowen Basin, Queensland	Eastern Australia	Collins (1978)
7.7.1	1974–1975	Fiordland South Island NZ	New Zealand	Davey and Broadbent (1980)
7.7.1	1975	Long range earthquake profile	Central Australia	Hales et al. (1980)
7.7.1	1976–1978	Lachlan Foldbelt, NewSouthWales	Eastern Australia	Finlayson et al. (1979)
7.7.1	1976–1978	Deep seismic reflection experiments	Northeast Australia	Mathur (1983)
7.7.1	1977, 1979	Pilbara-Yilgarn craton projects	Northwest Australia	Drummond (1979)
7.7.1	1979	Mount Isa–Tennant Creek profile	Central Australia	Finlayson (1982)
7.7.2	1975	Damara orogen	Namibia	Baier et al. (1983)
7.7.2	1975	Damara orogen	Namibia	Baier et al. (1983)
7.7.3	1973	Narino III Pacific Ocean–Northern Andes	Colombia	Meyer et al. (1976)
7.7.3	1976	Cordilleras Northern Andes	Colombia	Mooney et al. (1979)
7.7.3	1978	Cordilleras Northern Andes	Colombia	Flueh et al. (1981)
7.7.4	1979–1980	Polish Antarctica expedition	West Antarctica	Guterch et al. (1985)
7.8.2	1970	Northeast Pacific Ocean	Canada	Keen and Barrett (1971)
7.8.2	1970–1971	"*Vitiaz*" cruise no 49	Pacific	Kosminskaya et al. (1973)
7.8.2	1972–1973	Peru-Chile trench	Pacific-Peru	Hussong et al. (1976)
7.8.2	1973	East Papua crustal survey	Papua New Guinea	Finlayson et al. (1977)
7.8.2	1973–1974	Cocos Plate east of East Pacific Rise	Pacific	Lewis and Snydsman (1979)
7.8.2	1973–1974	Longshot Experiment off Japan	Pacific	Asada and Shimamura (1976)
7.8.2	1973, 1976	Mariana long range experiments	Japan	Nagumo et al. (1981)
7.8.2	1974	East Pacific Rise at Siqueiros Fracture Zone	Pacific	Orcutt et al. (1976)
7.8.2	1974	Offshore large shot experiment, Pacific	Off Japan	Okada et al. (1979)
7.8.2	1976	Offshore large shot experiment, Sea of Japan	Off Japan	Okada et al. (1978)
7.8.2	1976	600 km long-range profile	Northeast Pacific	Orcutt (1977)
7.8.2	1976	Banda Sea	North off Australia	Jacobson et al. (1979)
7.8.2	1976	Timor Sea	North off Australia	Rynn and Reid (1983)
7.8.2	1976	Great Australian Bight	South off Australia	Talwani et al. (1979)
7.8.2	1976	Explorer Ridge W Vancouver	Canada	Cheung and Clowes (1981)
7.8.2	1976	East Pacific Rise crest	Eastern Pacific	Herron et al. (1978)
7.8.2	1976, 1978	Hawaii Big Island projects	Hawaii	Zucca et al. (1982)
7.8.2	1977–1979	Shirshov Institute of Oceanology world cruise	Oceans	Neprochnov (1989)
7.8.2	1979	Rivera Ocean Seismic Experiment (ROSE)	East Pacific Rise	Ewing and Meyer (1982)
7.8.3	1975	Offshore Sumatra	Indian Ocean	Kiekhefer et al. (1980)
7.8.3	1978	Agulhas Plateau	Southern Indian Ocean	Tucholke et al. (1981)
7.8.3	1978	Madagascar Ridge, Crozet Plateau	Indian Ocean	Goslin et al. (1981)
7.8.4	1972	NASP Iceland to Scotland	North Atlantic	Bott and Gunnarson (1980)
7.8.4	1973	Mid-Atlantic Ridge at 37°N	Southeast of Azores	Whitmarsh (1975)
7.8.4	1974–1975	Mid-Atlantic Ridge long range	North of Azores	Steinmetz et al. (1977)

(*continued*)

TABLE 2.7. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1970S (*continued*)

Chapter	Year	Project	Location	Reference
7.8.4	1974	"*Meteor* (1964)" expedition M33	Off West Africa	Sarnthein et al. (2008)
7.8.4	1975	"*Meteor* (1964)" expedition M39	Off West Africa	Sarnthein et al. (2008)
7.8.4	1975	Mid-Atlantic Ridge at 45°N	Atlantic	Fowler (1978)
7.8.4	1975	Hebridean Margin Seismic Project	West of Scotland	Bott et al. (1979)
7.8.4	1975–1976	OBS tests in Bay of Biscay	West of France	Avedik et al. (1978)
7.8.4	1976–1977	OBS tests in Norwegian Sea–Blue Norma	West of Norway	Avedik et al. (1978)
7.8.4	1976, 1978	Spitsbergen expeditions	Spitsbergen	Sellevoll et al. (1982)
7.8.4	1977	Kane fracture zone, Mid-Atlantic Ridge	Atlantic	Detrick and Purdy (1980)
7.8.4	1977	"*Meteor* (1964)" expedition M46	Off West Africa	Sarnthein et al. (2008)
7.8.4	1977	Reykjanes Ridge at 60°30°W	Atlantic	Bunch (1980)
7.8.4	1977	"*Meteor* (1964)" M45 Reykjanes Ridge	Atlantic	Reykjanes Ridge Seismic Project Working Group (1980)
7.8.4	1977	Reykjanes Ridge–Iceland Seismic Project	Iceland	Reykjanes Ridge Seismic Project Working Group (1980)
7.8.4	1977–1978	Eastern Canada margin	Canada	Keen and Barrett (1981)
7.8.4	1978	Azores–Biscay rise	Atlantic Ocean	Whitmarsh et al. (1982)
7.8.4	1978	Mid-Atlantic Ridge 45°N	Atlantic	White and Whitmarsh (1984)
7.8.4	1978	"*Meteor* (1964)" expedition M48	Iceland–Faeroe	Sarnthein et al. (2008)
7.8.4	1979	Long Island Platform marine multichannel seismic survey	Eastern USA	Hutchinson et al. (1986)
7.8.4	1979ff	Onshore-offshore reflection work	Eastern USA	Behrendt (1986)

the first digital equipment, the Portable Refraction Seismograph (PRS1), was being developed by the Geological Survey of Canada and afterwards built by EDA Instruments Ltd. (Asudeh et al., 1992). By the end of the 1980s both in Canada and in the United States, not only had a large number of instruments become available, but also the age of digital recorders had started, pushed forward in particular by the foundation of LITHOPROBE in Canada and of IRIS/PASSCAL in the United States.

In Europe, three different approaches to detailed crustal studies were undertaken. First, crustal research in Europe received a new impulse from reflection seismology. Second, the European Geotraverse involved a large-scale seismic-refraction traverse. Third, continental deep drilling was accompanied by detailed reflection-refraction surveys.

Following the establishment of COCORP in the United States and COCRUST in Canada in the late 1970s, in Europe national groups such as BIRPS in Britain (Klemperer and Hobbs, 1991; see Fig. 8.3.1-01), DEKORP in Germany (Meissner et al., 1991a; see Fig. 8.3.1-07), or ECORS in France (Bois et al., 1986; see Fig. 8.3.1-03) were rapidly formed in the early 1980s. In Switzerland, Czechoslovakia, and Italy (CROP), similar research activities were initiated, and finally the multinational program BABEL investigating the Baltic Sea was born. Since 1985, the Australian Geological Survey Organisation (AGSO) has run a large program of deep seismic reflection surveys offshore and onshore Australia (Finlayson, 2010; Appendix 2-2). They all followed the ideas developed in the late 1970s by COCORP in North America to investigate the Earth's crust in great detail by applying vertical-incidence reflection work in a big style. In contrast to most of the early near-vertical incidence seismic reflection work in the 1950s and 1960s in Canada, Germany, the USSR, United States, and in Australia, the initiators of COCORP had hired a commercial reflection company for the field work and also applied their processing and interpretation techniques (Oliver et al., 1976) on the new data involving the whole crust. The same philosophy was now also applied by the initiators of the national European large-scale seismic reflection programs. All seismic reflection surveys accomplished by 1988 were compiled in a location map by Sadowiak et al. (1991) which is reproduced in Figure 2.8-01.

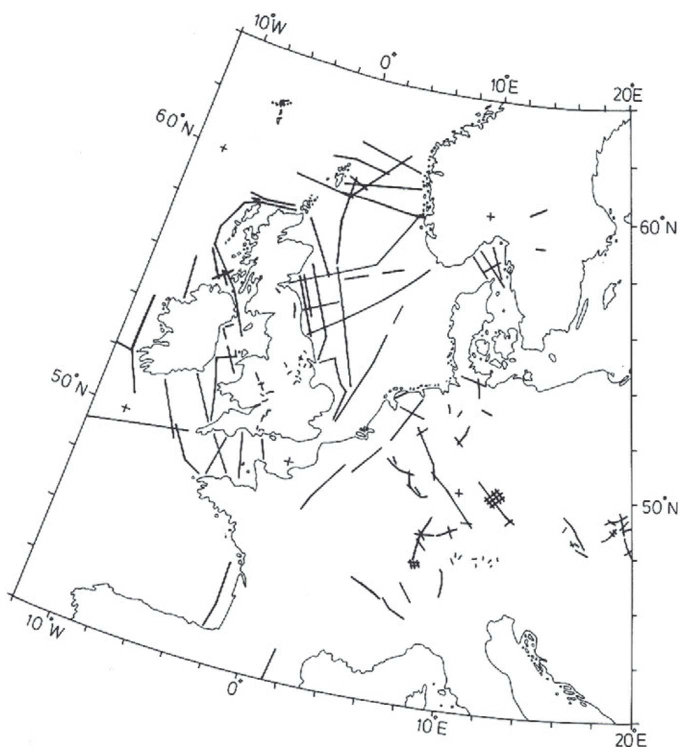

Figure 2.8-01. Location map of seismic reflection lines in western Europe observed until 1988 (from Sadowiak et al., 1991, fig. 1). [Geophysical Monograph 105, p. 45–54. Copyright John Wiley & Sons Ltd.]

In 1984, a series of international symposia on the seismic probing of the continents and their margins was started which in the beginning had the main focus to discuss large-scale seismic-reflection surveys and their impetus on our knowledge of the Earth's crustal structure (Barazangi and Brown, 1986a, 1986b; Matthews and Smith, 1987; Leven et al., 1990; Meissner et al., 1991a).

In the frame of the large-scale interdisciplinary project "European Geotraverse" (Fig. 2.8-02), covering a corridor through all major tectonic units of Europe from the North Cape to Tunisia, North Africa, a large-scale seismic-refraction survey was initiated (Ansorge et al., 1992). The seismic-refraction investigation was split into northern, central, and southern sections and was carried out over a period of several years. The Swiss national seismic reflection profile NFP20 through the central Alps was integrated into the EGT refraction observations (Valasek et al., 1991) and detected the European subduction under the Alps. Finally the Iberian Lithosphere Heterogeneity and Anisotropy (ILIHA) Project was designed as project no. 11 of the European Geotraverse, because only the Iberian peninsula had dimensions where large sea shots could be recorded up to 600–800 km distance on reversed long-range profiles on more or less homogeneous Hercynian crust.

The increasing interest in deep continental drilling and the search for suitable super-deep drill sites led to a variety of large-scale seismic-refraction and reflection surveys, particularly in Russia around the Kola super-deep drillhole and in central

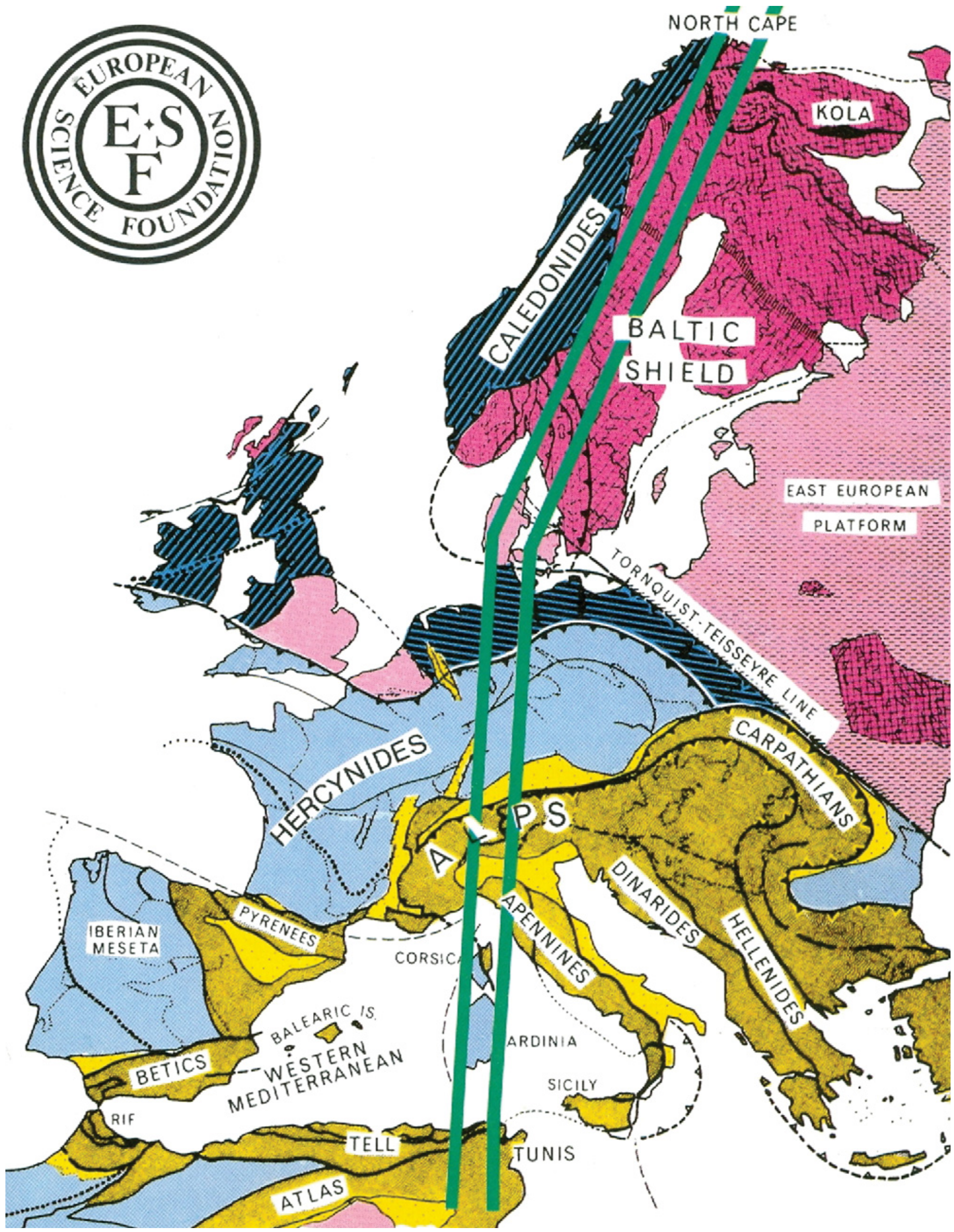

Figure 2.8-02. Location map of the European GeoTraverse (from European Science Foundation, 1990, cover). [European Science Foundation, Strasbourg, 67 p. Reproduced by kind permission of the European Science Foundation, Strasbourg, France.]

Europe at two proposed drill sites in Germany, which partly coincided with the national reflection programs (Emmermann and Wohlenberg, 1989).

Besides BIRPS, other British projects in the 1980s investigated the North Sea, northern Britain, and the Irish Sea. The North Sea project involved both refraction and reflection work (Barton, 1986). The Caledonian Suture Seismic Project profile traversed northern Britain with shots in the North and Irish Seas (Bott et al., 1983) and stimulated the first seismic crustal profile through Ireland (Jacob et al., 1985). In addition to the seismic reflection profiling of BIRPS, a major seismic investigation followed using both land and sea profiling in and around Ireland (Landes et al., 2005).

In the USSR, the third period of Russian deep-seismic sounding investigations, which had started at the end of the 1970s, continued through the 1980s (Pavlenkova, 1996). The network of seismic profiles covered almost the whole territory of the USSR (Fig. 2.8-03). This seismic research included three-component magnetic recordings of shots of varying sizes recorded by up to 300 stations on profiles with 2500–3000 km length, involving both large conventional explosives and peaceful nuclear explosions (PNE).

In North America, COCORP continued its seismic-reflection program and many new areas were systematically covered (Brown et al., 1986; see Fig. 8.5.3-01). Furthermore, many seismic-refraction experiments were carried out. The new seismic-refraction equipment of the U.S. Geological Survey led to considerably increased activity, parallel to the efforts of COCORP. For example, a large-scale seismic-refraction experiment traversed the Basin and Range province, more or less parallel to the 40° COCORP survey (Catchings and PASSCAL Working Group, 1988). The goal of the PACE (Pacific to Arizona Crustal Experiment) project was to study the evolutionary history of metamorphic core complexes of the western Cordillera (McCarthy et al., 1991). New crustal data were collected in the southern Rio Grande rift area. In northeastern United States and adjacent Canada a seismic refraction/wide-angle reflection experiment crossed the northern Appalachians and the Adirondack Massif and ended in the Grenville province of the North American craton (Hughes and Luetgert, 1991). Braile et al. (1989) and Mooney and Braile (1989) summarized all seismic-refraction profiles, recorded in North America until ca. 1988 (Fig. 2.8-04).

The Canadian geophysical institutions subsequently formulated the joint programs COCRUST (Mereu et al., 1989; see

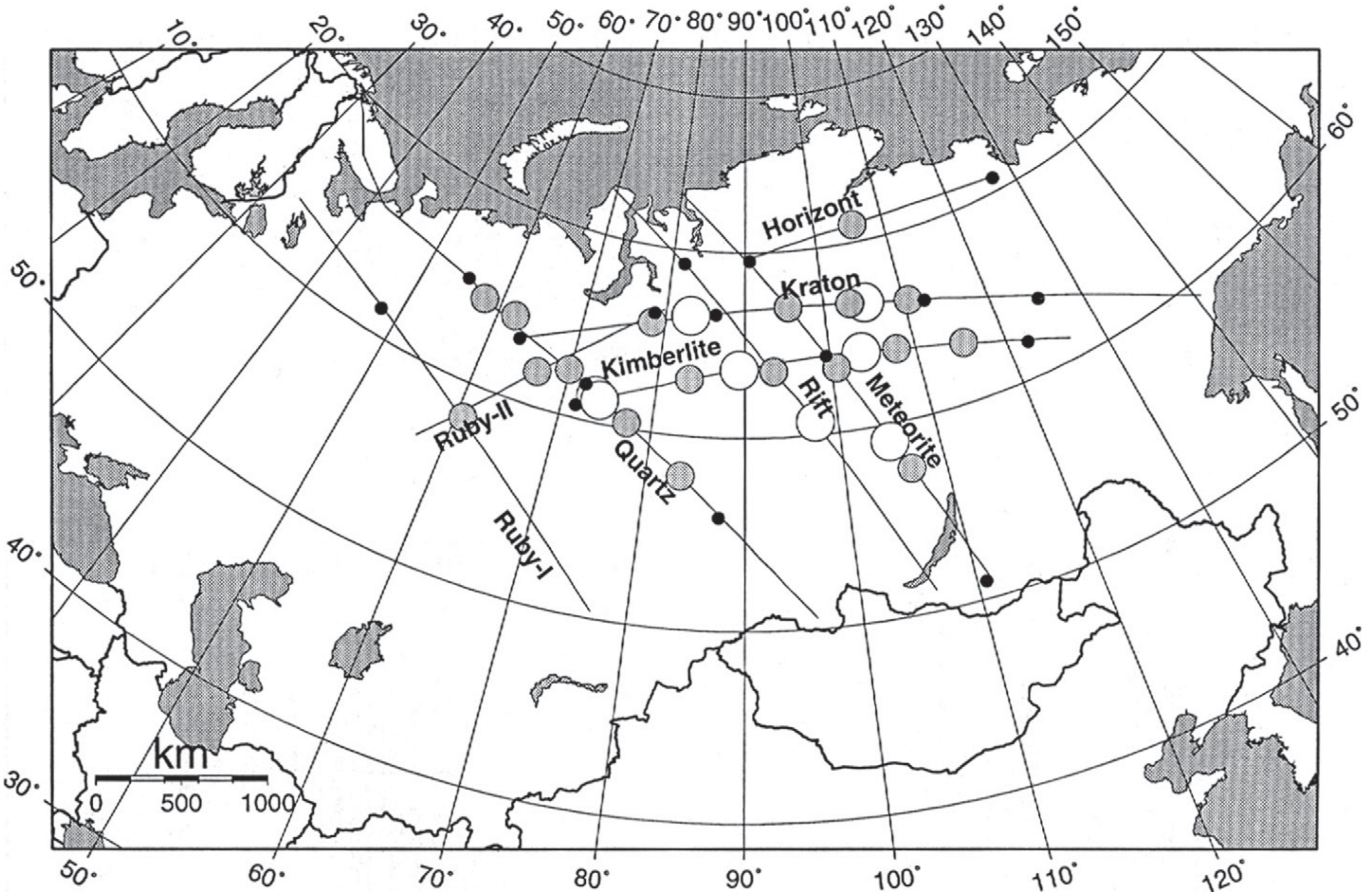

Figure 2.8-03. Location map of deep seismic sounding profiles in the USSR and locations of the peaceful nuclear explosions (PNE) (from Ryberg et al., 1998, fig. 1). [Journal of Geophysical Research, v. 103, p. 811–822. Reproduced by permission of American Geophysical Union.]

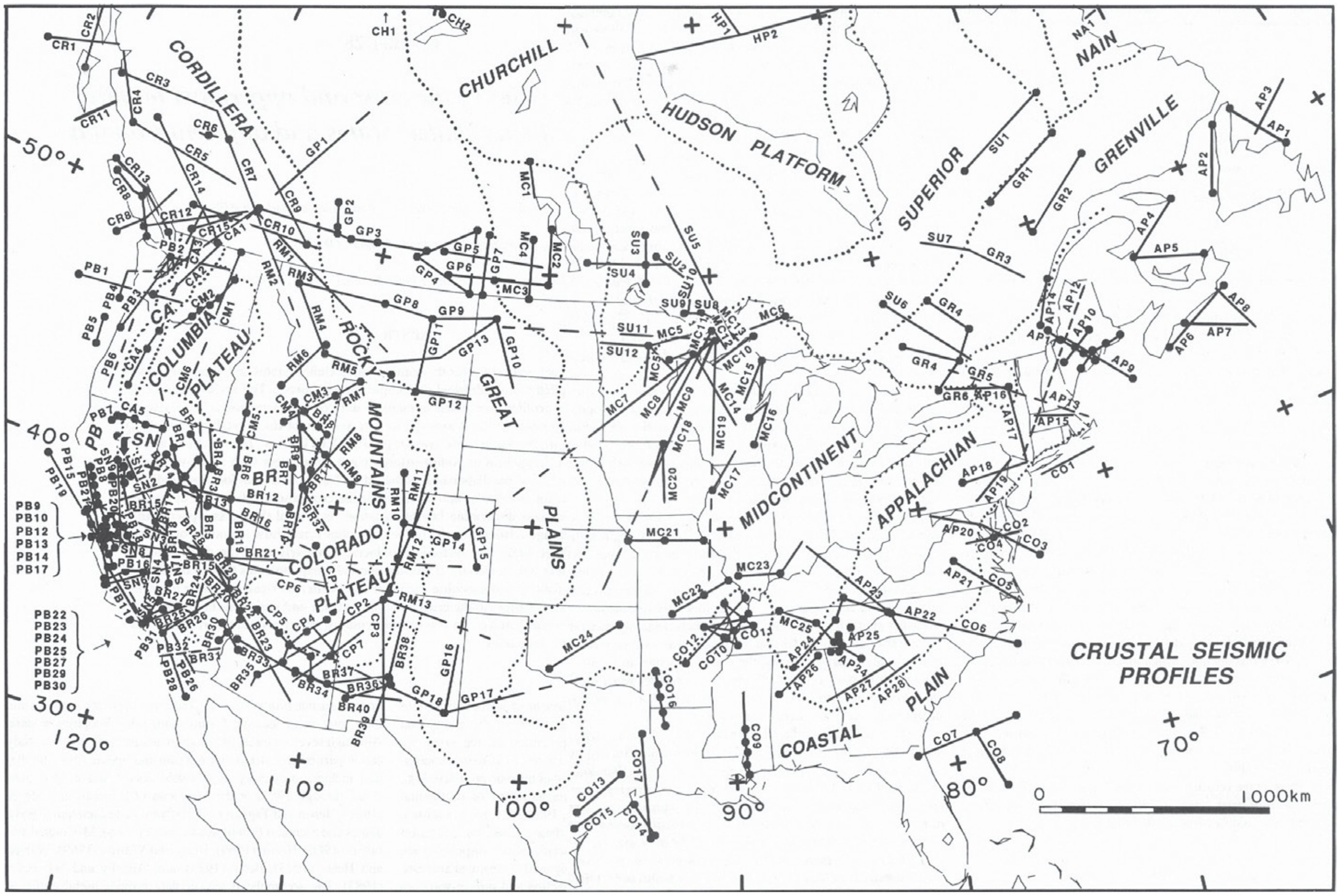

Figure 2.8-04. Location of seismic refraction surveys in Canada and the United States until 1988 (from Braile et al., 1989, fig. 1). For additional seismic profiles in Alaska, northern Canada and Mexico see Mooney and Braile (1989, fig. 1). [*In* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 655–680. Reproduced by permission of the Geological Society of America.]

also Fig. 8.5.2-01) and LITHOPROBE (e.g., Clowes, 1993) for a systematic crustal and uppermost-mantle investigation of the Canadian territory by a joint application of seismic-refraction and -reflection methodology. Most of the Canadian profiles are included in Figure 2.8-04. Furthermore, a seismic transect through Alaska, the Trans-Alaska Crustal Transect project (TACT; see Fig. 8.5.4-01), was undertaken in several steps from 1984 to 1990 (Plafker and Mooney, 1997).

The Afro-Arabian rift saw major activities of crustal research. Following the 1977 crustal investigation of the Jordan–Dead Sea transform in Israel (Ginzburg et al., 1979a), in 1984 a second survey explored the eastern part in Jordan (El-Isa et al., 1987a). The East African Rift in Kenya became the target of the first KRISP operation in 1985 (Henry et al., 1990). Most surveys, however, concentrated on the Red Sea area (for locations, see Fig. 2.9-02). Several symposia were held to report on the state of the art (e.g., Le Pichon and Cochran, 1988; Makris et al., 1991).

In India a total of 6000 km of long-range refraction and wide-angle reflection observations had been obtained by the end of the 1980s by deep-seismic sounding surveys throughout India along 20 profiles (Mahadevan, 1994; see Fig. 8.7.1-01). The investigations aimed in particular on the deep structure of basins and rift systems, adopting continuous profiling over major portions of the deep-sounding profiles using geophone spacings of 200 m and shotpoint intervals of 20–40 km. Recordings with useful energy were obtained up to distances of 400 km.

In China, a major cooperative program between Chinese institutions and European and North American institutions was started. The first explosion seismology operation was a joint Sino-French study, which was carried out in Tibet investigating the Himalayan border and the adjacent Lhasa block to the north. A 500-km-long east-west line consisting of a system of reversed and overlapping profiles was recorded. For detailed crustal studies of whole of China, some 250 standardized instruments for deep-seismic sounding, recording on two-channel magnetic tape cassettes, were distributed among various research groups within China belonging to the State Seismological Bureau. Thus, in the 1980s a major activity of seismic research started (see Fig. 8.7.2-06) and has continued since then (Li and Mooney, 1998).

In Japan, onshore seismic crustal research in the 1980s was mainly carried out in the frame of the national Earthquake Prediction Program and focused on the upper crustal structure, searching particularly for major fault zones and tectonic lines (e.g., Ikami et al., 1986; Matsu'ura et al., 1991).

In Australia, several major seismic reflection surveys were undertaken (Finlayson, 2010; Appendix 2-2; see Fig. 8.8.1-03). For example, during 1980–1982 deep reflection data were obtained in the central Eromanga basin in southwestern Queensland. It resulted in 1400 km of traversing in a regional grid on continuous profiles up to 270 km long (Moss and Mathur, 1986). Following these successful studies, an Australian Continental Reflection Profiling Program (ACORP) was initiated and subsequently, in 1985, two major north-south–oriented deep seismic reflection surveys were conducted in central Australia acquiring 486 line kilometers across the Arunta block and the Amadeus basin (Wright et al., 1990).

Major activities of crustal seismic research started in South America, when in 1982 at the Free University of Berlin, Germany, a geoscientific interdisciplinary research group "Mobility of active continental margins" was established. Its main aim was the investigation of the Andes of Chile. Its funding enabled the recording of a number of onshore seismic-refraction lines up to distances of 260 km (see Fig. 8.8.3-01) in northern Chile and adjacent Bolivia and Argentina (Wigger et al., 1994). Energy was primarily obtained by using large quarry blasts of various copper mines, but also some self-organized borehole shots were added. Underwater shots fired by the Chilean navy close to the Chilean coast in the Pacific Ocean were also arranged.

With improved technology, extremely hostile climatic areas such as Antarctica became the focus of extensive seismic research projects. The Institute of Geophysics of the Polish Academy of Sciences undertook several expeditions to explore the structure underneath West Antarctica (Janik, 1997) beginning in 1979 and 1980 and continuing in 1984–1985 and 1987–1988 (see Fig. 8.8.4-01). McMurdo Sound at the southern end of the Ross Sea was the focus of the U.S. Louisiana State University to investigate the east-west boundary of the McMurdo Sound (McGinnis et al., 1985) with seismic refraction profiles in 1980 and 1981.

With advanced techniques, the number of marine seismic experiments carried out in the past three decades literally exploded. From the early 1980s onwards, large dynamic ranges and dense spatial sampling were targeted for the investigation of the crustal structure. For this reason experiments were designed for obtaining large offsets and large-aperture seismic refraction/wide-angle reflection data as well as near-vertical incidence reflections. In the 1980s, the development of non-explosive sources had become effective enough to be successfully recorded over long distance ranges of several 100 km at sea and also, in onshore-offshore experiments, on land. Of greatest importance for the advance of marine deep-seismic sounding was the fact that gradually over the years more and more ocean bottom seismographs came into use, giving much better signal-to-noise ratios than was possible to obtain with strings of hydrophones which suffered also from the noise produced by the moving towing ship.

A worldwide study of the lower crust and upper mantle using ocean bottom seismographs (OBS) and big airguns in the oceans was performed by the Shirshov Institute of Oceanology (Neprochnov, 1989) in the period from 1977 to 1984 (see Fig. 8.9.2-01). The North Atlantic Transect (NAT Study Group, 1985) provided a major improvement on the knowledge of the structure of the oceanic crust and its variability on a large regional scale. Other spectacular images of the internal structure of the oceanic crust were published by White et al. (1990). They showed widespread occurrence of intracrustal reflectivity in the western Central Atlantic Ocean The research project RAPIDS (Rockall and Porcupine Irish Deep Seismic) project of the Dublin Institute for Advanced Studies and partners consisted of two orthogonal wide-angle seismic profiles totaling 1600 km. The individual lines were typically 200–250 km long and produced a 1000-km-long east-west seismic profile from Ireland to the Iceland Basin crossing various troughs, basins and intervening banks (e.g., Hauser et al., 1995).

Various projects dealt with the ocean-continent transition at continental margins. For example, seismic surveys were carried out in the vicinity of the northern Japan trench (Suyehiro and Nishizawa, 1994) or across the east Oman continental margin north of the Masirah Island ophiolite (Barton et al., 1990). An extended offshore marine survey targeted the crustal structure off Norway on the Voering plateau (Zehnder et al., 1990) and along the Lofoten margin (Mjelde et al., 1992). Detailed seismic investigations aimed for the deep structure in the transition zones west and north of Spitsbergen (Czuba et al., 1999) as well as eastern Greenland and its margin on the western side of the northernmost Atlantic Ocean (e.g., Mandler and Jokat, 1998). The 1981 Large Aperture Seismic Experiment (LASE) was one of the first experiments along the Atlantic continental margin of North America (e.g., Trehu et al., 1989b).

Only a few examples of research projects could be mentioned in this overview. A summary of all projects mentioned in Chapter 8 is compiled in Table 2.8.

A particular aspect of the new era of continental crustal research in the 1980s was the compatibility of results obtained either from the very detailed seismic-reflection projects or from the less dense seismic-refraction observations. In the beginning of COCORP, accompanying wide-angle piggyback experiments were rare. The different techniques and different frequency ranges of the seismic signals of near-incidence reflection research work and of wide-angle reflection profiling led to quite different presentations of crustal structure, and it took a while before the different philosophies were jointly discussed.

However, in central Europe as well as in Canada and Australia, close cooperation between the "reflection" and "refraction" groups started. The Canadian research programs COCRUST and LITHOPROBE involved the simultaneous use of both methods.

TABLE 2.8. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1980S

Chapter	Year	Project	Location	Reference
8.3.1.1	1980–1982	IGS land reflection surveys	British Isles	Whittaker and Chadwick (1983)
8.3.1.1	1981	BIRPS MOIST line	Northwest British Isles	Matthews and Cheadle (1986)
8.3.1.1	1982	SHELL UK82-101	North Sea	Klemperer and Hurich (1990)
8.3.1.1	1982	BIRPS WINCH lines	Northwest British Isles	Matthews and Cheadle (1986)
8.3.1.1	1983	BIRPS-ECORS Southwest AT lines	English Channel	Matthews and Cheadle (1986)
8.3.1.1	1983	NOPEC SNST83-07	South North Sea	Holliger and Klemperer (1990)
8.3.1.1	1983	North Sea BIRPS along SALT	North Sea	Barton (1986)
8.3.1.1	1984	BIRPS SHET (Sheltland survey)	North Sea	McGeary (1987)
8.3.1.1	1984–1985	BIRPS North Sea Deep Profile	North Sea	Matthews and Cheadle (1986)
8.3.1.1	1985	SAP-5 and N-11 (Rockall Trough)	Northwest of Ireland	Joppen and White (1990)
8.3.1.1	1985	BIRPS NEC (North East Coast line)	North Sea	Freeman et al. (1988)
8.3.1.1	1985	BIRPS WAM	Southwest of Channel	Peddy et al. (1989)
8.3.1.1	1986–1987	BIRPS GRID lines	North of Scotland	Blundell and Docherty (1987)
8.3.1.1	1987	BIRPS SLAVE	ESP experiment	Blundell and Docherty (1987)
8.3.1.1	1987	BIRPS WIRE	West of Ireland	Blundell and Docherty (1987)
8.3.1.1	1987	BIRPS MOBIL	South North Sea	Blundell and Docherty (1987)
8.3.1.1	1988	BIRPS WISPA	Onshore United Kingdom	Ward and Warner (1991)
8.3.1.1	1990	BIRPS WESTLINE	West of Ireland	England (1995)
8.3.1.2	1983–1984	ECORS Paris basin	Northern France	Bois et al. (1986)
8.3.1.2	1984	ECORS Aquitaine Basin N-S line	France	Marillier et al. (1988)
8.3.1.2	1985ff	ECORS Aquitaine Basin–Pyrenees	France	ECORS Pyrenees team (1988)
8.3.1.2	1985ff	ECORS Gulf of Biscay	France	Pinet et al. (1987)
8.3.1.2	1986–1987	ECORS Bresse-Jura	France	Guellec et al. (1990)
8.3.1.3	1986	CROP-ECORS Torino-Geneva	Italy-France	Scrocca et al. (2003)
8.3.1.3	1988	CROP-NFP20 South-Central Alps	Italy-Switzerland	Scrocca et al. (2003)
8.3.1.3	1988	CROP-ECORS Gulf of Lions–Sardinia	Western Mediterranean	Scrocca et al. (2003)
8.3.1.4	1982	VibroSeis Swiss unfolded Jura	Northern Switzerland	Finck et al. (1986)
8.3.1.4	1986, 1988	NFP20 Swiss reflection line	Switzerland	Valasek et al. (19
8.3.1.5	1984	DEKORP-2 South Main-Danube line	Southern Germany	DEKORP Research Group (1985)
8.3.1.5	1984	Black Forest reflection line	Southwest Germany	Lüschen et al. (1987)
8.3.1.5	1985	DEKORP-4 KTB–Eastern Bavaria	Southeastern Germany	DEKORP Research Group (1988)
8.3.1.5	1986	DEKORP-2 North Rhenish Massif	Western Germany	Franke et al. (1990)
8.3.1.5	1987, 1988	BELCORP-DEKORP-1 Rhen Massif	Western Germany	DEKORP Research Group (1991)
8.3.1.5	1988	DEKORP-9 N Northern Rhinegraben	Southwest Germany	Wenzel et al. (1991)
8.3.1.5	1988	ECORS-DEKORP-9S South Rhinegr	Southwest Germany	Brun et al. (1991)
8.3.1.5	1989	DEKORP 3-D survey KTB drill site	Southeastern Germany	Dürbaum et al. (1992)
8.3.1.5	1990	DEKORP-3 and DEKORP-MVE	Eastern Germany	DEKORP Research Group (1994)
8.3.1.6	1980s	West Carpathians deep reflection lines	Czechoslovakia	Tomek et al. (1987)
8.3.1.7	1989	BABEL Baltic Shield	Baltic Sea	BABEL WG (1991)
8.3.1.7	1989	BALTIC SEA profile	Baltic Sea	Ostrovsky (1993)
8.3.2	1980–1981	North Sea wide-angle SALT	North Sea	Barton (1986)
8.3.2	1981	WISE offshore W Scotland	British Isles	Summers et al. (1982)
8.3.2	1982	CSSP Caledonian Suture	Northern England	Bott et al. (1983)
8.3.2	1982	ICSSP Caledonian Suture	Ireland	Jacob et al. (1985)
8.3.2	1983	"*Meteor* (1964)" expedition M66	Skagerak	Behrens et al. (1986)
8.3.2	1984	MAVIS Midland Valley Scotland	British Isles	Dentith and Hall (1990)
8.3.2	1985	COOLE Caledonian onshore	Ireland	Lowe and Jacob (1989)
8.3.2	1987	BB87 North Sea–Ireland	Ireland	Bean and Jacob (1990)
8.3.3.1	1982	Wildflecken fan profiles	Southern Germany	Zeis et al. (1990)
8.3.3.1	1984	Black Forest wide-angle seismic	Southwest Germany	Gajewski and Prodehl (1987)
8.3.3.1	1984	Black-Zollern-Forest wide-angle seism	Southwest Germany	Gajewski et al. (1987)
8.3.3.2	1985	KTB wide angle seismics	Southeastern Germany	Gebrande et al. (1989)
8.3.4.1	1981	EGT SVEKA wide-angle profile	Central Finland	Luosto et al. (1984)
8.3.4.1	1981–1983	Kola peninsula seismic profiles	Northwest Russia	Azbel et al. (1989)
8.3.4.1	1982	BALTIC wide-angle profile	Southeastern Finland	Luosto and Korhonen (1986)
8.3.4.1	1983	Skagerrak offshore lines	Denmark-Norway	Behrens et al. (1986)
8.3.4.1	1984	Tornquist-Teysseire Zone	Denmark-Sweden	EUGENO-S WG (1988)
8.3.4.1	1985	POLAR wide-angle profile	Finland-Norway	Luosto et al. (1989)
8.3.4.2	1981, 1984	Northern German Basin hydrocarbon survey	Northern Germany	Yoon et al. (2008)
8.3.4.2	1983	EGT N-Appenines crustal profiles	Northern Italy	Biella et al. (1987)
8.3.4.2	1986	EGT central segment	Germany-Italy	Aichroth et al. (1992)
8.3.4.2	1987	Alpine wide-angle profiles	Switzerland	Ye (1991)
8.3.4.3	1983	EGT southern section Corsica-Sardinia	Western Italy	Egger et al. (1988)

(*continued*)

TABLE 2.8. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1980S (*continued*)

Chapter	Year	Project	Location	Reference
8.3.4.3	1985	EGT southern segment Tunisia	Tunisia	Research Group for Lithospheric Structure in Tunisia (1992)
8.3.4.3	1983, 1986	Atlas and Anti Atlas crust	Morocco	Wigger et al. (1992)
8.3.4.4	1980 ff	Northwest corner of Iberia	Spain	Cordoba et al. (1987)
8.3.4.4	1988	Valencia Trough	Spain	Pascal et al. (1992); Torné et al. (1992)
8.3.4.4	1989	Valencia Trough	Spain	Danobeitia et al. (1992)
8.3.4.4	1989	EGT ILIHA long range lines	Spain and Portugal	ILIHA DSS Group (1993)
8.3.5	1983–1985	West Carpathians reflection lines	Czechoslovakia	Tomek et al. (1987)
8.3.5	1986	LT-7 Tornquist-Teisseyre Zone	Northwest Poland	Guterch et al. (1991b)
8.3.5	1987	GB2 near-vertical recording	Northwest Poland	Guterch et al. (1991a)
8.4	1981–1988	Crustal data on PNE lines	USSR	Egorkin et al. (1991)
8.4	1981–1988	PNE athenosphere profiles	USSR	Mechie et al. (1993)
8.4	1981, 1983	Mirnyi kimberlite field in Siberia	USSR	Suvorov et al. (2006)
8.5.2	1980	COCRUST Vancouver Island project	Western Canada	Green et al. (1986)
8.5.2	1981	COCRUST Williston Basin	Central Canada	Hajnal et al. (1984)
8.5.2	1982	COCRUST Bonnechere-Grenville	Southeastern Canada	Mereu et al. (1986)
8.5.2	1984	COCRUST Kapuskasing	South-central Canada	Mereu et al. (1989)
8.5.2	1984	LITHOPROBE Vancouver Island	Western Canada	Green et al. (1990a)
8.5.2	1984–1985	LITHOPROBE LE off Newfoundland	Southeastern Canada	Mariller et al. (1994)
8.5.2	1984–1988	Canadian Arctic ice shelf project	Northern Canada	Forsyth et al. (1990)
8.5.2	1985	LITHOPROBE Vancouver on-offshore	Western Canada	Clowes et al. (1987b)
8.5.2	1985	COCRUST Peace River Arch	Northwest Canada	Stephenson et al. (1989)
8.5.2	1985	LITHOPROBE Cordillera reflection	Western Canada	Cook et al. (1987)
8.5.2	1986	LITHOPROBE GLIMPCE GreatLakes	South-central Canada	Green et al. (1989)
8.5.2	1988	GRAP-88 Ontario–New York	Southeastern Canada	Mariller et al. (1994)
8.5.2	1989	LITHOPROBE off Newfoundland	Southeastern Canada	Van der Velden (2004)
8.5.2	1989–1990	LITHOPROBE SCoRE Cordillera	Western Canada	Clowes et al. (1995)
8.5.3.1	1980–1981	COCORP Adirondack–New England	Northeastern United States	Brown et al. (1983a)
8.5.3.1	1980–1981	James River corridor, Virginia	Eastern United States	Pratt et al. (1987)
8.5.3.1	1981	COCORP Kansas reflection survey	Central United States	Brown et al. (1983b)
8.5.3.1	1981	COCORP Ouachita Arkansas OUC	South-central United States	Nelson et al. (1982)
8.5.3.1	1981	USGS Carolina-Georgia GAC-CHP	Southeastern United States	Behrendt (1986)
8.5.3.1	1981–1985	USGS Northeast California	Western United States	Zucca et al. (1986)
8.5.3.1	1982	COCORP west-central Utah	Western United States	Allmendinger et al. (1986)
8.5.3.1	1982	USGS Central California reflection survey	Western United States	Hamilton (1986)
8.5.3.1	1982–1983	Mono Craters–Long Valley refraction lines	Western United States	Hill et al. (1985)
8.5.3.1	1982–1984	COCORP 40°N Transect	Western United States	Allmendinger et al. (1987)
8.5.3.1	1983	USGS Maine–N Appalachians reflection survey	Northeastern United States	Hamilton (1986)
8.5.3.1	1983–1985	COCORP Georgia-Florida Transect	Southeastern United States	Nelson et al. (1985)
8.5.3.1	1984	COCORP Northwest Cordillera	Northwest United States	Potter et al. (1986)
8.5.3.1	1984	USGS Newark Basin rift tectonics	Eastern United States	Ratcliffe et al. (1986)
8.5.3.1	1984	USGS Alaska pipeline reflect survey	Alaska	Hamilton (1986)
8.5.3.1	1985	COCORP Death Valley	Western United States	de Voogd et al. (1988)
8.5.3.1	1985	USGS Southern California–Arizona reflection survey	Western United States	Hamilton (1986)
8.5.3.1	1985	ADCOH site study ADC	Eastern United States	Coruh et al. (1987)
8.5.3.1	1986	COCORP Arizona PACE line	Western United States	Hauser et al. (1987a)
8.5.3.1	1987	COCORP Montana plains	Northwest United States	Latham et al. (1988)
8.5.3.2	1980–1981	USGS Western Mojave desert	Western United States	Harris et al. (1988)
8.5.3.2	1980–1982	USGS Livermore–Santa Cruz Mountains	Western United States	Williams et al. (1999)
8.5.3.2	1982	USGS Great Valley Californa	Western United States	Walter and Mooney (1987)
8.5.3.2	1982–1983	USGS Morro Bay, California	Western United States	Murphy and Walter (1984)
8.5.3.2	1982–1983	USGS Long Valley Caldera	Western United States	Meador et al. (1983, 1985)
8.5.3.2	1983	USGS Coalinga, California, refraction lines	Western United States	Walter (1990)
8.5.3.2	1984	USGS Columbia Plateau, Oregon	Western United States	Catchings and Mooney (1988a)
8.5.3.2	1984	USGS Newberry Volcano, Oregon	Western United States	Catchings and Mooney (1988a)
8.5.3.2	1986	USGS San Luis Obispo, California	Western United States	Sharpless and Walter (1988)
8.5.3.2	1986	PG&E EDGE Central California margin	Western United States	Howie et al. (1993)
8.5.3.2	1989	Cascade Mountains off-onshore project	Western United States	Trehu and Nakamura (1993)
8.5.3.3	1980–1982	Yucca Mountain, Nevada	Western United States	Hoffman and Mooney (1983)

(*continued*)

TABLE 2.8. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1980S (*continued*)

Chapter	Year	Project	Location	Reference
8.5.3.3	1988	Yucca Mountain, Nevada	Western United States	Brocher et al. (1990)
8.5.3.3	1980–1983	Southern Rio Grande Rift	Western United States	Sinno et al. (1986)
8.5.3.3	1981	CARDEX Valles Caldera, New Mexico	Western United States	Ankeny et al. (1986)
8.5.3.3	1985, 1987	CALCRUST PACE, California–Arizona	Western United States	McCarthy et al. (1991)
8.5.3.3	1986	PASSCAL Basin & Range province, Nevada	Western United States	Whitman and Catchings (1987)
8.5.3.3	1989	PACE Colorado Plateau	Western United States	McCarthy et al. (1994)
8.5.3.4	1983	Canadian part Quebec-Maine reflection survey	Southeastern Canada	Stewart et al. (1986)
8.5.3.4	1984	USGS Maine refraction survey QMT	Eastern United States	Spencer et al. (1989)
8.5.3.4	1985	USGS Maine refraction survey MRP	Eastern United States	Luetgert et al. (1987)
8.5.3.4	1988	Adirondack-Grenville refraction line	Northeastern United States	1990 Luetgert et al. (1990)
8.5.4	1984–195	Southern Alaska	Alaska	Fuis et al. (1991)
8.5.4	1987	Alaska Range–Yukon River	Alaska	Brocher et al. (2004a)
8.5.4	1988	Prince William Sound–Gulf of Alaska	Alaska	Brocher et al. (1991a)
8.5.4	1990	Brooks Range, northern Alaska	Alaska	Fuis et al. (1997)
8.6.1	1981	Northern Red Sea–Egypt	Egypt	Rihm et al. (1991)
8.6.1	1984	Jordan–Dead Sea transform refraction	Jordan	El Isa et al. (1987a)
8.6.1	1984	Jordan–Dead Sea transform reflection	Israel	Rotstein et al. (1987)
8.6.1	1986	Gulf of Suez–Northern Red Sea	Red Sea	Gaulier et al. (1988)
8.6.1	1988	Red Sea–Sudan and Red Sea–Yemen	Red Sea	Egloff et al. (1991)
8.6.2	1985	KRISP85 East African Rift	Kenya	Henry et al. (1990)
8.7.1	1980–1988	Multichannel reflection lines	India	Mahadevan (1994)
8.7.2	1981–1982	Sino-French exploration Tibet	China	Hirn and Sapin (1984)
8.7.2	1981–1982	Tibetan plateau	China	Teng (1987)
8.7.2	1980–1986	Seismic refraction surveys	Eastern China	Li and Mooney (1998)
8.7.2	1982	Yunnan Province, Southwest China	Southwest China	Kan et al. (1986)
8.7.2	1988	Altai Mountains–Altyn Tagh Fault	Northwest China	Wang et al. (2003)
8.7.3	1980	Ito-Matsuzaki Profile, Izu Peninsula	Central Japan	Yoshii et al. (1985)
8.7.3	1981	DSS in and around Nagano prefecture	Central Japan	Ikami et al. (1986)
8.7.3	1982	DSS Nagano and Yanamashi prefectures	Central Japan	Sasatani et al. (1990)
8.7.3	1984	Niikappu-Samani line, Southwest Hokkaido	Northern Japan	Iwasaki et al. (1998)
8.7.3	1985	Haruno-Tsukude profile, Honshu	Central Japan	Matsu'ura et al. (1991)
8.7.3	1988	DSS Kii peninsula	Southwest Japan	Research Group for Explosion Seismology (1992)
8.7.3	1989	Fujihashi–Kamigori, W Honshu	Japan	Research Group for Explosion Seismology (1995)
8.7.3	1990	Kitakami Massif refraction line	Japan	Iwasaki et al. (1994)
8.8.1	1980–1982	Eromanga Basin, Queensland	Australia	Finlayson et al. (1989)
8.8.1	1982–1983	Central Volcanic Region North Island	New Zealand	Stern (1985)
8.8.1	1983	Yilgarn craton projects	Northwest Australia	Drummond (1988)
8.8.1	1983	Central South Island	New Zealand	Smith et al. (1995)
8.8.1	1984	Eromanga–East Coast, Queensland	Australia	Finlayson et al. (1989)
8.8.1	1984	New England batholith traverse	East Australia	Finlayson and Collins (1993)
8.8.1	1984	Hikurangi zone N Island–Pacific	New Zealand	Davey et al. (1986)
8.8.1	1985	AGSO reflection central Australia	Australia	Wright et al. (1990)
8.8.1	1985	Hikurangi zone south of N Island	New Zealand	Davey (1987)
8.8.1	1987–1989	Lachlan orogen	East Australia	Finlayson (2010)
8.8.1	1989	Bowen Basin–New England Orogen	East Australia	Korsch et al. (1992)
8.8.1	1989	Hikurangi zone Southwest of N Island	New Zealand	Davey and Stern (1990)
8.8.2	1982	Whitwatersrand refraction lines	South Africa	Durrheim (1986)
8.8.2	1988	Whitwatersrand 112 km reflection line	South Africa	Durrheim et al. (1991)
8.8.2	1987–1988	Reconnaissance seismic survey	Botswana	Wright and Hall (1990)
8.8.3	1982–1984	Chuquicamata mine profiles Andes	Chile-Bolivia	Wigger (1986)
8.8.3	1987–1989	Mine blasts and ocean shots Andean lines	Chile-Bolivia	Wigger et al. (1994)
8.8.4	1981–1982	McMurdo Sound, Ross Sea	Antarctica	McGinnis et al. (1985)
8.8.4	1984–1985	Bransfield Strait Polish Expedition	Western Antarctica	Janik (1997)
8.8.4	1987–1988	Bransfield Strait Polish Expedition	Western Antarctica	Janik (1997)
8.9.2	1981	Juan de Fuca Ridge	Northeast Pacific	Morton et al. (1987)
8.9.2	1981–1982	Tohuku subduction zone	East off Japan	Suyehiro and Nishizawa (1994)
8.9.2	1979ff	Refraction around ODP hole 504B	Costa Rica rift	Detrick et al. (1994)

(*continued*)

TABLE 2.8. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1980S (*continued*)

Chapter	Year	Project	Location	Reference
8.9.2	1982	Shirshov Institute of Oceanology world cruise	Northern Pacific Ocean	Neprochnov (1989)
8.9.2	1982	Hawaiian–Emperor Seamount chain	Central Pacific	Watts et al. (1985)
8.9.2	1982	MAGMA East Pacific Rise	East Pacific	Orcutt et al. (1984)
8.9.2	1982, 1984	Valu Fa Ridge, Lau Basin	Southwest Pacific	Morton and Sleep (1985)
8.9.2	1983	Ngendei expedition south Pacific	South Pacific	Shearer and Orcutt (1985)
8.9.2	1985	East Pacific Rise 8°50 N to 13°30 N	East Pacific	Detrick et al. (1987)
8.9.2	Mid-1980s	Juan de Fuca Ridge	East Pacific	Rohr et al. (1988)
8.9.2	1985–1989	Australian margins marine deep seismics	Southern and eastern Australia	Finlayson (2010)
8.9.2	1989	Tasmania margin and Southern Ocean	Off western Tasmania	Finlayson (2010)
8.9.2	1988	East Pacific Rise at 9°30	East Pacific	Toomey et al. (1990)
8.9.2	1989	Society Island Hotspot Chain	Pacific Ocean	Grevemeyer et al. (2001b)
8.9.2	1990	Juan de Fuca Ridge	Northeast Pacific	Mcdonald et al. (1994)
8.9.3	1984	Shirshov Institute of Oceanology world cruise	Indian Ocean	Neprochnov (1989)
8.9.3	1985	Agulhas Bank off South Africa	Indian Ocean	Durrheim (1987)
8.9.3	1985	Kerguelen Plateau	Indian Ocean	Ramsay et al. (1986)
8.9.3	1986	Owen Basin off Oman	Indian Ocean	Barton et al. (1990)
8.9.3	1986	Exmouth Plateau	Off Northwest Australia	Mutter et al. (1989)
8.9.3	1986	North Perth Basin	Off Western Australia	Finlayson (2010)
8.9.3	1988	South Perth Basin	Off Western Australia	Finlayson (2010)
8.9.4	1980s	North Atlantic Transect near 23°N	North Atlantic	NAT StudyGroup (1985)
8.9.4	1981	LASE Baltimore Cyn	North American Atlantic margin	LASE StudyGroup (1986)
8.9.4	1982	Kane fracture zone, Mid-Atlantic Ridge	Atlantic	Cormier et al. (1984)
8.9.4	1982	Charlie-Gibbs Fracture Zone	North Atlantic	Whitmarsh and Calvert (1986)
8.9.4	1982	Tydeman Fracture Zone	North Atlantic	Calvert and Potts (1985)
8.9.4	1983	Shirshov Institute of Oceanology world cruise	Southern Atlantic Ocean	Neprochnov (1989)
8.9.4	1983	Alpha Ridge Arctic Ocean	Arctic Ocean	Forsyth et al. (1986)
8.9.4	1983–1984	Southwest Newfoundland transform margin	Eastern Canada	Todd et al. (1988)
8.9.4	1984	"*Meteor* (1964)" expedition M67	Off Northwest Africa	Sarnthein et al. (2008)
8.9.4	1984–1985	USGS Gulf of Maine	Northeastern United States	Hutchinson et al. (1987)
8.9.4	1984–1987	Newfoundland continental margin	Eastern Canada	Keen et al. (1990)
8.9.4	Mid-1980s	Labrador Sea	Northwest Atlantic	Osler and Louden (1992)
8.9.4	1985	WAM Western Approaches Margin	Southwest of Britain	Peddy et al. (1989)
8.9.4	1985	COOLE Caledonian offshore	South and southwest off Ireland	O'Reilly et al. (1991)
8.9.4	1985	Hatton bank volcanic margin	West off Ireland	Morgan and Barton (1990)
8.9.4	1985	Svalbard Polish expedition	W and N Spitsbergen	Czuba et al. (1999)
8.9.4	1985	LASE Carolina Trough	North American Atlantic margin	Trehu et al. (1989b)
8.9.4	1987	Canary basin	West off Canary Islands	Banda et al. (1992)
8.9.4	1987	Goban Spur continental margin	Southwest of Britain	Horsefield et al. (1994)
8.9.4	1987	Aegir rift	East of Iceland	Grevemeyer et al. (1997)
8.9.4	1987–1989	Soviet ice-station North Pole-28 (NP-28)	Arctic Ocean	Langinen et al. (2009)
8.9.4	1988	Madeira-Tore Rise, Josephine seamount	West of northwest Africa	Peirce and Barton (1991)
8.9.4	1988	Lofoten-Voring margin	Off Norway	Mjelde et al. (1992)
8.9.4	1988, 1989	Scoresby Sud on-offshore	Eastern Greenland	Weigel et al. (1995)
8.9.4	1988	LASE Southeastern Georgia embayment	North American Atlantic margin	Oh et al. (1991)
8.9.4	1988, 1989	Jameson Land onshore	Eastern Greenland	Mandler and Jokat (1998)
8.9.4	1988, 1990	RAPIDS Rockall and Porcupine basins	West off Ireland	Shannon et al. (1994)
8.9.4	End-1980s	PROBE survey off equatorial Africa	South Atlantic	Rosendahl et al. (1991)
8.9.4	1989	On-offshore wide-angle seismics	Western Greenland	Clement et al. (1994)
8.9.4	1989	Makarov Basin, Arctic Ocean	Arctic Ocean	Sorokin et al. (1999)
8.9.4	1990	Scoresby Sud on-offshore	Eastern Greenland	Mandler and Jokat (1998)
8.9.4	1990	EDGE Mid-Atlantic MSC experiment	North American Atlantic shelf	Holbrook et al. (1992b))
9.7.1	1987ff	AGSO Australian offshore lines	Australia	Goleby et al. (1994)
9.7.1	1989–1992	AGSO on-offshore program	Australia	Goleby et al. (1994)

In Europe, ECORS profiling, for example, was always accompanied by simultaneous wide-angle operations as were the first long reflection profiles accompanying the search for deep drill sites in southern Germany. Also the Alpine part of the EGT refraction line was covered by the Swiss reflection seismic program. Mooney and Brocher (1987) compiled a global review of coincident seismic reflection/refraction studies of the continental lithosphere up until the mid-1980s. An important result was that the Moho was identical, if observed by refraction–wide-angle observations or by near-vertical incidence reflection profiles. At almost all seismic-reflection profiles of BIRPS, ECORS, and DEKORP, as far as they were recorded over Caledonian and Variscan basement, the Moho was clearly identified as the lowest boundary of the laminated lower crust. The same observation was made on seismic-reflection profiles recorded in the Basin and Range province and other extensional areas of the mobile western United States.

Comprehensive reviews on the seismic velocity structure of the deep continental lower crust which represent the state of the art by the end of the 1980s have been published, e.g., by Holbrook et al. (1992a), including a table of lower-crust velocities and corresponding references typical for different tectonic environments. Mooney and Meissner (1992) investigated the multi-genetic origin of crustal reflectivity by reviewing deep seismic reflection profiles around the world. Other compilations contain summaries of crustal and upper mantle structure based on controlled-source seismology observations, both seismic reflection and refraction, for different continents or large parts of those continents, e.g., by Meissner et al. (1987b) for Europe (Fig. 2.8-05), Pavlenkova (1996) for the territories of the former Soviet Union, Braile et al. (1989) and Mooney and Braile (1989a) for North America (Fig. 2.8-06), or Mechie and Prodehl (1988) for the Afro-Arabian rift. Based on a series of discussions at meetings of experts (Olsen, 1995; Ziegler, 1992a, 1992b, 1992c), different authors compiled reviews for continental rifts around the world.

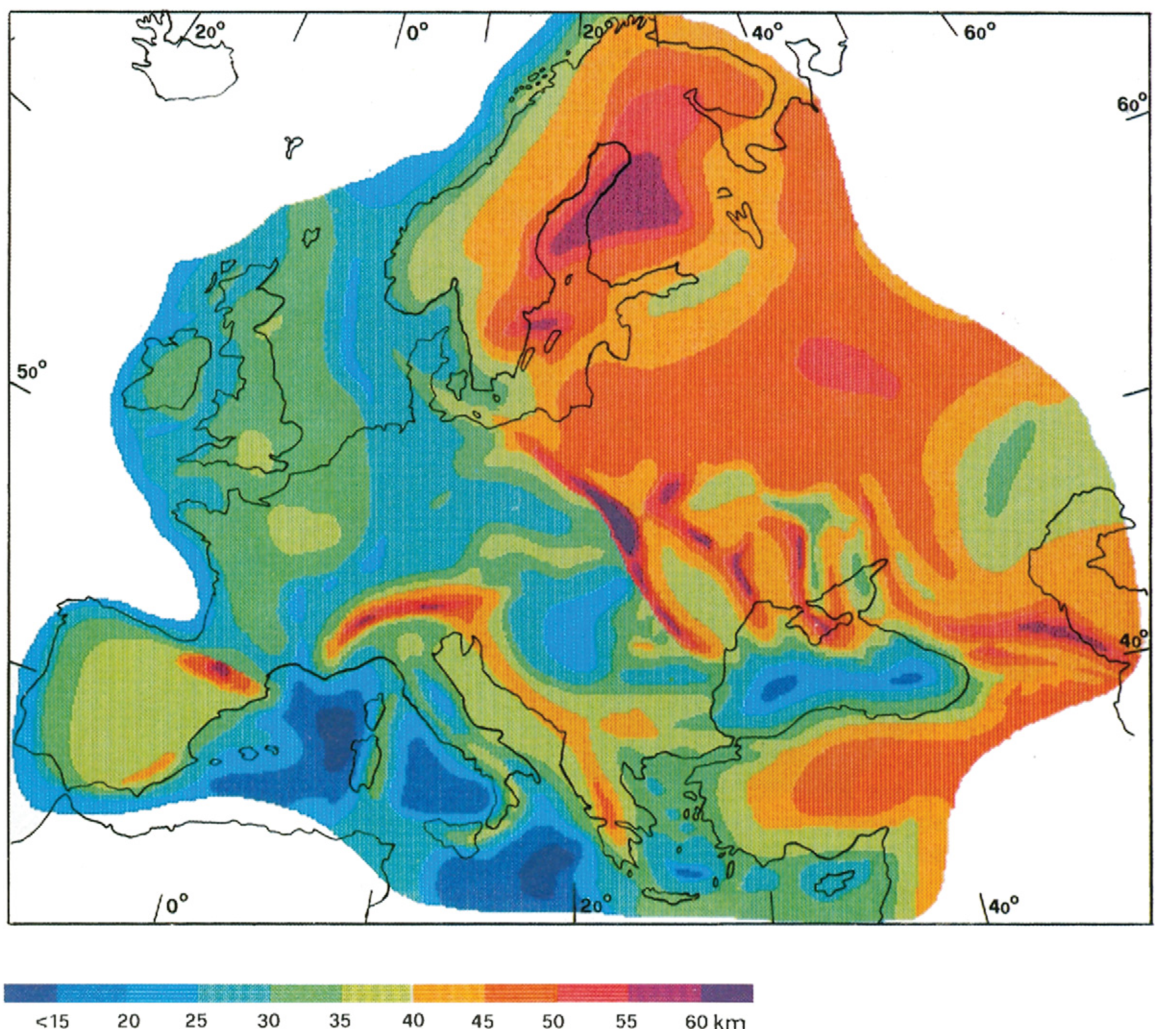

Figure 2.8-05. Contour map of crustal thickness across Europe (from Meissner et al., 1987b, fig. 3). [Annales Geophysicae, 5B, p. 357–364. Reproduced by permission of the author.]

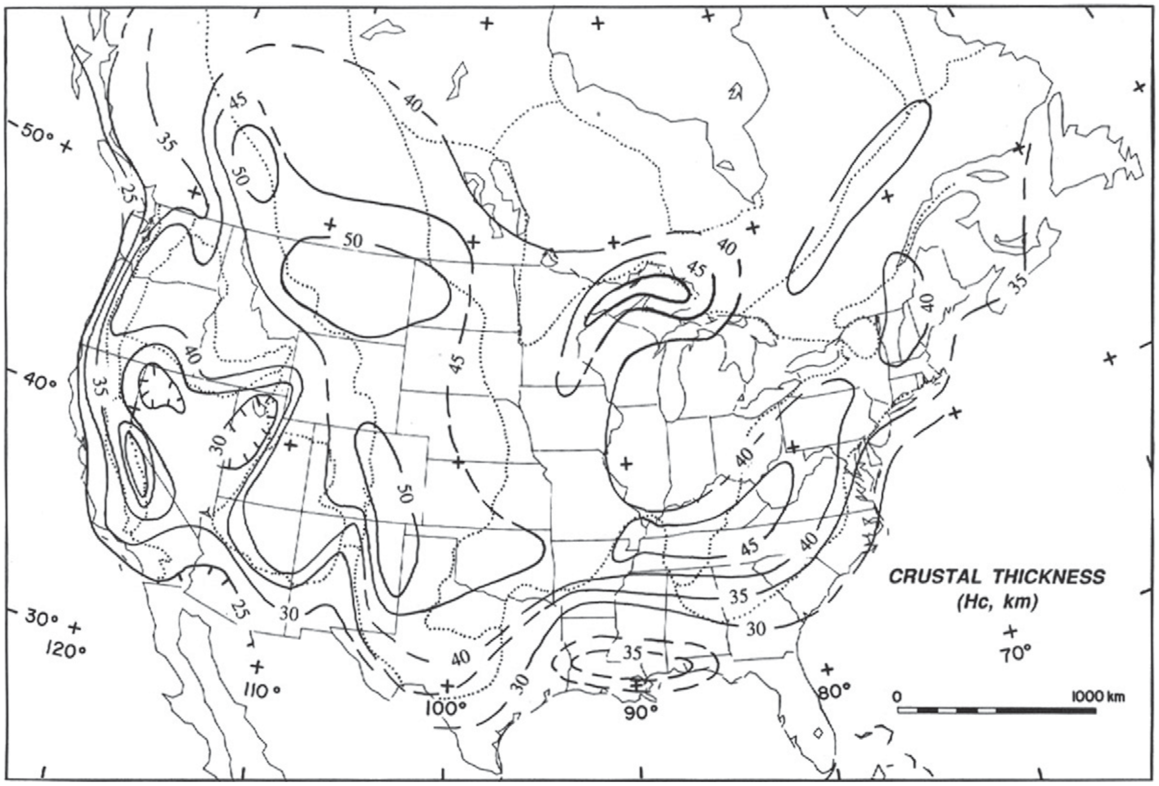

Figure 2.8-06. Contour map of crustal thickness for North America (from Braile et al., 1989, fig. 3). [*In* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 655–680. Reproduced by permission of the Geological Society of America.]

2.9. THE 1990s AND EARLY 2000s (1990–2005)

With advanced technology, seismic projects had become more and more expensive, using multiple energy sources and a large number of sophisticated recording devices. In the early 1990s, the change from analog to digital recording caused a major breakthrough toward modern recording and interpretation techniques. Most projects were neither projects of individual researchers nor of individual research institutions, but became mostly imbedded in large-scale research programs which involved a multitude of cooperating institutions and an interdisciplinary cooperation of scientists from various geoscientific fields. Starting in the 1980s, and continuing in the 1990s, this was reflected in the formulation of large reflection programs on national scales such as COCORP and BIRPS, which were followed by the foundation of IRIS/PASSCAL in the United States and LITHOPROBE in Canada and by international and interdisciplinary geoscientific programs in Europe, dealing with large-scale tectonic topics.

An important prerequisite for the successful worldwide cooperation in seismic projects was the development of new digital equipment, which had started by the end of the 1980s and continued into the 1990s both in North America and in Europe. In particular the North American equipment not only stimulated and enabled new large-scale seismic-refraction/reflection experiments in Canada and in the United States, but it would also enable many large-scale projects in Europe and Africa. The U.S. Geological Survey–Stanford instrumentation SGR led to the powerful RefTek generation and was fundamental for successful joint European–United States projects in Kenya, France, and Spain in the early 1990s. The IRIS/PASSCAL and LITHOPROBE instrument pools were combined for many large-scale projects in North America, and the IRIS/PASSCAL instrument pool was vital for the large-scale projects in eastern Europe and in Ethiopia at the end of the 1990s and beginning of the 2000s. European research groups also supported several seismic projects in North America.

In 1992, supported by the European Science Foundation, EUROPROBE, a lithosphere dynamics program concerned with the origin and evolution of the continents (Gee and Zeyen, 1996; Gee and Stephenson, 2006) was founded in Europe. EUROPROBE's focus was mainly on, but not restricted to, Europe and was particularly driven to emphasize and encourage East-Central-West European collaboration. It was dedicated to enable the realization of major projects, which aimed to investigate the whole lithosphere and which required the close multinational cooperation of geologists, geophysicists, and geochemists.

Particular EUROPROBE projects (Fig. 2.9-01) that involved major controlled-source seismic experiments were the TESZ project, investigating the Trans-European fault zone TTZ in Scandinavia and Poland; the Uralides, with major seismic campaigns in the Urals; Georift, emphasizing the Dniepr-Donets basin; Eurobridge, establishing a seismic crustal traverse from Lithuania to the Ukraine; and PANCARDI, an interdisciplinary geoscientific frame for large-scale investigations in the Carpathian area, in particular focusing on the deep-earthquake region of Vrancea in the Romanian Carpathians.

Other large-scale interdisciplinary projects in Europe were a seismic-reflection traverse through the Eastern Alps (Gebrande et al., 2006), a German priority program focusing on the tectonics of the Central European Variscides (Franke et al., 2000), and VARNET, a major research program studying the Variscan front in Ireland (Landes et al., 2003).

In North America during the LITHOPROBE project (see Fig. 9.4.1-01), a large number of seismic projects systematically investigated crust and uppermost mantle of Canada (e.g., Clowes et al., 1999). The results were published in the context of interdisciplinary summary volumes for the different LITHOPROBE transects (e.g., Ludden, 1994, 1995; Wardle and Hall, 2002a; Hajnal et al., 2005a). Numerous detailed seismic studies were undertaken in the western United States along the coast, of which the projects SHIPS around Seattle (Snelson, 2001), BASIX (Brocher et al., 1991b) around San Francisco, and LARSE (Fuis et al., 1996, 2001b) around Los Angeles investigated the crustal structure in earthquake-prone regions in much detail. A similar project, JTEX, targeted the crustal structure beneath a large

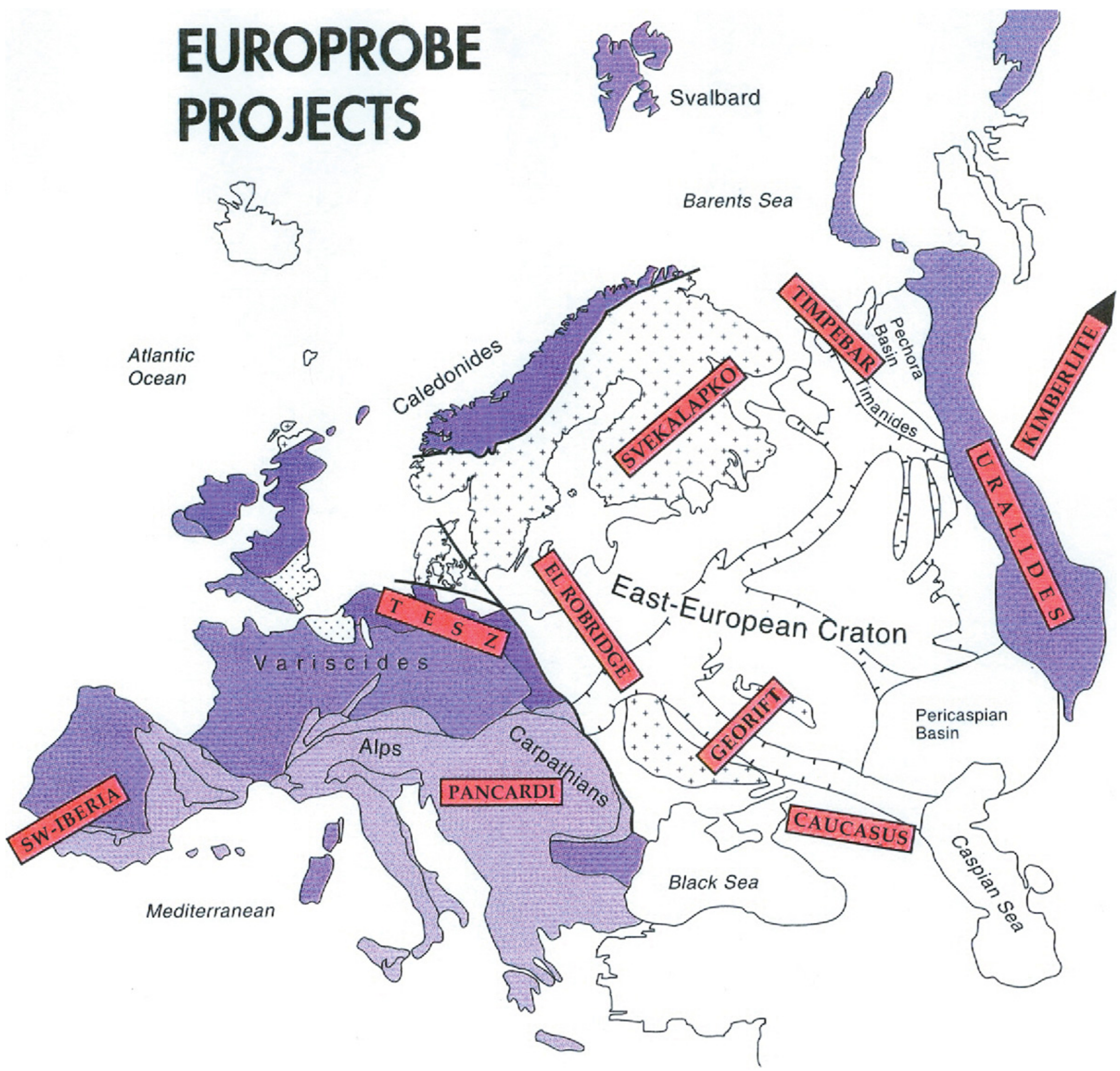

Figure 2.9-01. Map of EUROPROBE projects (from Gee and Zeyen, 1996, p. 12). [EUROPROBE Secretariat, Upssala University, 138 p., Copyright EUROPROBE.]

continental silicic magmatic system in the Jemez Mountains of New Mexico (Baldridge et al., 1997). The "Deep Probe" experiment of 1995 (Snelson et al., 1998; Gorman et al., 2002) followed approximately the 110th meridian and spanned a distance of 3000 km from the southern Northwest Territories to southern New Mexico. It targeted the velocity structure from the base of the crust to depths as great as the mantle transition zone near 400 km depth. Also in 1995, 14 institutions of the United States created the interdisciplinary geoscience project CD-ROM (Continental Dynamics–Rocky Mountain) with the aim to realize a detailed crustal and upper mantle interdisciplinary investigation of the Southern Rocky Mountains from central Wyoming to central New Mexico, following approximately the 101st meridian and involving tectonics, structural geology, regional geophysics, geochemistry, geochronology, xenolith studies, and seismic studies (Karlstrom and Keller, 2005). The seismic component involved seismic reflection and seismic refraction experiments in 1999 as well as teleseismic studies along a 1000-km-long north-south–directed traverse along the southern Rocky Mountains.

Major efforts were undertaken to unravel the details of crustal structure beneath the Afro-Arabian rift system, based on the experiences collected by the earlier expeditions. In 1990 and 1994, two major international campaigns explored the crust and upper mantle under the East African rift of Kenya combining seismic refraction and teleseismic tomography investigations (Prodehl et al., 1994a, 1997a; Fuchs et al., 1997). Figure 2.9-02 summarizes all projects undertaken within the Afro-Arabian Rift System from 1969 until 1995. In 2001, the northern end of the East African Rift system in Ethiopia was the target of a major seismic experiment (Maguire et al., 2003), and the Dead Sea transform saw the beginning of a major international seismic campaign in 2000, covering both sides of the rift in Jordan and Israel (DESERT Group, 2004).

Following the large-scale seismic reflection programs in North America and Europe, the National Geophysical Research Institute at Hyderabad undertook large-scale COCORP-equivalent studies in India. Special targets were the structure and tectonics of the Aravalli-Delhi fold belt in northwestern India (Rajendra Prasat et al., 1998) and in southern India. Other investigations in the Himalayas and southern India used seismological observations (Rai et al., 2006; Krishna et al., 1999).

The seismic investigations of the crust and upper mantle of China with explosion seismology of the 1980s were continued even more intensively with many deep-seismic sounding profiles in mainland China in the 1990s (e.g., Li et al., 2006). It was, however, Tibet in particular that attracted scientists from all over the world. One of the largest cooperative seismic projects was INDEPTH in southern Tibet, involving both near-incident and wide-angle seismic reflection methodology as well as teleseismic tomography, which was accomplished with major U.S. and German participation in several phases, starting in 1992 (e.g., Nelson et al., 1996).

Controlled-source seismology in Japan was activated in the 1990s as part of the Japanese Earthquake Prediction Program.

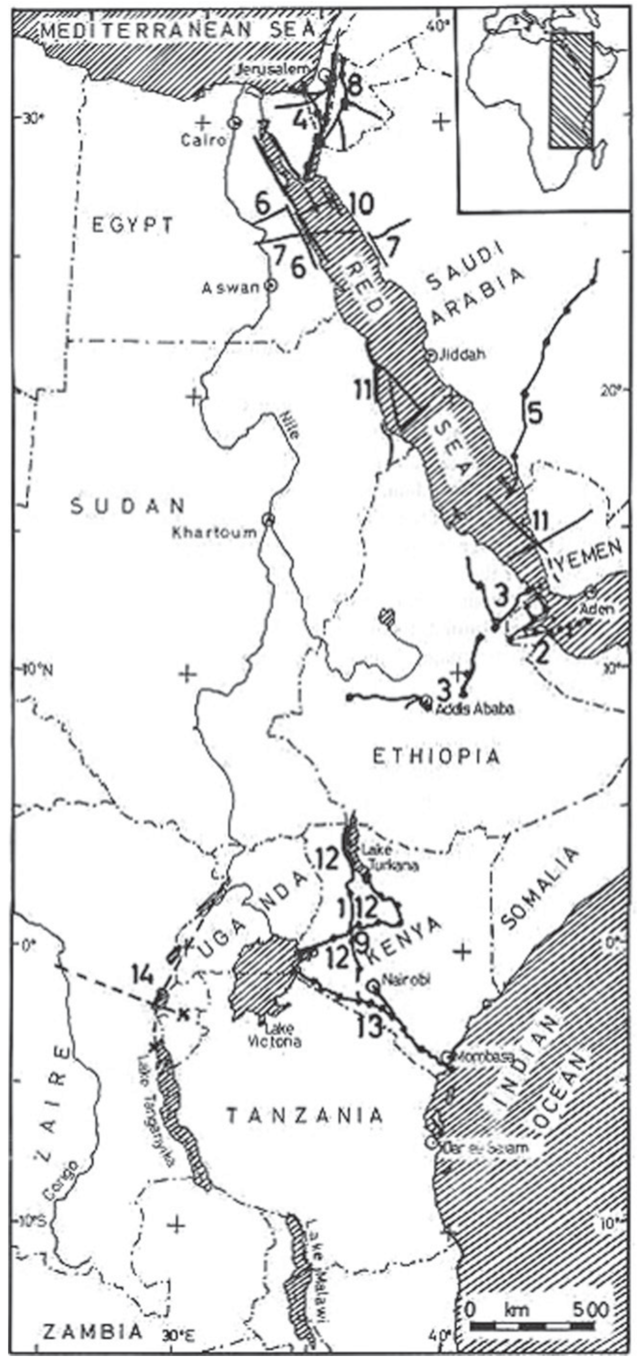

Figure 2.9-02. Map of long-range seismic lines in the Afro-Arabian rift system. Continuous lines: seismic-refraction surveys; full circles mark shotpoints where locations were published. Dashed lines: approximate lines through epicenters of local earthquakes. 1—Kenya rift 1968; 2–Djibouti 1971; 3—Afar depression 1972; 4—Jordan–Dead Sea–Gulf of Aqaba transform system 1977; 5—Arabian Shield 1978; 6—Northern Red Sea 1978; 7—Northern Red Sea 1981; 8—Jordan 1984; 9—Kenya rift 1985; 10—Northern Red Sea; 11—Southern Red Sea; 12—Kenya rift 1990; 13—southern Kenya 1994; 14—Western Rift: local earthquakes recorded at two stations UVI and BTR (marked by crosses) of the IRSAC network near Bukavu, evaluated as seismic profiles UVI-N and BTR-WNW. For references, see Prodehl et al. (1997a, fig. 1). [Tectonophysics, v. 278, p. 1–13. Copyright Elsevier.]

Following the destructive Kobe earthquake of 17 January 1995, seismic refraction (Research Group on Underground Structure in the Kobe-Hanshin Area, 1997; Research Group for Explosion Seismology, 1997; Ohmura et al., 2001) and reflection (Sato et al., 1998) measurements were carried out in the surroundings of Kobe. Other experiments in the first half of the 1990s in Japan focused on the investigation on the deeper crustal structure including lower crust and Moho beneath the SW and NE Japan arcs (e.g., Iwasaki et al., 1994, 1998). In 1994, for the first time in Japan, a seismic reflection survey for deep structural studies was undertaken through the Hidaka Collision zone, Hokkaido (Arita et al., 1998). The subsequent reflection surveys in 1996–1997 provided a clear image of a delamination structure and a reflective lower crust in the collision zone (Tsumura et al., 1999; Ito, 2000, 2002). Since then, seismic surveys using both of reflection and refraction methods became more common in Japan and detailed crustal sections were presented for NE Japan and Hokkaido (e.g., Iwasaki et al., 2001a, 2004; Sato et al. 2002).

Since 1985, the Australian Geological Survey Organisation (AGSO) ran a large program of deep seismic reflection surveys offshore and onshore Australia (Drummond et al., 1998; Finlayson et al., 1996, 1998; Finlayson, 2010, Appendix 2-2; Glen et al., 2002; Goleby et al., 2002; Korsch et al., 1992, 1997, 2002; Petkovic et al., 2000). Several reviews (e.g., Collins et al., 2003; Finlayson, 2010; Goleby et al., 1994) have summarized the results of crust and upper-mantle studies for Australia. Collins et al. (2003) published a crustal thickness map based primarily on the results of controlled-source seismology investigations. In general, within Archean regions of western Australia, the Moho appeared to be relatively shallow with a large velocity contrast, while the Moho is significantly deeper under the Proterozoic North Australian platform, under central Australia and under Phanerozoic southeastern Australia.

To understand the processes involved in continental collision, New Zealand, being deformed by the oblique collision of several plates, was the goal of a joint U.S.–New Zealand geophysical project SIGHT (South Island Geophysical Transect), undertaken in 1995 and 1996. The project involved both active source and passive seismology. The experiment had two main components. The first was a wide-angle reflection-refraction experiment along two land transects across the central South Island. The second experiment consisted of three offshore-onshore transects, two along the two land profiles of the first phase and a third along southeastern South Island. This third transect was a tie line across the eastern part of the two main transects (Davey et al., 1998). Another project in 2001 and 2002 investigated the Central Volcanic Region or Taupo Volcanic Zone (TVZ) occupying the northern half of the North Island of New Zealand (Harrison and White, 2006).

In South America, several seismic profiling projects investigated the area of the deep drilling project in the Chicxulub impact crater at the coast of the Yucatan peninsula, Mexico (e.g., Snyder et al., 1999; Morgan et al., 2005), northern Venezuela (Schmitz et al., 2002, 2005), and central Brazil (Berrocal et al., 2004).

The majority of seismic investigations in South America, however, concentrated on the Andean region of Chile and the adjacent Pacific Ocean (Fig. 2.9-03). For example, a Collaborative Research Center 267 (CRC 267) program "Deformation Processes in the Andes" at the Free University of Berlin, the GeoScience Center of Potsdam, and the University of Potsdam (Germany) was funded by the German Research Society for 15 years (Giese et al., 1999).

The new investigations enabled extended seismic research, but also involved other geoscientific disciplines available at the three research institutions and included strong support by various South American research facilities. In the years 1994–1996, three major seismic projects—PISCO 94, CINCA 95, and ANCORP 96—were conducted in northern Chile and adjacent parts of Bolivia and Argentina (Fig. 2.9-03, northern box; see also Fig. 9.7.3-10). Besides northern Chile, southern Chile became the target of the same research groups, who had cooperated in 1995 in the CINCA project. Also in 1995, within the multidisciplinary CONDOR (Chilean Offshore Natural Disaster and Ocean Environmental Research) project, a marine operation investigated the Valparaiso Basin offshore from Valparaiso, central Chile, along two marine-seismic reflection and refraction profiles north and south of the latitude 33°S (Flueh et al., 1998a). In 2000, the Collaborative Research Center CRC 267 at Berlin and Potsdam, Germany, started a detailed research project in southern Chile (Fig. 2.9-03, southern box; see also Fig. 9.7.3-24). The first approach was the project ISSA 2000 (Sick et al., 2006) and consisted of a temporary seismological network and a seismic-refraction profile. This project was followed by the project SPOC in 2001 (Krawczyk et al., 2006), which involved a shipborne geophysical experiment and two predominantly land-based onshore-offshore experiments. All seismic arrays also recorded teleseismic, regional, and local events. Furthermore broadband stations were deployed along some of the lines.

During the 1990s, digital equipment for marine seismic research also became available, with both digital streamers for details of sedimentary structure beneath the ocean bottom as well as a new generation of ocean-bottom seismometers, which were built in large numbers. Underwater explosions as energy sources had been banned almost completely; instead powerful airgun arrays became available, providing sufficient energy to be recorded over hundreds of kilometers.

Seismic research projects in the 1990s and ongoing in the 2000s were largely devoted to the investigation of details of the mid-ocean rises, such as the East Pacific Rise. Here, for example, projects around the Galapagos hot spot and the Cocos-Nazca Spreading Center (e.g., Sallares et al., 2003) and the Garrett Fracture Zone (Grevemeyer et al., 1998) were undertaken. A large number of Japanese marine surveys, some of which also had land components, targeted the trench system in the Philippine Sea and northwestern Pacific Ocean around Japan. In particular, the Nankei Trough and the Japan trench south and east of Honshu was intensively investigated (e.g., Kodaira et al., 2000; Miura et al., 2003, 2005; Takahashi et al., 2004; Tsuru et al., 2002).

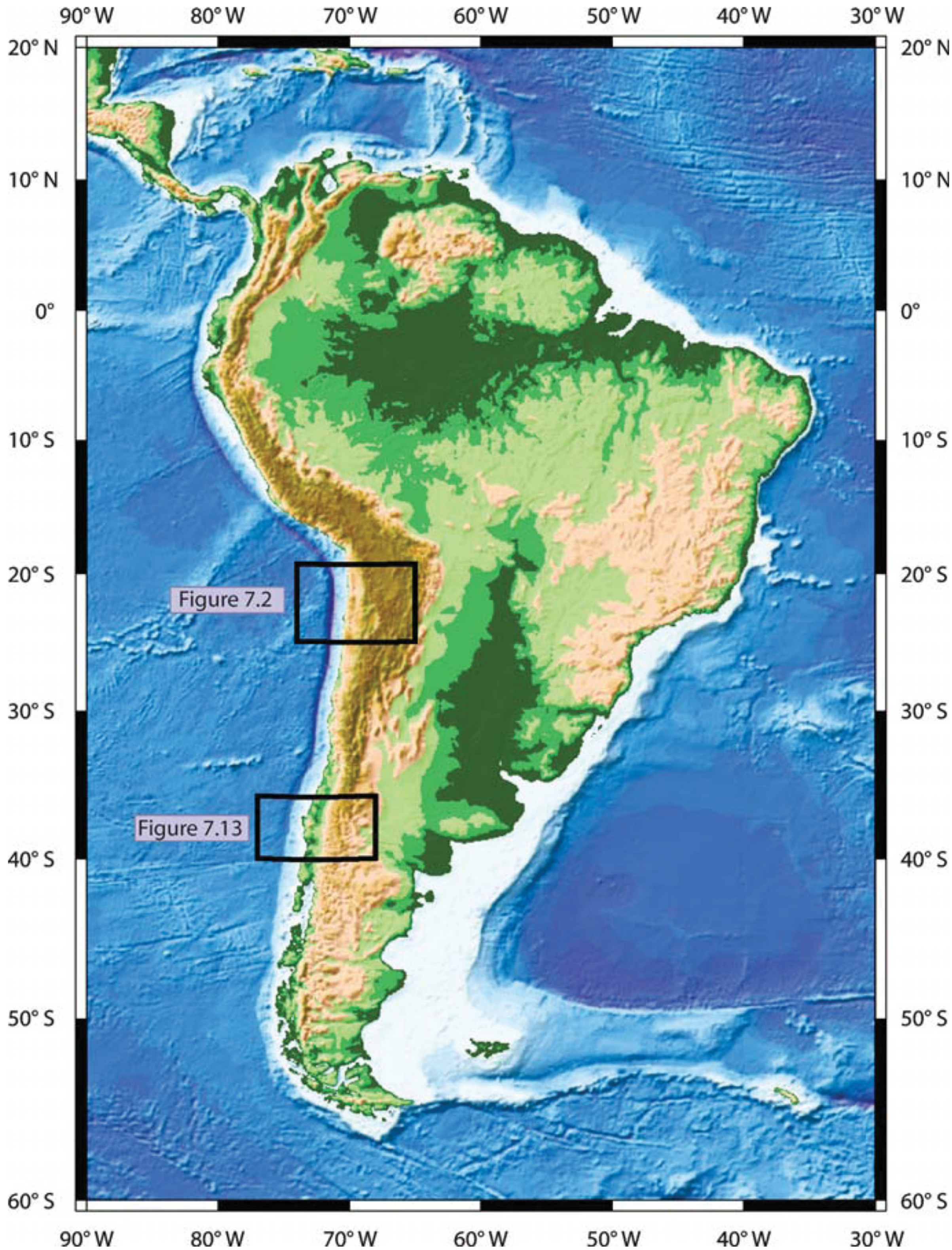

Figure 2.9-03. Topographic map of South America showing the seismic investigation areas in Chile (from Sick et al., 2006, fig. 7-1). Northern box labeled "Figure 7.2" indicates the location of the research projects PISCO94 CINCA95, ANCORP96, and PRECORP; the southern box labeled "Figure 7.13" indicates the location of the research projects ISSA 2000 and SPOC 2001. [Oncken et al., 2006, The Andes: Berlin-Heidelberg-New York, Springer, p. 147–169. Reproduced with kind permission of Springer Science+Business Media.]

A large number of seismic reflection surveys studied the margins of Australia (Finlayson, 2010; Appendix 2-2). In the Indian Ocean the Ninetyeast Ridge was investigated (Grevemeyer et al., 2001a). In the Atlantic the Mid-Atlantic Ridge (e.g., Hooft et al., 2000), but also the continent-ocean transitions were major targets. In particular in the northern Atlantic Ocean projects targeted the microcontinents and intervening basins off Ireland (e.g., Mackenzie et al., 2002), the Norwegian margin (e.g., Raum et al., 2002), the Faeroe–Iceland Ridge (e.g., Smallwood et al., 1999), the northwestern Barents Sea southeast of Spitsbergen (Breivik et al., 2002) and eastern Greenland (e.g., Korenaga et al., 2000, Schmidt-Aursch and Jokat, 2005). The Arctic-2000 transect in the Arctic Ocean between 164°W and 165°E (Lebedeva-Ivanova et al., 2006) and the investigation of the North American margin off Canada (e.g., Funck et al., 2003) were other large marine projects.

In this overview of projects conducted during the various decades, only a limited selection of major research projects could be mentioned. For the 1990s, a summary of all projects mentioned in Chapter 9 is presented in Table 2.9.

Beginning in the 1990s, large-scale teleseismic tomography projects (so-called passive studies, i.e., long-term recording of earthquakes) were carried out in association with large-scale seismic refraction programs (so-called active source studies, i.e., recording controlled sources, such as quarry blasts, borehole and underwater explosions, vibrators, or airguns), thus extending crustal and uppermost mantle research to greater depth ranges. Examples, to name a few, are the KRISP and EAGLE investigations of the East African Rift System in Kenya (Prodehl et al., 1994a; Fuchs et al., 1997) and Ethiopia (Maguire et al., 2003); the onshore-offshore investigations of the Andean region in South America (e.g., ANCORP Working Group, 2003; Flueh et al., 1998a; Giese et al., 1999; Krawczyk et al., 2003, 2006; Rietbrock et al., 2005); the INDEPTH expeditions to Tibet (e.g., Brown et al., 1996; Nelson et al., 1996; Zhao et al., 1993, 1997, 2001); the SKIPPY experiments across Australia (Van der Hilst et al., 1994, 1998; Finlayson, Appendix 2-2); and the CD-ROM project in the Southern Rocky Mountains (Karlstrom and Keller, 2005). The interpretation of these data required special inversion methods used originally in passive experiments, but which in the course of time proved to be practical also for controlled-source seismology data. In particular, the method for studies of crust and upper mantle with P-wave receiver functions, which was being developed since the early 1980s, and later S-wave receiver function studies in the late 1990s, proved to be a very efficient and relatively cheap interpretation tool of the large-scale teleseismic data.

An overview of interpretation methods used in the 1990s to interpret combined active and passive studies was given at one of the Commission on Controlled Source Seismology workshop meetings, held in Dublin in 1999 (Jacob et al., 2000). Introduced in the 1970s (Červený et al., 1977), the ray-tracing method has remained an almost universal method for data interpretation. The most commonly used programs include ray-theoretical and Gaussian-beam synthetic seismograms (Červený, 1985). Based on finite-difference methods for calculating the full wavefield in horizontally inhomogeneous media, it became possible to make calculations for refraction/wide-angle reflection data on a crustal/lithosphere scale over several hundreds of kilometers and at realistic frequencies. Other groups also wrote ray synthetic seismogram routines, e.g., McMechan and Mooney (1980) in the United States or Spence et al. (1984) in Canada. Ray-tracing using a finite-difference approximation of the eikonal equation was improved in the 1990s and extended in a way that reflected arrivals and second arrival refractions from prograde traveltime branches could be calculated (Hole and Zelt, 1995). In addition, commonly used methods in the processing of near-vertical incidence seismic reflection data, such as normal moveout correction and migration, were applied to refraction/wide-angle reflection data (e.g., Lafond and Levander, 1995).

In the 1990s, theory and associated computer programs on traveltime tomography developed by Colin Zelt and others became popular and evolved to a method widely applied as a first approach to model large amounts of data as well as a last check of the validity of a model (Zelt and Smith, 1992; Zelt, 1998, 1999). Nowadays, there is hardly a publication on crustal and upper mantle interpretation which does not first apply a tomographic approach to the seismic data, before refined raytracing modeling is applied (for example, interpretations of the Polonaise and Celebration 2000 data, see, e.g., Guterch et al., 2003a, 2003b).

2.10. OUTLOOK

Textbooks on seismic theory, published in large numbers over the decades, have accompanied and guided the development of interpretation methods to deal with the proper interpretation of active source seismic data obtained on land and at sea (e.g., Nettleton, 1940; Bullen, 1947; Worzel and Ewing, 1947; Grant and West, 1965; Musgrave, 1967; Maxwell, 1970; Kosminskaya, 1971; Officer, 1974; Červený et al., 1977; Kennett, 1983; Bullen and Bolt, 1985; Yılmaz, 1987; Lay and Wallace, 1995; Aki and Richards, 1980, 2002; Jones, 1999; Kennett, 2001; Chapman, 2004; Borcherdt, 2009). There are in addition numerous articles that address various aspects concerning the theory for interpretations of controlled-source seismology data (e.g., Steinhart et al., 1961c; Ewing, 1963a; Ludwig et al., 1970; Fuchs and Mueller, 1971; Bessonova et al., 1974; Braile and Smith; 1975; Giese, 1976; McMechan and Mooney, 1980; Červený and Horn, 1980; Spence et al., 1984; Červený, 1979, 1985; Zelt and Smith, 1992; Hole, 1992; Hole and Zelt, 1995; Zelt, 1999). Similarly, compilations of interpretation methods commonly used were also summarized from time to time (e.g., James and Steinhart, 1966; Mooney, 1989; Braile et al., 1995). Levander et al. (2007) provided a convenient review of theory and application of controlled-source seismic data.

The large number of digital recording devices available by the year 2000, as well as the ability to record continuously over long time periods, has opened a new dimension in crustal investigations.

TABLE 2.9. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1990s

Chapter	Year	Project	Location	Reference
9.2.1	1996	VARNET96 Variscan crust	SW Ireland	Landes et al. (2003)
9.2.1	1999	LEGS Leinster Granite Seismics	SE Ireland	Hodgson et al. (2000)
9.2.2	1990	DEKORP 3/MVE	Central eastern Germany	DEKORP Research Group (1994)
9.2.2	1990–1991	Rhinegraben D-90/DJ-91	SW Germany	Mayer et al. (1997)
9.2.2	1991–1992	French Massif Central	South-central France	Zeyen et al. (1997)
9.2.2	1994	Rhinegraben RU-94	SW Germany	Mayer et al. (1997)
9.2.2	1995	GRANU95 Saxon Granulite Mountain	Central eastern Germany	Enderle et al. (1998)
9.2.2	1995	DEKORP 95 Saxon Granulite Mountain	Eastern Germany	Krawczyk et al. (2000)
9.2.2	1996	DEKORP-BASIN	Northern Germany	Krawczyk et al. (1999)
9.2.2	1996	BASIN'96 Bornholm	Baltic Sea	Bleibinhaus et al. (1999)
9.2.2	1998–2001	TRANSALP Eastern Alps	Germany-Italy	Lueschen et al. (2004)
9.2.3	1990	ESCI-Catalan–Mallorca	NE Spain	Gallart et al. (1994)
9.2.3	1990	CROP 03 southern Apennines	Southern Italy	Scrocca et al. (2003)
9.2.3	1990	Southern Calabria Hercynian crust	Southern Italy	Lueschen et al. (1992)
9.2.3	1991	CROP MARE 1	NW, SW and S off Italy	Scrocca et al. (2003)
9.2.3	1991, 1993	ESCIN Northern Iberian Pensinsula	Northern Spain/Bay Biscay	Alvarez-Marron (1996)
9.2.3	1992	Cantabrian Mountains	Northern Spain	Fernandez-Viejo (2000)
9.2.3	1992	STREAMERS Ionian Sea	Italy-Greece	Hirn et al. (1996)
9.2.3	1992–1993	CROP 04 northern Apennines	Central Italy	Scrocca et al. (2003)
9.2.3	1993–1994	CROP MARE 2	SW and S and E off Italy	Scrocca et al. (2003)
9.2.3	1995	CROP 18 northern Apennines	Central Italy	Scrocca et al. (2003)
9.2.3	1996–1999	CROP 11 central Apennines	Central Italy	Scrocca et al. (2003)
9.2.3	1998–1999	CROP 1A Transalp	Northern Italy	Scrocca et al. (2003)
9.2.4	1992	Pannonian Geotraverse	Hungary	Hajnal et al. (1996)
9.2.3	1993	IAM Iberian Atlantic Margins	Iberia-Atlantic	Banda et al. (1995)
9.2.3	1995	LISA Ligurian Sea	Western Mediterranean	Nercessian et al. (2001)
9.2.3	1993	ESCI-Betics reflection lines	Southern Spain	Carbonell et al. (1998a)
9.2.3	1997	SEISGRECE Ionian islands	W Greece	Clement et al. (2000)
9.2.4	1997	POLONAISE Polish lithosphere	Poland	Guterch et al. (1999)
9.2.4	1999	VRANCEA 1999 SE Carpathians	Romania	Hauser et al. (2001)
9.2.4	2000	CELEBRATION E and SE Europe	Poland-Hungary	Guterch et al. (2003b)
9.2.4	2001	VRANCEA 2001 SE Carpathians	Romania	Hauser et al. (2007a)
9.2.5	1992	BIRPS reflection/refraction project	North Sea	Singh et al. (1998a)
9.2.5	1993	MONA LISA	North Sea	MONA LISA WG (1997)
9.2.5	1995	COAST Profile Baltic Sea	Sweden	Lund et al. (2001)
9.3	1991	GRANIT anisotropy ASTRA	Russia	Lueschen (1992)
9.3	1991	GRANIT Middle Urals	Russia	Juhlin et al. (1996)
9.3	1992	Kola borehole seismics	NW Russia	Ganchin et al. (1998)
9.3	1993–2003	ESRU Middle Urals	Russia	Kashubin et al. (2006)
9.3	1994–1996	EUROBRIDGE'95 and '96	Lithuania-Ukraine	EUROBRIDGE WG (1999)
9.3	1995	Kola borehole–Franz-Josef land	NW Russia	Sakoulina et al. (2000)
9.3	1995	URSEIS'95 reflection seismics Urals	Russia	Knapp et al. (1998)
9.3	1995	URSEIS'95 refraction seismics Urals	Russia	Carbonell et al. (2000b)
9.3	1995–2001	Barents Sea–Novaya Zemlya-	Russia	Roslov et al. (2009)
9.3	1997	EUROBRIDGE'97	Ukraine	Thybo et al. (2003)
9.3	1997–00	Kola borehole CMP lines to N and W	NW Russia	Berzin et al. (2002)
9.3	1999	DOBRE Donbas Foldbelt	Ukraine-Russia	DOBRE WG (2003)
9.3	2000–02	Mezen Basin–Timan Range	NW Russia	Kostyuchenko et al. (2006)
9.4.1.1	1991	LITHOPROBE LE91 on-offshore	SE Canada	Mariller et al. (1994)
9.4.1.2	1991, 1996	LITHOPROBE ESCOOT	SE Canada	Wardle and Hall (2002)
9.4.1.3	1991–1992	Abitibi-Grenville Transect	Canada	Clowes et al. (1992)
9.4.1.4	1996	Western Superior Transect	Canada	Musacchio et al. (2004)
9.4.1.5	1991–1994	THOT Trans-Hudson Orogen Transect	Canada	Hajnal et al. (2005b)
9.4.1.5	1993	THORE Trans-Hudson Long Refraction	Canada	Nemeth et al. (2005)
9.4.1.6	1992	CAT92 3D seismic reflection experiment	W Canada	Kanasewich et al. (1995)
9.4.1.6	1994, 1995	PRAISE94/SALT95/VAULT	W Canada	Mandler and Clowes (1998)
9.4.1.6	1995	SAREX/Deep Probe	W Canada	Clowes et al. (2002)
9.4.1.7	1994	ACCRETE marine shots	W Canada	Hammer et al. (2000)
9.4.1.7	1997	SNORCLE transect refraction	W Canada	Clowes et al. (2005)
9.4.2.1	1990	Brooks Range, Northern Alaska	N Alaska	Fuis et al. (1997)
9.4.2.1	1994	EDGE Prince William Sound	Southern Alaska	Ye et al. (1997)
9.4.2.1	1994	Aleutian volcanic arc	Southern Alaska	Fliedner and Klemperer (1999)
9.4.2.1	1994	Continental shelf	Alaska-Siberia	Brocher et al. (1995a)
9.4.2.2	1991	Pacific NW Experiment	Washington, USA	Trehu et al. (1993)
9.4.2.2	1991, 1995	Western Washington on-offshore	Washington, USA	Parsons et al. (1999)
9.4.2.2	1994	Cape Blanco, southern Oregon	Oregon, USA	Brocher et al. (1995b)
9.4.2.2	1996	Oregon continental margin	Oregon, USA	Flueh et al. (1997)
9.4.2.2	1998	Wet SHIPS, Puget Sound	Washington, USA	Brocher et al. (1999)
9.4.2.2	1999	Dry SHIPS, Seattle basin	Washington, USA	Brocher et al. (2000)
9.4.2.2	2000	Kingdome SHIPS	Washington, USA	Snelson (2001)

(*continued*)

TABLE 2.9. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1990s (*continued*)

Chapter	Year	Project	Location	Reference
9.4.2.3.1	1993–1994	Mendocino Triple Junction	California, USA	Godfrey et al. (1998)
9.4.2.3.2	1990	Loma Prieta refraction line	California, USA	Brocher et al. (1992)
9.4.2.3.2	1991	BASIX San Francisco Bay Area	California, USA	Holbrook et al. (1996)
9.4.2.3.2	1991, 1993	USGS refraction San Francisco Bay area	California, USA	Kohler and Catchings (1994)
9.4.2.3.2	1995	San Francisco Bay inline and fan lines	California, USA	Parsons (1998)
9.4.2.3.3	1995	San Andreas fault project	California, USA	Thurber et al. (1996)
9.4.2.3.4	1994	LARSE I Los Angeles area	California, USA	Fuis et al. (1996)
9.4.2.3.4	1999	LARSE II Los Angeles area	California, USA	Fuis et al. (2001)
9.4.2.4	1992–1993	Ruby Mountains seismic surveys	Nevada, USA	Satarugsa and Johnson (1998)
9.4.2.4	1993	South Sierra Nevada	California, USA	Ruppert et al. (1998)
9.4.2.4	1993	Delta Force experiment, Basin and Range	California-Nevada-Arizona, USA	Hicks (2001)
9.4.2.4	1994	Yucca Mountain project	Nevada, USA	Brocher et al. (1996)
9.4.2.5	1993, 1995	JTEX Valles Caldera	New Mexico, USA	Baldridge et al. (1997)
9.4.2.5	1995	Deep Probe 110°W long range	Canada–New Mexico	Snelson et al. (1997)
9.4.2.5	1999	CD-ROM Southern Rocky Mountains	Wyoming–New Mexico	Karlstrom and Keller (2005)
9.4.2.6	1991	Atlantic coastal plain profile	South Carolina, USA	Luetgert et al. (1994)
9.4.2.6	1996–1997	E Tennessee Seismic Zone	Eastern Tennessee, USA	Hawman et al. (2001)
9.5.1	1990	KRISP90 Kenya Rift seismics	Kenya	Prodehl et al. (1994a)
9.5.1	1994	KRISP94 southern Kenya Rift	Kenya	Fuchs et al. (1997)
9.5.3	2000	Jordan–Dead Sea Transform	Israel-Jordan	DESERT Group (2004)
9.6.1	1993	Southern India aftershock lines	India	Krishna et al. (1999)
9.6.1	1996	Nagaur-Kunjer deep reflection project	India	Rajendra Prasat (1998)
9.6.1	1998	Active source Merapi	Java, Indonesia	Wegler and Lühr (2001)
9.6.2	1992	INDEPTH I Tibet	China	Zhao et al. (1993)
9.6.2	1994–1995	INDEPTH II Tibet	China	Nelson et al. (1996)
9.6.2	1994, 1997	Dabie Shan Orogen	China	Wang et al. (2000)
9.6.2	1998	INDEPTH III Tibet	China	Zhao et al. (2001)
9.6.2	1999*	Sino-French network NE Tibet	China	Galve et al. (2002)
9.6.2	2000*	Altyn Tagh Range	China	Zhao et al. (2006)
9.6.2	2000*	1000 km NE-Tibet to Ordos basin	China	Liu et al. (2006)
9.6.3	1991	180 km line central Honshu	Japan	Research Group for Explosion Seismology (1994)
9.6.3	1992	Central Hokkaido	Japan	Iwasaki et al. (1998)
9.6.3	1993	Deep seismic sounding in Kanto and Tohoku districts	Japan	Research Group for Explosion Seismology (1996)
9.6.3	1994–1997	Hokkaido deep reflection survey	Japan	Arita et al. (1998)
9.6.3	1995	Kobe eq region profiles	Japan	Research Group for Explosion Seismology (1997)
9.6.3	1997	N Honshu on-offshore	Japan	Research Group for Explosion Seismology (1997)
9.6.3	1998	Backbone range in northern Honshu	Japan	Research Group for Explosion Seismology (2008)
9.6.3	1998–1999	Hokkaido reflection lines	Japan	Iwasaki et al. (2004)
9.6.3	1999–2000	Hokkaido refraction lines	Japan	Iwasaki et al. (2004)
9.6.3	2000	On-offshore Kuril Arc, Hokkaido	Japan	Nakanishi et al. (2009)
9.6.3	2000	NE-Hokkaido coast	Japan	Taira et al. (2002)
9.7.1.1	1987ff	AGSO Australian offshore lines	Australia	Goleby et al. (1994)
9.7.1.1	1989–1992	AGSO on-offshore program	Australia	Goleby et al. (1994)
9.7.1.1	1991	Bowen B–New England Orogen	Eastern Australia	Korsch et al. (1997)
9.7.1.1	1991	Kalgoorlie traverse EGF01	Western Australia	Drummond et al. (2000a)
9.7.1.1	1992	Otway basin onshore lines	Southern Australia	Finlayson et al. (1996)
9.7.1.1	1993	550 km reflection line Musgrave block	Central Australia	Korsch et al. (1998)
9.7.1.1	1994	Mount Isa inlier line	NE Australia	Drummond et al. (1998)
9.7.1.1	1994–1995	Otway basin offshore lines	Southern Australia	Finlayson et al. (1998)
9.7.1.1	1995	Tasmania offshore refl lnes	Southern Australia	Drummond et al. (2000b)
9.7.1.1	1996–1999	Broken Hill reflection lines	Eastern Australia	Finlayson (2010)
9.7.1.1	1996, 1998	OBS-Transects off N Australia	N Australia	Petkovic et al. (2000)
9.7.1.1	1997, 1999	Lachlan Fold Belt reflection lines	Eastern Australia	Finlayson (2010)
9.7.1.1	1997, 1999	Goldfield Province	W Australia	Goleby et al. (2002)
9.7.1.1	2001	AGSNY Goldfield Province	Western Australia	Goleby et al. (2004)
9.7.1.2	1990	Bay of Plenty, N-Island marine	New Zealand	Davey and Lodolo (1995)
9.7.1.2	1994	MOOSE, S-Island marine	New Zealand	Henrys et al. (1995)
9.7.1.2	1994	Central South Island land survey	New Zealand	Kleffman et al. (1998)
9.7.1.2	1994	Stewart Island southern S Island	New Zealand	Davey (2005)
9.7.1.2	1995–1996	SIGHT Southern Alps	Southern New Zealand	Davey et al. (1998)
9.7.1.2	1996	Stewart Island–Puysegur Bank	Southern New Zealand	Melhuish et al. (1999)
9.7.2	1995	MAMBA Continental margin Namibia	Namibia	Bauer et al. (2000)
9.7.2	1999	ORYX Erongo Mountains	Namibia	www.gfz-potsdam.de/GIPP
9.7.3.1	1995	TICOSECT Nicoya Peninsula	Off Costa Rica	Christeson et al. (1999)

(*continued*)

TABLE 2.9. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN THE 1990s (*continued*)

Chapter	Year	Project	Location	Reference
9.7.3.1	1996	COTCOR Nicoya Peninsula	Costa Rica	Sallares et al. (1999)
9.7.3.1	1996	Chicxulub BIRPS reflection lines	Mexico	Snyder et al. (1999)
9.7.3.2	1997	Toncantins Province	Brazil	Berrocal et al. (2004)
9.7.3.2	1998	ECOGUAY Guayana Shield	Venezuela	Schmitz et al. (1999)
9.7.3.2	2001	ECCO Oriental basin	Venezuela	Schmitz et al. (2005)
9.7.3.3	1994	PISCO W Cordillera	Northern Chile-Bolivia	Schmitz et al. (1999)
9.7.3.3	1995	CINCA off-onshore Andes	Northern Chile	Patzwahl et al. (1999)
9.7.3.3	1995	PRECORP reflection test profile Andes	Northern Chile	Yoon et al. (2003)
9.7.3.3	1995	CONDOR off-onshore refl lines	Central Chile	Flueh et al. (1998a)
9.7.3.3	1996	ANCORP reflection line Andes	Northern Chile	ANCORP Working Group (2003)
9.7.3.3	2000	ISSA southern Andes	Southern Chile	Lueth et al. (2003)
9.7.3.3	2001	SPOC Subduction Offshore Chile	Chile	Krawczyk et al. (2003)
9.7.4	1990–1991	Antarctic Peninsula Polish expedition	Antarctica	Grad et al. (1997)
9.7.4	1990–1991	SERIS Ross Ice shelf	Antarctica	ten Brink et al. (1993)
9.7.4	1993–1994	ACRUP southern Ross Sea	Antarctica	Trey et al. (1999)
9.8.2	1989	Society Island Hotspot Chain	Pacific Ocean	Grevenmeyer et al. (2001b)
9.8.2	1991	TERA East Pacific Rise	Pacific Ocean	Detrick et al. (1993)
9.8.2	1992	Izu-Ogasawara island arc	South off Japan	Suyehiro et al. (1996)
9.8.2	1993	East Pacific Rise at 9°–10°N	East Pacific	Christeson et al. (1997)
9.8.2	1993	Hess Deep rift valley	Pacific Ocean	Wiggins et al. (1996)
9.8.2	1994	Macquarie Ridge	SW off New Zealand	Finlayson (2010)
9.8.2	1994	Nankai Trough ERI94 line	SW Japan	Kodaira et al. (2000)
9.8.2	1995	Nankai Trough ERI95 line	SW Japan	Kodaira et al. (2000)
9.8.2	1995	EXCO S East Pacific Rise	Pacific Ocean	Grevemeyer et al. (1998)
9.8.2	1995	TAICRUST off Taiwan	Pacific Ocean	Schnuerle et al. (1998)
9.8.2	1996	MELT, East Pacific Rise 15°–18°S	E Pacific	Canales et al. (1998)
9.8.2	1997	East Pacific Rise at 9°05′N	E Pacific	Singh et al. (2006)
9.8.2	1996–2001	MCS Japan trench off northern Honshu	Off N Japan	Tsuru et al. (2007)
9.8.2	1997	Nankai Trough MO104 line	SW Japan	Kodaira et al. (2000)
9.8.2	1997	Sanriku region, off northern Honshu	Off NE Japan	Takahashi et al. (2004)
9.8.2	1998	Japan trench cross lines	Off N Japan	Miura et al. (2003)
9.8.2	1999	On-offshore in Shikoku	SW Japan	Kodaira et al. (2002)
9.8.2	1999	Japan trench off Myagi, Honshu	Off northern Japan	Miura et al. (2005)
9.8.2	1999	PAGANINI Galapagos Hot Spot	Pacific Ocean	Sallares et al. (2003)
9.8.2	2000	GEOPECO off Peru	Peru-Pacific	Krabbenhoeft et al. (2004)
9.8.2	ca. 2000	Nankai Trough MCS lines	S off Japan	Park et al. (2002)
9.8.2	2000	G-PRIME Galapagos Hot Spot	Pacific Ocean	Sallares et al. (2005)
9.8.2	2001	SALIERI Galapagos Hot Spot	Pacific Ocean	Sallares et al. (2005)
9.8.3	1990–1993	AGSO profiling off NW Australia	Australia margin	Finlayson (2010)
9.8.3	1991	Kerguelen Plateau	Indian Ocean	Operto and Charvis (1996)
9.8.3	1990s	SW Indian Ridge	Indian Ocean	Muller et al. (1999)
9.8.3	1992	Banda Sea	Indian Ocean	Finlayson (2010)
9.8.3	1997	Makran subduction off Pakistan	Indian Ocean	Kopp et al. (2000)
9.8.3	1998	Ninetyeast Ridge	Indian Ocean	Grevemeyer et al. (2001a)
9.8.4.1	1989–1991	Continental margin basins off NE Brazil	Southern Atlantic Ocean	Mohriak et al. (1998)
9.8.4.1	1991	Ghana transform margin	South of Ghana	Edwards and Whitmarsh (1997)
9.8.4.1	1992	LEPLAC project off NE Brazil	Southern Atlantic Ocean	Gomes et al. (2000)
9.8.4.1	1995	MAMBA continental margin Namibia	Southern Atlantic Ocean	Bauer et al. (2000)
9.8.4.1	1998	Colorado Basin off Argentina	Southern Atlantic Ocean	Franke et al. (2006)
9.8.4.2	1990	Great Meteor and other seamounts	NE Atlantic	Weigel and Grevemeyer (1999)
9.8.4.2	1993	RAMESSES, Reykjanes Ridge	North Atlantic	Navin et al. (1998)
9.8.4.2	1995	ICEMELT	Central Iceland	Darbyshire et al. (1998)
9.8.4.2	1996	B96	North-central Iceland	Menke et al. (1998)
9.8.4.2	1996	MARBE Mid-Atlantic Ridge	North Atlantic Ocean	Canales et al. (2000)
9.8.4.2	1996?	BRIDGE Reykjanes Ridge	North Atlantic Ocean	Sinha et al. (1999)
9.8.4.2	2000	"*Meteor* (1986)" M47 5°S Fracture	Off NW Africa	Borus (2001)
9.8.4.3	1990	Scoresby Sud on-offshore	Eastern Greenland	Mandler and Jokat (1998)
9.8.4.3	1992	Voering Margin off Lofoten	Atlantic off Norway	Mjelde et al. (1997)
9.8.4.3	1994	FIRE Faeroe-Iceland Ridge Exp	North Atlantic Ocean	Smallwood et al. (1999)
9.8.4.3	1990s	FAST-UNST-FLARE	Faroe– Shetland Isl	England et al. (2005)
9.8.4.3	1994	Scoresby Sud on-offshore	Eastern Greenland	Schmidt-Aursch and Jokat (2005)
9.8.4.3	1994	SE Greenland coast	SE Greenland	Dahl-Jensen et al. (1998)
9.8.4.3	1996	Voering Basin off Lofoten	Atlantic off Norway	Mjelde et al. (1998)
9.8.4.3	1996	SIGMA Greenland Margin	Eastern Greenland	Korenaga et al. (2000)
9.8.4.3	1997	Porcupine Basin	West off Ireland	Reston et al. (2004)
9.8.4.3	1998	NW Barents Sea SE Spitsbergen	North Atlantic Ocean	Breivik et al. (2002)
9.8.4.3	1999	RAPIDS 3 Rockall Project	North Atlantic off Ireland	Mackenzie et al. (2002)
9.8.4.3	1999	ARKTIS VV/2 NW Spitsbergen	North Atlantic Ocean	Czuba et al. (2004)
9.8.4.3	2000	SCREECH Newfoundland basin	Canada	Funck et al. (2003)
9.8.4.3	2000	Mendelejev Ridge	Arctic Ocean	Lebedeva-Ivanova et al. (2006)

*Date of experiment assumed, not indicated by authors.

For example, by the year 2000, the PASSCAL and UTEP instrument pools in the United States had a total of 840 of the 1-component Texan instruments. In Europe, various groups had purchased 200 of the same instrument (Guterch et al., 2003a). Jones (1999) reports in detail on the equipment used by the end of the 1990s in marine seismic surveys.

The new decade starting in 2000 brought continuing advances in recording techniques. Digital technology, which had taken over recording devices for controlled-source seismology in the 1990s, was further improved, and, after many successful deployments, an updated design (RefTek-125A) for the Texan instrument was finalized in 2004. PASSCAL and the EarthScope program began to purchase these models immediately, and the UTEP (University of Texas at El Paso, USA) group focused on an upgrade path for the existing instruments. Via grants from several sources, UTEP obtained the funds needed to upgrade almost 400 of its units, and upgrades were under way by 2005 (Keller et al., 2005b). In a similar manner, the Australian equipment was steadily improved (Finlayson, 2010; Appendix 2-2).

In Britain, Leeds University purchased the Orion digital recording system and in 2000 the British seismic community (the NERC Geophysical Equipment Pool, Leicester, Cambridge, Leeds, and Royal Holloway) was awarded a grant to acquire large numbers of Guralp 6TD and 40T seismometers, together with a number of the Guralp 3Ts, bringing the British scientists to the forefront of observational broadband seismology (Maguire and SEIS-UK, 2002). In Germany during 2000, the GeoScience Center Potsdam started to gradually renew its instrumental pool for short-period and broadband seismology and replaced the worn-out RefTek and PDAS data loggers with a new system, Earth Data PR6-24. Up to mid-2007 almost 240 of these new data loggers have been acquired and made available to the geophysical community. In addition, for special purposes 10 broadband GURALP units were bought. A major German cooperation between land and sea investigations promises a new instrumental pool, named DEPAS (Deutscher Pool für Aktive Seismologie). In early 2006, it consisted of 30 OBS and 65 GURALP seismometers plus Earth Data Loggers (EDL). This was the result of a joint venture between the German institutions GFZ (GeoForschungsZentrum Potsdam) and AWI (Alfred-Wegener-Institut Bremerhaven) for marine seismology (Schulze and Weber, 2006; Schmidt-Aursch et al., 2006). When completed, 100 Earth Data Loggers PR6-24 and 100 GURALP CMG-3ESP Compact units will be available for the land part of DEPAS. For the offshore part, 68 standard and 12 deep-sea OBS (Guralp CMG-40T seismometers plus hydrophones) and 5 OBH (hydrophones only) will be available.

With the large number of recording devices available, projects can now be planned which extend seismic surveys into three dimensions. Large-scale research programs which involved a multitude of cooperating institutions and interdisciplinary cooperation of scientists from various geoscientific fields continued to dominate the scene in the early 2000s. However, with the increasing number of recording devices and the capacity to deploy instruments over large areas, tomographic methodologies such as teleseismic tomography became viable. Many earth scientists started to prefer long-term deployments of instruments using natural events as energy sources instead of short-term projects using expensive controlled sources.

IRIS/PASSCAL in the United States and LITHOPROBE in Canada continue to support large seismic (active) and seismological (passive) projects, occasionally combined with international and interdisciplinary geoscientific priority programs in Europe and Africa, dealing with large-scale tectonic topics. EUROPROBE, supported by the European Science Foundation, continues to support programs concerned with the origin and evolution of the continents (Gee and Stephenson, 2006) emphasizing East-Central-West European collaboration and close multinational cooperation of geologists, geophysicists and geochemists. Examples include the multinational projects ALP 2002 and SUDETES 2003. Another example of trans-Atlantic partnership is the EAGLE project in Ethiopia.

Special sessions on large national and international seismic programs became important parts of the annual meetings of the various national and international geoscientific organizations, such as, e.g., the American Geophysical Union or the European Geophysical Union. Special meetings of earth scientists at regular intervals also continue such as the meetings of the special subcommission of the ESC (European Seismological Commission) "Structure of the Earth's Interior," and the series "International Symposia on Deep Seismic Profiling of the Continental Lithosphere," which continues biannually into the twenty-first century with meetings at Ulvik, Norway, in 2000 (Thybo, 2002), in Taupo, New Zealand, in 2003 (Davey and Jones, 2004), in Mont-Tremblant, Quebec, Canada, in 2004 (Snyder et al., 2006), in Hayama, Japan, in 2006 (Ito et al., 2009a), in Saariselkä, Finland, in 2008, and in Cairns, Queensland, Australia, in 2010.

In a similar way the seismic investigation of the oceanic lithosphere depended greatly on the development of instrumentation, logistics and theory and needed close cooperation with other marine sciences. The seismic structure of the oceanic crust and passive margins was reviewed by Minshull (2002) and published in Part A of the International Handbook of Earthquake and Engineering Seismology, edited by Lee et al. (2002). The structure of the oceanic crust, as known by 2000, is shown in chapters on P- and S-wave velocity structure, anisotropy and attenuation, and variations of crustal structure with spreading rate and with age. Other chapters deal with the seismic structure of the Moho and the uppermost oceanic mantle, of mid-ocean ridges, of oceanic fracture zone and segment boundaries, and hotspots, ocean islands, aseismic ridges and oceanic plateaus. In a textbook *Marine Geophysics*, Jones (1999) has described in much detail the instrumentation and methodologies, as used in marine seismic exploration until the end of the 1990s. Another summary of our knowledge of the structure of the lithosphere under the oceans, as obtained until 2000, was published in the *Encyclopedia of Ocean Sciences* (Steele et al., 2001), with individual contributions on instrumentation and on results on the seismic structure of the ocean in general and of special features as, e.g., mid-ocean ridges. For example, to concentrate the efforts of mid-oceanic ridge research worldwide, "InterRidge" was founded in 1993 to promote interdisciplinary, international studies of oceanic spreading centers through scientific exchange and the sharing of new technologies and facilities among international partners. Its members are research institutions dealing with marine research around the world. InterRidge is dedicated to sharing knowledge amongst the public, scientists, and governments and to provide a unified voice for ocean ridge researchers worldwide (www.interridge.org).

We have compiled a small number of major seismic projects, undertaken from 2001 to 2005 and mentioned in Chapter 10, in Table 2.10. For many projects undertaken since 2001, only limited information has become available by the end of 2005. We therefore emphasize that Table 2.10 is far from complete.

We have terminated our historical review of controlled-source seismic experiments with projects planned and carried out through 2005. The large number of recording devices available nowadays and their ability to record continuously over long time periods has enabled seismic surveys to be extended into three dimensions in a tendency to plan for seismic tomography surveys with teleseismic and/or local events as energy sources. Nevertheless, the interest within the geological and exploration communities for detailed crustal and upper mantle structure has remained until the present day. Many new controlled-source seismic projects have been performed just recently or are in the planning stage. In many situations, details of crustal structure can only be achieved by controlled-source seismic near-vertical incidence reflection seismics and/or seismic refraction/wide-angle reflection experiments with densely spaced controlled sources and a multitude of seismic recorders.

Based on the incredible wealth of data gathered during the past 50 years on seismic crustal structure studies, Walter Mooney started to build up a database, which we describe in some detail in Chapter 10. Its preliminary versions have so far enabled the construction of worldwide syntheses of crustal parameters (e.g., Christensen and Mooney, 1995; Mooney et al., 1998; Mooney, 2002). Another example is a synthesis of the seismic structure of the crust and uppermost mantle of North America and adjacent oceanic basins (Chulick and Mooney, 2002). Based on the database, crustal thickness maps were plotted for the world and for the individual continents, accompanied by maps showing the data points available in the database until ca. 2008.

TABLE 2.10. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN 2001–2005

Chapter	Year	Project	Location	Reference
10.2.1	2001	IBERSEIS southwest Iberia Vibroseis survey	Spain	Carbonell et al. (2004)
10.2.1	2001	IBERSEIS southwest Iberia wide-angle lines	Spain	Palomeras et al. (2009)
10.2.1	2000–2002	Baltic Shield Kola peninsula lines	Russia	Kostyuchenko et al. (2006)
10.2.1	2001–2003	FIRE deep seismic reflection survey	Finland	FIRE consortium (2006)
10.2.1	2002–2003	ISLE teleseismic project	Ireland	Landes et al. (2005)
10.2.1	2004–2005	ESTRID Denish basin	Denmark	Thybo et al. (2006)
10.2.2	2001	VRANCEA 2001 southeast Carpathians	Romania	Hauser et al. (2007a)
10.2.2	2001	DACIA PLAN Focsani basin	Romania	Panea et al. (2005)
10.2.2	2001	SEISMARMARA	Turkey	Laigle et al. (2007)
10.2.2	2002	ALP 2002 Alps and eastern plains	Poland-Hungary	Brueckl et al. (2003)
10.2.2	2002–2003	ESRU Europrobe Urals	Russia	Kashubin et al. (2006)
10.2.2	2003	SUDETES Bohemian Massif	Czech Republic and Poland	Guterch et al. (2003a)
10.2.2	2003	GRUNDY 2003	Poland	Malinowsky et al. (2007)
10.2.2	2004	DRACULA southeast Carpathians	Romania	Enciu et al. (2009)
10.2.2	2005	Black Sea basin	Turkey	Scott et al. (2006)
10.2.2	2005–2006	DOBRE 2 Donbas fold belt	Ukraine	Starostenko et al. (2006)
10.3.1	2002	SHIPS Georgia Street	Northwestern USA–Canada	Brocher et al. (2003)
10.3.1	2004	SAFOD central California refraction line	California, USA	Hole et al. (2006)
10.3.2	2002	Walker Lane refraction survey	California-Nevada, USA	Louie et al. (2004)
10.3.2	2004	Northwest Basin and Range	California-Nevada, USA	Lerch et al. (2007)
10.3.2	2003	Rio Grande rift (Potrillo Volcanic Field)	Southwest New Mexico, USA	Averill (2007)
10.4.1	2001	EAGLE East African Rift	Ethiopia	Maguire et al. (2003)
10.4.1	2002	"*Meteor* (1986)" M52 offshore Israel	Eastern Mediterranean	Hübscher et al. (2003)
10.4.2	2004	Jordan–Dead Sea Transform	Israel-Jordan	ten Brink et al. (2006)
10.4.2	2006	DESIRE southern Dead Sea	Israel-Jordan	Mechie et al. (2009)
10.5.1	2004	Naga thrust and fold belt	NE India	Jaiswal et al. (2008)
10.5.2	2000*	Altyn Tagh Range	China	Zhao et al. (2006)
10.5.2	2000*	1000 km northeast Tibet to Ordos basin	China	Liu et al. (2006)
10.5.3	2001	South-central Honshu	Japan	Iidaka et al. (2004)
10.5.3	2000s	Nankai Trough–central Japan on-offshore	Central Japan	Kodaira et al. (2004)
10.5.3	2002–2003	Reflection lines Tokyo area	Central Japan	Sato et al. (2006)
10.5.3	2002	WNW-ESE line south Korean peninsula	South Korea	Kim et al. (2007)
10.5.3	2004	Reflection lines Kinki area	Southwestern Japan	Sato et al. (2006)
10.5.3	2004	NNW-SSE line south Korean peninsula	South Korea	Kim et al. (2007)
10.6.1	2001	AGSNY Goldfield Province	Western Australia	Goleby et al. (2004)
10.6.1	2003	Gawler Craton South Australia	Southern Australia	Drummond et al. (2006)
10.6.1	2003–2004	Curnamona region southern Australia	Southern Australia	Finlayson (2010)

(*continued*)

TABLE 2.10. MAJOR CONTROLLED-SOURCE SEISMIC INVESTIGATIONS OF THE CRUST IN 2001–2005 (*continued*)

Chapter	Year	Project	Location	Reference
10.6.1	2005	Yilgarn Orogen on-offshore experiment	Western Australia	Finlayson (2010)
10.6.1	2005	Thomson-Lachlan orogens traverse	Eastern Australia	Finlayson (2010)
10.6.1	2005	Tanami region Northern Territory	Central Australia	Finlayson (2010)
10.6.1	2001	NIGHT Taupo Volcanic Zone	Northern New Zealand	Henrys et al. (2003)
10.6.1	2001	Chatham Rise, offshore New Zealand	Off New Zealand	Davy et al. (2008)
10.6.1	2003	Bounty Trough east of South Island	Off New Zealand	Grobys et al. (2007)
10.6.1	2003	Great South Basin east of South Island	Off New Zealand	Grobys et al. (2009)
10.6.1	2005	Marine reflection experiment off east coast North Island	Off New Zealand	Barker et al. (2009)
10.6.2	2003	Onshore-offshore SW coast of South Africa	South Africa	Hirsch et al. (2009)
10.6.2	2005	On-offshore Cape Fold Belt–Karoo Basin	South Africa	Stankiewicz et al. (2007)
10.6.2	2005	Seismic reflection survey Karoo Basin	South Africa	Lindeque et al. (2007)
10.6.3	2001	ECCO Oriental basin	Venezuela	Schmitz et al. (2005)
10.6.3	2004	BOLIVAR off Venezuela	Venezuela-Caribbean	Magnani et al. (2009)
10.6.3	2001	SPOC Subduction processes off Chile	Chile	Krawczyk et al. (2003)
10.6.3	2004–2005	TIPTEQ seismic array project	Chile	Rietbrock et al. (2005)
10.7.2	2000–2004	Australian margins	East and south off Australia	Finlayson (2010)
10.7.2	2001	SALIERI Galapagos volcanic	East Pacific	Sallares et al. (2003)
10.7.2	2001	Tonga Ridge	Southwest Pacific	Crawford et al. (2003)
10.7.2	2004	New Caledonia	Southwest Pacific	Lafoy et al. (2005)
10.7.2	2004?	Nankai Trough 3 parallel lines	South off Japan	Kodaira et al. (2006)
10.7.2	2004	Izu arc wide-angle project	South off Japan	Kodaira et al. (2007a)
10.7.2	2005	Bonin arc wide-angle project	South off Japan	Kodaira et al. (2007b)
10.7.2	2005	Refr survey of Nicaragua	Off Central America	Ivandic et al. (2010)
10.7.3	2000–2004	Australian margins	West and south off Australia	Finlayson (2010)
10.7.3	2003	Seychelles-Laxmi Ridge	Indian Ocean	Collier et al. (2004)
10.7.4	2002	RAPIDS-4 Rockall basin off Ireland	North Atlantic	O'Reilly et al. (2006)
10.7.4	2002	HADES Hatton Deep	North Atlantic	Chabert et al. (2006)
10.7.4	2003	Onshore-offshore southwestern South Africa	South Atlantic	Hirsch et al. (2009)
10.7.4	2003	Continental margin off French Guiana	South Atlantic	Greenroyd et al. (2006)
10.7.4	2003	EUROMARGINS eastern Greenland	North Atlantic	Schmidt-Aursch and Jokat (2005)
10.7.4	2004	Continental margin off Uruguay	South Atlantic	Temmler et al. (2006)
10.7.4	2004	"*Meteor* (1986)" M62-3 Cape Verde Island	South Atlantic	Grevemeyer et al. (2009)
10.7.4	2004	"*Meteor* (1986)" M62-4 Mid-Atlantic Ridge 7°S	South Atlantic	Reston et al. (2009)
10.7.4	2004	"*Meteor* (1986)" M61-2 off Ireland	North Atlantic	Reston et al. (2006)
10.7.4	2004	Porcupine Basin off Ireland	North Atlantic	Hauser et al. (2007b)
10.7.4	2005	Onshore-offshore southern coast South Africa	South Atlantic	Parsiegla et al. (2007)

*Date of experiment assumed; not indicated by authors.