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CHAPTER 8 The 1980s (1980–1990)

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CHAPTER 8

The 1980s (1980–1990)

8.1. THE DECADE OF LARGE-SCALE REFLECTION SEISMOLOGY AND SEISMIC RAY TRACING

During the course of the 1960s, the technology of controlled-source seismology was very much improved so that in the beginning of the 1970s, this technique would not only obtain average properties of crustal structure, but could resolve major anomalous features. Furthermore, in the 1970s, improved shooting techniques allowed scientists to obtain resolvable energy up to distances of 1000 km or more. So, the fine structure of the lower lithosphere became one of the major goals of seismic-refraction projects including a rather good knowledge of details in the structure of the overlying crust. At the same time, the resolution was gradually increased by decreasing the interval distances between recording stations, and by increasing the number of shots along a profile. Also at this time, the interest in resolving the crustal structure in much more detail than hitherto led vertical-incident reflection seismic investigations into new dimensions. Large-scale reflection experiments such as COCORP in the United States, and special surveys in Europe which penetrated the whole crust were started and could be extended to continuous profiling up to 100 km profile length. In Europe, in most cases, these projects were supported by refraction piggy-back experiments to include the wide-angle reflection distance range.

The success of controlled-source seismology continued in the 1980s, but with increased interest as to the details of the crust. In Europe, a variety of seismic-refraction surveys was initiated in the frame of large-scale interdisciplinary projects, e.g., the establishment of the European Geotraverse from the North Pole to Tunisia, North Africa, and the increasing interest in deep continental drilling. Further stimulation was created by the establishment of large-scale seismic-reflection profiling leading to the establishment of national crustal-scale reflection programs such as BIRPS in Britain, DEKORP in Germany, or ECORS in France. In North America, the new seismic-refraction equipment of the U.S. Geological Survey led to considerably increased activities, parallel to the efforts of COCORP, and the Canadian geophysical institutions formulated subsequently the joint programs COCRUST and LITHOPROBE for a systematic crustal and upper-mantle investigation of the Canadian territory by a joint application of seismic-refraction and reflection methodology.

8.2. CONTROLLED-SOURCE SEISMOLOGY WORKSHOPS

The increasing wealth of explosion seismic data allowing the studying of the crust and the uppermost mantle in much detail, and in areas where strong anomalies were to be expected, led to an increasing need to improve the existing interpretation methods. As described in detail at the end of the foregoing Chapter 7, a first workshop of the CCSS (Commission on Controlled Source Seismology) working group had been held in 1977, at Karlsruhe, to discuss and compare current interpretation methods at the example of 1-D seismic-refraction data, which had been distributed beforehand to the participants of that workshop (Ansorge et al., 1982). The workshop had shown that the existing traveltime routines, and the application of the reflectivity method, led to very satisfying results (see Fig. 7.9-01), and the comparison of the different methods had proved that the interpretation results did not depend on the method used, but rather on the interpretation of seismic phases correlated in the raw data. Furthermore, most methods used had required horizontally homogeneous stratified media. However, it had become apparent that methods which allowed 2-D and 3-D approaches were needed. Already in the 1970s, the basic theory of the ray method in seismology had been published (Červený et al., 1977), and first computer routines to calculate traveltimes and ray paths for lateral inhomogeneous media (e.g., Červený and Horn, 1980; Gebrande, 1976; Will, 1976) as well as to compute ray theoretical seismograms (Červený, 1979; Červený and Pšenčik, 1984a; McMechan and Mooney, 1980; Spence et al., 1984) had been published. The following decade of the 1980s saw the systematic application of ray tracing methodology for 2-D interpretations of seismic-refraction surveys, which covered areas where the approach with 1-D modeling would have led to major errors.

As described in more detail at the end of Chapter 7, in 1980 another CCSS workshop, this time held at Park City, Utah, had the particular aim to study interpretation methods which could be applied to a long-range profile of several 100 km length with varying crustal structure and with a substantial number of shotpoints along the line. For data, the observations of a long-range profile through Saudi Arabia, recorded by the U.S. Geological Survey in 1978 (Gettings et al., 1986), could be used, which again were distributed to the participants beforehand and for which 17 separate interpretations (see Fig. 7.9-02) had been delivered (Mooney and Prodehl, 1984). It turned out that the individual interpretations showed only minor differences for the area of the Saudi Arabian shield and platform where lateral variations in structure were almost negligible. However, for the westernmost part of the line, the transition zone from the Arabian shield to the Red Sea, the individual models varied considerably.

As a consequence, and to ensure that differences in phase correlation could be ruled out, it was decided to hold another workshop, for which synthetic seismogram sections with clear secondary arrivals (Fig. 8.2-01), would be computed for a known

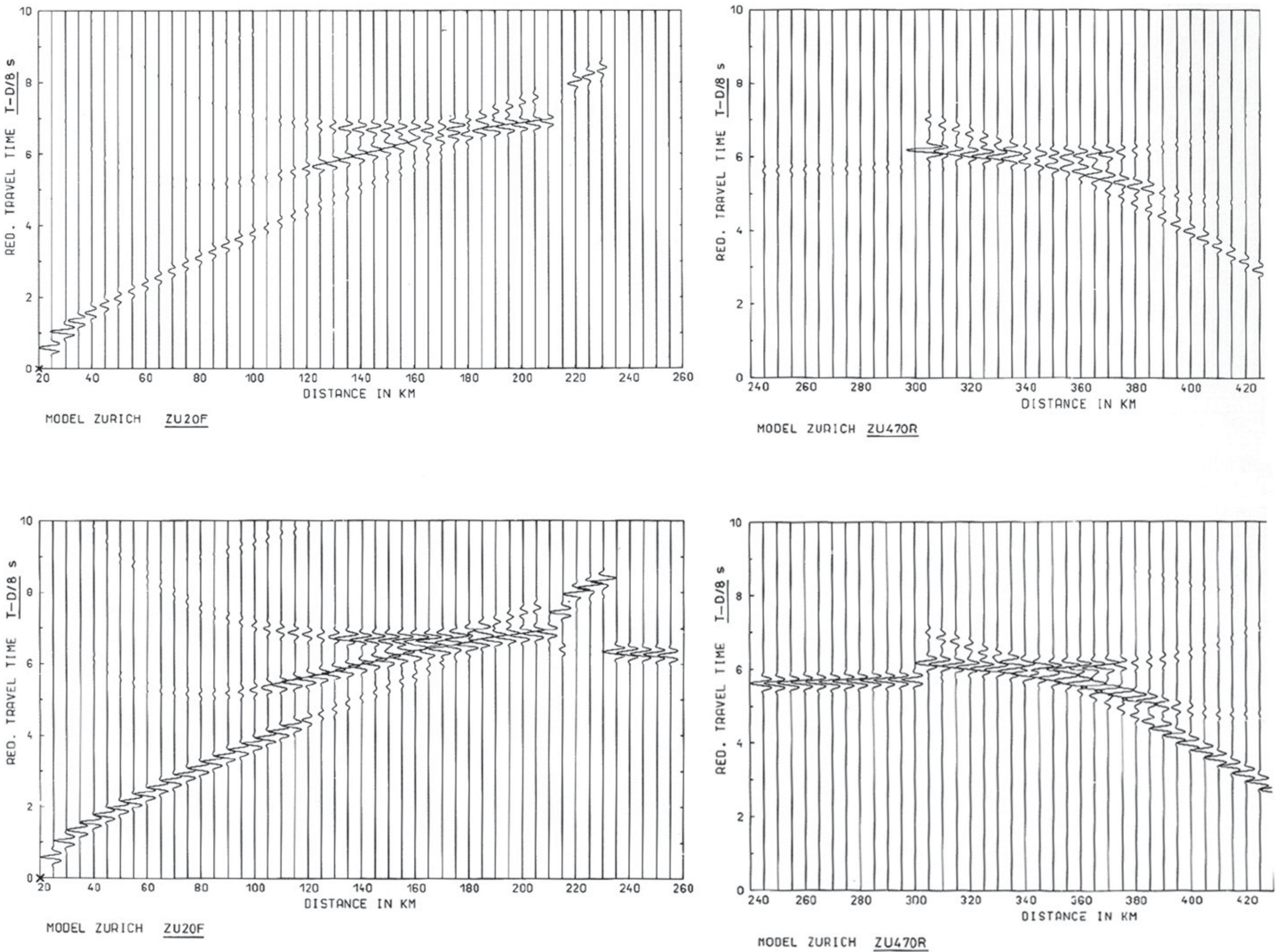

Figure 8.2-01. Synthetic data examples handed out prior to the workshop which were computed from the model shown in Figure 8.2-02 from the model sources at distances 20 km (left) and 470 km (right), normalized according to a distance scaling factor (top) and with equal maximum amplitude on all traces (bottom) (from Červený and Pšenčik, 1984a, Figs. 5 and 10). [*In* Finlayson, D.M., and Ansorge, J., 1984, Workshop proceedings: interpretation of seismic wave propagation in laterally heterogeneous structures: Bureau of Mineral Resources, Geology & Geophysics, report 258, Canberra, Australia, p. 3–14. Copyright by Commonwealth of Australia (Geoscience Australia).]

realistic structure and would be distributed to the participants for interpretation without knowing the original model (Fig. 8.2 02). The data preparation was taken care of by V. Červený and I. Pšenčik at Prague, Czechoslovakia, and the workshop was held in 1983, at Einsiedeln, Switzerland (Finlayson and Ansorge, 1984). Twenty-one interpretations of data set I—model Zurich—were presented at the workshop. In conclusion, the application of a variety of existing methods on these data led to a very satisfying result and ruled out that differing results were dependent on the particular method used, but were exclusively dependant on phase correlations.

Having ensured that the available methods would not lead to differing results, the emphasis was turned over to the joint interpretations of near-angle and wide-angle seismic-reflection and seismic-refraction data recorded along the same line. The problem of whether or not near-angle reflection data would see the same interfaces as wide-angle reflection and refraction data had already been approached at the CCSS workshop of 1983 at Einsiedeln, Switzerland, but would become the main focus of the next CCSS workshop held in Susono, Shizouka, Japan, in August 1985. In 1983, a data set III, consisting of seismic-reflection and refraction data obtained in 1978 in the area of the geothermal anomaly Urach, Germany (Bartelsen et al., 1982), and prepared by E.R. Flueh at Kiel, Germany, had been distributed and worked on by only three workshop attendees.

In 1985, the SJ-6 seismic-reflection/-refraction profile (Figs. 8.2-03 and 8.2-04), recorded through south central California perpendicular to and crossing the San Andreas Fault zone south of Parkfield, California, served as the only data set (Walter and Mooney, 1987; Appendix A8-3-3). One of the 11 separate

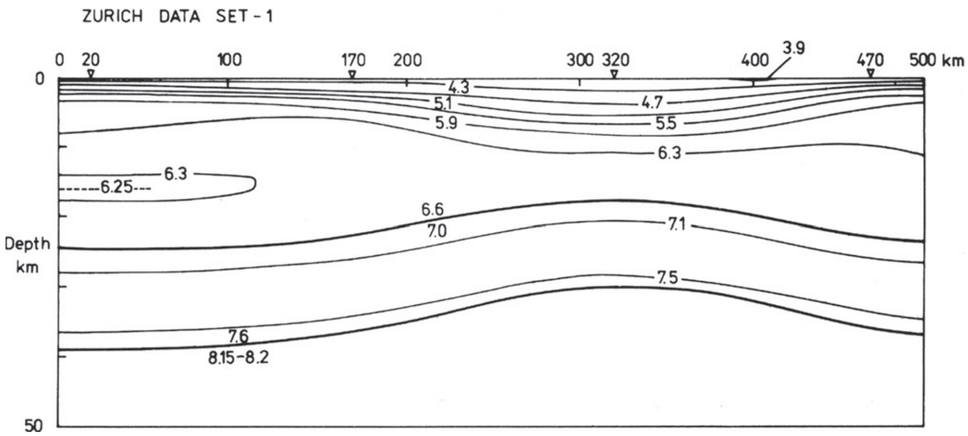

Figure 8.2-02. Model for which synthetic data (see examples in Fig. 8.2-01) handed out prior to the Workshop were computed (from Červený and Pšenčik, 1984b, fig. 1). [*In* Finlayson, D.M., and Ansorge, J., 1984, Workshop proceedings: interpretation of seismic wave propagation in laterally heterogeneous structures: Bureau of Mineral Resources, Geology & Geophysics, report 258, Canberra, Australia, p. 3–14. Copyright by Commonwealth of Australia (Geoscience Australia).]

models derived by workshop attendees and presented by Walter and Mooney (1987) is shown in Figure 8.2-05.

For the subsequent CCSS workshop, held in 1987 at Whistler near Vancouver, British Columbia, participants had been invited to work on one or more of the following topics: (1) a combined interpretation of multichannel seismic-reflection and seismic-refraction/wide-angle reflection data across Vancouver Island and the adjacent continental margin, collected by COCRUST and LITHOPROBE between 1981 and 1985, (2) enhanced processing of stacked data, and/or (3) processing of unstacked data from a land multichannel seismic-reflection profile collected on Vancouver Island. Data, results, and problems were discussed during the workshop (Green et al., 1990a, 1990b).

Data set (1) comprised the data of profile I, extending across Vancouver Island from near the volcanic arc to the deep ocean, and profile IV, shot along the length of Vancouver Island parallel to the continental margin, both recorded in 1980 (Fig. 8.2-06). Profile I comprised 32 land seismographs, deployed on a 160-km-long line on Vancouver Island, on islands in the Strait of Georgia, and on the British Columbia mainland, and it included four ocean-bottom seismometers (OBS) in the offshore region, of which three, shown in Figure 8.2-06, were of concern. Record sections from shotpoint J1 and from the shotpoints P8, P13, and P19, as well as the record sections recorded at the three OBS sites 1, 3, and 5 (Fig. 8.2-06), were distributed. In addition a reflection section of the marine profile 85-1, recorded in 1985, was handed out for the workshop.

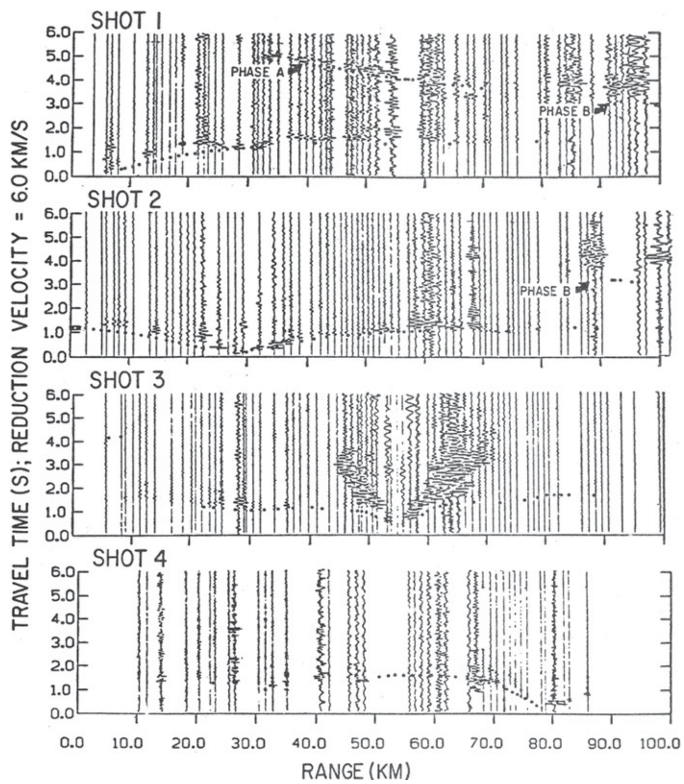

Figure 8.2-03. True-amplitude record sections of the of the original refraction data set handed out prior to the workshop (from Trehu and Wheeler, 1987, fig. 4a). [*In* Walter, A.W., and Mooney, W.D., 1987, Commission on Controlled Source Seismology (CCSS) proceedings of the 1985 workshop interpretation of seismic wave propagation in laterally heterogeneous terranes, Susono, Shizouka, Japan, 15–18 August 1985: Interpretations of the SJ-6 seismic reflection/refraction profile, south central California, USA: U.S. Geological Survey Open-File Report 87-73, p. 91–104.]

8.3. CONTROLLED-SOURCE SEISMOLOGY IN EUROPE

The great success of explosion seismology in the 1970s was due to close cooperation of research institutions on an international scale. This cooperation allowed scientists to explore the entire lithosphere in great detail. This effort to cooperate was continued in the 1980s on an even broader base. Furthermore, details of crustal structure became the main focus of explorations. Three major research projects were formulated almost simultaneously, involving not only seismologists, but the whole range of earth scientists: (1) national deep-seismic-reflection programs in western and central Europe; (2) detailed seismic-reflection and seismic-refraction research within the frame of continental deep drilling programs successfully carried out in Germany by the German KTB project (Kontinentale Tief-Bohrung = continental deep drill-

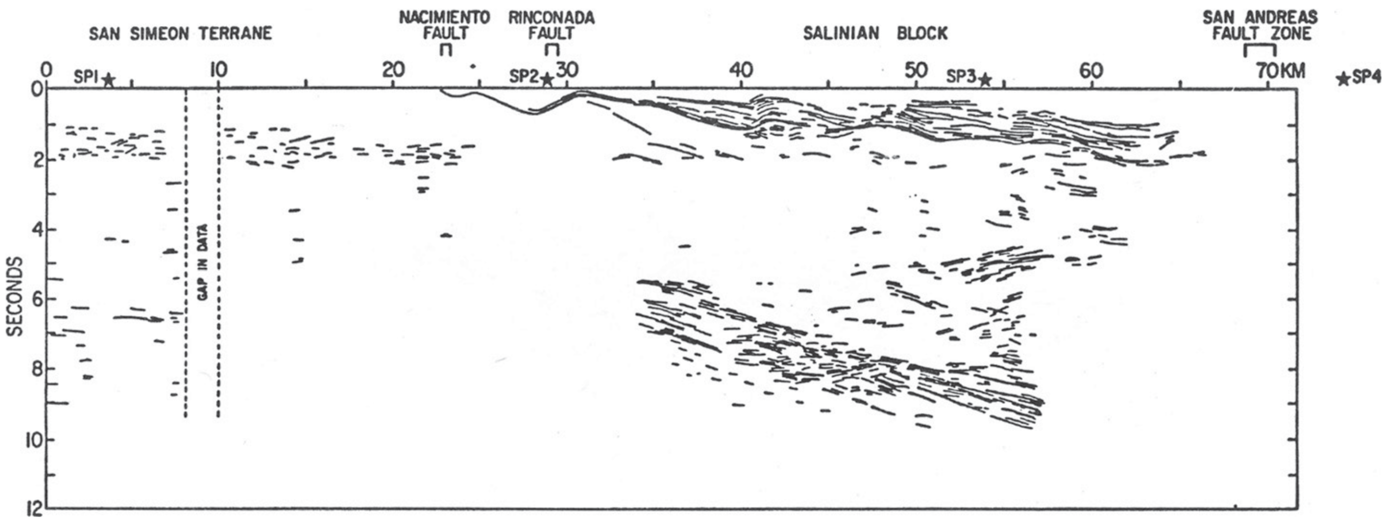

Figure 8.2-04. Line drawing of the original reflection data set handed out prior to the workshop (from Trehu and Wheeler, 1987, fig. 2). [*In* Walter, A.W., and Mooney, W.D., 1987, Commission on Controlled Source Seismology (CCSS) proceedings of the 1985 workshop interpretation of seismic wave propagation in laterally heterogeneous terranes, Susono, Shizouka, Japan, 15–18 August 1985: Interpretations of the SJ-6 seismic reflection/refraction profile, south central California, USA: U.S. Geological Survey Open-File Report 87-73, p. 91–104.]

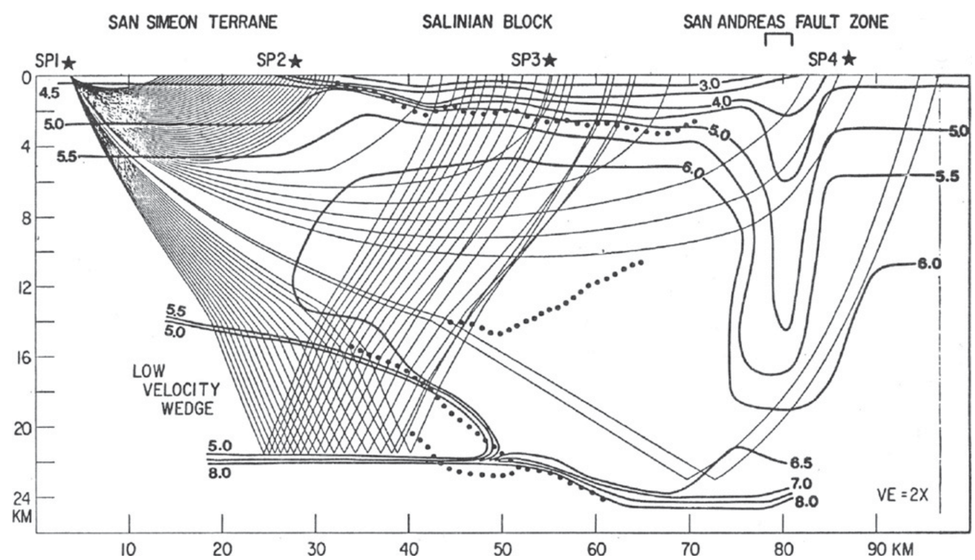

Figure 8.2-05. Velocity model derived by 2-D ray tracing from the data set handed out prior to the workshop (from Trehu and Wheeler, 1987, fig. 4b). [*In* Walter, A.W., and Mooney, W.D., 1987, Commission on Controlled Source Seismology (CCSS) proceedings of the 1985 workshop interpretation of seismic wave propagation in laterally heterogeneous terranes, Susono, Shizouka, Japan, 15–18 August 1985: Interpretations of the SJ-6 seismic reflection/refraction profile, south central California, USA: U.S. Geological Survey Open-File Report 87-73, p. 91–104.]

hole) as well as in Russia by the Kola deep drillhole on the Baltic Shield (which will be discussed further below); and (3) the European Geotraverse with major seismic-refraction surveys.

8.3.1. Large-Scale Seismic-Reflection Surveys in Western Europe

In contrast to most of the early near-vertical incidence seismic-reflection work in the 1950s and 1960s in Canada, Germany, the former USSR, and in Australia, the initiators of COCORP had hired a commercial reflection company for the fieldwork and also applied their processing and interpretation techniques (Oliver et al., 1976) on the new data involving the whole crust. The same philosophy was also applied by the initiators of the national European large-scale seismic-reflection programs. Such national programs were BIRPS (British Institutions Reflection Profiling Syndicate) in Britain, ECORS (Etude de la Croûte Continentale et Océanique par Réflexion et Réfraction Sismique) in France, BELCORP (Belgian Continental Reflection Program) in Belgium, DEKORP (Deutsches Kontinentales Reflexionsseismisches Programm) in Germany, NFP (Swiss National-Fond Project) in Switzerland, CROP (Crosta Profonda) in Italy, and others.

Phinney and Roy-Chowdhury (1989) have described in much detail the basic seismic-reflection techniques and the long procedure leading from the raw data to the seismic-reflection sections used for final geological interpretation which we will

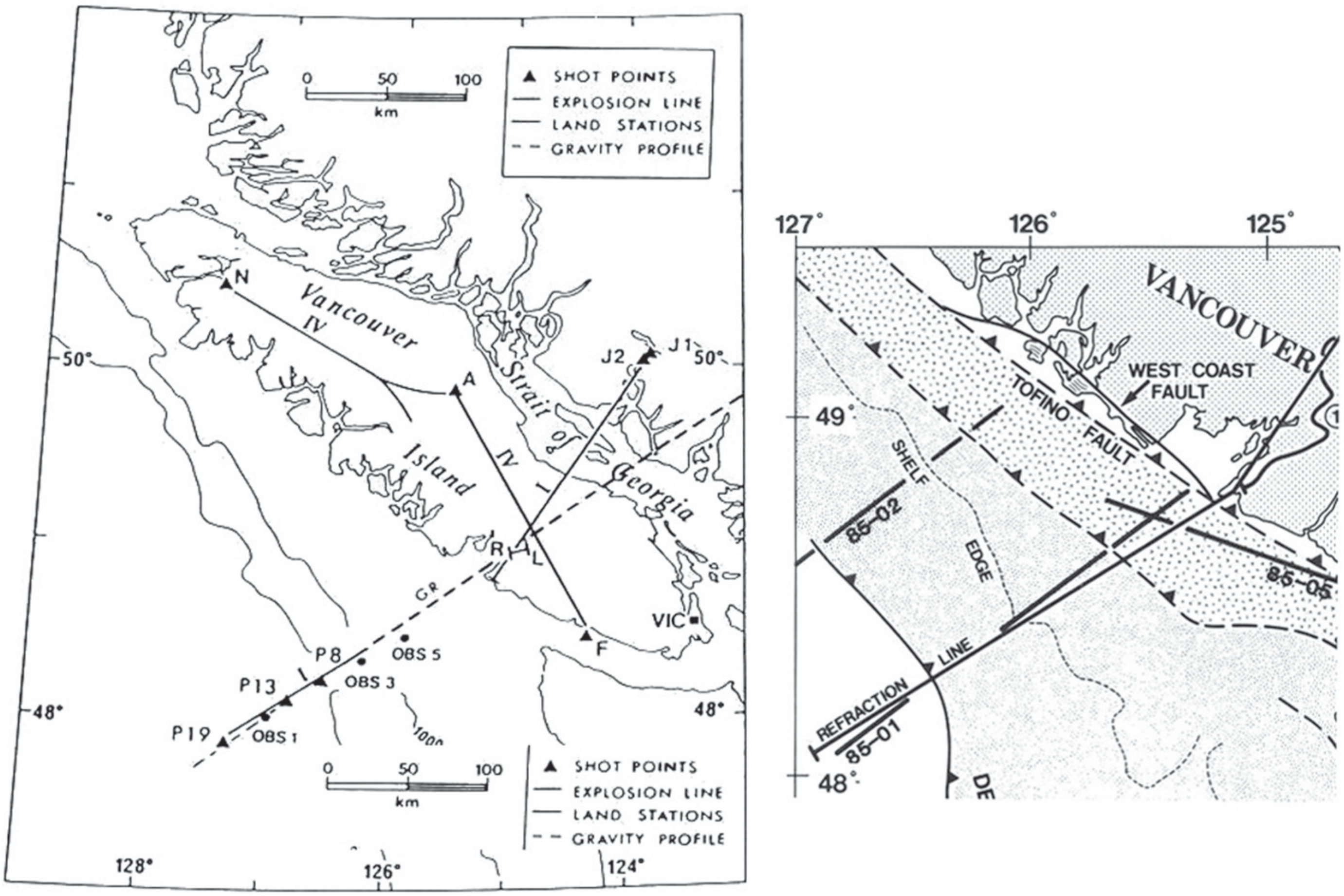

Figure 8.2-06. Location map of COCRUST and LITHOPROBE crustal study profiles across Vancouver Island (from Green et al., 1990b, figs. 4 and 1). Left: Map showing location of data handed out to workshop participants. Right: Location of reflection line 85-1 handed out to workshop participants. [Geological Survey Canada, paper 89-13: 3-25. Reproduced with the permission of Natural Resources Canada 2009, courtesy of the Geological Survey of Canada.]

briefly review. The conventional geometry for reflection profiling is an array of geophone groups, cabled together, to record seismic signals from a shotpoint or vibrator point within or slightly off-end the array. The seismic traces recorded from one such source point constitute a source gather. The arrivals in a source gather may include reflections, refractions, ground-roll, shear waves, air waves, converted waves, multiples and the like. The collection of all source gathers forms a 3-D data set (source, receiver group, time). The goal of seismic data processing is to convert this raw 3-D data manifold into a 2-D cross-sectional representation of subsurface structure. Phinney and Roy-Chowdhury (1989) have summarized the usual conventional seismic processing steps in table 2 of their publication. These steps are, in detail:

(1) involving production of shot gathers (demultiplex and Vibroseis correlation),
(2) initial clear-up (frequency filtering, resampling, trace editing, true amplitude recovery, datum statics, removal of shear and air waves and ground roll);
(3) preparation of common-depth point (CDP) gathers (rearrangement of traces, deconvolution, etc.);
(4) CDP processing (suppression of refraction arrivals, velocity analysis, residual statics, normal moveout, stack);
(5) post-stack processing (deconvolution, frequency filter);
(6) imaging the zero-offset wavefield (automatic gain control, coherency filter, convert digital data to graphic display); and
(7) imaging the subsurface (migration, inversion, convert subsurface image to graphic display).

Some of the steps described are mandatory, some optional. Of all steps described above, migration and stacking are the most important ones. Migration places the reflectors into their spatially correct locations. The final graphic display serves the same purpose as do record sections in seismic-refraction interpretation, where phases are to be correlated over larger distance ranges and identified as refractions or wide-angle reflections from discontinuities. The processed near-vertical incidence seismic-reflection sections show similarly reflecting horizons by correlating reflections over larger distance ranges and identifying them as geological features.

For the interpretation of seismic-reflection surveys it has become common use to present either the graphic display of a profile or corresponding line drawings as the final product and interpret the most evident features with depth indications in s TWT (two-way traveltime) and not, in many cases due to missing velocity information, to draw corresponding velocity-depth sections as is used in the interpretation of seismic-refraction surveys.

8.3.1.1. British Isles (BIRPS and Other Seismic-Reflection Surveys)

The continental region of the British Isles adjoins the Northeast Atlantic margin and includes the onshore regions of the British Isles as well as the stretched continental crust beneath the seas to the south and west of Ireland and northern Norway and beneath the North Sea.

Between 1980 and 1982, the Deep Geology Unit of IGS (Institute of Geological Sciences) continued their land-based seismic-reflection surveys which they had started in 1979 (Whittaker and Chadwick, 1983). In 1980, three surveys reached the base of the crust: the IGS 1980 Wiltshire and Dorset Survey, the IGS/NERC 1980 Hampshire Survey and the IGS/Leicester University 1980 Survey. For the interpretation of the Dynamite Survey 1981–1982 East Yorkshire and 1982 South Yorkshire data, the LISPB (Lithospheric Seismic Profile through Britain) 1974 data could be used to produce velocity profiles. Striking horizontal deep reflections around 11 s TWT were also seen on the Dynamite Survey 1982 Dorset. The preliminary interpretation of the geographically scattered data revealed a certain consistency of crustal structure for those areas with good quality dynamite lines. Beneath the sedimentary sections with flat-lying reflectors, the upper to mid-crustal zone was interpreted to be characterized by strongly tectonized rocks with brittle forms of thrusting and faulting. The lower crust appeared to support the concept of deformation by a dominantly ductile strain release mechanism. Discrete high-amplitude, subhorizontal events occurring between 8 and 11 s TWT were attributed to reflectors at or below the base of the crust (Whittaker and Chadwick, 1983).

A major impact on seismic studies in the UK came from the marine work undertaken by the group of scientists at Cambridge under the leadership of Drummond Matthews. Plans to investigate the Earth's crust in the British Isles at a large scale in much more detail than was possible by seismic-refraction work were born when Drummond Matthews visited COCORP to gain insight into the procedures of deep seismic reflection and how such a group functioned, and so to initiate deep seismic-reflection work.

The fact that the British Isles are surrounded by sea offered a relatively economical way to apply the reflection method to long distance ranges of several 100 km. BIRPS—the British Institutions Reflection Profiling Syndicate—was conceived in 1976 by a Royal Society working group and was first funded in 1981 by the British government through the Natural Environment Research Council to serve the interests of UK university groups and the British Geological Survey.

From its formation, BIRPS was pushed forward by the Cambridge group. Derek Blundell of London also became heavily involved. From its very beginning, it was supported by British-based oil companies. It was accepted that the objectives of reflection and refraction were different, the former providing near-vertical traveling ray-paths and highlighting structure, while the latter provided subhorizontal traveling ray-paths providing well-constrained velocities for the mid- and lower-crust and mantle, so highlighting composition and physical state.

The basics of BIRPS acquisition were summarized by Klemperer and Hobbs (1991) in their introduction to the BIRPS Atlas. The energy source used by BIRPS was based on airgun technology. For deep seismic profiling, the source had to produce in excess of 100 bar m in the bandwith from 5 to 80 Hz. It had to be rich in low frequencies, because frequencies below 20 Hz are best transmitted through the crystalline crust and get least attenuated. Typically, the source used by BIRPS consisted of 36 airguns which were distributed among six sub-arrays and were towed at ~7 m depth in an areal pattern of up to 175 m length and up to 100 m width behind the ship. The shot interval varied from 50 m for 15-s records to 100 m for 30-s records. The streamer was the same as used by seismic contractors for oil prospecting and was constantly exchanged whenever new technology became available. The streamer length was ~3000 m, consisted of 60 groups of hydrophones, and was towed at 15 m water depth. The data were recorded in digital format on magnetic tape. Each hydrophone group was recorded on one seismic data channel (Klemperer and Hobbs, 1991). The processing of the data followed the scheme described above by Phinney and Roy-Chowdhury (1989).

From early 1981 to midsummer 1984, a total of 3000 km of deep seismic-reflection profiles were acquired north, west, and south of Britain recording to 15 s TWT (Fig. 8.3.1-01), all being located within 500 km of the rifted margin of the continental shelf of NW Europe. Furthermore, Figure 8.3.1-01 shows 2600 km of seismic-reflection lines acquired in the North Sea by September 1984 and a few deep lines on land in Britain shot and observed by the British Geological Survey (Whittaker and Chadwick, 1983). Klemperer and Hobbs (1991) have compiled an atlas of 100 sections of the BIRPS surveys.

The first line, the Moine and Outer Isles Seismic Traverse (MOIST) was shot and processed in 1981. Figure 8.3.1-02 shows the MOIST traverse as a typical example of a BIRPS record. The reflections sketched have been interpreted as Mesozoic sedimentary basins and as subhorizontal layering in the lower crust extending from ~6 s to a relatively abrupt cut-off at ~10 s, the two-way reflection time to the Moho. Reflections dipping at ~30° from near-surface have been interpreted as low-angle normal faults, being reactivated Caledonian and Variscan thrust faults, merging with and being lost in the layering of the lower crust. Occasionally dipping events reach into the upper mantle as, e.g., the Flennan thrust in Figure 8.3.1-02. In order to see how far down the Flennan thrust penetrates, in 1984 the short line DRUM (Deep Reflections

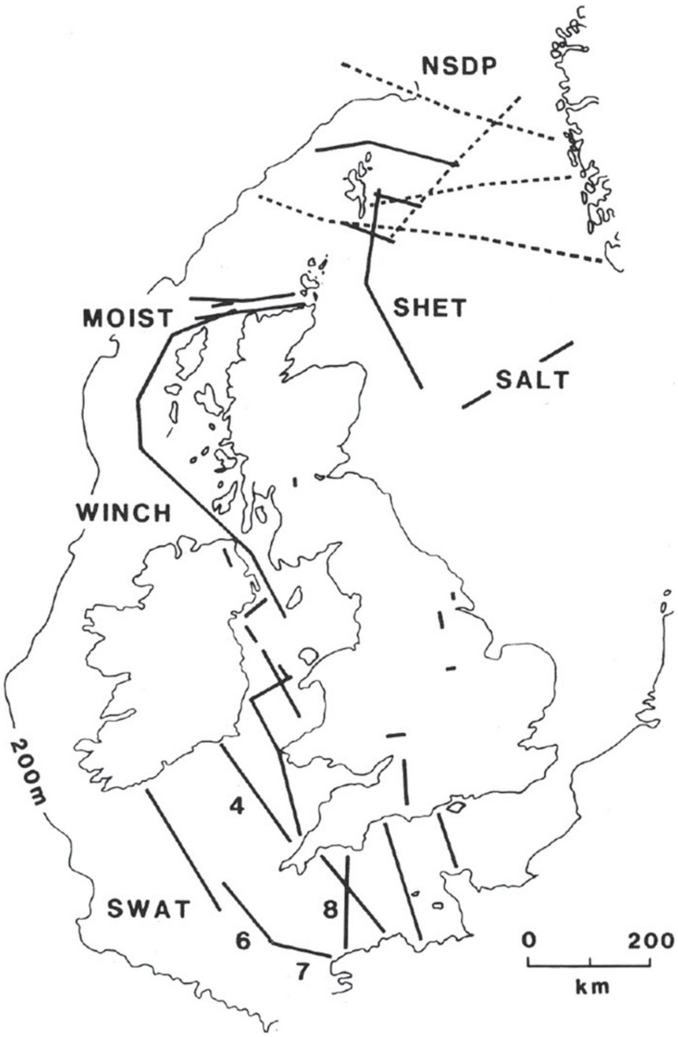

Figure 8.3.1-01. BIRPS deep seismic profiles completed prior to June 1984 over the continental shelf of NW Europe between Ireland, Britain, France, and Norway (from Matthews and Cheadle, 1986, fig. 1). [*In* Barazangi, M., and Brown, L., eds., Reflection seismology: a global perspective: American Geophysical Union, Geodynamics Series, v. 13, p. 5–19. Reproduced by permission of American Geophysical Union.]

from the Upper Mantle) was recorded to 30 s TWT parallel to the MOIST traverse. The Flennan thrust could be traced to 28 s as a nearly continuous bright reflector, corresponding to 80 km depth and 50 km below Moho (Blundell and Docherty, 1987).

The WINCH lines (Western Isles and North Channel traverse) followed in 1982 and confirmed the reality of the sub-Moho Flennan thrust. Deep seismic-reflection observations on the western side of Britain continued through the SWAT profiles (South-West Approaches Traverse), acquired jointly by BIRPS and the French group ECORS in late 1983 and processed in 1984. Thus, a more-or-less continuous set of deep seismic-reflection lines could be revealed from Scotland to France crossing the main faults of the Caledonian and Variscan orogenic belts, including the Variscan Front and several Permian and Mesozoic extensional basins. These were discussed and interpreted by Matthews and Cheadle (1986) who also refer to the corresponding original sources. Also jointly funded by BIRPS and ECORS, in 1985 a 600-km-long line WAM (Western Approaches Margin) was recorded off Cornwall in west-southwesterly direction to determine whether the layering of the lower crust could be related to extension or not (Peddy et al., 1989). The line started at the offset of the SWAT 6 line (Fig. 8.3.1-01) and ran out to the strongly stretched continental margin and further across the slope into the deep ocean up to magnetic anomaly 34. The Moho could be seen under the deep ocean, but could not be traced onto the continent (Blundell and Docherty, 1987).

In the North Sea, the line SHELL-UK82-101 was acquired in 1982 as a commercial profile by Shell UK showing the transition from the southern North Sea basin to the London-Brabant massif (Klemperer and Hurich, 1990). Another industrial line made available to BIRPS was the single deep profile SNST83-07 (Southern North Sea Tie 1983) recorded in 1983 in the southern North Sea, which provided a regional transect from East Anglia to Denmark across the southern part of the Central Graben and the Horn graben (Holliger and Klemperer, 1990). BIRPS reflection lines SALT (named for the Zechstein salt) were recorded in 1983, coinciding with the location of a wide-angle seismic experiment recorded in 1980 and 1981 across the Central Graben

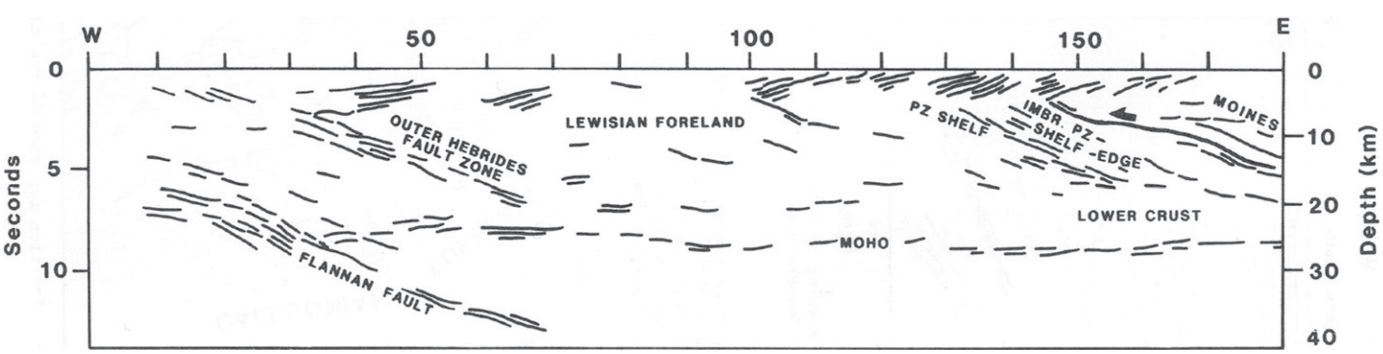

Figure 8.3.1-02. Line drawing of the BIRPS deep seismic line MOIST (from Matthews and Cheadle, 1986, fig. 3a). [*In* Barazangi, M., and Brown, L., eds., Reflection seismology: a global perspective: American Geophysical Union, Geodynamics Series, v. 13, p. 5–19. Reproduced by permission of American Geophysical Union.]

of the North Sea (Barton and Wood, 1984, Barton, 1986). Other BIRPS reflection surveys shot in 1984 in the North Sea, covering the northwest shelf of Europe, were SHET (Shetland survey), recorded in August 1984 along the shelf of northeastern Scotland (McGeary, 1987), and NSDP (North Sea Deep Profile), recorded in October 1984 between northern Scotland and southern Norway (Matthews and Cheadle, 1986).

Matthews and Cheadle (1986) argued that the BIRPS results in general support the idea of a ductile lower crust, showing numerous short reflections with a sharp downward cutoff at the Moho and that its flat-lying foliation is related to Mesozoic extension of the lower crust preceding the opening of the Atlantic. Dipping events reaching into the upper mantle are interpreted as imbricate faulting of a brittle layer in the uppermost mantle.

From 1985 to 1988, more surveys were carried out by BIRPS around the British Isles (Blundell and Docherty, 1987; Snyder and Hobbs, 1999). All surveys were recorded to 15 s TWT. The NEC (North East Coast line) project of 1985 was designed to confirm the north-dipping reflector seen on WINCH, which had been interpreted as the Iapetus suture (Freeman et al., 1988). NSDP was extended in 1985 by another 1600 km. GRID was a grid of lines shot in 1986 and 1987 north of Scotland around MOIST and DRUM to map the 3-D shape of the reflectors. The recording times varied between 16 and 48 s. SLAVE (Synthetic Large Aperture Velocity Experiment) in 1987 consisted of two ships towing airguns and 3.2 km digital streamers which steamed at constant offset to collect all the ray paths of a 16 km streamer. WIRELINES (West of Ireland Lines) in 1987 comprised 1265 km of reflection profiling crossing Caledonian structures to the northwest of Ireland and the Variscan front off the Shannon estuary. The survey extended a study of the deep crust to the Porcupine Bank, the westernmost part of Europe. Three short lines north of Ireland were designed to provide 3-D control on structures in the mantle and successfully imaged the northward-dipping structure of the Iapetus suture. MOBIL (Measurements Over Basins to Image Lithosphere) in 1987 was an extensive program in the southern North Sea. In addition, four onshore UK seismic recording stations extended the experimental network with wide-angle recordings. The three northern lines were designed to study the Iapetus suture in detail, the southern lines to investigate the gas basins. Finally WISPA (Weardale Integrated S- and P-wave Analysis) in 1988, a 20 km on-land acquisition program, was BIRPS' first onshore deep seismic-reflection experiment (Ward and Warner, 1991). Two crossing lines were shot across the Weardale granite, west of Durham, where in 1986 the British Geological Survey, using vibrators, had obtained good P-wave reflections down to the Moho. The BIRPS project was to provide corresponding S-waves applying a three-hole shooting technique and 3-component recordings. In 1990, the WESTLINE profile crossed the Rockall Trough west of Ireland (England and Hobbs, 1995, Snyder and Hobbs, 1999). It was a 450-km-long, normal-incidence, deep seismic-reflection profile which was shot perpendicular to the edges of the trough in order to image its conjugate margins.

8.3.1.2. ECORS (France)

The French national deep seismic-reflection program ECORS (Etude de la Croûte Continentale et Océanique par Réflexion et Réfraction Sismique) was designed to investigate the deep geology of the continental crust in France and to improve current seismic methodology both in fieldwork and in data processing (Bois et al., 1986, 1989). It aimed in particular to study deep basins which were of prime interest to the participating oil industry. The program started in 1983 and was jointly carried out by the Institut Français de Pétrole, Elf Aquitaine, and the Institut National d'Astronomie et de Géophysique (INAG) and assisted by the Centre National pour l'Exploitation des Océans for offshore operations. The first project in 1983 was cooperation with BIRPS in the Channel as described above (BIRPS and ECORS, 1986).

On land, more than 15 regional lines had been planned across France, of which fieldwork in northern France was completed by 1984 (double hatched line in Fig. 8.3.1-03). This first ECORS profile was 230 km long, and its goal was to study the Variscan belt below the Mesozoic and Tertiary cover of the Paris basin (Figs. 8.3.1-03 and 8.3.1-04). The originality of this first ECORS land profile was its combination of reflection, refraction and wide-angle reflection seismic surveying on the same con-

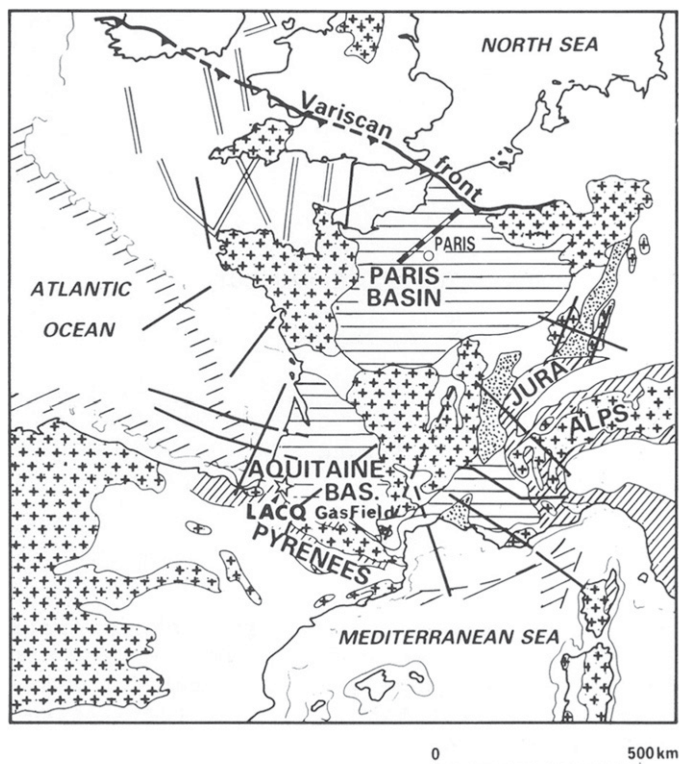

Figure 8.3.1-03. The ECORS project in France (from Bois et al., 1986, fig. 1a). [*In* Barazangi, M., and Brown, L., eds., Reflection seismology: a global perspective: American Geophysical Union, Geodynamics Series, v. 13, p. 21–29. Reproduced by permission of American Geophysical Union.]

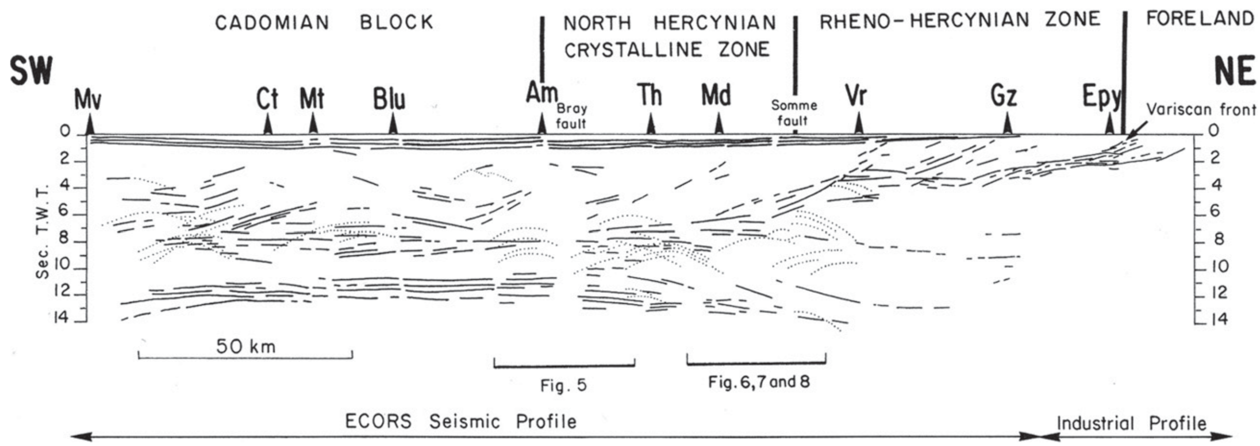

Figure 8.3.1-04. Line drawing of the deep seismic reflection profile in northern France (from Bois et al., 1986, fig. 4). The symbols on top mark borehole positions drilled down to the Paleozoic basement. [*In* Barazangi, M., and Brown, L., eds., Reflection seismology: a global perspective: American Geophysical Union, Geodynamics Series, v. 13, p. 21–29. Reproduced by permission of American Geophysical Union.]

tinuous profile, providing both resolution and velocity data. A 15-km-long geophone spread of 192 traces and 80 m separation recorded both sweeps from heavy vibrators placed every 6.6 m, six explosive shots at offsets of 0, 15, and 30 km on both sides of the spread and two more shots at offsets of 90 and 105 km to the north. Having thus recorded near-angle reflections, direct and reverse refraction data and direct wide-angle reflection data, the 15 km spread moved on and the procedure was repeated. The length of recording was 20 s. In addition, all waves from vibrators and explosive shots were also recorded by portable self-recording INAG stations which were distributed on both sides of the profile with offsets of 90–100 km. A line-drawing of the deep reflection profile in northern France is shown in Figure 8.3.1-04.

In 1984, a seismic-reflection survey was conducted in the Bay of Biscay along the Aquitaine shelf, with participation of FSH Hispanoil. The 300-km-long offshore seismic-reflection line ran in north-south direction (Marillier et al., 1988), and several perpendicularly oriented seismic-refraction lines were added. The long reflection line included a zero-offset and a 7.5 km constant offset vertical seismic-reflection profile and six expanding spread profiles with offsets larger than 100 km. As energy source an airgun array was used with very high energy in the 7–60 Hz frequency range. With a 3000 m streamer a 30-fold coverage was achieved. A second ship behind the first one also recorded the shots with a 2400 m streamer (Pinet et al., 1987).

After the completion of the detailed ECORS line through the Paris Basin, other lines followed in the east and south of France, partly again as international projects. Two profiles traversing the Central European Rift System in the Rhinegraben area will be described below in connection with the German deep seismic-reflection program.

The Bressegraben (Bergerat et al., 1990; Guellec et al., 1990; Truffert et al., 1990) was part of a long-range deep seismic-reflection line starting in the Massif Central and crossing the Alps toward Torino (Bayer et al., 1987), a project which was jointly executed by ECORS and CROP (Crosta Profonda), a deep reflection program initiated by Italian institutions.

The Aquitaine Basin was studied in conjunction with a line through the Pyrenees (ECORS Pyrenees Team, 1988) and extended the above mentioned 1984 line in the Gulf of Biscay onto land.

Overviews of all ECORS activities in the 1980s were published by Bois et al. (1987) and Bois and ECORS Scientific Parties (1991).

8.3.1.3. CROP (Italy)

Crosta Profonda (CROP), the Italian deep seismic-reflection program, was planned between 1982 and 1984 and finally launched in 1986, supported by the Italian National Research Council (CNR) and the two leading companies in the energy sector, ENI-AGIP and ENEL (Bernabini and Manetti, 2003). The main goal of CROP was to investigate the crustal structure of Italy by near-vertical reflection seismic profiling, similar to the seismic-reflection programs in the United States and western European countries. From the very beginning, CROP had two components: onshore and offshore investigations (for location, see Fig. 9.2.3-05). The initial phase lasted from 1985 to 1988 and comprised two land projects in the Alps and one marine project in the western Mediterranean Sea, the second phase with the majority of acquired land and sea profiles was realized in the 1990s (see Chapter 9.2). The data of all acquired land and marine lines were assembled as sections in the CROP Atlas (Scrocca et al., 2003).

The initial phase was focused on the acquisition of crustal seismic profiles in the Alps, in cooperation with working groups from surrounding countries that were working on the same type of projects. The first task was, in cooperation with the French group ECORS (see section 8.3.1.2), to explore the Western Alps on a profile from Torino to Geneva. The fieldwork was carried out in 1986, when the 93-km-long Italian part of the 300-km-long line was recorded, crossing the 2999-m-high Col de la Galise (for location, see Figs. 8.3.1-03 and 9.2.3-05).

The second project was achieved from September to December 1988 in collaboration with the Swiss NFP 20 (see section 8.3.1.4), to explore the Central Alps on three lines in the area of Mount Generoso, Valle dello Spluga, and Val Brembana. In total, 102 km of seismic profiles were recorded.

The third project was the first marine project. In collaboration with ECORS, a seismic profile CROP-MARE I was recorded in the western Mediterranean from the Provence to NW Sardinia across the Sardinian-Balearic-Provencal Basin. It was part of the French-Italian ECORS-CROP project and consisted of a 570-km-long ECORS part and a 210-km-long Italian part, acquired in October 1988. It represents the Italian transect of a discontinuous line linking the continental inner shelf of the Gulf of Lyon and the northwestern Sardinian slope.

The data of all three projects were processed and interpreted by joint working groups and the results presented in crustal cross section along the complete lines. From the interpretation of the data of the ECORS-CROP traverse, two conclusions were drawn: (1) the existence of mantle fragments at different structural levels demonstrated that the mantle was also involved in the orogenesis, and (2) the predominant west-vergence of major crustal discontinuities confirmed that the European plate is being subducted to the southeast in the Western Alps (Bayer et al., 1987; Nicolas et al., 1990; Thouvenot et al., 1990; Roure et al., 1996; Bernabini et al., 2003). The data of the NFP20-CROP profiles through the Central Alps were interpreted jointly with the Swiss colleagues and partly combined with the interpretation of the seismic-refraction data of the European Geotraverse (e.g., Valasek et al., 1991; Ye, 1991; Ansorge et al., 1992). The Italian part contributed especially to the conclusion that the South Alpine upper crust appeared to be rootless and cut off along a basal thrust and could be linked with the south-verging Milano belt, while on the other hand the deeper Adria lithospheric elements wedged northward in the opposite direction into the remnants of the accretionary prism and into the European crust (Montrasio et al., 2003). The Mediterranean traverse indicated the complete absence of a spreading center or ridge in its oceanic sector. The structural pattern of the opposite margins appeared to be asymmetrical (de Voogd et al., 1991; Gorini et al., 1993; Fanucci and Morelli, 2003).

8.3.1.4. Switzerland

Deep seismic-reflection work in Switzerland started in 1982 when a total of 180 km Vibroseis lines were recorded in northern Switzerland to investigate the suitability of the crystalline basement as host rock for the storage of highly radioactive waste. Most of the lines were set up to resolve details in the uppermost 4 s; i.e., the upper crust, but part of the lines was selected for a reprocessing procedure to extend the correlated recording length to a maximum of 14 s (Finckh et al., 1984, 1986). Another, but only shallow detailed reflection survey dealt with the structure of the Swiss Rhône valley (Finckh and Frei, 1991).

The most important project was the project NFP 20 (Swiss National-Fond Project) with activities from 1986 to 1990. In connection with the European Geotraverse project, three deep seismic-reflection lines were established (Fig. 8.3.1-05). They crossed the Swiss Alps in a north-south direction (Heitzmann et al., 1991; Stäuble and Pfiffner, 1991; Valasek et al., 1991). What 20 years of seismic-refraction work in the Alps did not find, the Swiss reflection surveys in the 1980s showed clearly: the European subduction. The program also included the Swiss part of the European Geotraverse refraction program, described in more detail below. The combination of both reflection and refraction seismology contributed essentially to our knowledge of crustal structure and tectonics of the Alps.

Valasek et al. (1991) have outlined a crustal framework based on the initial results of the seismic-reflection profiles across the central Alps. It involves northward indentation of the Adriatic hinterland into the subducting European foreland. This occurs beneath the collapsed oceanic basins of the Penninic allochthon which is defined by highly reflective crystalline nappes. The present crustal thickness within the Alpine collision zone has doubled to ~60 km by both vertical and horizontal displacements along an inferred complex detachment system controlled by the Adriatic wedge. The south-plunging European foreland implies that portions of the thickened crust have been subducted into the upper mantle. Figure 8.3.1-06 shows NFP seismic-reflection data recorded in Switzerland in 1986 and 1988 (Valasek et al., 1991) along the European Geotraverse (EGT). The distances were measured from the seismic-refraction shotpoint E, also shown are locations of EGT shotpoints D and C (shotpoints CE, CD, and AC in Figure 8.3.4-02 in section 8.3.4.3 below).

8.3.1.4. DEKORP (Germany)

In Germany, deep seismic-reflection investigations had been pursued consistently since the end of the 1950s. It had started with long-time recording of oil prospecting reflection seismic investigations (Dohr, 1957, 1972), later specially planned seismic-reflection experiments were carried out in Southern Germany and the Rhenish Massif (Meissner, 1966; Dürbaum et al., 1971; Meissner et al., 1981), and in the mid-1970s a special working group “Deep Reflections” had been established. Following the example of COCORP, finally, in 1983 a ten-year program, DEKORP (Deutsches Kontinentales Reflexionsseismisches Programm = German continental reflection seismic program), was founded and funded by the German Ministry for Research and Technology.

Its basic scientific aim was to explore the deep geology of the German Variscides which had not been touched by commercial reflection seismic investigations (Dürbaum et al., 1997). Basically the Vibroseis technique was to be applied, and only occasionally some explosive sources should be added in particular for piggyback wide-angle investigations. For planning individual projects and their subsequent data interpretation, Regional Working Groups would be responsible, the final decision and application for funding would be made by the DEKORP steering

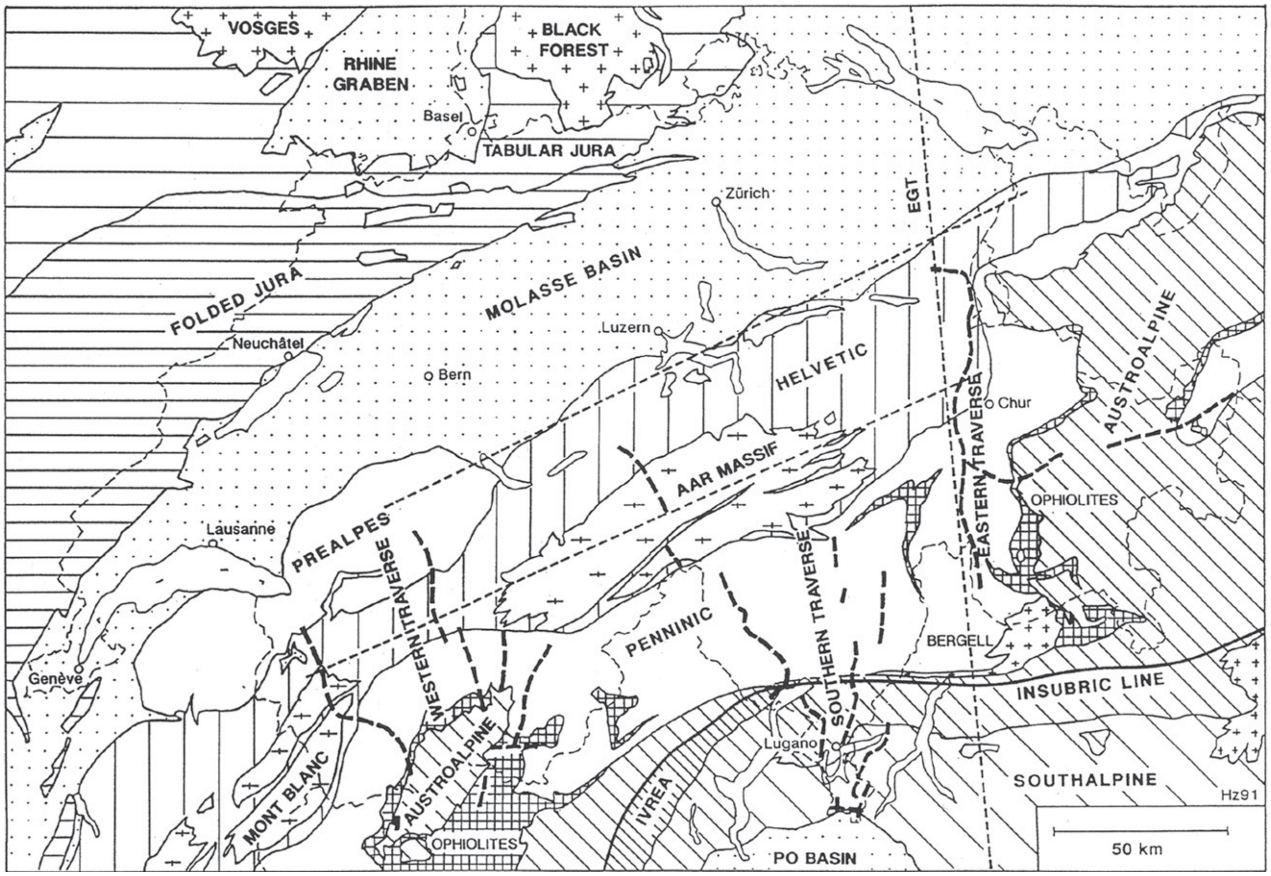

Figure 8.3.1-05. Location map of NFP seismic reflection and refraction profiles recorded in Switzerland in 1986–1990 (from Heitzmann et al., 1991, fig. 1). [*In* Meissner, R., Brown, L., Dürbaum, H.-J., Franke, W., Fuchs, K., and Seifert, F., eds., 1991, Continental lithosphere: deep seismic reflections: American Geophysical Union, Geodynamics Series, v. 22, p. 161–176. Reproduced by permission of American Geophysical Union.]

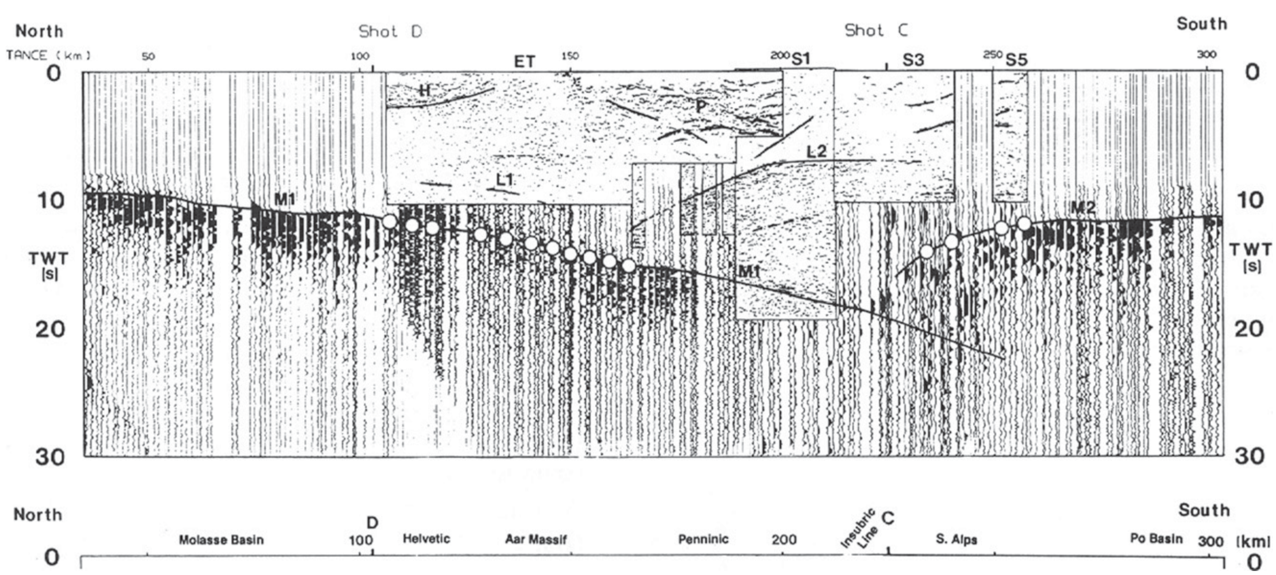

Figure 8.3.1-06. NFP seismic reflection data recorded in Switzerland in 1986 and 1988 (from Valasek et al., 1991, fig. 9) along the European Geotraverse (EGT). Distance measured from seismic-refraction shotpoint E, also shown are locations of EGT shotpoints D and C. [Geophysical Journal International, v. 105, p. 85–102. Copyright John Wiley & Sons Ltd.]

committee, the fieldwork would be submitted to a contractor, and the data would be processed in the DEKORP processing center at the University of Clausthal. Thus, in the following years from 1983 to 1993 a number of long-range seismic-reflection lines were realized (Fig. 8.3.1-07).

In total, seven individual projects were carried out until 1990 (Meissner et al., 1991a, 1991b). The first line, DEKORP-2 South (D2S in Fig. 8.3.1-07), was carried out in 1984. It crossed southern Germany between the rivers Main and Danube (DEKORP Research Group, 1985). In the upper crust down to 5–6 s TWT reflections were limited to occasionally dipping events, which were interpreted as thrusts, mostly marking boundaries between the Moldanubian, the Saxothuringian, and the Rhenohercynian. They transformed into flat-lying reflections when penetrating the lower crust. The lower crust was full of reflecting lamellae, most of them predominantly subhorizontal, which ended abruptly at the Moho. The distance range along which reflections could be correlated was generally less than 4 km (Meissner et al., 1987a).

Following DEKORP 2-S the seismic-reflection profiles K84 in the Black Forest (Lueschen et al., 1987, 1989) were recorded and funded by the KTB (continental deep drilling) project, which will be described in the next section. Also in the framework of KTB, in 1985 the DEKORP-4 line (D4) in northeastern Bavaria was recorded, together with some additional lines KTB 85/1 to KTB 85/6 (K85) around the proposed superdeep drillhole site in the Oberpfalz, and some 90 kg explosions for wide-angle seismics and expanding spread velocity recording (DEKORP Research Group, 1988). Finally, in 1989, a 3-D seismic-reflection survey was added (Dürbaum et al., 1992).

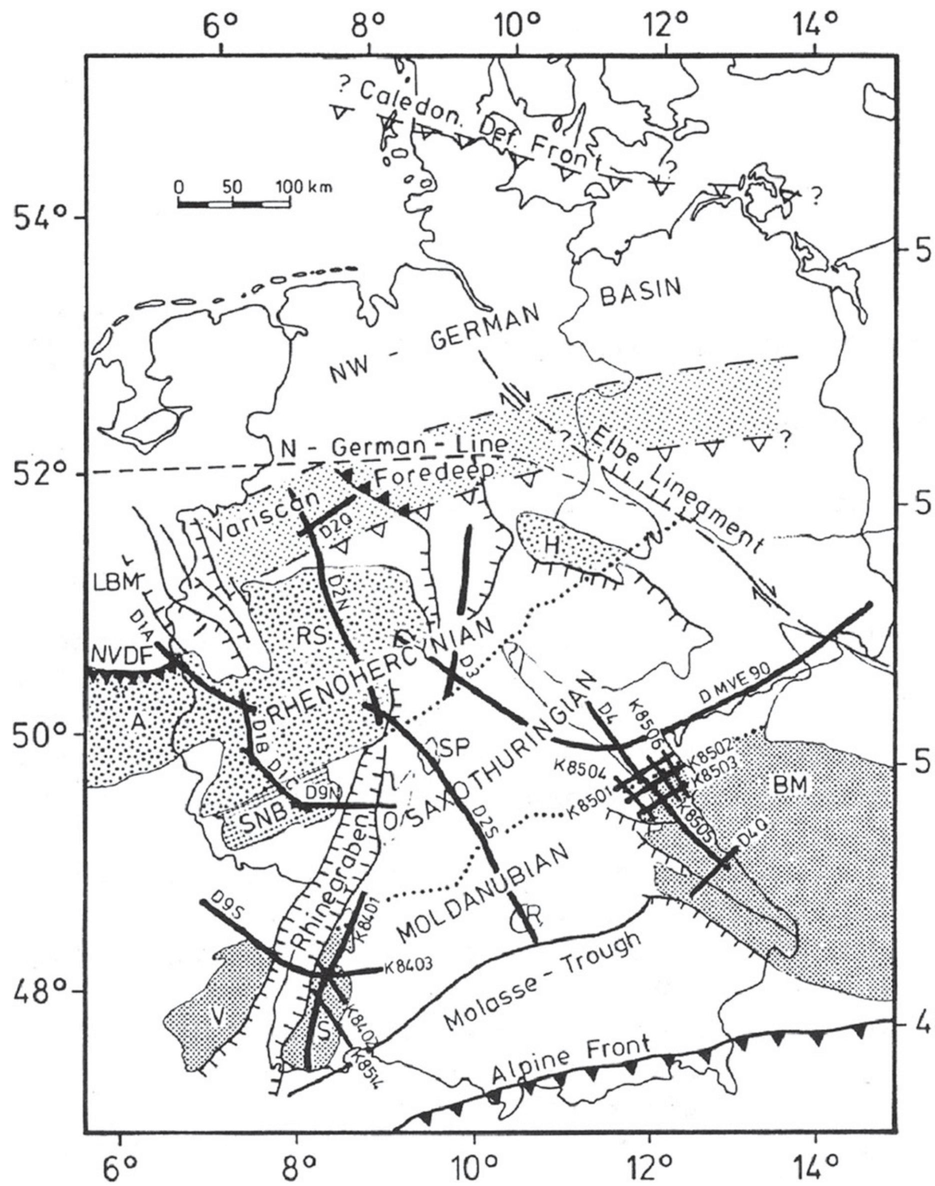

Figure 8.3.1-07. Location map of seismic reflection profiles recorded in 1984–1990 in Germany (from Meissner et al., 1991, fig. 1). D—DEKORP (German continental reflection-seismic program) lines, K—KTB (continental deep drilling) network. [*In* Meissner, R., Brown, L., Dürbaum, H.-J., Franke, W., Fuchs, K., and Seifert, F., eds., 1991, Continental lithosphere: deep seismic reflections: American Geophysical Union, Geodynamics Series, v. 22, p. 69–76. Reproduced by permission of American Geophysical Union.]

Closely connected with the Black Forest KTB profiles, the Rhinegraben and its flanks became the special target of two seismic-reflection lines. Both lines were cooperative projects with ECORS. DEKORP-9 South (D9S) traversed the southern Rhinegraben near Strasbourg where both Vibroseis technique and borehole shots were applied (Brun et al., 1991). DEKORP-9 North (D9N), starting in the Odenwald, traversed the Rhinegraben near Worms and led into the Saar-Nahe trench (Wenzel et al., 1991). Under the flanks of the Rhinegraben, the lower crust was characterized by strong reflectivity interpreted as a layered lower crust. The Moho was marked as a strong reflector at ~8 s below the eastern flank and the graben, but its depth increased gradually to the west to ~10 s TWT. East-dipping reflectors in the middle crust were attributed to Variscan features. In general, the Rhinegraben proved to be markedly asymmetric (Brun et al., 1991).

DEKORP-9 North (D9N) connected with DEKORP-1 (D1A–D1C) in the Saar-Nahe trench. DEKORP-1 crossed the Rhenish Massif west of the Rhine and the Aachen-Midi thrust zone and led as BELCORP line, organized by the Belgian Geological Survey, into southeastern Belgium (DEKORP Research Group, 1991). The aim of this 220-km-long line was to investigate the crustal structure of the western part of the Rhenish Massif. The results indicated the presence of NW-vergent tectonics of various styles which could often be traced into deeper parts of the crust. For the northern part Variscan compression playing a dominant role was inferred, while post-Variscan extension was seen to dominate in the Saar-Nahe trough. In the north, a deep extension of the Aachen thrust (Faille du Midi) was clearly observed. This prominent thrust with its characteristic ramp and flat structure could be followed over a distance range of 100 km down to 15 km depth. It contrasted sharply with the very complex deep fault system in the south, separating the post-orogenic Saar-Nahe trough from the Hunsrück Mountains (DEKORP Research Group, 1991).

East of the Rhine, the line DEKORP-2 North (D2N) was realized, traversing the Rhenish Massif and the Münsterland basin to the north (data example in Fig. 8.3.1-08), supplemented by DEKORP-2 NQ (D2Q), a perpendicularly oriented line (Franke et al., 1990). This line revealed an almost complete cross section through the Rhenohercynian zone. In the upper crust, many strong south-dipping reflections could be correlated with thrust faults known from surface geology. At depth, the thrusts flatten out in a relatively transparent zone between 3 and 5 s TWT. This zone could be correlated with high-conductivity layer detected in a magnetotelluric survey (Jödicke et al., 1983). The lower crust is relatively transparent in the north, but farther south, it is increasingly reflective, consisting of curvilinear thrust-related reflections which are cut by a conjugate set of weaker N- and S-dipping reflectors. The Moho was found to rise from north to south from ~11 to 8.5 s TWT (Franke et al., 1990).

Finally, in 1990, DEKORP-3 (D3) was realized, traversing the Hessen depression from Göttingen to the Main River in

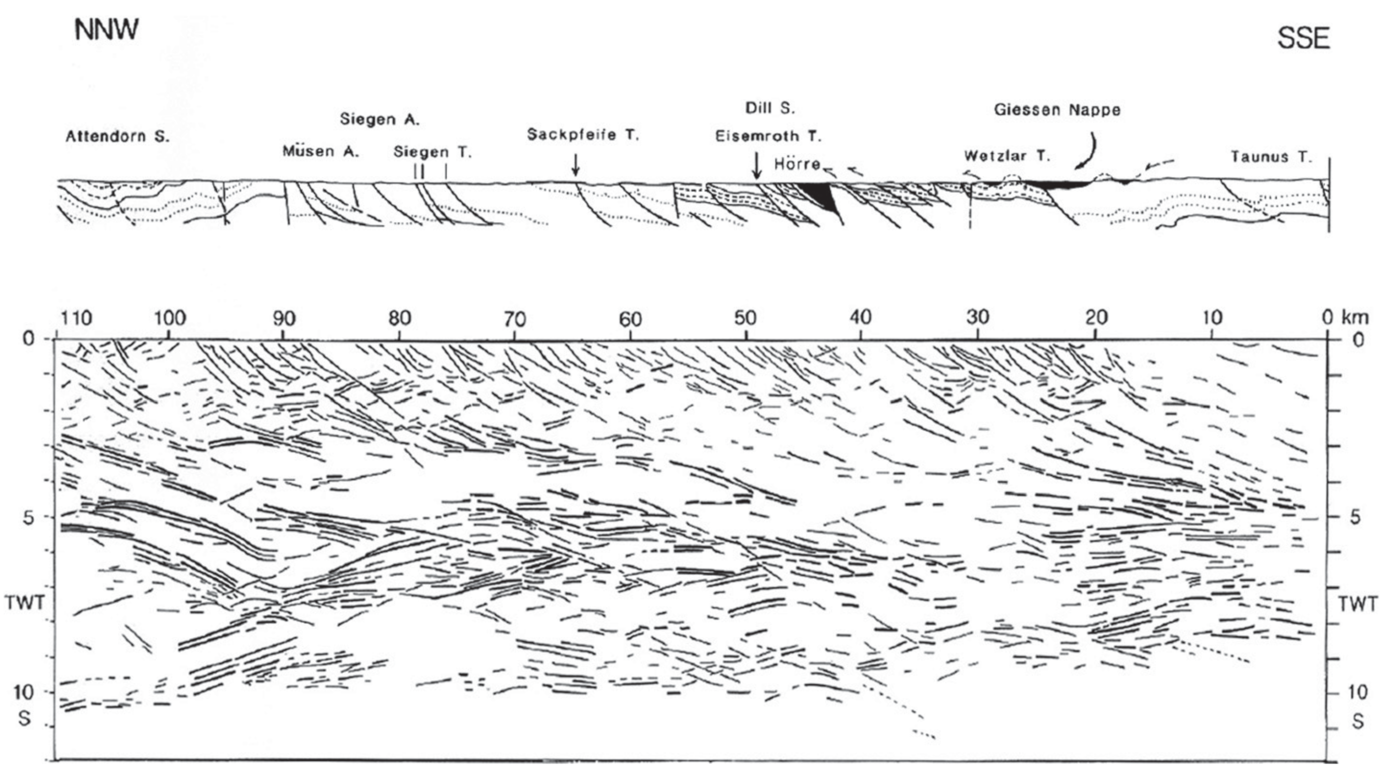

Figure 8.3.1-08. Line drawing of part of the deep seismic reflection profile DEKORP-2 North in western Germany (from Franke et al., 1990, fig. 6). [Geologische Rundschau, v. 79, p. 523–566. Reproduced with kind permission of Springer Science+Business Media.]

a north-south direction and then bending toward the east-north-east, to be continued as DEKORP-MVE-90 line D MVE90) into eastern Germany traversing the gneiss massif of Münchberg, the earthquake swarm area of the Vogtland and the Erzgebirge north of the Czech-German border (DEKORP Research Group, 1994). This line will be discussed in Chapter 9.2.2.

Based mainly on the dense deep-seismic network of DEKORP, Meissner and Sadowiak (1992) discussed the terrane concept as an important extension of plate tectonics and applied it successfully to the Variscides with their wide range of collisional belts. The DEKORP data reveal certain reflectivity patterns and enable to map old and new deep fault zones between the Variscan terranes which seem to consist of continental crust only, partly exclusively of rigid upper crust, and which are rooted in the ductile lower crust (Meissner and Sadowiak, 1992).

A systematic comparative study of the reflectivity of the continental crust was undertaken by Sadowiak et al. (1991), using all deep seismic-reflection data available in western, northern, and central Europe until 1988 (see Fig. 2.8-01). At almost all seismic-reflection profiles of BIRPS, ECORS, and DEKORP, as far as they were recorded over Caledonian and Variscan basement, the Moho is clearly identified as the lowest boundary of the laminated lower crust. They observed that the reflectivity changed dramatically from one seismic line to the next, and they classified the different seismic reflectivity patterns and established correlations between these seismic patterns and specific tectonic units. Lamellae and bands of reflections in the lower crust were widespread in post-orogenic extensional areas, "crocodiles" seemed to represent compressional zones that were occasionally accompanied by duplex structures. The "fishbone" pattern, consisting of many "crocodiles" was characteristic for the old London-Brabant Massif. The "ramp and flat" structure displayed a thin-skinned tectonics of the North Variscan Deformation Front over a length of 2000 km. Diffraction clusters in the lower crust accompanied by a dipping reflection in the upper crust was observed close to thick-skinned deformation fronts. Diffractions were also present in rift zones as in the North Sea. Some regions, where a decreasing reflectivity with depth, a concentration of reflections in the upper crust, and no Moho reflections were observed, were correlated to areas with Precambrian crust (Sadowiak et al., 1991).

A later review of the seismic-reflection profiles throughout central Europe was prepared by Meissner (2000) where he discusses the various reflectivity patterns and strongly varying characteristics with respect to the crustal evolution of central Europe by collision and collapse of continental terranes, considering the whole area of Western and Central Europe as a continental margin. In a similar way, England (2000) discusses the extensive grid of BIRPS offshore deep seismic-reflection profiles over the North Sea and the continental margins of Northwest Europe.

8.3.1.6. Czechoslovakia

Two deep seismic-reflection lines were observed in the 1980s in Czechoslovakia. One profile was 60 km long and was recorded through the Vienna and Pannonian basins in a NW-SE direction nearly parallel to the Austrian-Hungarian border, crossing the Little Carpathians north of Bratislava. The other profile ran through the Inner West Carpathians in a NNW-SSE direction from the Polish to the Hungarian border and consisted of two ~60-km-long parts. Cross lines were also recorded. All shots were dynamite charges. A 96-channel recording system was used with 50 m spacing on the western line and 80 m on the eastern line producing central offsets up to 2.4 km in the west and 3.8 km in the east. On both lines nominal 24-fold data resulted. Standard processing procedures, as described in the introduction above were applied.

The Czech profiles through the West Carpathians were the first systematic deep survey within the whole active Alpine-Himalayan mountain belt using near-incidence vertical seismic-reflection techniques (Tomek et al., 1987). On the western line, deep reflections up to 11.5 s were recorded underneath the Little Carpathians north of Bratislava, while at the southeastern end in the Danube Basin slightly westward dipping events at 10–11 s were observed. From the line through the Inner West Carpathians, only the northern portion was published by Tomek et al. (1987). The upper crust appeared highly reflective along the whole line. Underneath the northernmost 20 km section of the line also the lower crust between 7 and 12 s TWT was highly reflective expressed by a band of strong reflectors dipping southward. Farther south, the middle and lower crust were almost featureless; only at the southern end, under the center of the Carpathians, a short band of reflections appeared again from ~9–12 s TWT dipping in the reverse direction.

8.3.1.6. BABEL (Scandinavia)

Finally, in 1989 an international large-scale seismic-reflection experiment, BABEL (Baltic and Bothnian Echoes from the Lithosphere), was carried out as a joint venture by British, Danish, Finnish, German, and Swedish scientists from 12 research institutions in the Baltic Sea and the Gulf of Bothnia, parallel to the FENNOLORA (Fennoscandian Long Range Project) seismic-refraction survey of 1979 (BABEL Working Group, 1991, BABEL Working Group, 1993a, 1993b). It consisted of nine marine deep seismic-reflection profiles totaling 2268 km of high-quality data and formed a 1350 km traverse from the edge of the Archean nucleus to Phanerozoic western Europe. Lines 1–7 and line C (Fig. 8.3.1-09) followed more or less the Gulf of Bothnia, while lines B and A were planned parallel to the direction of the southeastern coasts of Sweden and Denmark. The BABEL lines were all located on the Precambrian Baltic Shield, with the exception of Line A which crossed the Tornquist Zone (TZ in Fig. 8.3.1-09) near Bornholm Island and continued into the North German Basin, underlain by Caledonian basement. In the same year (1989), the Institute of Oceanology of the Russian Academy of Sciences organized a 480-km-long profile, running NNE from the Bay of Gdansk ~50–100 km off the coast of the Baltic states and nearly parallel to the line B of the BABEL survey (Ostrovsky, 1993). The seismic signals of a powerful airgun (120 L) were recorded at five points by ocean-bottom seismometers equipped with hydrophones.

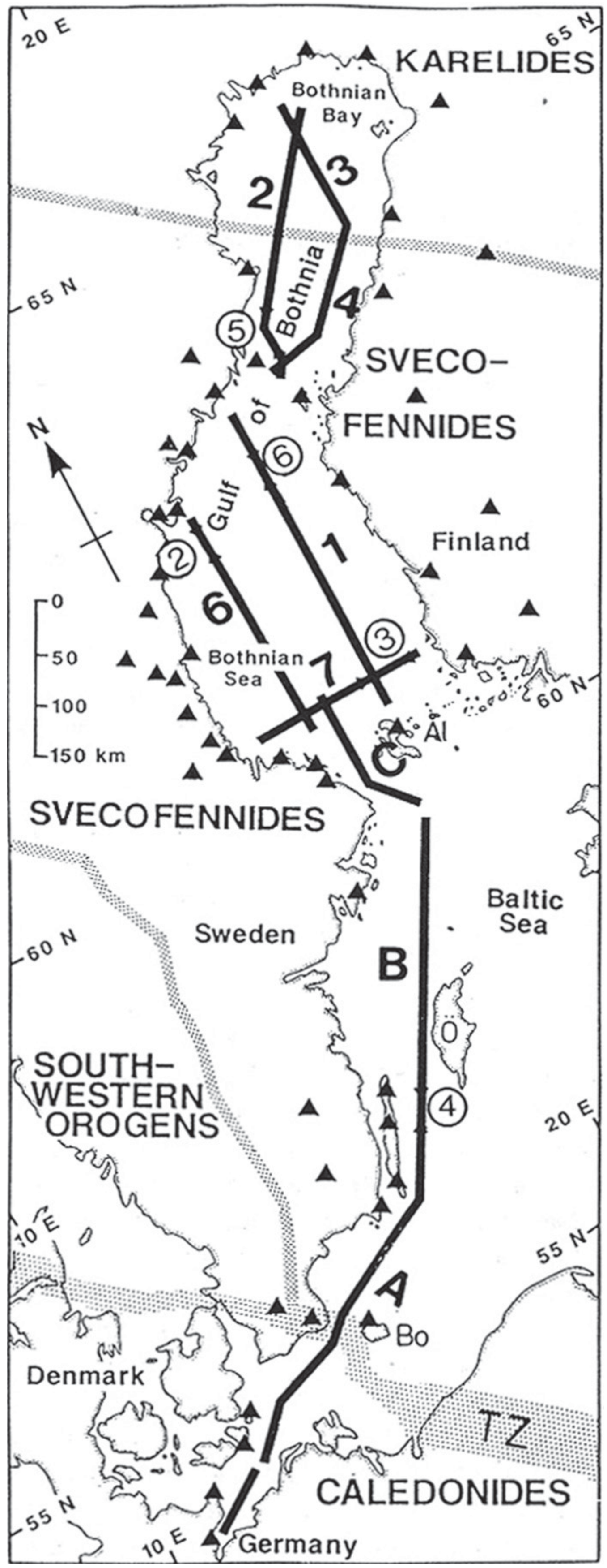

Figure 8.3.1-09. Location map of seismic reflection profiles of BABEL (from BABEL Working Group, 1991, fig. 1). Thick lines—reflection profiling; triangles—seismometer arrays or stations, stippled patterns—tectonic boundaries. A1—Aland islands, Bo—Bornholm island; Ö—Öland island; TZ—Tornquist Zone. [*In* Meissner, R., Brown, L., Dürbaum, H.-J., Franke, W., Fuchs, K., and Seifert, F., eds., 1991, Continental lithosphere: deep seismic reflections: American Geophysical Union, Geodynamics Series, v. 22, p. 77–86. Reproduced by permission of American Geophysical Union.]

The BABEL survey not only acquired deep seismic-reflection data, but provided also coincident refraction/wide-angle reflection data to study the crustal structure of the Baltic Shield and its transition to the Phanerozoic crust of western Europe across the Tornquist Zone. For this purpose the 12-l airgun array used for this profiling was also recorded by 64 land stations to provide coincident refraction profiles, fan-spreads and 3-D seismic coverage of much of the Gulf of Bothnia and the Baltic Sea area adjacent to southern Sweden and Denmark.

Shot-to-receiver offsets ranged from 200 m to 350 km. In one case, even offsets of up to 700 km proved successful. The near offsets of 200–3200 m were used for traditional deep seismic profiling with specifications which the British BIRPS group had developed over the years. So, hydrophone groups in a 3-km-long streamer were towed behind a seismic vessel which produced a multiplicity of coverage up to 24-fold. The far offsets were obtained using the airgun array towed from the ship as the seismic source and recording on land at 64 points around the Gulf of Bothnia and the Baltic Sea. The geometry of the coastlines and islands allowed some land stations to be located on sites which were at each ends of offshore seismic lines and so provided a reversed refraction profile. In other cases, fan observations resulted. The success of the survey was based on the short shot-spacing of 62–75 m that made the resulting high-density profiles so effective. A great diversity of types of seismometers and geophone configurations was used on land, ranging from three-component seismometers with 1–2 Hz geophones to single-component outstations connected with a central recording site to linear arrays with 48 vertical seismometer groups at 50 m spacing recorded as traditional land array data for stacking.

In the Bothnian Bay (for locations, see Fig. 8.3.1-09), a south-dipping, non-reflective zone was seen to coincide with a conductive Archean-Proterozoic boundary onshore in Finland. Between the Bothnian Bay and the Bothnian Sea observed reflectivity geometries and velocity models reaching Moho depths suggested structures inherited from a 1.9 Ga subduction zone, the upper crust having anomalously low velocities. From wide-angle reflections, the metasedimentary crust of the Bothnian Bay seemed to be 10 km thicker than the adjacent Svecofennian subprovinces.

The line drawing of line A (Fig. 8.3.1-10) shows a variable character of deep reflections. South of the Tornquist Zone, a band of reflections is clearly visible in the lower crust, while the crust north of Tornquist Zone is dominated by diffractions. In

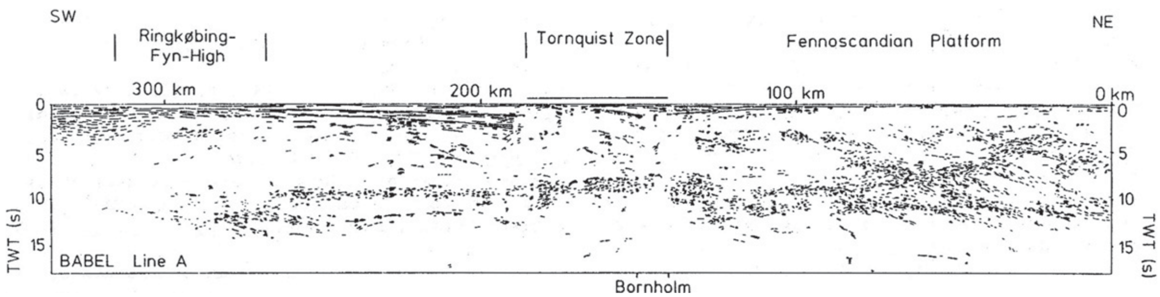

Figure 8.3.1-10. Line drawing of BABEL profile A (from BABEL Working Group, 1991, fig. 7). The line extends from the Caledonian German-Danish Basin in the SW across the Tornquist Zone (TZ) near Bornholm island into the Fennoscandian Platform in the NE. [*In* Meissner, R., Brown, L., Dürbaum, H.-J., Franke, W., Fuchs, K., and Seifert, F., eds., 1991, Continental lithosphere: deep seismic reflections: American Geophysical Union, Geodynamics Series, v. 22, p. 77–86. Reproduced by permission of American Geophysical Union.]

the shield parts of the profiles northeast of the Tornquist Zone, the Moho was found between 40 and 48 km, corresponding to 12–15 s TWT. From the wide-angle data, a three-layer crust was deduced with velocities of ~6.1–6.4, 6.6, and 6.9–7.2 km/s. South of the Tornquist Zone, a highly reflective lowermost crust between 8 and 10 s TWT corresponded to a depth range of 25–31 km and a high velocity gradient (6.7–7.1 km/s), but the wide-angle data did not show evidence for intracrustal discontinuities. The Ringkoebing-Fyn basement high could also be located in the data, and the crust underneath the North German lowlands was found underneath 10-km-thick post-Caledonian sediments, being 20 km thick with velocities between 6.0 and 6.9 km/s.

8.3.2. Seismic-Refraction Studies in the British Isles and Ireland

As mentioned above, when discussing the deep seismic-reflection surveys of BIRPS, the continental region of the British Isles includes the onshore regions of the British Isles as well as the stretched continental crust beneath the adjoining seas including the North Sea. Purely offshore marine surveys on the Northeast Atlantic margin to the south and west of Ireland, however, we will discuss in the section 8.9.4 (Atlantic Ocean).

In 1980 and 1981, a wide-angle offshore seismic line was shot across the Central Graben of the North Sea running from southern Scotland toward the southern tip of Norway. The location of its central part is identical with the location of the BIRPS line SALT (see Fig. 8.3.1-01). The object of the project was to test the lithospheric stretching model for the formation of sedimentary basins (MacKenzie, 1978). An array of twelve pull-up shallow-water seismometers was laid in the Central Graben and shots were fired in a line perpendicular to the axis of the basin (Barton and Wood, 1984; Barton, 1986). The data were analyzed using ray-tracing and amplitude modeling of the seismograms described in detail by Barton and Wood (1984). A model of the crust was developed with 2-D variations in both seismic velocity and structure. Seismic gradients were simulated by dividing the model into 1 km^2 elements, each of which contained a single velocity value. The model, containing ~20,000 such elements, was well constrained by the numerous crossing ray paths which connected twelve shots and twelve seismometers. The velocity-depth-distance model was then converted to a normal incidence TWT profile of the Moho. Traveltimes were calculated by integrating the traveltime contributions from each of the constant velocity elements vertically from the surface to the Moho and back. The data were then compared with the two deep normal incidence BIRPS profiles SALT mentioned above in section 8.3.1.1 which were recorded along the seismic-refraction line, each being 70 km long and 15 s deep. The experiment proved that the time-converted Moho trace from the wide-angle model falls clearly at the base of the layering in the lower crust.

In the southwest of Scotland, the Western Isles Seismic Experiment of 1979 (see Chapter 7.2.4) was continued in 1981. Explosive and airgun shots were recorded along a second profile between Mull and Kintrye aiming to map the Lewisian basement from the foreland to the Caledonian mountain belt (Summers et al., 1982).

In 1984, using two 90-km-long seismic-refraction lines, MAVIS (the Midland Valley Investigation by Seismology) aimed to study the structure of the Carboniferous basin of West Lothian in the Midland valley of Scotland (Conway et al., 1987; Dentith and Hall 1990). The data revealed details of the Paleozoic trench sequence and the depth to basement, but did not penetrate into deeper levels of the crystalline crust.

In 1982, under the direction of Martin Bott, a British long-range seismic-refraction experiment of the University of Durham in 1982 aimed to study the crustal structure underneath the Caledonian suture zone separating Variscan from Caledonian basement in northern England with very closely spaced shots and stations (Bott et al., 1983, 1985). Their line, named CSSP (Caledonian Suture Seismic Project) started in the North Sea, crossed the north of England and ended with a line of shots terminating in the Irish Sea near the coast of Ireland (Fig. 8.3.2-01). It was a unique sea-to-land wide-angle explosion seismology project that produced data of unprecedented quantity and quality. The principal innovation was the use of closely spaced shots, mainly at sea, and closely spaced stations, mainly on land, yielding a data

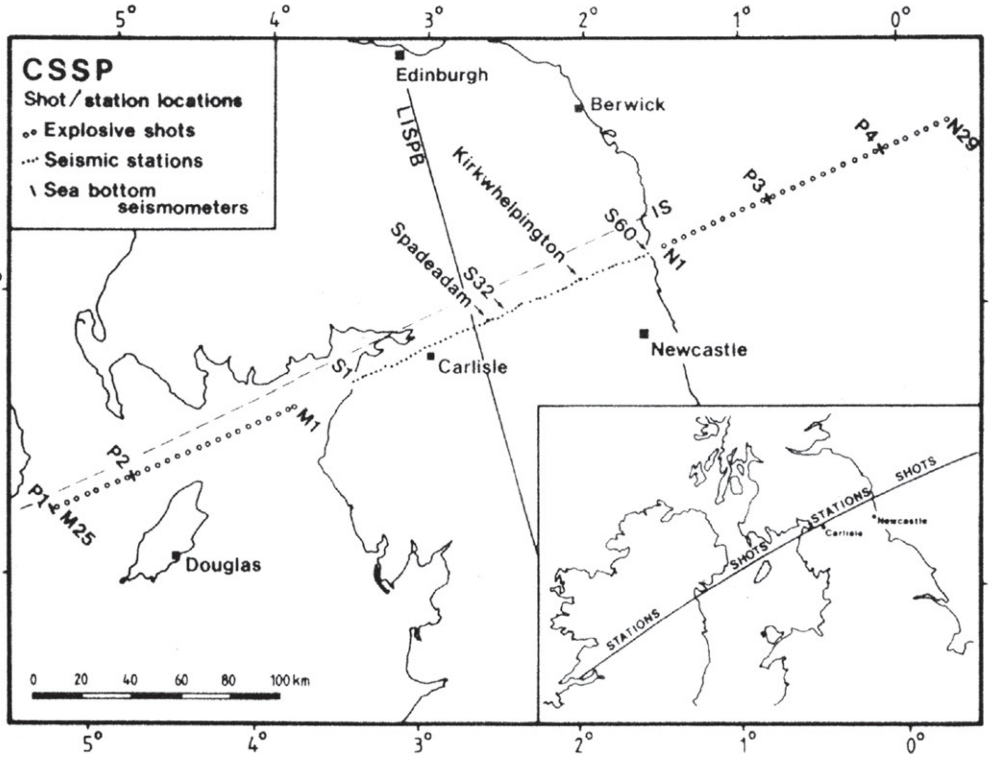

Figure 8.3.2-01. Location map of Caledonian Suture Seismic Project (CSSP) (from Bott et al., 1985, fig. 1), also showing the LISPB line of 1974 (see Chapter 7). [Nature, v. 314, no. 6013, p. 724–727. Reprinted by permission from Macmillan Publishers Ltd.]

set that permitted arrangement of the data in a variety of ways for phase correlation and modeling, such as in constant offset and common mid-point displays.

The results for this region differed radically from those of the earlier LISPB experiment (Bamford et al., 1978). The data allowed recognizing a well-defined pre-Caledonian metamorphic basement beneath most of the line at relatively shallow depth (Fig. 8.3.2-02). A well-defined mid-crustal refractor was also detected at ~16 km depth beneath the North Sea and northern England which was not recognized beneath the Irish Sea (Bott et al., 1985). Al-Kindi et al. (2003), concentrating on the lower crust beneath the Irish Sea, remodeled the data and identified a

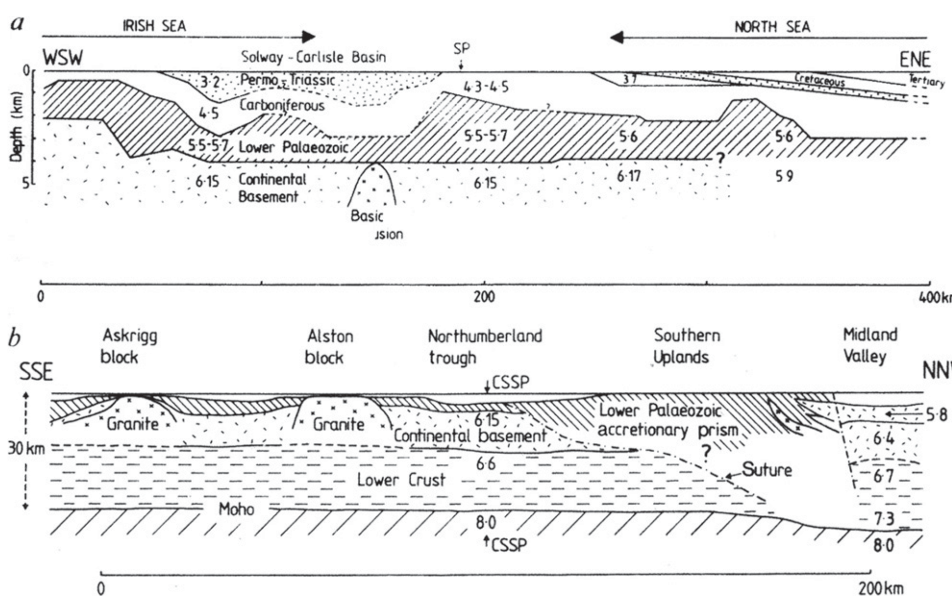

Figure 8.3.2-02. Crustal structure along the Caledonian Suture Seismic Project (CSSP) line through Northern England (from Bott et al., 1985, fig. 4). *a*—shallow crustal structure, *b*—speculative cross section through northern England, perpendicularly crossing the CSSP line. Crustal structure under the Midland Valley is from LISPB (Bamford et al., 1978). [Nature, 314, no. 6013, p. 724–72. Reprinted by permission from Macmillan Publishers Ltd.]

high-velocity crustal layer. They interpreted this layer as underplate resulting from a mantle thermal anomaly and causally related to Cenozoic uplift beneath this part of the British Isles.

The shots of the British CSSP project motivated Brian Jacob at the Dublin Institute for Advanced Studies (DIAS) to plan the first seismic crustal profile through Ireland. The CSSP line of shots in the Irish Sea was extended toward the southwest by the University of Durham to include five widely spaced shots with the outermost shot as close as possible to the Irish coast. This provided a starting point for the 250-km-long line of recording stations through Ireland along the Caledonian strike and roughly parallel to the postulated Caledonian suture zone (Appendix A2-1, p. 60–61). In total, there were 31 CSSP shotpoints in the Irish Sea. At the southwestern end of the line, the Irish group fired two additional shots in the Shannon river estuary and off the coast. These were small dispersed (50–100 kg) offshore shots (one at optimum depth) from which seismic energy was recorded at distances of almost 200 km. A quarry in the southwest of Ireland was also used as an additional shotpoint (Jacob et al., 1985). A total of 51 instruments from DIAS, Ireland, and Karlsruhe University, Germany, were deployed at 5 km spacing parallel to the postulated trace of the suture zone (Fig. 8.3.2-03).

The majority of the data is displayed in Appendix A2-1 (p. 60–61). The middle and lower part of Figure 8.3.2-04 demonstrate that the crustal structure is well constrained by the good coverage of shotpoints and recording stations.

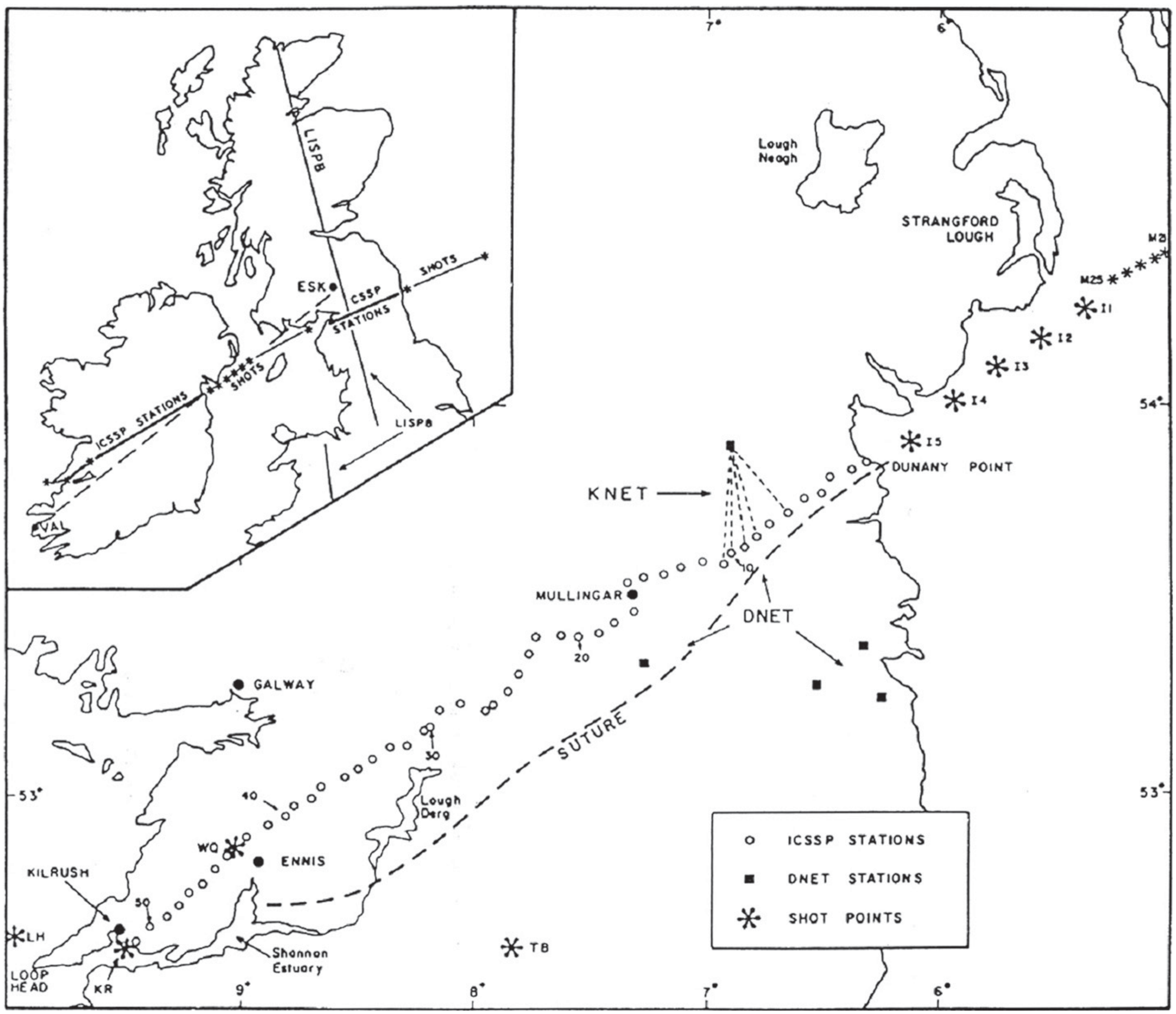

Figure 8.3.2-03. Location map of the Irish Caledonian Suture Seismic Project (ICSSP) project of 1982 (from Jacob et al., 1985, fig. 1). [Tectonophysics, v. 113, p. 75–103. Copyright Elsevier.]

This first seismic project in Ireland was soon to be followed by major activity to study the crust underneath Ireland and its surrounding seas. Figure 8.3.2-05 summarizes all seismic crustal observations in and around Ireland from the 1960s to the end of the 1990s.

In 1985 the Caledonian Onshore-Offshore Lithospheric Experiment (COOLE) was organized (Appendix A2-1, p. 62–63). It consisted of two separate seismic-refraction studies carried out onshore and offshore southern Ireland. The onshore part consisted of a 280-km-long N-S profile (COOLE'85-1 in Fig. 8.3.2-05) stretching from the southern coastline across the Irish Midlands up to Donegal Bay (Lowe and Jacob, 1989). A total of 6 shots was recorded by 59 seismic receivers deployed at ~3 km spacing. The profile was approximately perpendicular to the ICSSP profile of 1982 and the proposed surface trace of the suture zone. The main objectives of this project were to investigate the crustal structure across the suture zone and to provide seismic control for the very dense gravity data onshore Ireland.

The offshore study of the COOLE experiment concerned the investigation of the Celtic Sea to the southwest of Ireland. This will be discussed in more detail together with other offshore experiments in the subchapter 8.9.4, Atlantic Ocean.

In 1987, a 2-ton explosive source which was fired in the North Sea off Scotland, was recorded in southeastern Ireland on the so-called BB 1987 profile (BB'87 in Fig. 8.3.2-05) oriented in a SSW direction (Bean and Jacob, 1990; Jacob et al., 1991). Combined with the far distant shots of the CSSP project recorded along the ICSSP line in Ireland, a long-range line of ~600 km length resulted.

Thus together with the LISPB observations (Faber and Bamford, 1979), three long-range and intersecting refraction profiles resulted in Ireland and Britain which provided detailed information about the velocity-depth structure of the lower lithosphere and sampled the upper mantle along different azimuths. The observation that upper-mantle velocities were different for the CSSP and LISPB profiles, and that P-wave velocities of 8.6 km/s at 85 km depth were well in excess of the predicted isotropic velocities of 7.85 km/s (taking 80% olivine, 20% pyroxene and a calculated geotherm for the region), led Bean and Jacob (1990) to the conclusion that seismic anisotropy should be present in the lithospheric mantle.

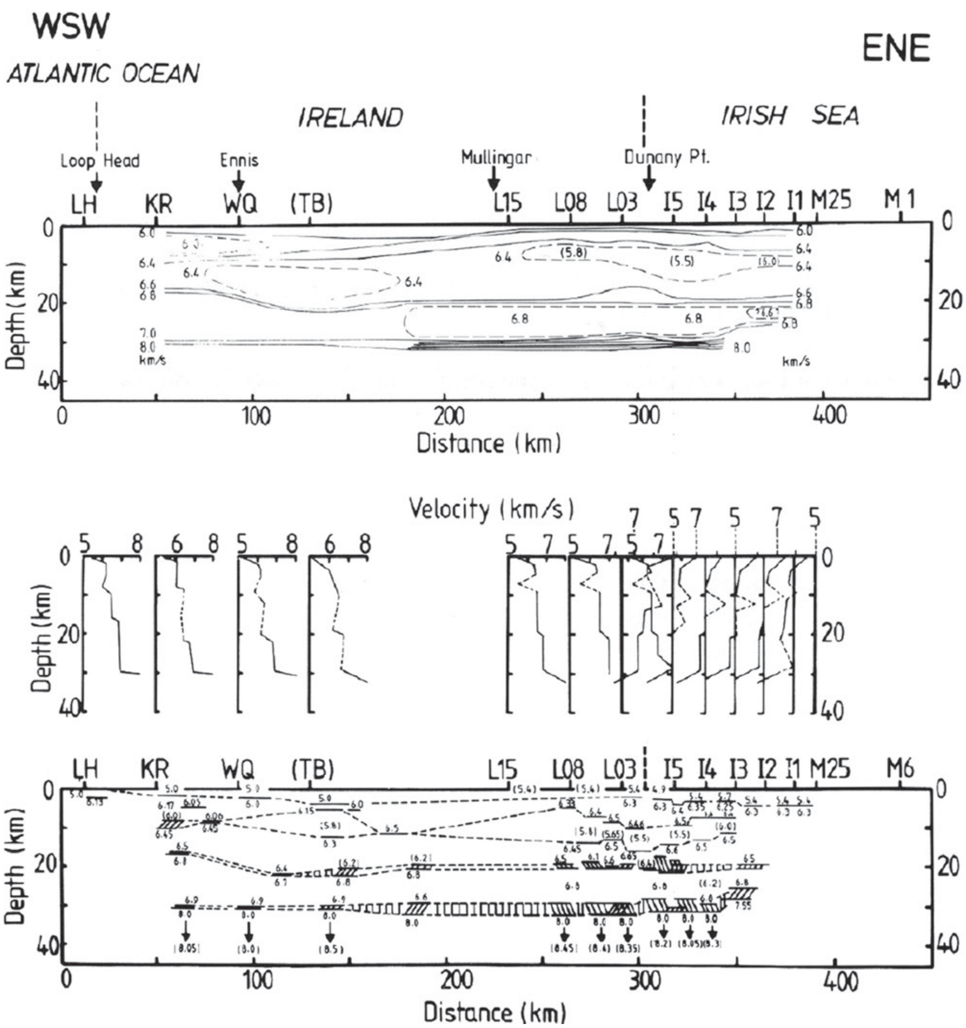

Figure 8.3.2-04. Crustal cross section resulting from the ICSSP project of 1982 (from Jacob et al., 1985, fig. 8). Upper part: Cross section with lines of equal velocity, middle part: 1-D velocity-depth functions, lower part: Position of zones where crustal reflected phases originate. [Tectonophysics, v. 113, p. 75–103. Copyright Elsevier.]

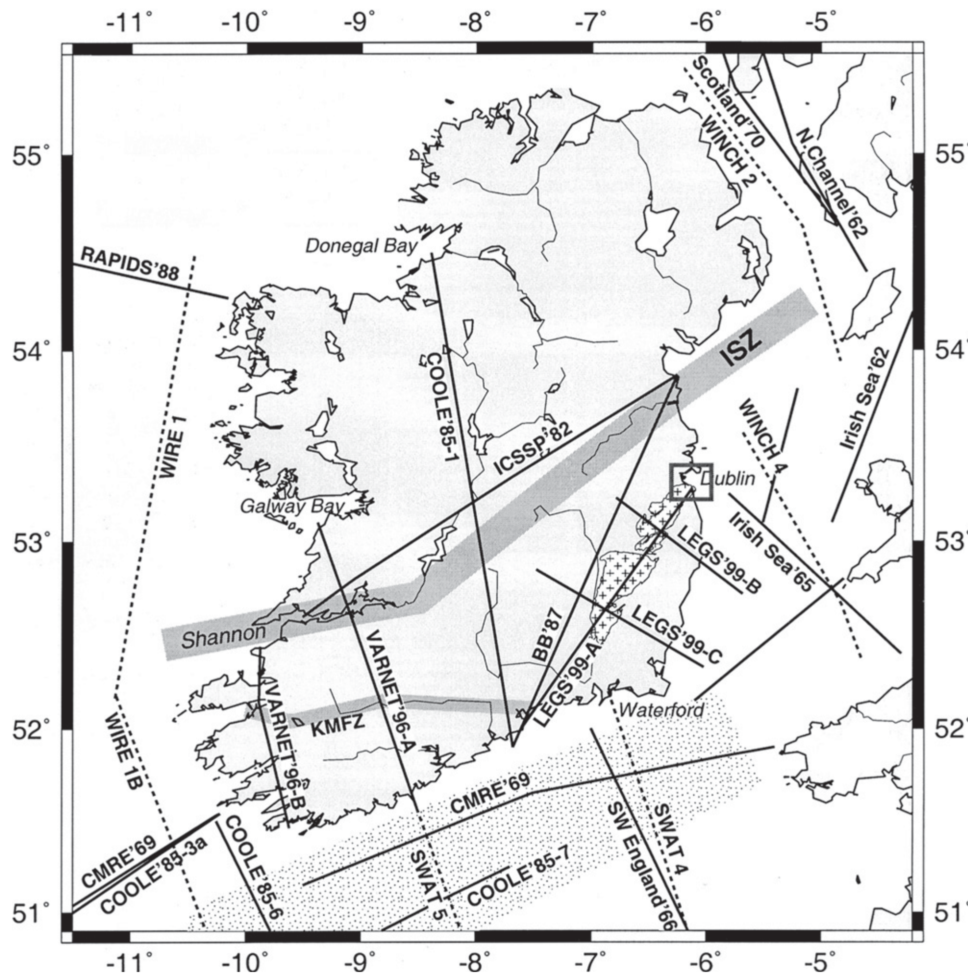

Figure 8.3.2-05. Seismic refraction and reflection profiles onshore/offshore Ireland recorded in the period of 1969–1999 (from Landes et al., 2005, fig. 1). Full lines: Irish Sea 1962, 1965 (Willmore, 1973), SW England 1966 (Willmore, 1973), CMRE 1969 (Bamford, 1971), ICSSP 1982 (Jacob et al., 1985), COOLE 1985 (Makris et al., 1988; Lowe and Jacob, 1989; O'Reilly et al., 1991), BB 87 RAPIDS 1988 (O'Reilly et al., 1995), VARNET-1996 Lines A and B (Landes et al., 2000; Masson et al., 1998), LEGS 1999 Lines A, Band C (Hodgson, 2001). Dashed lines: normal incidence reflection data by BIRPS: WIRE, WINCH, SWAT (Klemperer and Hobbs, 1991). Shaded: proposed locations of the Iapetus Suture Zone and the Killarney Mallow Fault Zone (ISZ, KMFZ). Dotted area offshore southern Ireland represents outlines of the North Celtic Sea Basin. Area with crosses in SE Ireland resembles surface outcrop of the Leinster Granite batholith (modified after Hodgson, 2001). [Terra Nova, v. 17, p. 111–120. Copyright Wiley-Blackwell.]

8.3.3. The German Deep Drillhole Project KTB

Following the successful completion of the super-deep drillhole KOLA SG3 which was located on the Baltic Shield of Russia and had penetrated 11 km of pre-Cambrian crust on the Kola peninsula (Kozlovsky, 1988), another super-deep drillhole project was planned. In 1981, the German geoscientific community started a similar project to unravel the petrology of the uppermost 10–15 km of the Hercynian crust in central Europe (Emmermann and Wohlenberg, 1989). A first funding for pre-investigations was provided in late 1981 and the active drilling and interpretation phase lasted from 1986 to 1996. At its first planning stage four locations were taken into consideration, but it was soon decided that the efforts of detailed seismic and other geophysical pre-investigations should be concentrated on two regions only: the central Black Forest around Haslach, and the Oberpfälzer Wald near Windischeschenbach, a small village close to the Czech border (Emmermann and Wohlenberg, 1989). In both areas, detailed seismic-refraction and seismic-reflection surveys were undertaken, partly within the framework of DEKORP, which will be discussed in more detail below.

8.3.3.1. Black Forest Location

For the Black Forest, a north-south line of 170 km in length was chosen following more or less the axis of the mountain range. Both a long-range near-incident seismic-reflection line (Lueschen et al., 1987, 1989) and a detailed seismic-refraction line (Gajewski and Prodehl, 1987; Gajewski, 1989) were planned and carried out (line S in Fig. 8.3.3-01). For logistical reasons, the refraction (full line with shotpoints S1 to S5) observations (Gajewski and Prodehl, 1987; Gajewski, 1989) were not completely coincident with the reflection line (double dashed lines), but workers made sure that the depth penetration of both surveys covered the same area. The favored proposed drill location was located near Haslach (about half-way between shotpoints S2 and S3 in Fig. 8.3.3-01) in the central part of the Black Forest within the central Black Forest gneiss complex. The reflection survey, organized by Ewald Lueschen, therefore included two side lines which crossed the main line in the area where the deep drillhole might be located, and where the W-E–directed side line connected with the Urach reflection survey of 1978 (Bartelsen et al., 1982) east of the refraction line Z. The goal of the second NW-SE–directed side line further south was

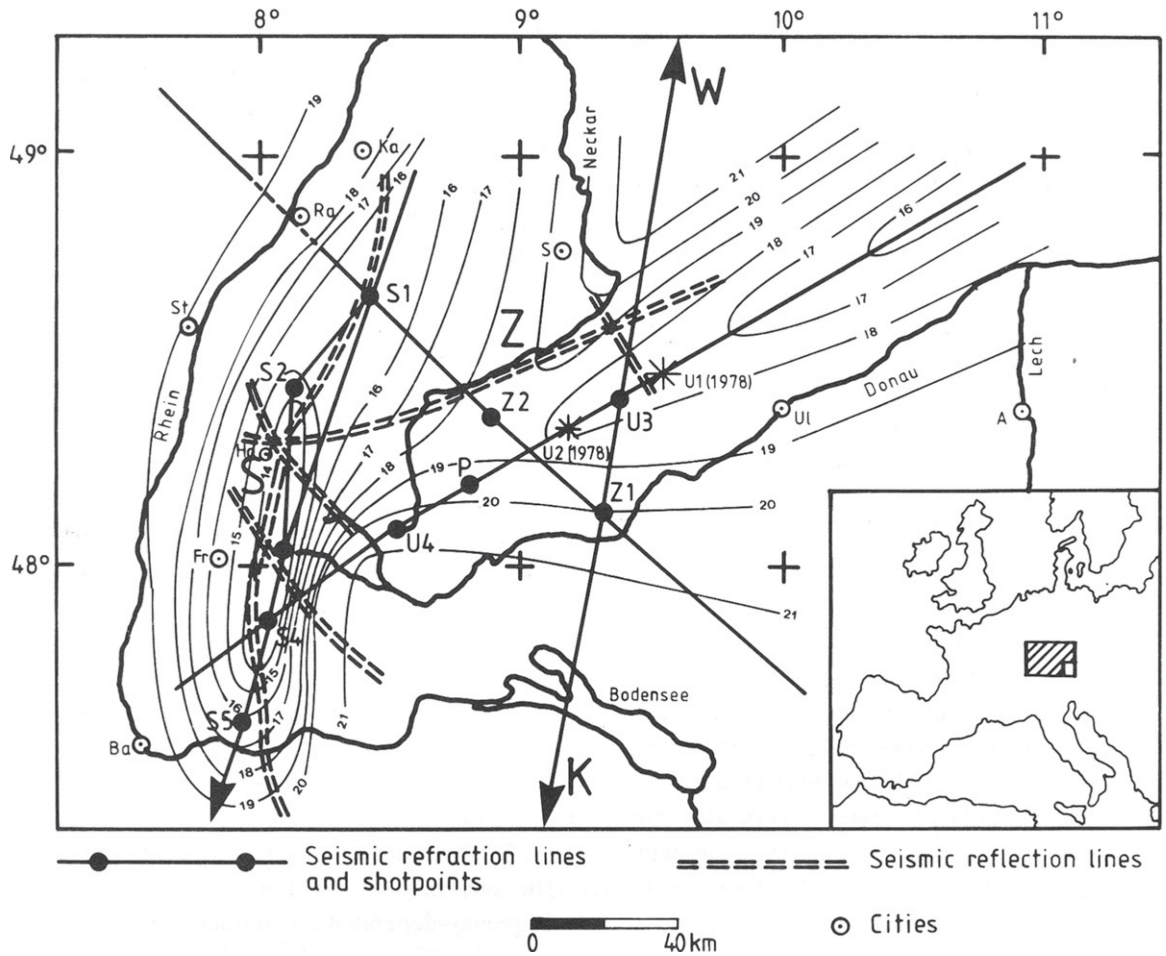

Figure 8.3.3-01. Location map of the seismic-refraction survey "Schwarzer Zollern-Wald" of 1984 and seismic-reflection surveys of 1978 (Urach) and 1984 (Black Forest), overlain on a depth contour map of the intracrustal boundary separating upper and lower crust (from Gajewski et al., 1987, fig. 11). [Tectonophysics, v. 142, p. 49–70. Copyright Elsevier.]

the investigation of the Badenweiler-Lenzkirch zone, bounding the central Black Forest gneiss complex in the south (Lueschen et al., 1987, 1989).

The refraction project, initiated and headed by Dirk Gajewski and Claus Prodehl, gained from additional projects. First, during several weekends in 1982, the German army organized a series of test explosions within the troop training area "Wildflecken" in the Rhön Mountains east of Frankfurt. Seventeen shots with charges of 450–1780 kg detonated in near-surface pits and shot times were arranged such that these explosions could be used to establish a series of fan profiles throughout southern Germany, the westernmost one being directed toward the Black Forest, the easternmost one toward the Bohemian Massif. (For location, see Fig. 8.3.4-08, no. 4; in the next section on the European Geotraverse, one of the lines is line W in Fig. 8.3.3-01, which is almost identical to the location of the European Geotraverse, recorded in 1986.) Forty recording stations were grouped such that the individual explosion were simultaneously recorded on all six lines at equivalent distances. The largest recording distance on each line was 240 km, and the average station spacing ranged from 2.5 to 5 km (Zeis et al., 1990; data shown in Appendix A2-1, p. 27–28, and Appendix A8-1-1, Gajewski et al., 1989).

Second, the Black Forest refraction program could be jointly organized together with another research program of the University of Karlsruhe so that additional refraction lines were established crossing the Black Forest in a northeasterly (line U in Fig. 8.3.3-01) and southeasterly (line Z in Fig. 8.3.3-01) direction (Gajewski et al., 1987). One of the goals was to investigate in more detail (line Z) the Hohenzollerngraben, the site of an anomalous earthquake activity and where therefore another originally proposed drillhole site was located. Furthermore, line U along the Swabian Jura had already been the target of the Urach geothermal project in 1978 (Gajewski and Prodehl, 1985) as well as of the Rhinegraben seismic-refraction survey of 1972 (Edel et al., 1975), and it was the aim of this 1984 project to complete the already existing data along that profile. Finally, lines W and K were established, of which line W reversed one of the fan profiles from the troop training area "Wildflecken."

The seismic-refraction data of all profiles were of high quality and allowed workers to recognize many details. An example is shown in Figure 8.3.3-02, the complete data set is shown in Appendix A2-1 (p. 19–26) and Appendix A8-1-1 (Gajewski et al., 1988).

The combined interpretation of seismic-reflection and refraction data revealed a lot of details which each method alone could not have resolved (Fig. 8.3.3-03). The lower part of the upper crust proved to be a low-velocity channel and is almost without any reflectivity except for a bright spot in the Haslach area. Below 15 km depth a highly reflective lower crust was identified, interpreted by a strong and laterally consistent lamination with alternating high and low P-wave velocities differing by ~10% and a vertical layering on a scale of 100 m.

The seismic-refraction data also contained a wealth of shear-wave data so that for all lines cross sections could be established for the P-wave, S-wave and Poisson's ratio distribution. Surprisingly, the S-wave data neither supported the existence of a low-shear-wave velocity zone in the upper crust nor did they show the existence of any lamination for shear-waves in the lower crust (Fig. 8.3.3-04).

Consequently Holbrook et al. (1988) proposed a petrological model, based on laboratory-measured rock velocities, indicating a probably granitic composition for upper and middle crust with a high quartz content in the middle crust (the P-wave low velocity zone) and a granulitic composition of the lower crust (Fig. 8.3.3-04 and Table 8.3.3-01). The subsequent calculation of synthetic seismograms showed a fair agreement between observed and synthetic data (Fig. 8.3.3-05). The horizontal-component synthetic seismograms predicted from the 1-D model in Figure 8.3.3-04 and Table 8.3.3-01 successfully predicted strong P_MP, S_MS, P_MP phases and P-wave reverberations from the lower crust (Pc) as well as weak S-wave lower crustal reverberations (Holbrook et al., 1988).

8.3.3.2. Oberpfalz Location

The second location for a super-deep drill-hole in the Oberpfälzer Wald in northeastern Bavaria was planned near the geological boundary between two structural units of the Variscan basement: the Moldanubian (MN in Fig. 8.3.3-06A) in the south and the Saxothuringian (ST in Fig. 8.3.3-06A) in the north which boundary was interpreted as a cryptic suture. This site was also investigated by detailed combined deep seismic-reflection and refraction studies.

First, the long-range seismic-reflection profile DEKORP-4 was arranged such that it passed the proposed drillhole site (Fig. 8.3.3-06, D4 in Fig. 8.3.1-07). Second, a number of 50–100-km-long crisscrossing seismic profiles were arranged like a net across the area (8501–8506 in Fig. 8.3.3-06, K85 in Fig. 8.3.1-07), organized by Helmut Gebrande. The whole reflection

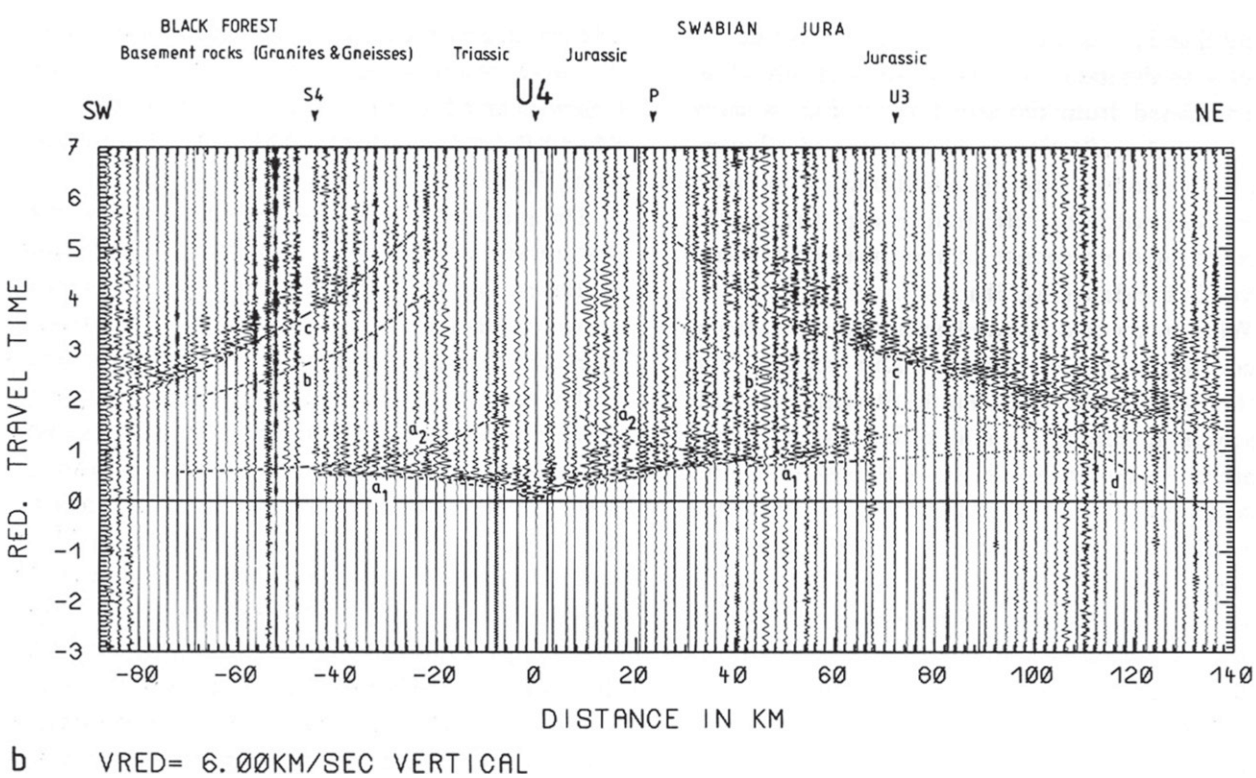

Figure 8.3.3-02. Data example of the seismic-refraction survey "Schwarzer Zollern-Wald" of 1984, record section of shot U4 on line U (from Gajewski et al., 1987, fig. 6b). [Tectonophysics, v. 142, p. 49–70. Copyright Elsevier.]

survey was carried out with the Vibroseis technique (Schmoll et al., 1989). Third, along the northwestern part of the DEKORP-4 line, 96 borehole shots with charges of 90 kg and 1 km spacing were fired and recorded threefold (Fig. 8.3.3-07): (1) for mapping wide-angle reflections from the upper crust by the contractor's 200-channel reflection spread at 42–58 km offset, (2) for mapping lower crustal and Moho wide-angle reflections by a mobile array of 24 MARS-66 stations at 60–90 km offset, and (3) for two expanding spread experiments with the midpoints in the Moldanubian and in the Saxothuringian zone, respectively. Seismic-refraction data recorded between 1968 and 1983 added to the amount of available data (Gebrande et al., 1989, 1991). Fourth, a 3-D vertical incidence seismic-reflection survey was undertaken (Stiller, 1991).

Similarly, as in the Black Forest, the superimposition of the velocity-depth interpretation of the refraction data onto the seismic-reflection data resulted in a perfect agreement as shown by Gebrande et al. (1989, Fig. 8.3.3-08). In contrast to the Black Forest site, however, the upper crust in the area of the proposed drillsite appeared more reflective than the lower crust. The

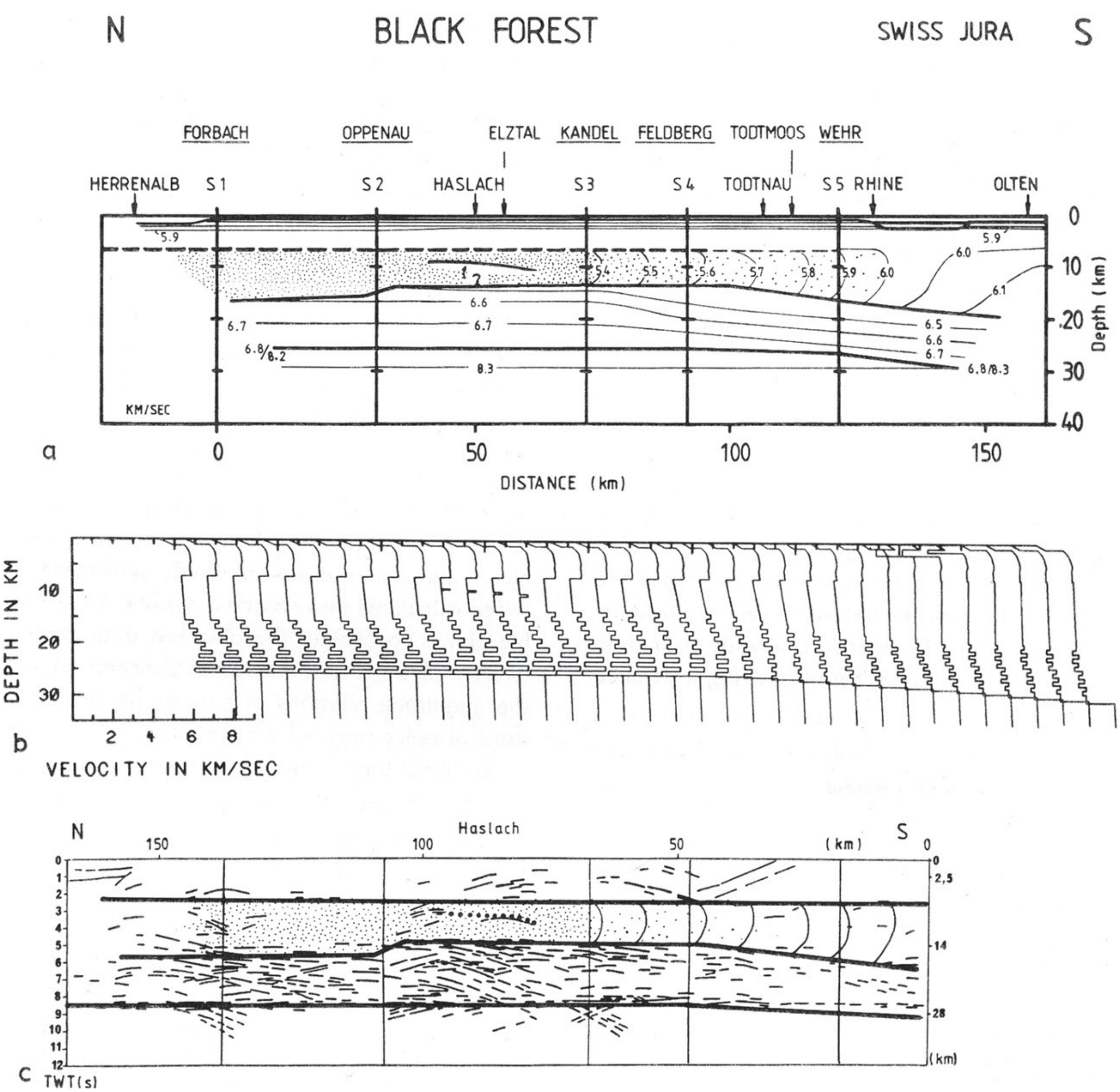

Figure 8.3.3-03. Crustal model of the Black Forest (from Gajewski and Prodehl, 1987, fig. 8). (a) Model with lines of equal velocity, derived from seismic-refraction data. (b) Velocity-depth sections along line S, derived from seismic-refraction data. (c) Line drawing of the seismic-reflection section along the Black Forest (simplified after Lueschen et al., 1987). Two-way traveltimes as calculated from model (a) are plotted as thick lines in (c). [Tectonophysics, v. 142, p. 27–48. Copyright Elsevier.]

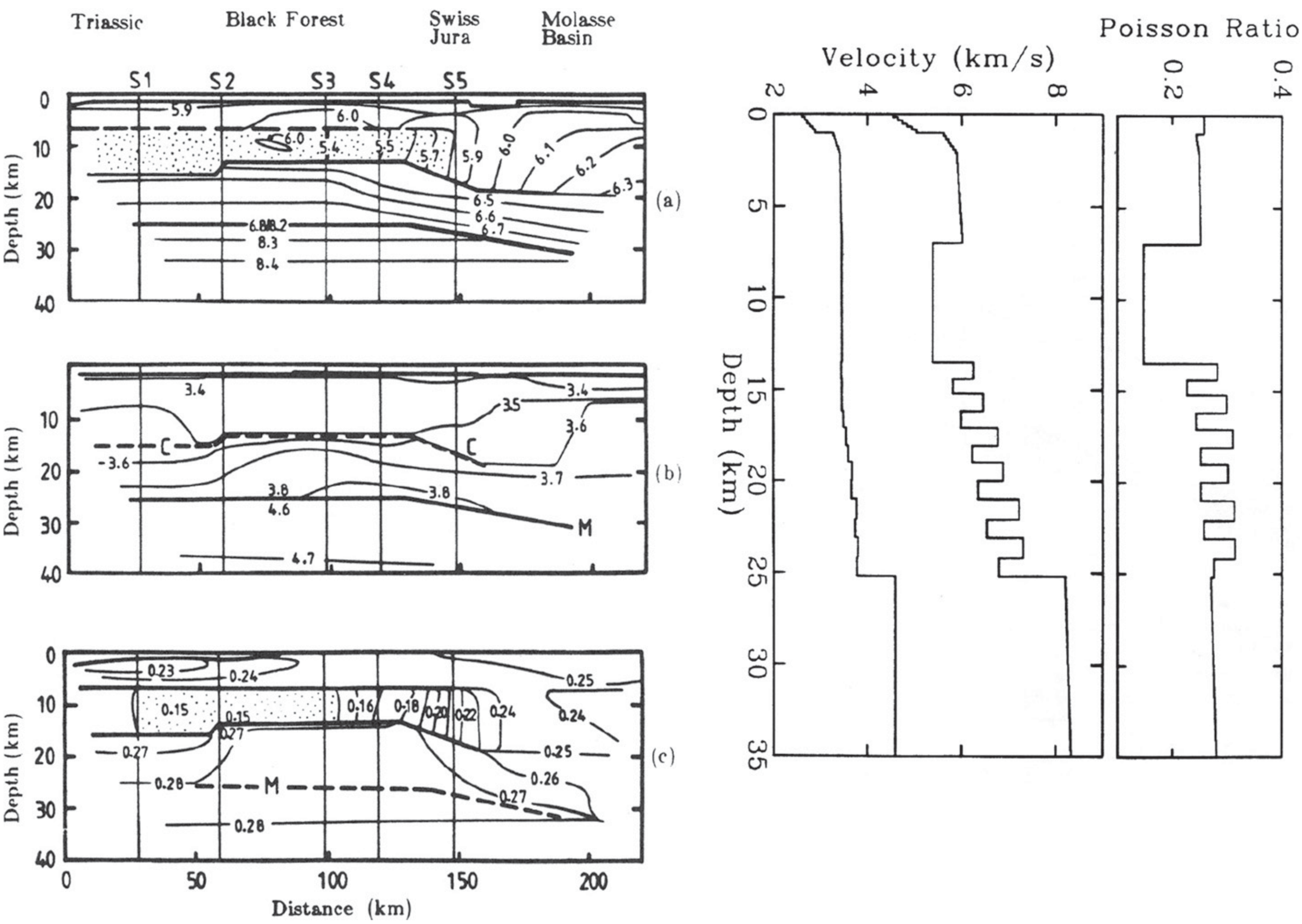

Figure 8.3.3-04. 3-component interpretation of the Black Forest data (line Z in Figure 8.3.3-01): Left: (a) P-wave velocity model, (b) S-wave velocity model, (c) Poisson's ratio model (from Holbrook et al., 1988, fig. 12). Right: 1-D depth functions of S-velocity (left), P-velocity (center), Poisson ration (right), which agree with the laboratory-measured rock velocities compiled in Table 8.3.3-01 (from Holbrook et al., 1988, fig. 16) and which were used to calculate synthetic seismograms. [Journal of Geophysical Research, v. 93, p. 12,081–12,106. Reproduced by permission of American Geophysical Union.]

TABLE 8.3.3-01. TWELVE-LAYER PETROLOGICAL MODEL OF THE BLACK FOREST LOWER CRUST (FIG. 8.3.3-04) USED TO CALCULATE REFLECTIVITY SYNTHETIC SEISMOGRAMS (FIG. 8.3.3-05)

Layer	h (km)	v_p (km/s)	v_s (km/s)	σ	ρ (g/cm³)	Mineralogy
1	0.9	6.27	3.45	0.28	2.71	Granite (qtz-biot-fspar)
2	0.8	5.83	3.46	0.23	2.63	Granite (fspar-qtz)
3	1.0	6.47	3.46	0.30	2.73	Gabbro-anorthosite granulite
4	0.9	6.00	3.49	0.24	2.74	Diorite
5	1.0	6.78	3.55	0.31	2.78	Gabbro-anorthosite granulite
6	0.9	6.24	3.59	0.25	3.03	Gabbroic granulite (plg-cpx-biot)
7	1.0	6.89	3.67	0.30	3.08	Hornblende granulite (hbl-plg-cpx)
8	1.0	6.36	3.66	0.25	2.93	Quartz diorite
9	1.1	7.23	3.77	0.31	3.08	Garnet gabbroic pyriclasite(plg-px-gnt)
10	1.0	6.55	3.74	0.26	2.95	Al-rich gneiss (qtz-gnt-sil)
11	1.1	7.31	3.80	0.31	2.99	Gabbro (plg-epx-opx)
12	1.0	6.80	3.78	0.28	3.07	Gabbroic granulite (plg-cpx-opx)
Total	11.7	6.60	3.63	0.28	2.90	

Note: h—thickness of layer; v_p—*P* velocity; v_s —S velocity; σ—Poisson's ratio; ρ—density. For references, see Holbrook et al. (1988). [Journal of Geophysical Research, v. 93: 12,081–12,106. Reproduced by permission of American Geophysical Union.]

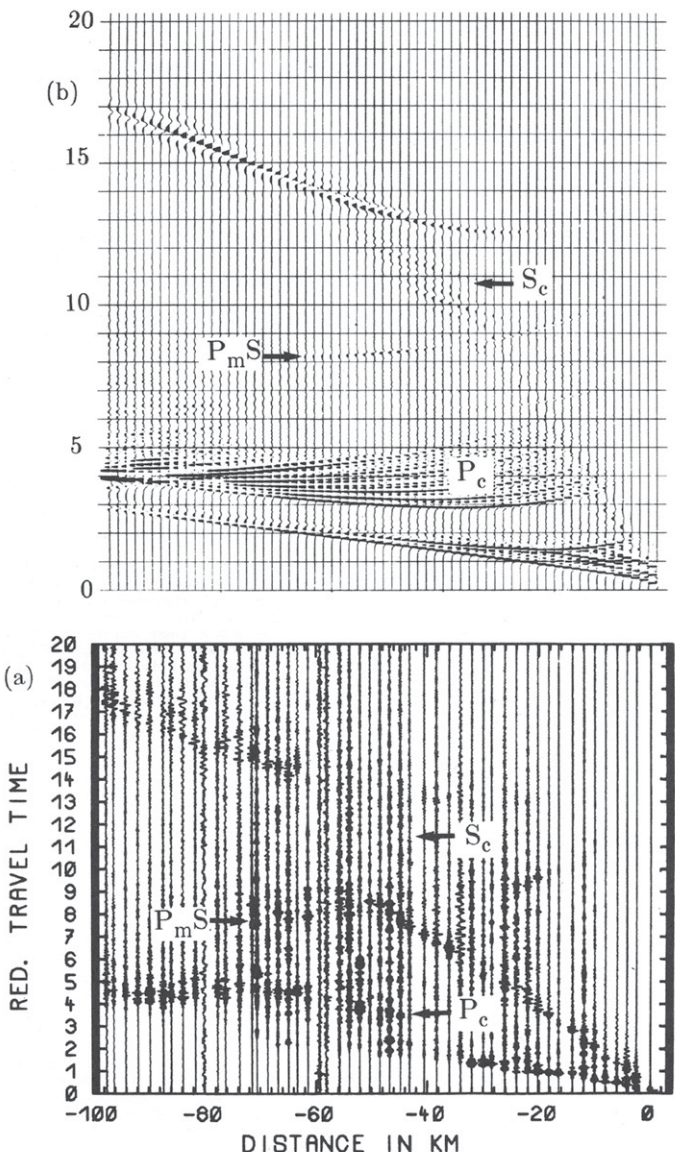

Figure 8.3.3-05. Synthetic and observed data (from Holbrook et al., 1988, fig. 17). Top: horizontal-component synthetic seismograms predicted from the 1-D model in Figure 8.3.3-04 and Table 8.3.3-01. Bottom: Transverse-component data from shotpoint S3 to south, reduction velocity = 7 km/s. [Journal of Geophysical Research, v. 93, p. 12,081–12,106. Reproduced by permission of American Geophysical Union.]

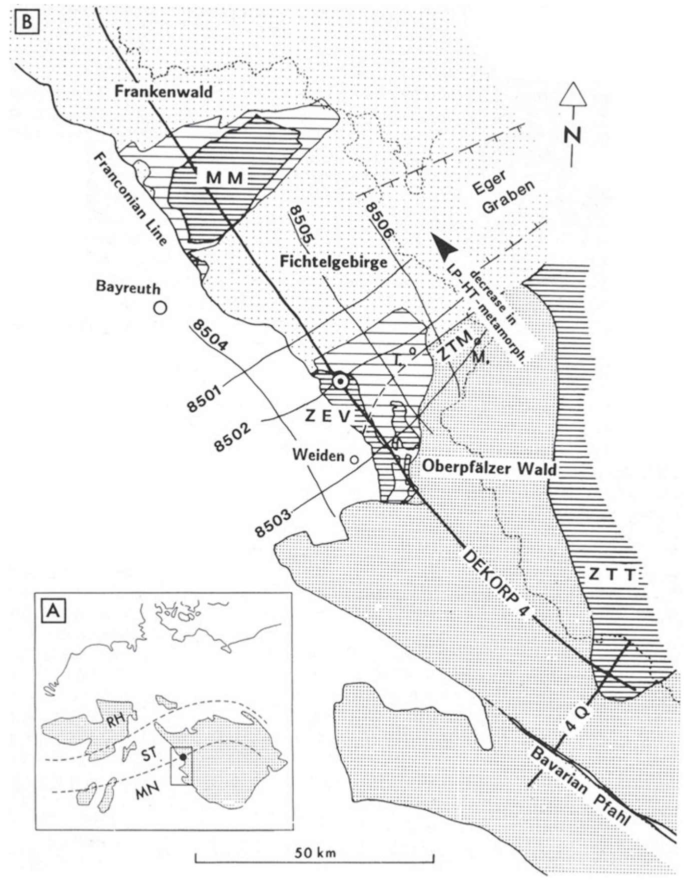

Figure 8.3.3-06. Geological sketch map of the western rim of the Bohemian Massif in NE Bavaria, Germany, showing the location of the DEKORP 4 and KTB (lines 8501 to 8506) seismic network (from Schmoll et al., 1989, fig. 1). Dot in (A) and circled dot in (B) is KTB (continental drillhole) site. [*In* Emmermann, R., and Wohlenberg, J., eds., 1989, The German continental deep drilling program (KTB)—site-selection studies in the Oberpfalz and Schwarzwald: Berlin-Heidelberg, Springer, p. 99–149. Reproduced with kind permission of Springer Science+Business Media.]

authors concluded that below a poorly defined upper crustal low velocity zone a marked velocity increase to 6.3–6.4 km/s was to be expected at ~7–8 km depth. The most spectacular feature, however, was a high-velocity zone detected at ~12–14 km.

At the end of 1985, a two-day meeting was held to review the data and results around the two drillhole sites in the Black Forest and in the Oberpfalz. Eighty-five projects had been supported until that time. The decision was finally made to choose the site in the Oberpfalz in NE Bavaria, and drilling started there on 18 September 1987.

8.3.4. The European Geotraverse

Following the tradition of European-wide international cooperation of geophysical research institutions, in 1980 the European Geotraverse was formulated. Based on the experience and excellent results of the FENNOLORA project of 1979 (Guggisberg et al., 1991; Guggisberg and Berthelsen, 1987), it was proposed in 1980 to elucidate the structure, composition, and dynamics of the continental lithosphere along a 4600-km-long and 100-km-wide corridor throughout Europe. The corridor would traverse all age provinces of Europe from Archean in Scandinavia through the Caledonian and Hercynian parts of central Europe to the Alpine orogenic belts of the Mediterranean area. This European Geotraverse would extend from the North Cape to Tunisia (Fig. 8.3.4-01). As a backbone of the European Geotraverse project, a comprehensive seismic-refraction investigation was planned

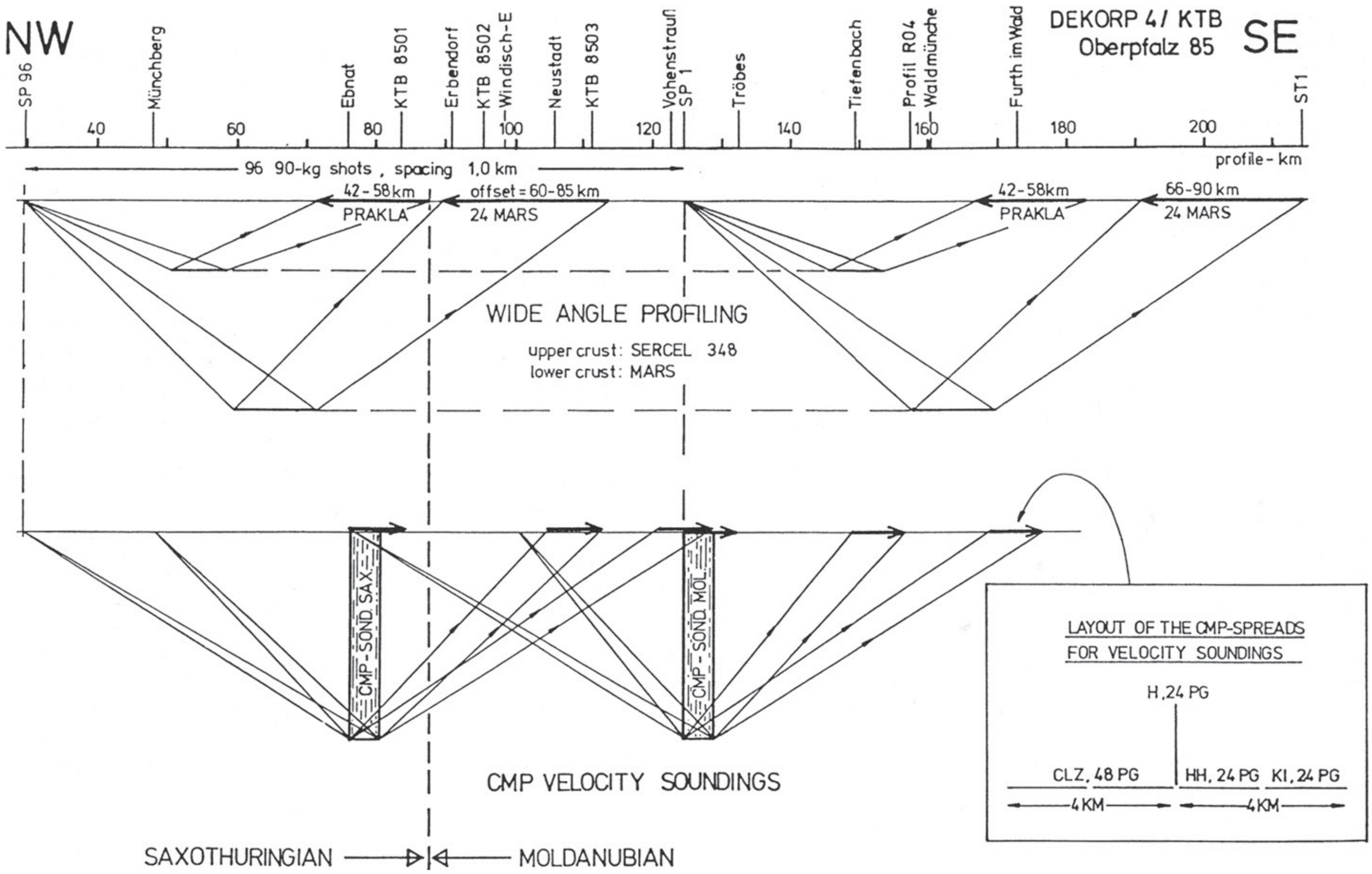

Figure 8.3.3-07. Observational scheme for wide-angle reflection seismics along DEKORP-4 (from Gebrande et al., 1989, fig. 4). [*In* Emmermann, R., and Wohlenberg, J., eds., 1989, The German continental deep drilling program (KTB)—site-selection studies in the Oberpfalz and Schwarzwald: Berlin-Heidelberg, Springer, p. 151–176. Reproduced with kind permission of Springer Science+Business Media.]

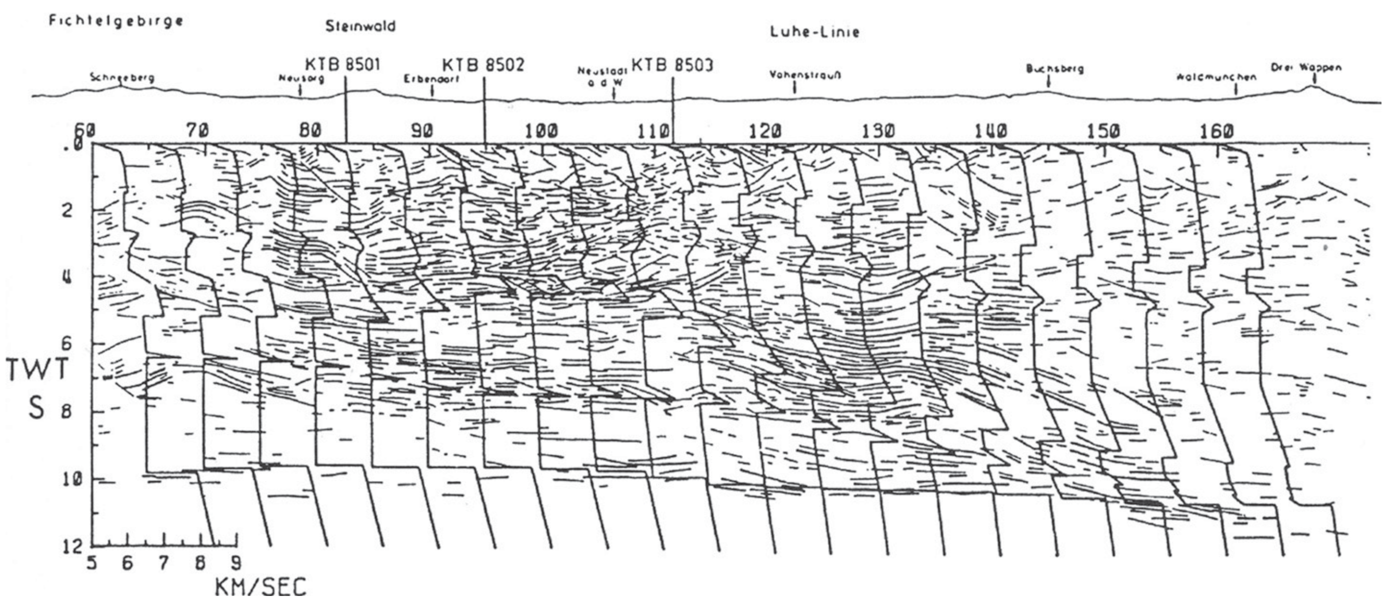

Figure 8.3.3-08. Line drawing of part of the DEKORP-4 near-vertical reflection data and superimposed velocity-depth functions, converted into two-way traveltimes (from Gebrande et al., 1989, fig. 13b). [*In* Emmermann, R., and Wohlenberg, J., eds., 1989, The German continental deep drilling program (KTB)—site-selection studies in the Oberpfalz and Schwarzwald: Berlin-Heidelberg, Springer, p. 151–176. Reproduced with kind permission of Springer Science+Business Media.]

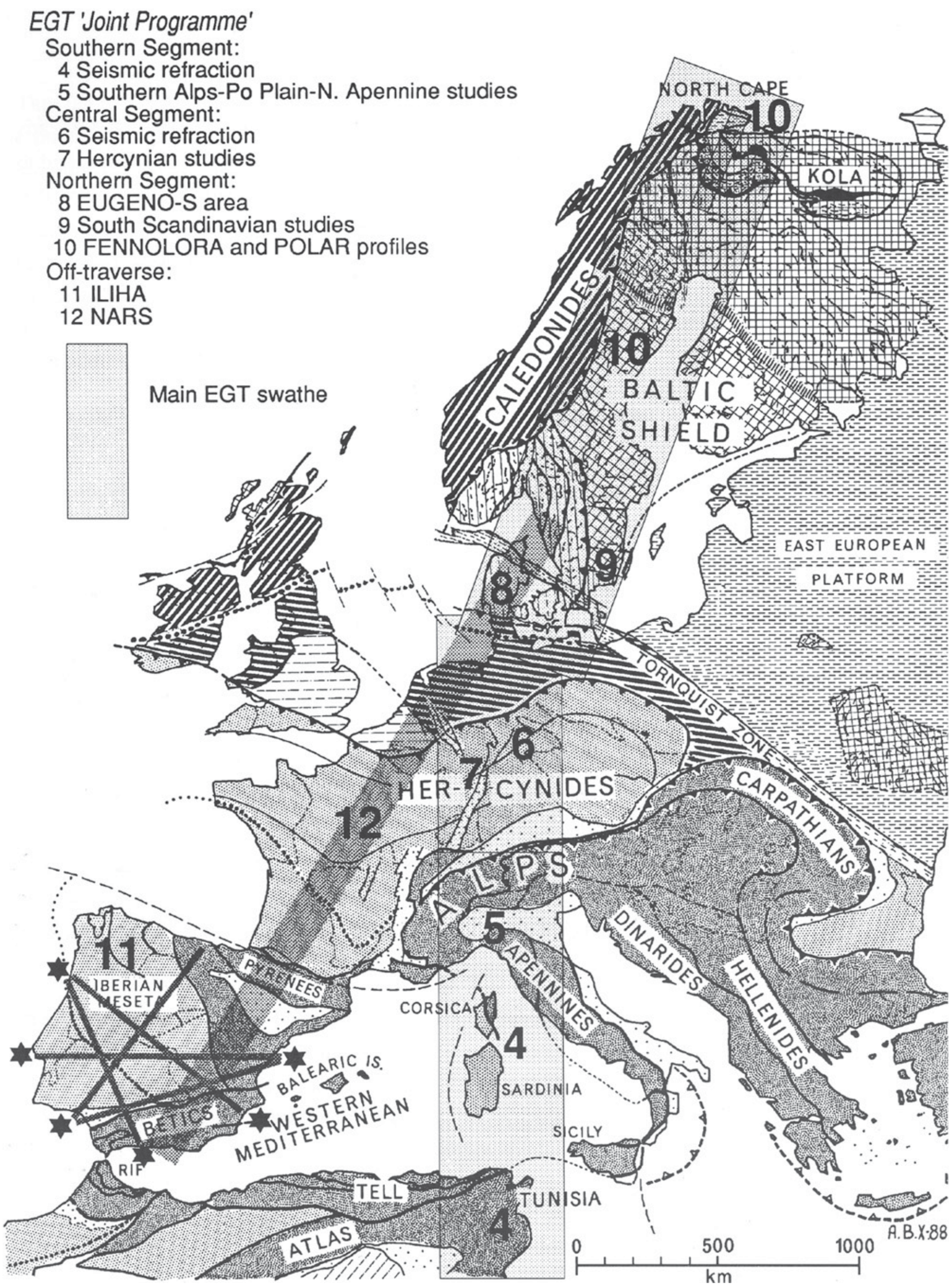

Figure 8.3.4-01. Tectonic map of Europe outlining the joint programme of the European Geotraverse (EGT, from European Science Foundation, 1990, fig. 1). [European Geotraverse Project (EGT) 1983–1990, final report: European Science Foundation, Strasbourg, 67 p. Reproduced by kind permission of the European Science Foundation, Strasbourg, France.]

in order to study the detailed crustal and upper-mantle structure along the entire line.

The realization of the European Geotraverse was enabled by approval of and subsequent coordination by the European Science Foundation (ESF). A working group composed of scientists and administrators nominated by the participating organizations from 16 countries was set up.

In total, 13 major projects, and numerous geographically regional studies, were approved by ESF and, under the framework of the European Geotraverse, were recommended for funding to the appropriate national research foundations.

For logistical reasons, the Geotraverse was subdivided into three segments: The northern segment (nos. 8–10 in Fig. 8.3.4-01) comprised the already existing seismic-refraction line FENNOLORA of 1979 through Scandinavia, several projects in Finland (recorded in1981–1985; not shown in Fig. 8.3.4-02) and a transition zone between northern and central Europe in Denmark and southernmost Sweden (EUGENO-S of 1983). The central section of 1986 (nos. 6–7 in Fig. 8.3.4-01) would cover the Hercynian part of central Europe. For logistical reasons, the seismic-refraction line across central Europe also included the Alps and the Po Plain of northern Italy (no. 5 of Fig. 8.3.4-01). The

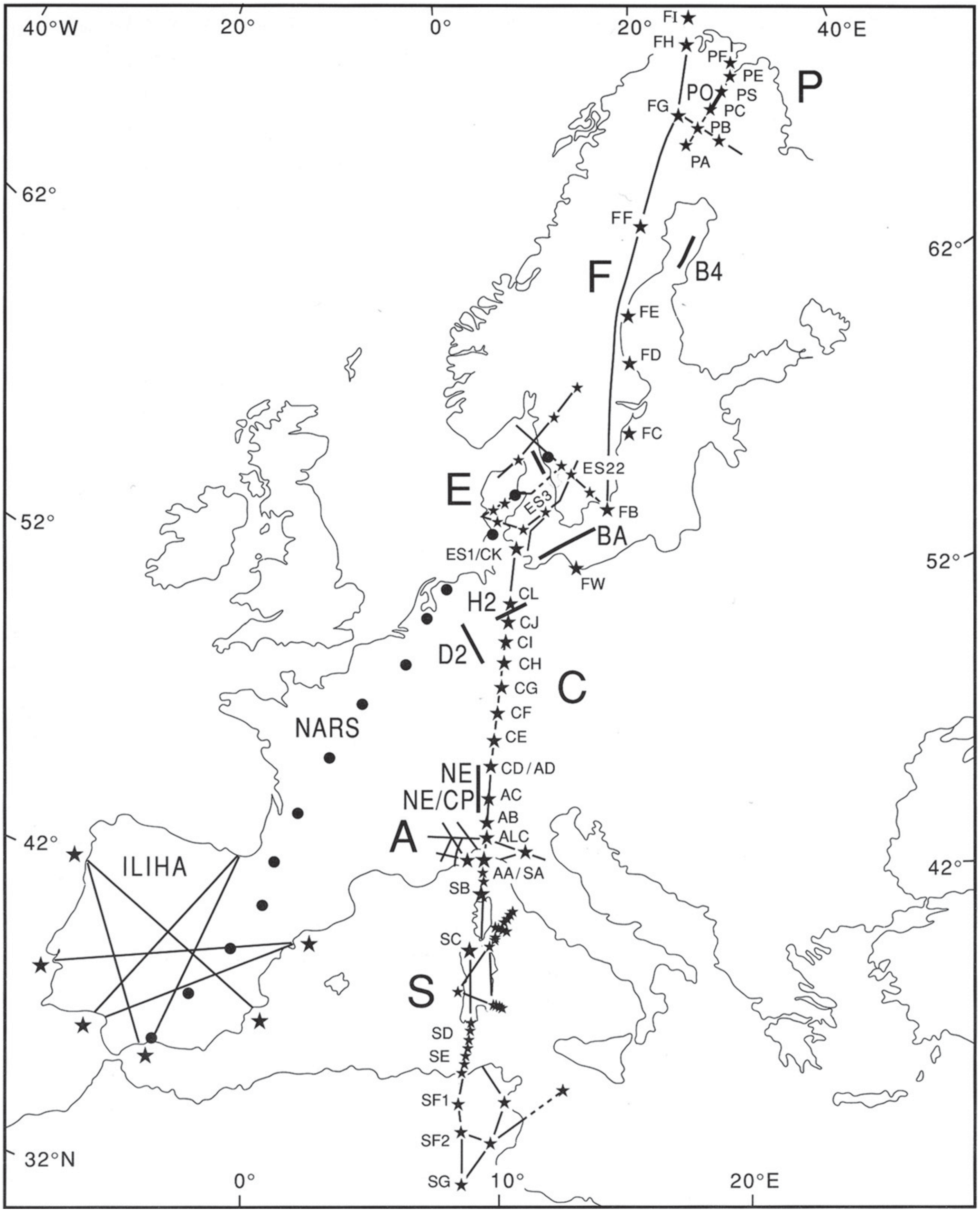

Figure 8.3.4-02. Location map of EGT seismic experiments (from Ansorge et al., 1992, fig. 3-1). Stars—shotpoints. Thin lines—seismic-refraction profiles: P—POLAR profile, F—FENNOLORA, E—EUGENO-S, C—EUGEMI, A—EGT-S86, S—EGT-South, ILIHA—Iberian Lithospheric Heterogeneity and Anisotropy project. Thick lines—deep seismic-reflection profiles: B4—BABEL line 4, BA—BABEL line BA, H2—North German basin, D2—DEKORP-2N, NE-NE/CP—NFP-20/CROP eastern and southern traverses. Filled circles—NARS (Network of Autonomously Recording Stations) array stations. [*In* Blundell, D., Freeman, R., and Mueller, S., eds., 1992, A continent revealed—the European Geotraverse: Cambridge University Press, p. 33–69. Copyright Cambridge University Press.]

southern segment (nos. 4–5 in Fig. 8.3.4-01) finally reached from the Alps to northern Africa, traversing northern Italy (1983), crossing the western Mediterranean Sea including the islands of Corsica and Sardinia (1983) and ending in northern Tunisia (1985). In addition, a large-scale anisotropic seismic-refraction experiment was planned on the Iberian peninsula (no. 11 in Fig. 8.3.4-01) and a wide-aperture seismological array NARS (no. 12 in Fig. 8.3.4-01) was to be installed to collect data on the upper mantle along the traverse Göteborg-Malaga (Nolet et al., 1986).

Being the backbone of the European Geotraverse project and other EGT-related seismic projects, for the EGT seismic-refraction experiments a comprehensive map (Fig. 8.3.4-02), showing all shotpoints, was compiled by Ansorge et al. (1992) in Chapter 3 of the major research publication *A Continent Revealed—The European Geotraverse* edited by Blundell et al. (1992). The joint program (European Science Foundation, 1990) also included experiments not specifically identified in Figure 8.3.4-01: simultaneous geomagnetic observations along the EGT (experiment no. 1), mapping of the resistosphere and conductosphere along the EGT (experiment no. 2), mapping of the lithosphere-asthenosphere system along the EGT (experiment no. 3), and integrated geothermal studies along the EGT (experiment no. 13). In an interdisciplinary approach Blundell et al. (1992) reviewed all geological and geophysical data collected in the framework of the European Geotraverse.

In this review, a special section dealt with a compilation of all seismic surveys along and around the European Geotraverse (Ansorge et al., 1992) which was republished in a compressed scale (Fig. 8.3.4-03) by Mooney et al. (2002).

All projects, including the various deep seismic sounding projects, were carried out in the 1980s depending on the availability of financial resources. The results were discussed at seven workshops, concentrating on specific areas and published shortly afterwards in internal report volumes by the European Science Foundation for immediate use by the scientists involved: (1) the northern segment (Copenhagen, Denmark, 28–30 October 1983),

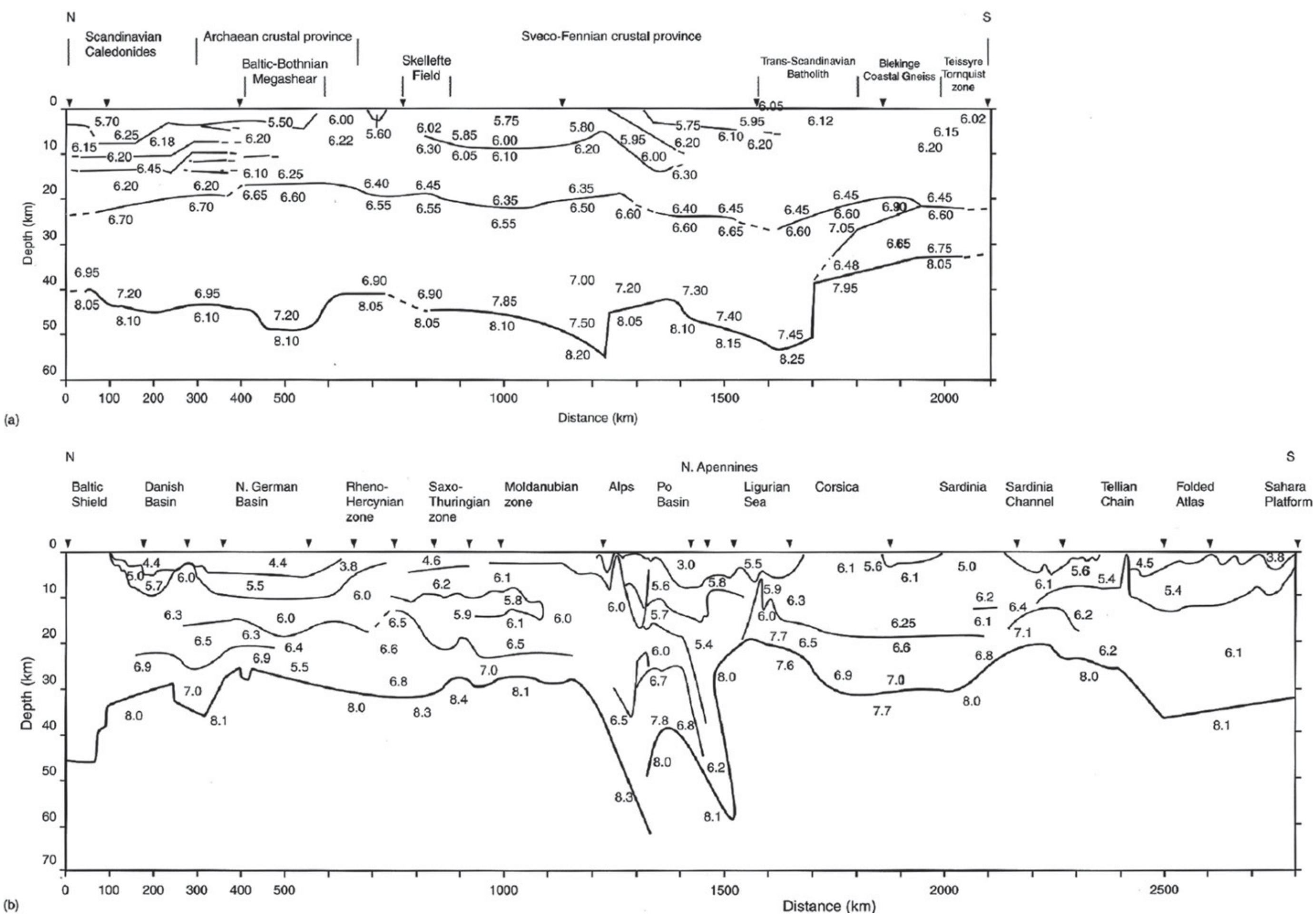

Figure 8.3.4-03. Crustal cross section through Europe along the EGT (from Mooney et al., 2002, fig. 9, after Ansorge et al., 1992, Figs. 3-4, 6, 9, 11, 12, 15, 16). Depth versus horizontal distance is 10:1. (a) Northern segment at approximately 20°E, (b) Central and Southern Segments at approximately 10°E. [*In* Lee, W., Kanamori, H., Jennings, P.C., and Kisslinger, C., eds., 2002, International Handbook of Earthquake and Engineering Seismology, Part A: Academic Press, Amsterdam, p. 887–910. Copyright Elsevier.]

(2) the southern segment (Venice, Italy, 7–9 February 1985), (3) the central segment (Bad Honnef, Germany, 14–16 April 1986), (4) the upper mantle (Utrecht, Netherlands, 11–12 March 1988), (5) the Iberian peninsula (Estoril, Portugal, 11–12 November 1988)), (6) data compilations and synoptic interpretation (Einsiedeln, Switzerland, 29 November to 5 December 1989), and (7) integrative studies (Rauischholzhausen, Germany, 26 March to 7 April 1990). In addition, other workshops for planning as well as for data interpretation of individual projects had been organized, for which only internal protocols were distributed.

All seismic-refraction data were collected in Open-File reports: the Northern Segment FENNOLORA by Stangl (1990; see also Appendix A2-1, p. 69–71; Appendix A7-4-2, p. A3–A58), its southern extension by Gregersen et al. (1987; see also Appendix A8-1-2), the Central Section by Aichroth et al. (1990; see also Appendix A2-1; p. 29–31, and Appendix A8-1-3) and Maistrello et al. (1991; see also Appendix A8-1-4), the Southern Segment by Egger (1990, 1992; see also Appendix A8-1-4) and Maistrello et al. (1990).

Most results were subsequently published in eight special issues of *Tectonophysics* entitled "The European Geotraverse": (1) 126, no. 1 (1986), (2) 128, nos. 3-4 (1986), (3) 142, no. 1 (1987), (4: Eugeno-S) 150, no. 3 (1988), (5: The Polar Profile) 162, nos. 1-2 (1989), (6) 176, nos. 1-2 (1990), (7) 195, nos. 2-4 (1991), (8) 207, nos. 1-2 (1992), and in a special issue on "Seismic studies of the Iberian peninsula": 221, no. 1 (1993). Finally, a comprehensive book was edited by Blundell et al. (1992) including an atlas of 13 maps and a database on CD-ROM, compiled by Freeman and Mueller (1992).

The individual seismic projects will be described here in geographical order, independent from the year of operation.

8.3.4.1. The Northern Segment

The already existing seismic lines FENNOLORA, extending from southeastern Sweden through northern Finland and northernmost Norway to the North Pole, and FINLAP, an unreversed lateral profile into Finland, both recorded in 1979, formed the core of the northern segment (Fig. 7.2.6-05 and no. 10 in Fig. 8.3.4-01). For details the reader is referred to section 7.2.6. Along the FENNOLORA line (Fig. 7.2.6-05 and F in Fig. 8.3.4-02 and *a* in Fig. 8.3.4-04) shots had been recorded up to 2000 km distance thus penetrating to a depth of 450 km (Guggisberg and Berthelsen, 1987; Guggisberg et al., 1991; Appendix A2-1, p. 69–71). Furthermore, in Finland and the adjacent USSR, a variety of additional seismic experiments had been carried out since the early 1980s. In their discussion of the POLAR profile (part of no. 10 in Fig. 8.3.4-01 and P in Fig. 8.3.4-02), Luosto et al. (1989) showed all modern deep seismic sounding profiles dealing with the lithospheric structure of the northern Baltic Shield (Fig. 8.3.4-04).

The first line in Finland was the 320-km-long SVEKA profile recorded in 1981 in central Finland. Forty-five shots with charges of 100–1000 kg were detonated in five lakes, ~80 km apart, and recorded by a continuously moving array of 19 recording units with 2 km station separation (Luosto et al., 1984; Luosto and Korhonen, 1986). In 1982 the 430-km-long BALTIC profile followed with 7 shotpoints in southeastern Finland (Luosto and Korhonen, 1986; Luosto et al., 1990). The seismic experiment along the BALTIC profile also included a very detailed seismic-reflection survey across the Granulite belt (Behrens et al., 1989).

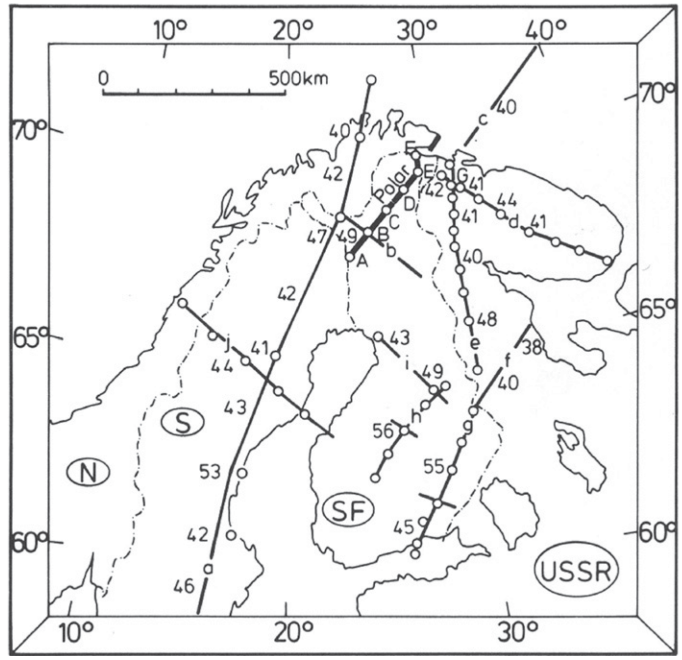

Figure 8.3.4-04. Modern deep seismic sounding profiles on the northern Baltic Shield (small letters *a* to *j*, from Luosto et al., 1989, fig. 2): *a*—FENNOLORA profile, *b*—FINLAP profile, *c*—Barents Sea profile, *d*—Nickel-Umbozero profile, *e*—Pechenga-Kostamuksha profile, *f*—Kem-Tulos profile, *g*—BALTIC profile, *h*—SVEKA profile, *I*—quarry blast line, *j*—BLUE ROAD profile. Average crustal thickness (in km) is indicated. *A* to *G*: large explosions along the POLAR profile. [Tectonophysics, v. 162, p. 51–85. Copyright Elsevier.]

The Russian part of the Baltic Shield was the target of two seismic lines recorded in 1981–1983: the Nickel-Umbozero profile recorded with 7 shotpoints through the center of the Kola Peninsula and the Pechenga-Kostamuksha profile recorded with 10 shotpoints in a north-south direction close to the Finnish border (Azbel et al., 1989). Davydova et al. (1985) described a seismic line recorded in 1976 in the Barents Sea, where shots of 135 kg were set off at 90 m depth and at 3–5 km intervals and recorded by OBSs on 19 sites with an approximate spacing of 50 km.

Finally, in 1985, the POLAR profile of 440 km length was recorded with 2 km station spacing to resolve the crustal structure of the northern Baltic Shield in northern Finland and northeastern Norway (Freeman et al., 1989; Luosto et al., 1989; Von Knorring and Lund, 1989; Walther and Flueh, 1993). Six shotpoints with large explosions of 200–1680 kg and three shotpoints with smaller explosions of 80 kg provided high-quality data. For the Finnish part, data were compiled in Appendix A2-1 (p. 72–81).

Figure 8.3.4-05. Left: *Meteor 66* cruise seismic reflection and refraction offshore lines of 1983 (from Behrens et al., 1986, fig. 1). [Tectonophysics, v. 128, p. 209–228.]. Right: EUGENO-S profiles of 1984 (from EUGENO-S Working Group, 1988, fig. 5). [Tectonophysics, v. 150, p. 253–348. Copyright Elsevier.]

In 1983, a multidisciplinary study of the Tornquist-Teisseyre Line, which connects to the FENNOLORA line of 1979, was conducted. The study of the Tornquist-Teisseyre Line, otherwise known as the contact zone between Precambrian and Hercynian Europe, was conducted using a network of seismic-refraction profiles (Fig. 8.3.4-05) from northern Germany through Denmark, and from Denmark to southern Sweden (EUGENO-S Working Group, 1988). The study also involved a marine survey with offshore and onshore observations (Behrens et al., 1986).

The offshore survey of the *Meteor 66* cruise in 1983 involved a streamer, OBSs, and seismic land stations which enabled both vertical-incidence and wide-angle reflection observations. Seismic energy was provided by an airgun array fired at two-minute intervals, thus providing for the vertical-incidence reflection observations one-fold coverage only, but a suitable energy source for crustal refraction measurements out to distances of more than 100 km. Thus, both the sedimentary horizons could be studied in some detail and a model for the whole crust could be obtained.

Figure 8.3.4-06 shows a data example of line IV where reflections from intracrustal boundaries and from the crust-mantle boundary near 40 km depth are clearly visible.

The EUGENO-S (European Geotraverse North–Southern extension) was achieved by a cooperative effort of scientists and funding from Denmark, Sweden, Norway, Finland, Germany, Switzerland, Great Britain, and Poland. The seismic project was carried out in summer 1984 and consisted of 5 intersecting lines covering southern Sweden and Denmark and adjacent areas with a total length of 2100 km. The spacing between shotpoints varied from 50 to 200 km, the station spacing on land being between 1.5 and 3.0 km. In total, 51 explosions were fired at 20 locations. Most of the shots were fired in boreholes, 5 shotpoints were in small lakes, and two shotpoints were in the Baltic Sea; charges ranged from 50 to 1200 kg. Most of the recording stations were MARS 66 stations (50 units) and Finnish SN-PCM-80 stations (4 units). Furthermore, 7 OBSs bridged the gap across the intervening marine part of the Kattegat.

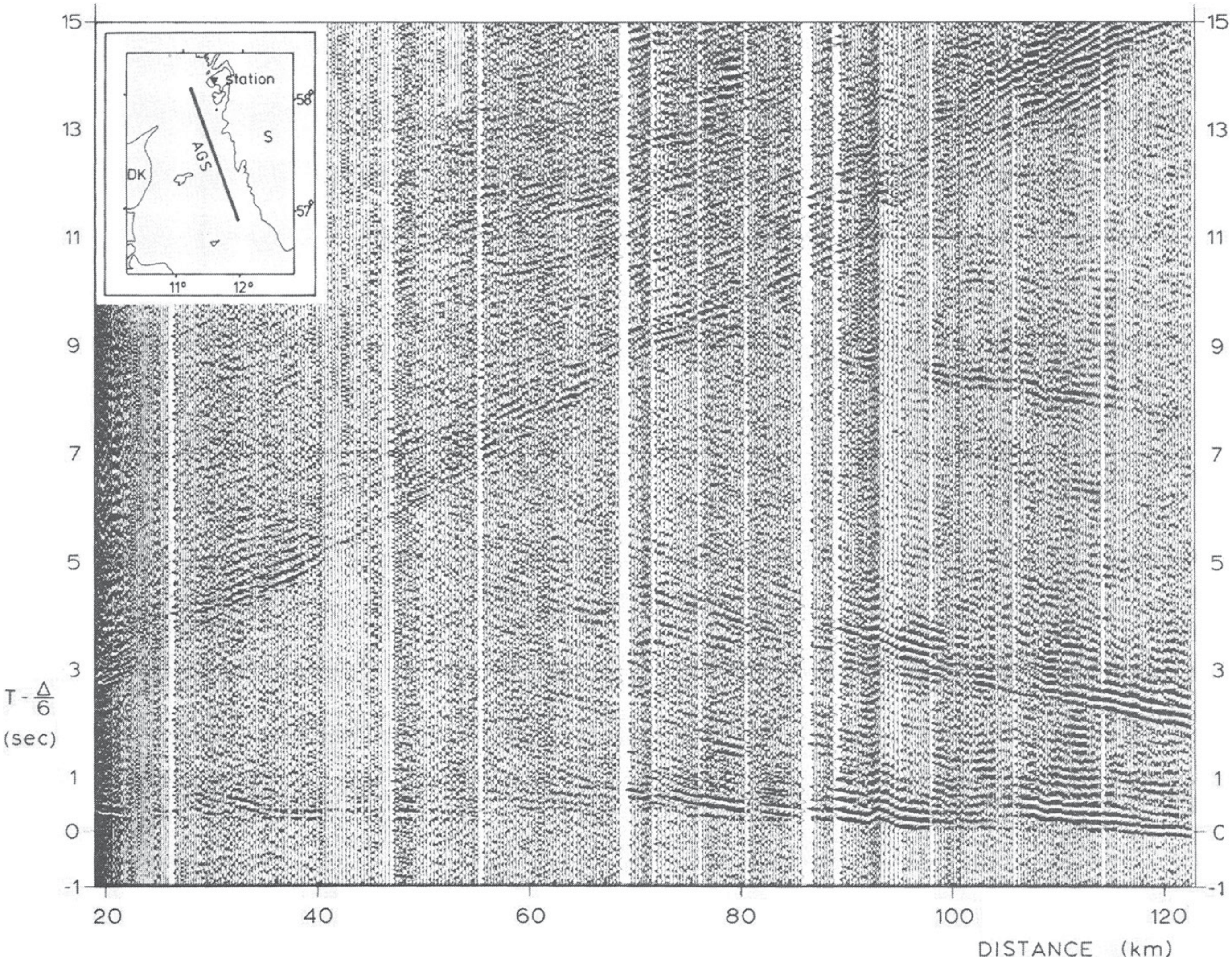

Figure 8.3.4-06. Record section of the air gun shots along profile IV recorded by a land station on hard rock onshore on the Tjörn peninsula, Sweden (from Behrens et al., 1986). [Tectonophysics, v. 128, p. 209–228. Copyright Elsevier.]

Along the offshore parts of the profiles, airgun shooting was also undertaken, which was not only recorded by the OBSs but also by land stations at up to 250 km in Sweden. The airgun array consisted of 4 airguns of 8 L each, fired simultaneously. Airgun shots were fired every 2 min corresponding to an average shot spacing of 300 m. Many of the data were published by EUGENO-S Working Group (1988) and are reproduced in Appendix A8-1-2.

Most of the interpretation was achieved during a 2-week interdisciplinary study center organized by the editorial team and supported by the European Science Foundation (Stege on Mon, Denmark, 4–21 November 1985); the results were subsequently published by EUGENO-S Working Group (1988). One of the principal results was the Moho map (Fig. 8.3.4-07), which was based on the EUGENO-S seismic results, but for which the gravity map was also used to infer the trends of the contours.

8.3.4.2. The Central Segment

Much of the area of the Central Segment of the European Geotraverse had already seen earlier seismic-refraction work in the 1970s (e.g., nos. 1–3 in Fig. 8.3.4-08, described in Chapter 7) and in the early 1980s. This data added substantially to the success of the EGT seismic survey of 1986. In 1982 and 1984, two major surveys in southern Germany had been performed in the framework of a special research project of the University of Karlsruhe: In 1982, a series of explosions on the troop training area “Wildflecken” in the Rhön Mountains in south-central Germany enabled scientists to simultaneously record a fan-like series of profiles throughout southern Germany (no. 4 in Fig. 8.3.4-08: profiles radiating from EGT-shotpoint H, Zeis et al., 1990). In 1984, a detailed crustal survey covered southwestern Germany (“Black Zollern-Forest,” no. 5 in Fig. 8.3.4-08) in a triangle between Rhinegraben, the Swabian Jura and Lake Constance

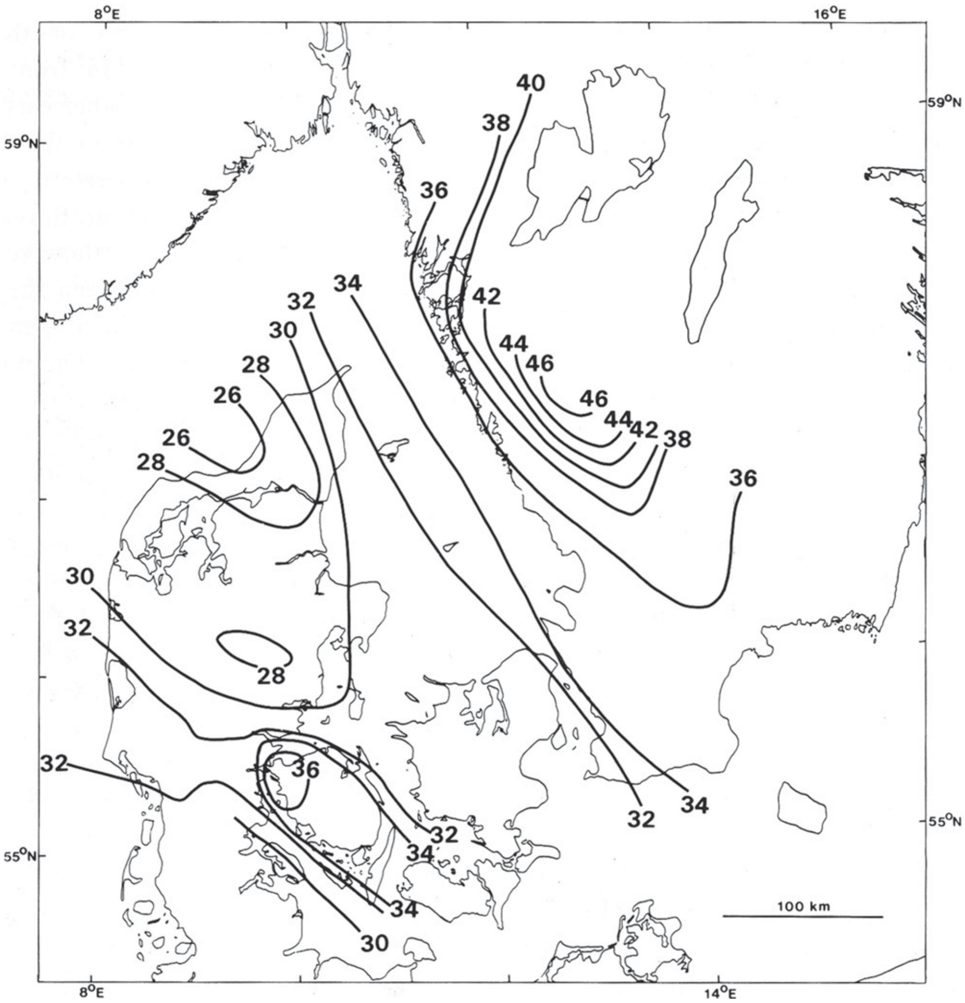

Figure 8.3.4-07. Depth of Moho (in km) in the transition zone between the Baltic Shield and Caledonian–Variscan Europe (from EUGENO-S Working Group, 1988, fig. 40). [Tectonophysics, v. 150, p. 253–348. Copyright Elsevier.]

(Gajewski et al., 1987). This survey had served to investigate the crustal structure underneath proposed sites for a deep drillhole in Germany and was already described in more detail in the previous section.

In North Germany, the hydrocarbon industry had continued to acquire an extensive seismic-reflection database in the North German Basin near the Elbe lineament between Hamburg to the south, Kiel to the north, the North Sea to the west and the Baltic Sea to the east (Dohr et al., 1989; fig. 2 of Yoon et al., 2008) The results of three more profiles, recorded in 1981 and 1984, were reprocessed (Yoon et al., 2008). Similar to the first line, recorded in 1974 (see Chapter 7.2.5), the data had been obtained with dynamite explosive sources recorded by 120 geophones with 20–100 m receiver spacings and 80–120 m shotpoint spacings down to 15 s TWT, resulting in mean common mid-point folds of ~20. Total profile lengths ranged from 30 to 100 km. The reprocessed sections showed an improved image quality at all time levels. Especially the reflections from the salt events and the Moho at 11.5–12 s TWT could be enhanced (Yoon et al., 2008).

The central segment of the European Geotraverse, organized by scientists from Germany (Beate Aichroth and Claus Prodehl), Switzerland (Jörg Ansorge), and Italy (Carlo Morelli, R. Cassinis, S. Scarascia, and others), was covered by a detailed seismic-refraction survey in 1986 (Fig. 8.3.4-08; EUGEMI Working Group, 1990; Aichroth et al., 1992; Prodehl and Aichroth, 1992; Appendix A2-1, p. 29–31, and Appendix A8-1-3; Aichroth et al., 1990).

This EGT project covered a distance of 1200 km and reached from its northern shotpoint in the Baltic Sea, off Northern Germany, across the whole of Germany (no. 6 in Fig. 8.3.4-01, C in Fig. 8.3.4-02), into Switzerland and northern Italy, thus covering the central Alps and the northern Po Plain (no. 5 in Fig. 8.3.4-01, A in Fig. 8.3.4-02). It was here that it overlapped with the northern end of the southern EGT segment. Its southernmost shotpoint was located in the Gulf of Genova and several fan profiles were arranged in the Apennines and the Western Alps to study lateral variations in crustal structure.

In total, 235 recording stations, most of them (~200) being MARS-66 equipment, were recording during three deployments. The stations recorded 15 shots in the southern part (Italy and

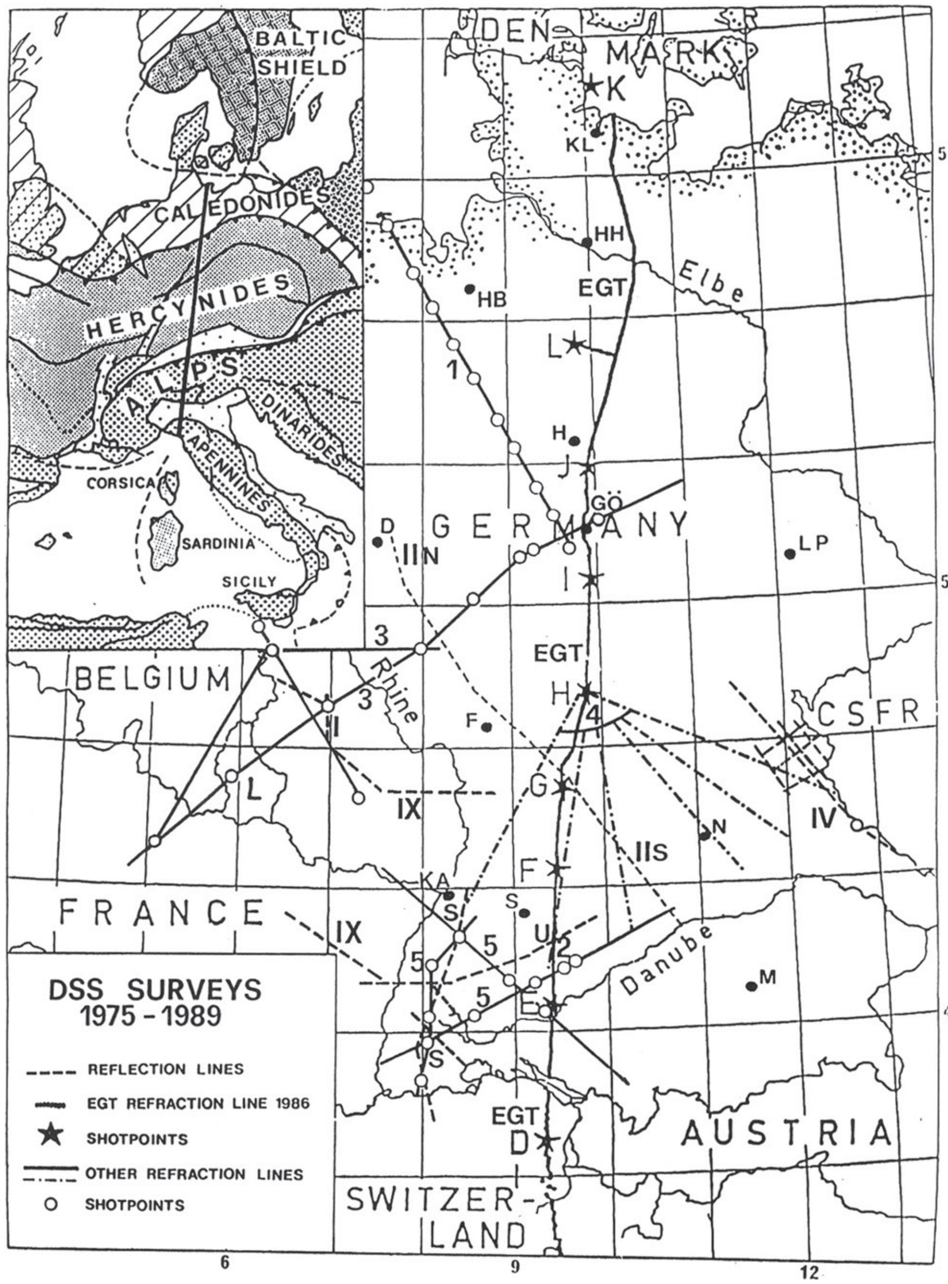

Figure 8.3.4-08. Location map of the 1986 seismic-refraction survey along the EGT Central Segment and other detailed seismic-refraction and -reflection lines in western Germany (from Prodehl and Aichroth, 1992, fig.1). EGT-86 shotpoints are denoted by stars and large capital letters D to K, observation sites by dots. Dashed lines represent seismic-reflection lines of DEKORP (I to IX) and other reflection surveys (U—Urach 1978, S—KTB Black Forest 1984). Single fat lines represent densely observed seismic-refraction surveys: 1—North Germany 1975/1976, 2—Urach 1978, 3—Rhenish Massif 1979, 4—"Wildflecken" 1982 (dash-dotted lines), 5—"Black Zollern-Forest." Cities (small capital letters): D—Dortmund, F—Frankfurt, G—Göttingen, H—Hanover, HB—Bremen, HH—Hamburg, KA—Karlsruhe, KL—Kiel, LP—Leipzig, M—München, N—Nürnberg, S—Stuttgart. The inset shows the tectonic sketch map of Europe (Berthelsen, 1983). [*In* H. Kern and Y. Gueguen, eds., Structure and composition of the lower continental crust: Terra Nova, v. 4, p. 14–24. Copyright Wiley-Blackwell.]

Switzerland), 10 shots in the central part (Hercynian part of Germany), and 5 shots in the northern part (North German lowlands). Most of the shots were drillhole shots; only at the southernmost and northernmost ends were underwater shots used. Participants came from Denmark, Germany, Finland, France, Ireland, Italy, Spain, Sweden, Switzerland, and the UK. A special seismic workshop from 27 February to 4 March 1989 at Karlsruhe, Germany, and an interdisciplinary EGT Study Center from 25 March to 5 April 1989 at Rauischholzhausen, Germany, served in particular to model and to interpret the data of the central segment of the EGT, leading to the seismic model and its petrological interpretation shown in Figure 8.3.4-09.

The data, obtained in 1986 and 1987 in the Alpine area around the European Geotraverse, were separately interpreted (Fig. 8.3.4-10). Ye (1991) interpreted the seismic-refraction data of the central segment from shotpoint F near the northern border of the Bavarian Molasse Basin to shotpoint A in the Ligurian Sea (data presentation in Appendix A8-1-4), in conjunction with a reinterpretation of other existing seismic-refraction profiles in the central Swiss Alps (Fig. 8.3.4-10, top), including a line along the northern border of the central Swiss Alps which was recorded from Jaun Pass to Saentis in 1987 (Maurer and Ansorge, 1992, also in Appendix A8-1-4). Valasek et al. (1991) discussed the model in conjunction with the deep seismic-reflection line

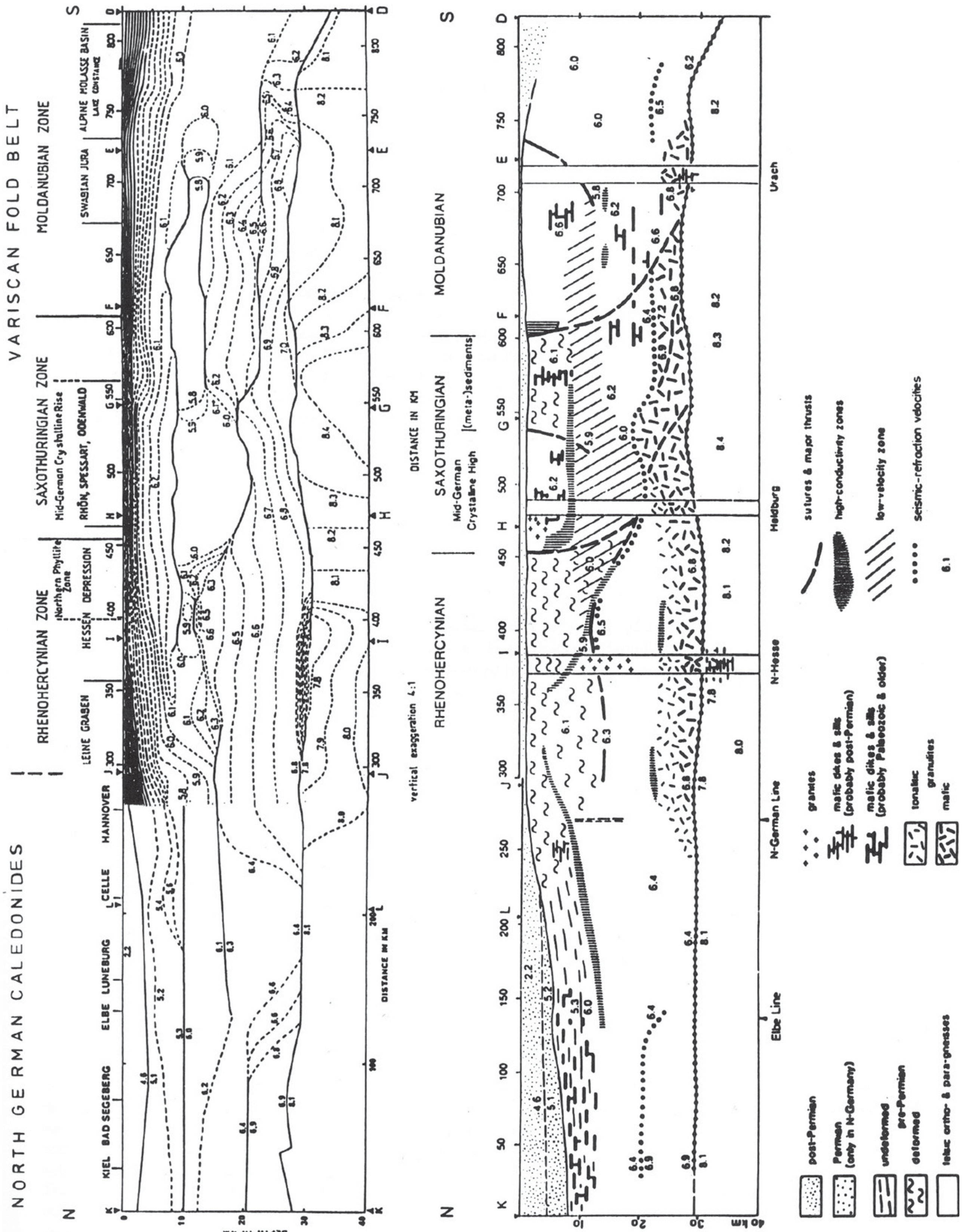

Figure 8.3.4-09. Crustal cross section of the EGT central segment from the Baltic Sea to Lake Constance (from Prodehl and Aichroth, 1992, fig. 3). Depth versus distance is exaggerated by 4:1. Top: Seismic velocity model. Bottom: Petrological interpretation. [*In* H. Kern and Y. Gueguen, eds., Structure and composition of the lower continental crust: Terra nova, v. 4, p. 14–24. Copyright Wiley-Blackwell.]

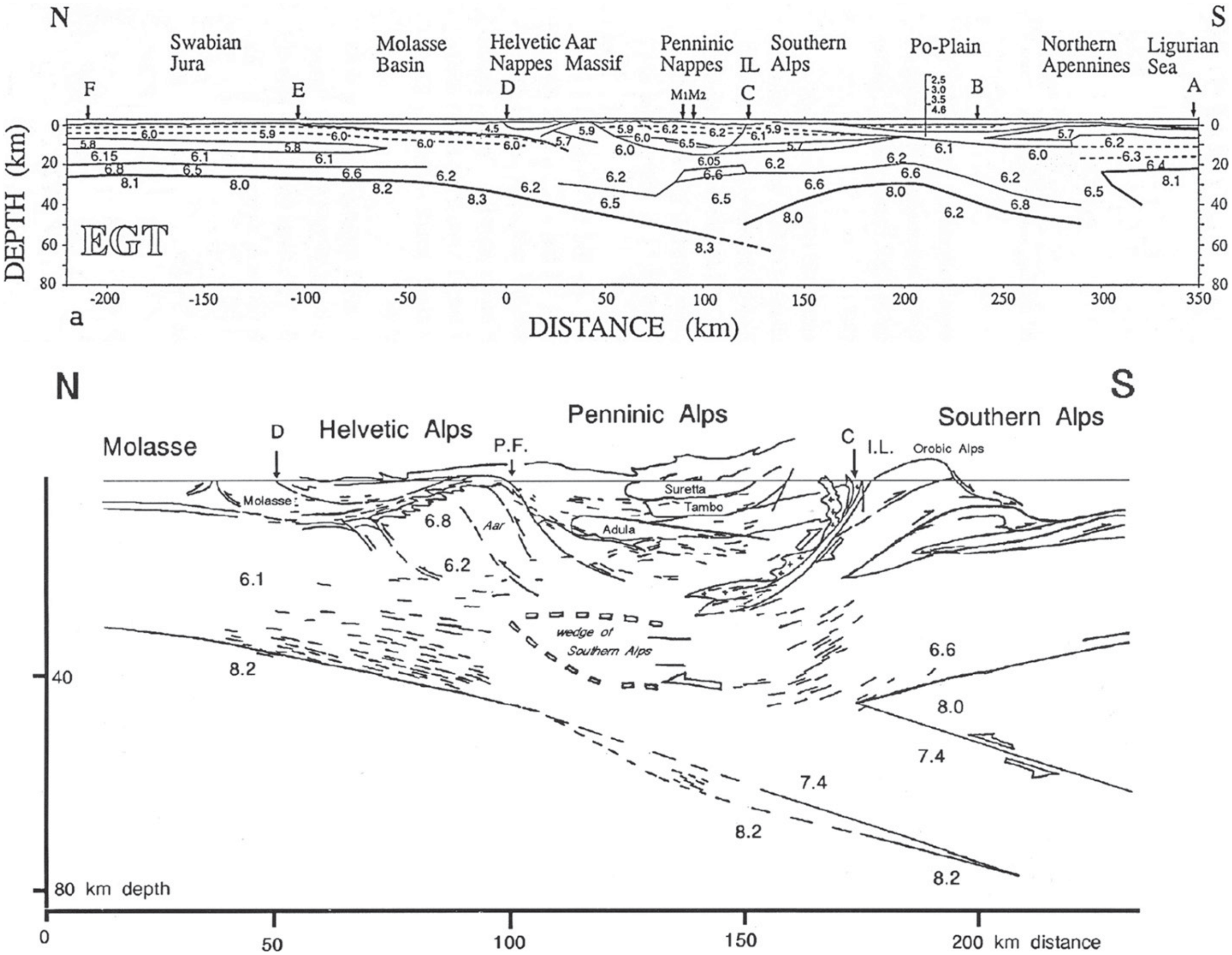

Figure 8.3.4-10. Top: Crustal cross section of the Alps along EGT from seismic-refraction data (from Ye, 1991, fig. 7-1a). Bottom: Geological-geophysical cross section of the Alps along EGT from EUGEMI, NFP 20 and other data (from European Science Foundation, 1990, fig. 8). [Ph.D. Thesis, Swiss Federal Institute of Technology Zürich (ETH), 114 p.] [European Geotraverse Project (EGT) 1983–1990, final report: European Science Foundation, Strasbourg, 67 p. Reproduced by kind permission of the European Science Foundation, Strasbourg, France.]

NFP 20 (Fig. 8.3.4-10, bottom), recorded in 1986 across the eastern part of the Swiss Alps which was already discussed in more detail in the previous section, "Large-Scale Seismic-Reflection Surveys in Western Europe" (for location, see Fig. 8.3.1-05).

As was discussed in subchapter 8.3.1.4, only by the combination of the seismic-refraction data with the much more detailed and with higher frequency recorded seismic-reflection data of the NFP 20 project was the detection of the European subduction shown in Figure 8.3.4-11 enabled.

In conjunction with the seismic exploration of the southern segment in 1983, which is discussed below, in northern Italy sea shots at shotpoint locations A1 to A4 shots not only provided energy for the main N-S line, but also, together with other borehole shots, served to record several perpendicularly oriented 30–80-km-long reversed and unreversed side lines (area A of Fig. 8.3.4-02). The goal of this special study was to obtain a detailed upper-crustal structure of the northern Apennines part of the EGT (Cassinis, 1986; Biella et al., 1987).

The complex crustal structure of the region between Alps and Ligurian Sea was discussed by a variety of authors. As an example, the interpretation of P. Giese and co-workers is shown in Figures 8.3.4-11 and 8.3.4-12, demonstrating the complex structure of the crust-mantle boundary in this area (Giese, 1985; Giese et al., 1982).

8.3.4.3. The Southern Segment and Other Investigations in Northwest Africa

The southern segment reached from northern Italy to northern Tunisia, crossing Corsica and Sardinia, and was organized by scientists from Italy (Trieste and Milano), Switzerland (ETH

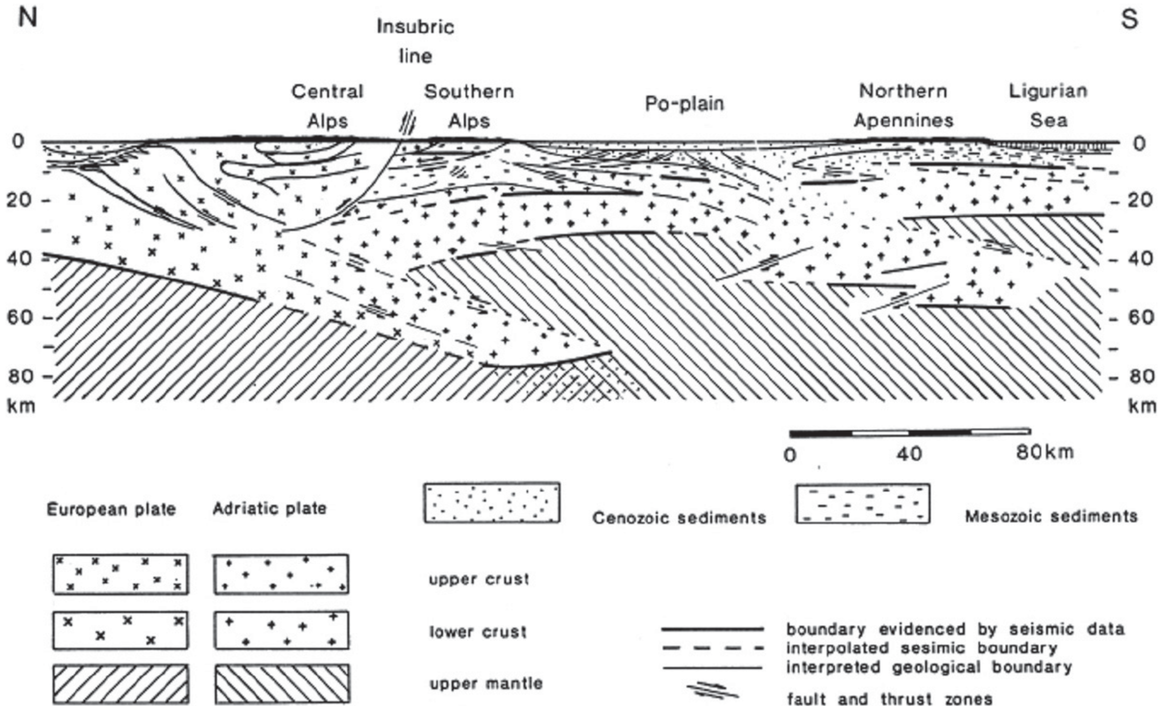

Figure 8.3.4-11. Tectonic interpretation of crustal structure along the EGT from the Alps to the Ligurian Sea, after P. Giese (from European Science Foundation, 1990, fig. 9). [European Geotraverse Project (EGT) 1983–1990, final report: European Science Foundation, Strasbourg, 67 p. Reproduced by kind permission of the European Science Foundation, Strasbourg, France.]

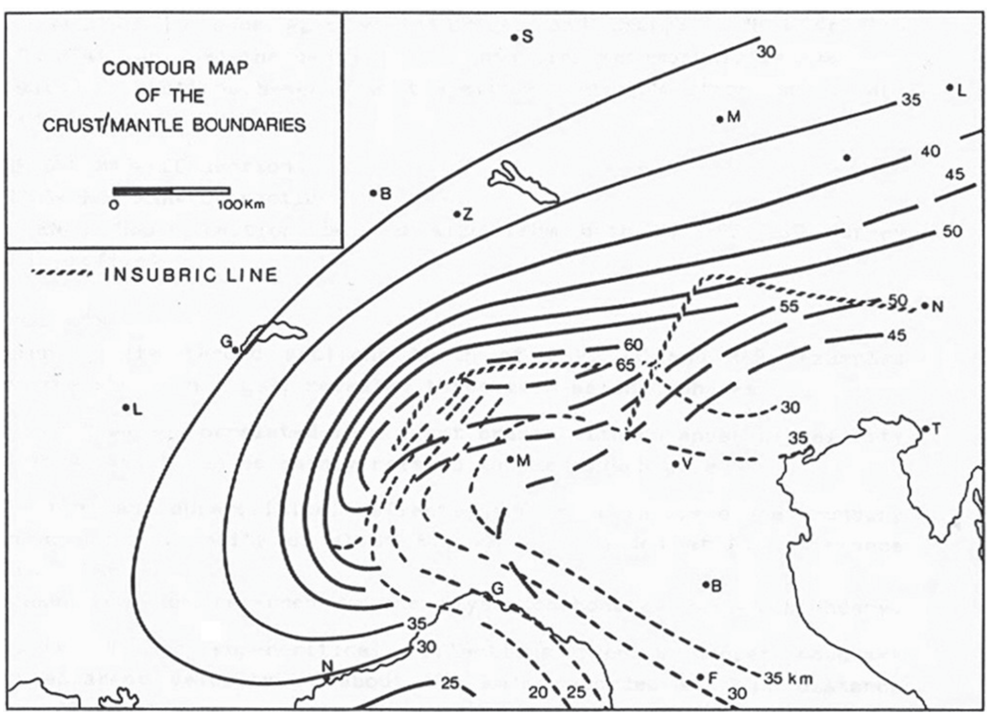

Figure 8.3.4-12. Moho surfaces in the region of Alps to Northern Apennines (from Giese, 1985, fig. 9). [*In* Galson, D.A., and Mueller, S., eds., 1985, Proceedings of the Second Workshop on the Geotraverse Project, the southern segment: European Science Foundation, Strasbourg, p. 143–153. Reproduced by kind permission of the European Science Foundation, Strasbourg, France.]

Zürich, and Germany (FU Berlin). It was investigated by two major seismic-refraction campaigns, performed in 1983 and 1985. The 1983 campaign covered northern Italy, Corsica, and Sardinia.

Following marine test profiles around the Corsica-Sardinia block in 1982, a marine survey, conducted in September 1983 in conjunction with the main experiment of 1983, covered the Ligurian Sea between Genova and Corsica (Ginzburg et al., 1986), using 45 small dynamite charges of 75–100 kg each and spaced 2–5 km apart. They were recorded by 10 OBSs, placed in the northern half of the line, and by land stations east of Genova and on northwestern Corsica, resulting in a number of partially overlapping reversed profiles.

The main profile of 1983 aimed to study the lithosphere under Corsica and Sardinia, using major depth charges of 1000–1125 kg, which were shot at four positions A to D (Fig. 8.3.4-13, SA to SD in Fig. 8.3.4-02; Appendix A8-1-4). MARS-66 land recording stations were positioned on both islands (Egger et al., 1988; Egger, 1990, 1992; see Appendix A8-1-4). The interpretation (Fig. 8.3.4-14) included earlier crustal surveys of 1974 around Corsica, of 1979 in Sardinia, and of 1982, as well. Their positions are included in Figure 8.3.4-13.

The southernmost segment in Tunisia (Fig. 8.3.4-15) was a separate project, carried out in 1985. It consisted of marine surveys in the Sardinia Channel, between Sardinia and Tunisia as well as in the Pelagian Sea, off Tunisia toward northeast (Morelli and Nicolich, 1990), and of a land survey in Tunisia. The land survey in Tunisia used two offshore and five land shotpoints. Recording was achieved by 120 MARS-66 stations, arranged as a network of nine reversed profile segments (Research Group for Lithospheric Structure in Tunisia, 1992; Appendix A8-1-4), of

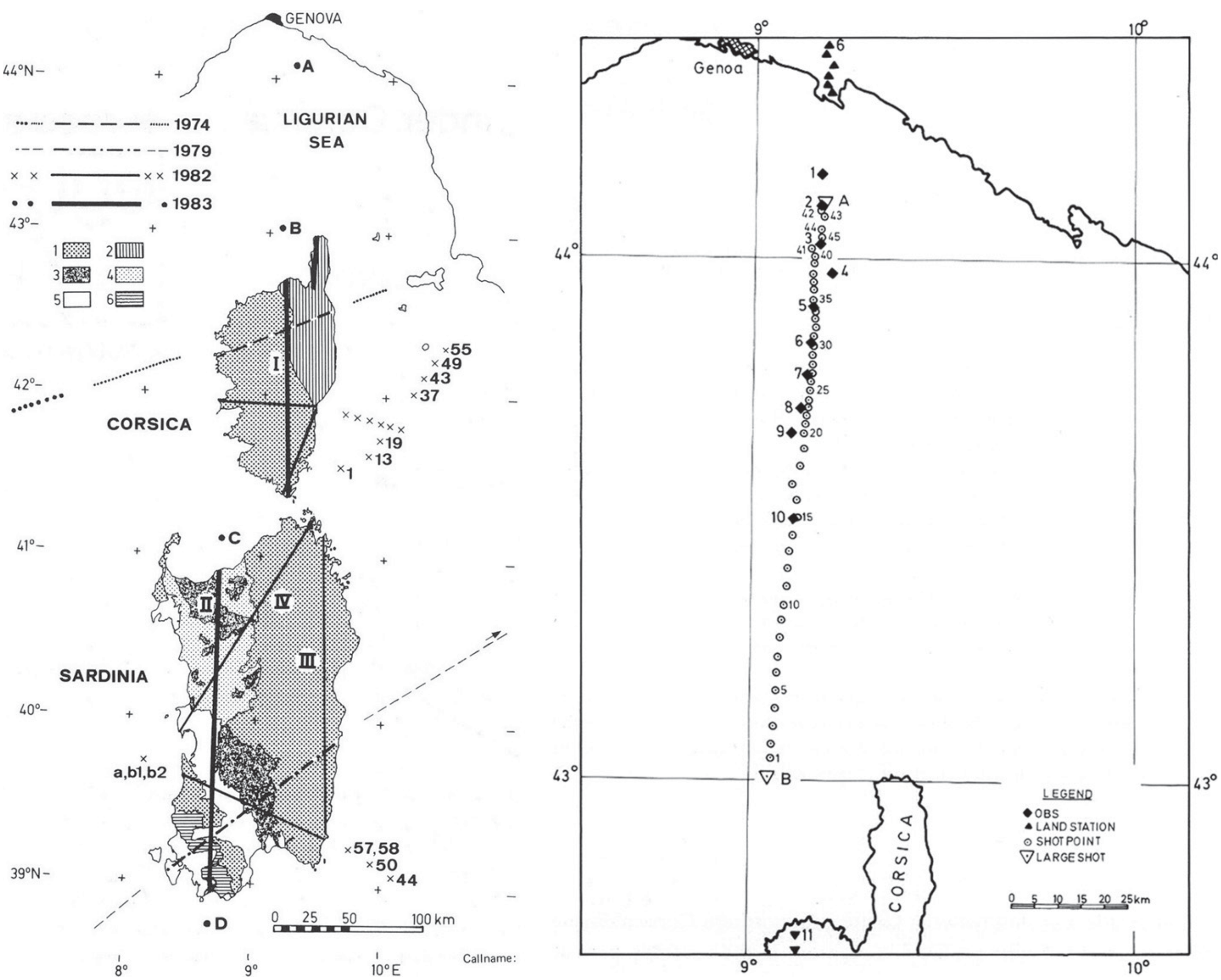

Figure 8.3.4-13. Left: Shotpoints and seismic profiles recorded on Corsica and Sardinia (from Egger et al., 1988, fig. 1). [Tectonophysics, v. 150, p. 363–389.]. Right: Location of ocean-bottom seismometers, land stations and shotpoints of the Ligurian Sea EGT segment (from Ginzburg et al., 1986, fig. 1). [Tectonophysics, v. 126, p. 85–97. Copyright Elsevier.]

which the main north-south line comprised 435 km on land, two sea shots at position SE and three land shots at positions SF1, SF2, and SG (Fig. 8.3.4-02).

Morelli and Nicolich (1990) have compiled a simplified cross section of the lithosphere from the Alps to Tunisia, summarizing the results from the individual sections along the southern segment (Fig. 8.3.4-16).

Also in North Africa, but not under the auspices of the European Geotraverse, a major seismic survey, carried out by the Free University of Berlin, Germany, was performed in 1983 and 1986 (Wigger et al., 1992; Appendix A8-1-5) in Morocco, Northwest Africa (Fig. 8.3.4-17, thick lines). The investigations added new information on the crust to the east of the crustal survey, which had been performed by the University of Hamburg (Fig. 8.3.4-17, thin lines) in 1975 (Makris et al., 1985).

The seismic investigations made use of commercial blasts of a phosphate mine near Oued Zem with charges between 4600 and 12600 kg and two specially arranged shot sites. In a lake near Zaida charges of 500 kg and in an abandoned shaft near Taklimt charges of 250 and 1000 kg were detonated. A trial experiment along the main line had been made already in 1983, using small charges at a then-active lead mine near Zaida (Wigger and Harder,

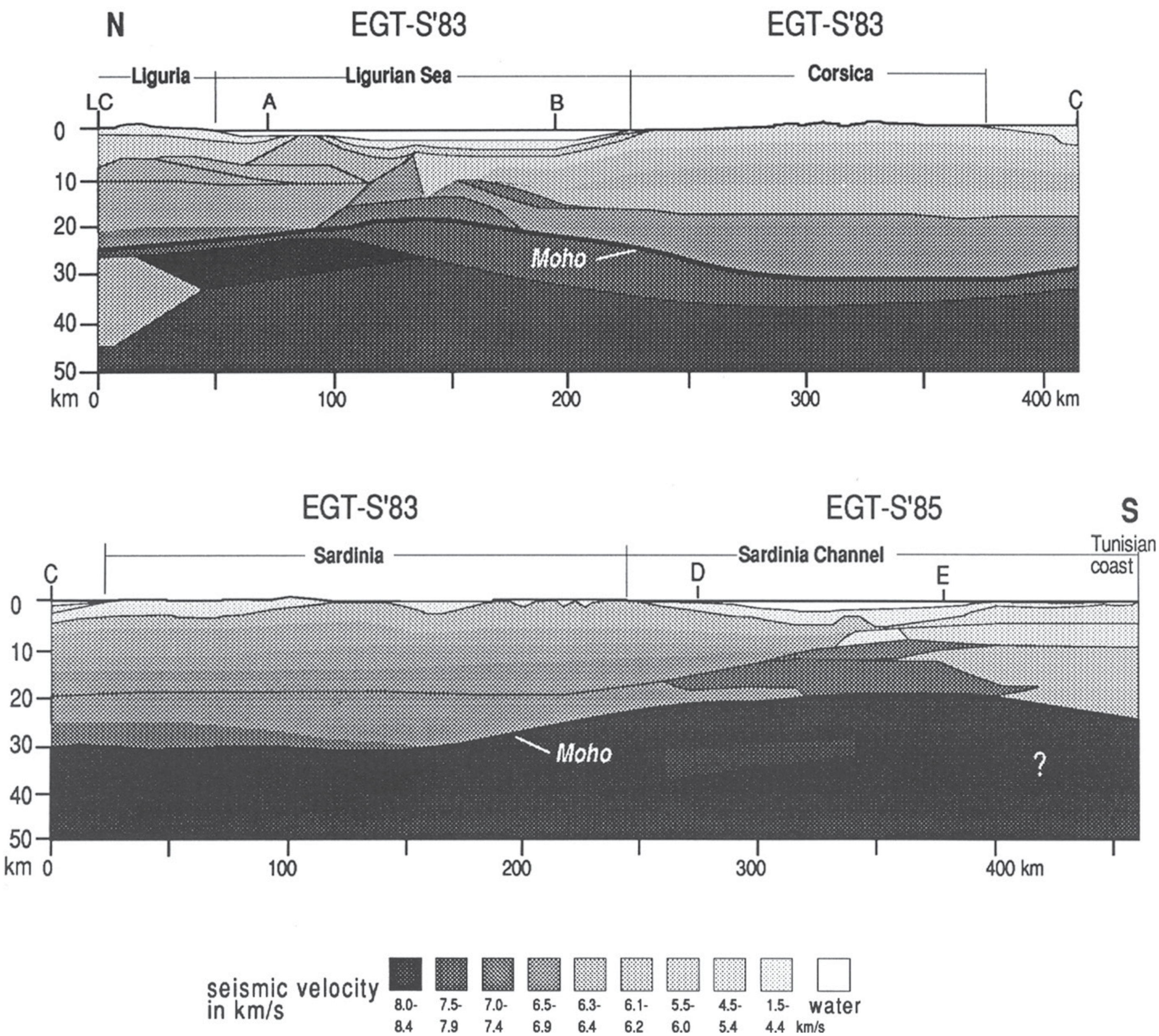

Figure 8.3.4-14. Crustal cross section of the EGT southern segment from the Ligurian Sea to Tunisian coast line (from European Science Foundation, 1990, fig. 10). Depth versus distance is exaggerated by 2:1. [European Science Foundation, Strasbourg, 67 p. Reproduced by kind permission of the European Science Foundation, Strasbourg, France.]

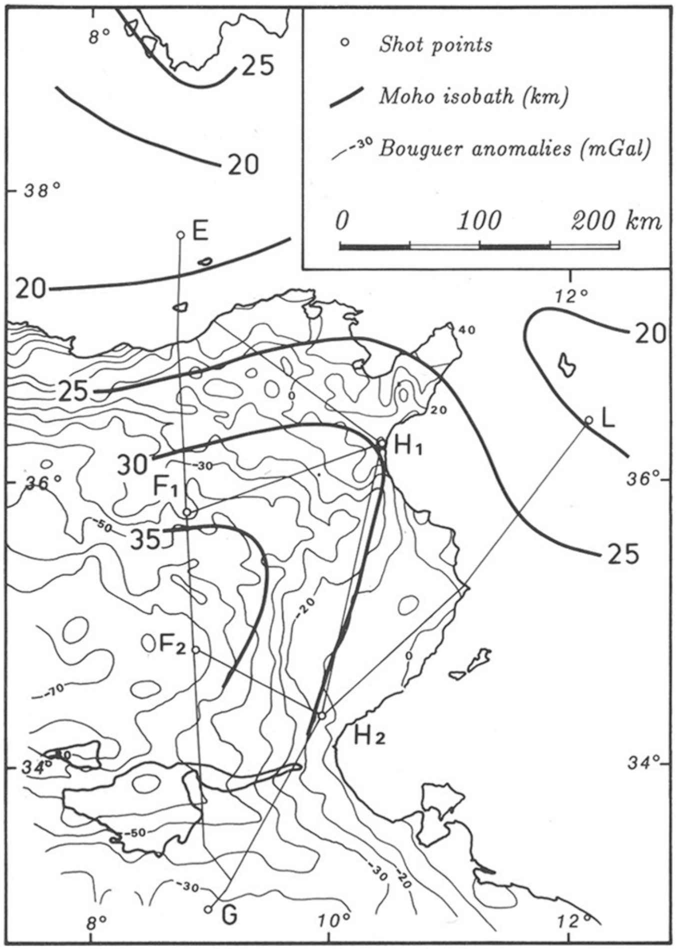

Figure 8.3.4-15. Location of shotpoints and profiles in and around Tunisia, and derived Moho depths overlain on a Bouguer gravity map (from Research Group for Lithospheric Structure in Tunisia, 1992, fig. 23). [Tectonophysics, v. 207, p. 245–267. Copyright Elsevier.]

1986). For recording, 30 stations were available, the station spacing ranged from 5 to 20 km. In total, three profiles were established, the longest line being a 350-km-long traverse between the Rif and the Anti Atlas, crossing the Middle and High Atlas mountains. The interpretation yielded several velocity inversions and gave an average Moho depth of 35 km, which under the High Atlas increased slightly to 40 km (Wigger et al., 1992).

8.3.4.4. Iberian Lithosphere Heterogeneity and Anisotropy Project

Finally, a project was designed to study possible anisotropy of the Hercynian lithosphere in Europe. Already in the 1970s, detailed seismic-refraction studies had explored the crust in southern and central Spain. In the early 1980s, the seismic exploration activity on land was focused in the Iberian Massif. The NW corner of Iberia was studied in a widespread survey, involving station spacing of 1–2.5 km (e.g., Cordoba et al., 1987).

As 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 Iberian Lithosphere Heterogeneity and Anisotropy (ILIHA) Project was designed as project no. 11 of the European Geotraverse. Following initial ideas formulated as early as 1984, during several special meetings in 1986 and 1987, a proposal to conduct a large-scale seismic anistropy experiment on the Iberian Peninsula was prepared and finally approved by the European Community, Directorate General XII, in 1988.

In 1989, the ILIHA deep seismic sounding experiment was conducted. Large sea shots of 500–1000 kg at positions B to F and X off the coasts of Portugal and Spain and land shots at positions G and P were recorded with 140 mobile recording stations along four reversed and two unreversed long-range profiles of 600–800 km length (Fig. 8.3.4-18) across the Iberian Peninsula (ILIHA DSS Group, 1993a, 1993b; Arlitt et al., 1993; Banda et al., 1993; Appendix A8-1-6). Unfortunately, the proposed shot at site A could not be realized.

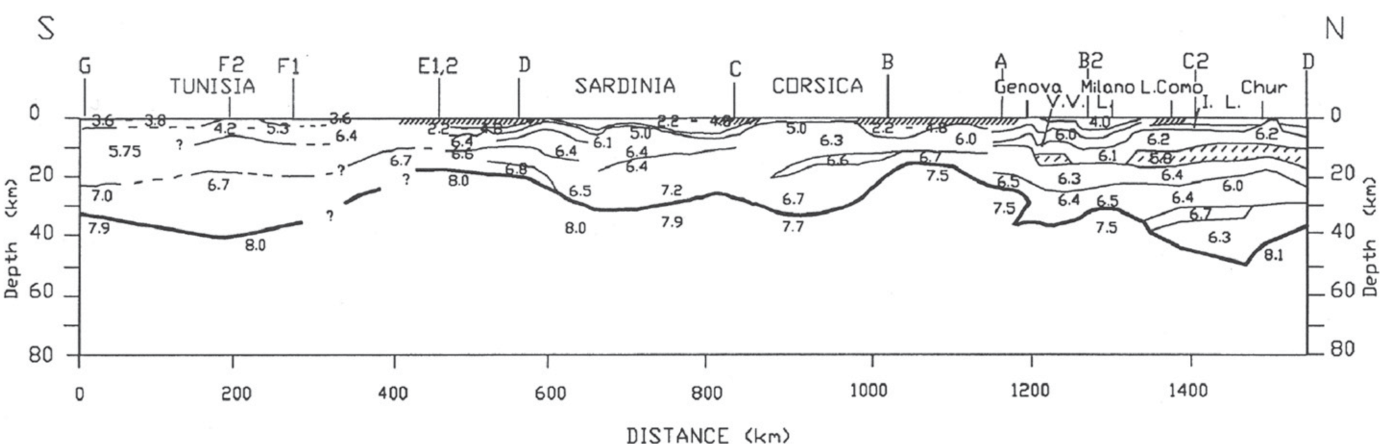

Figure 8.3.4-16. Crustal sketch along the EGT southern segment (from Morelli and Nicolich, 1990, fig. 4). [Tectonophysics, v. 176, p. 229–243. Copyright Elsevier.]

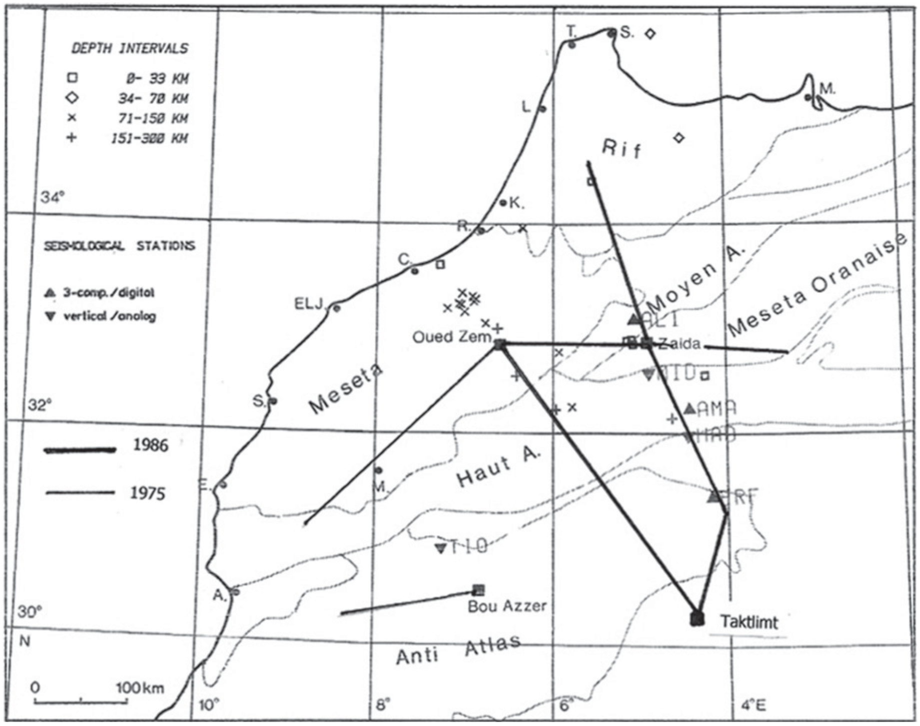

Figure 8.3.4-17. Location of seismic-refraction lines and seismological stations and epicenters in Morocco (base map with seismological information from Wigger and Harder, 1986, fig. 1). [Berliner Geowissenschaftliche Abhandlungen, v. A66, p. 273–288. Published by permission of Institut für Geologische Wissenschaften, Freie Universität Berlin.]

The ILIHA shots were also used for a special investigation of the Betic Cordillera (Banda et al., 1993; Appendix A8-1-6) where additional six 1500 kg borehole shots on land and three quarry blasts (4000 kg each) served as energy sources for two profiles, one across the Cordillera with 250 km length reaching the coast near Almeria, and one parallel to the Alboran Sea from Malaga to Alicante (profiles I and II in Fig. 8.3.4-18, right). The shots were recorded by 90 analog seismic stations of type LOBS of the University of Hamburg.

The data of the successful seismic-refraction experiment were interpreted by several working groups. Data examples of the long-range profiles are shown in Figure 8.3.4-19. Besides the seismic-refraction observations, the ILIHA project also involved a broadband seismology investigation as well as other seismo-

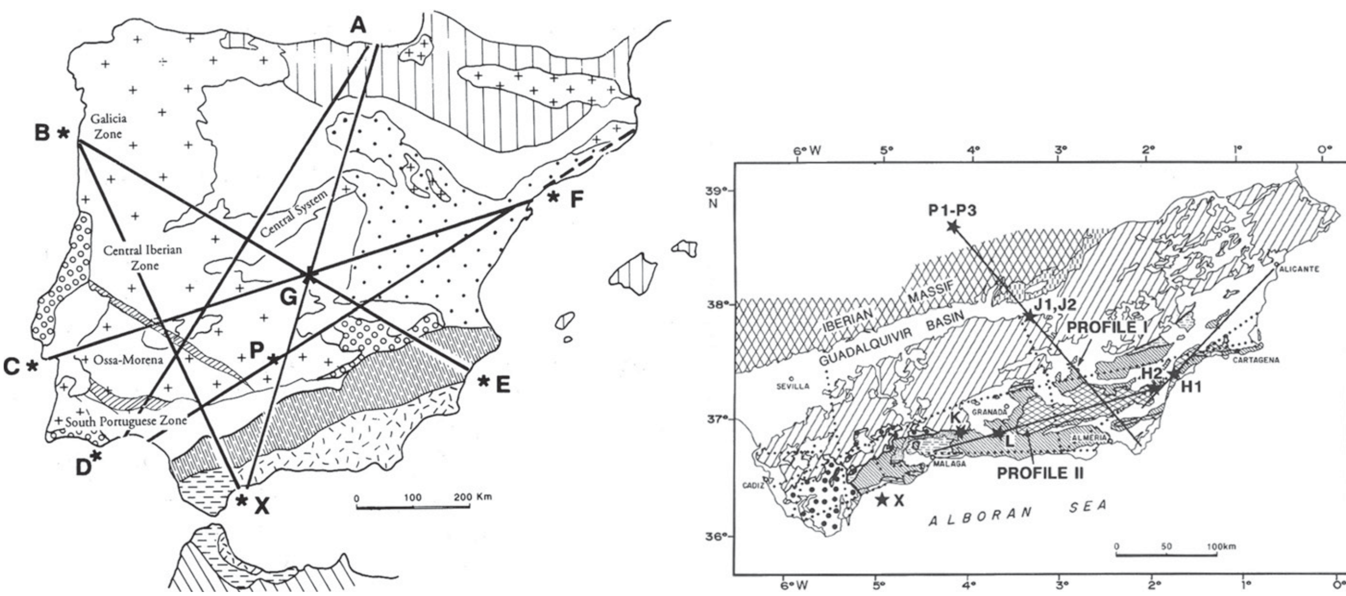

Figure 8.3.4-18. Left: Geotectonic map of the Iberian Peninsula displaying ILIHA deep seismic sounding shotpoints and profiles (from ILIHA DSS Group, 1993a, fig. 1). [Tectonophysics, v. 221, p. 35–51]. Right: Seismic survey of the Betic Cordillera, southern Spain (from Banda et al., 1993, fig. 1). For reference see position of shotpoint X. [Tectonophysics, v. 221, p. 35–51. Copyright Elsevier.]

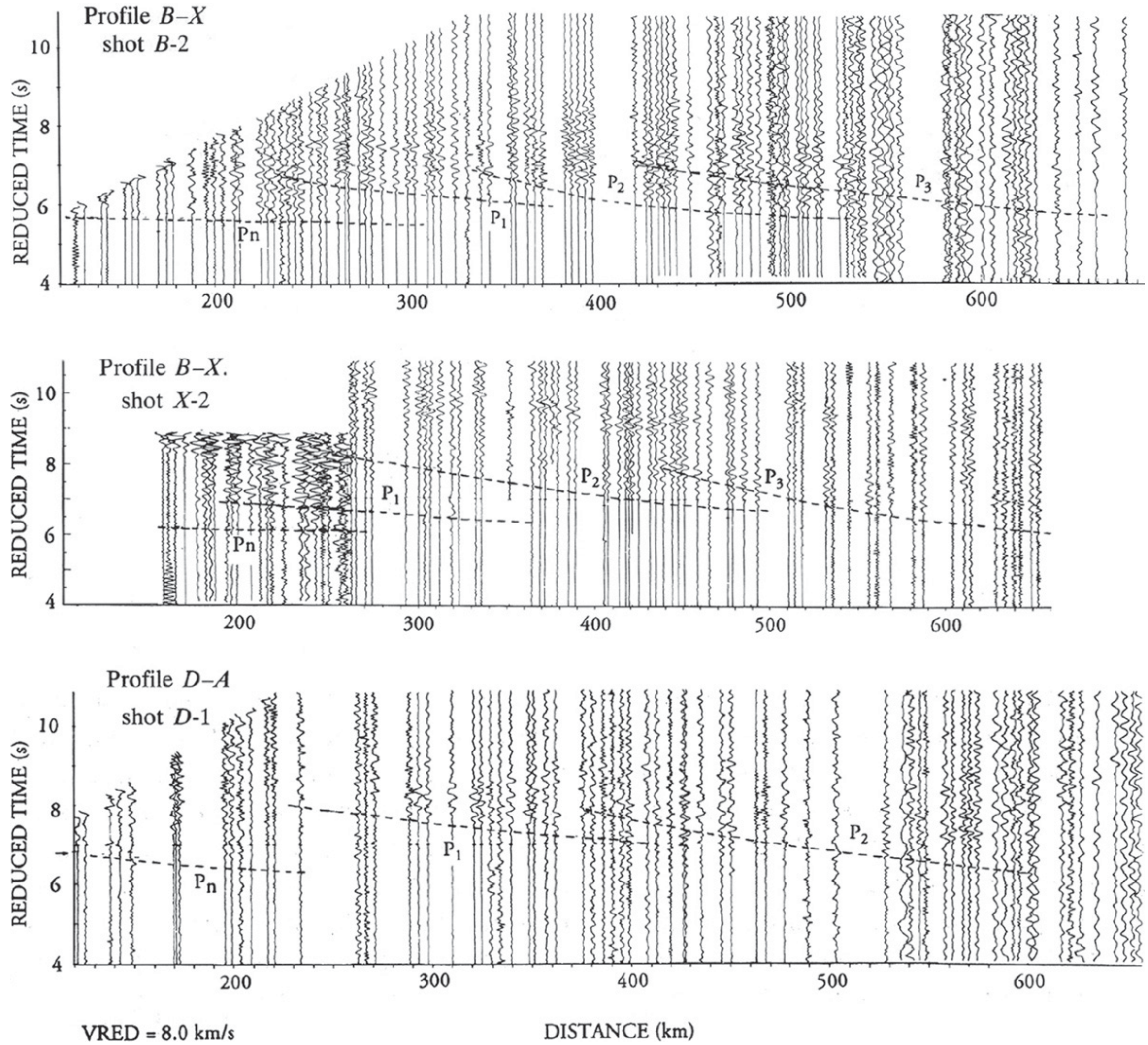

Figure 8.3.4-19. Data example of ILIHA long-range profiles (from ILIHA DSS Group, 1993a, Figs. 5, 6, and 8). [Tectonophysics, v. 221, p. 35–51. Copyright Elsevier.]

logical and geodynamical topics such as gravity, Rayleigh wave, focal mechanism, and delay time tomographic investigations which, together with 10 contributions on the deep-seismic sounding project, were jointly published in a special monograph edited by Mezcua and Carreno (1993).

The modeling of the mantle data allowed researchers to obtain fine structure of the lower lithosphere down to 90 km. The authors conclude that the seismic structure of the lithosphere is more uniform than expected, as significant lateral heterogeneities were not recognized within the lower lithosphere as would be expected if the frozen-in Hercynian structure was evident at these depths. However, there is an incompatibility between shear-wave velocities derived from Rayleigh and Love waves, suggesting anisotropy at depths greater than the 100 km penetrated by the ILIHA DSS experiment. Under the Betic Cordillera, a distinct crustal thickening to 35 km was modeled.

Following the overview of Díaz and Gallart (2009), one year before the ILIHA experiment, in 1988, the Valencia trough was explored within the VALSIS experiment. Up to 200 km of multichannel seismics were acquired including common depth point, common offset and expanding spread profiles (Pascal et al., 1992; Torné et al., 1992). The shots from some of these profiles were recorded onshore, providing the first onshore-offshore transects in Iberia (Gallart et al., 1990). The same area was explored further in 1989 with a wide-angle experiment using explosive sources, recorded by 110 land stations and 10 OBS (Danobeitia et al., 1992).

8.3.5. Deep-Seismic Sounding Projects in Eastern Europe

In the 1980s, only minor fieldwork in Poland was accomplished, but the interpretation of the whole set of existing profiles was pushed forward (Fig. 8.3.5-01).

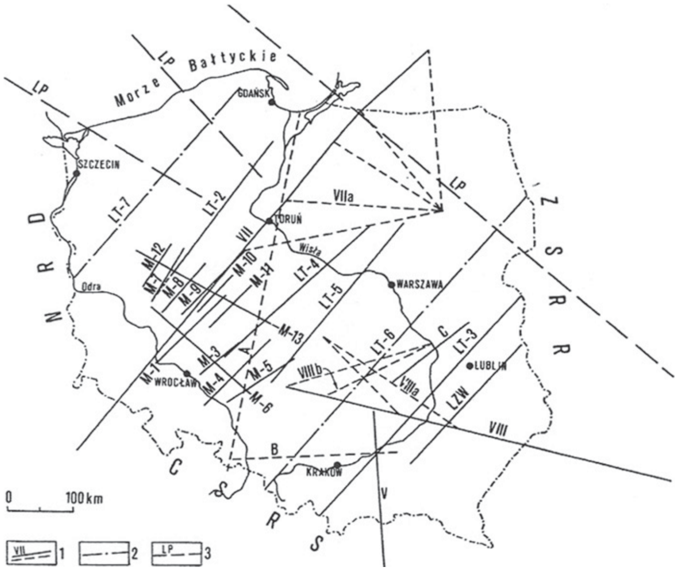

Figure 8.3.5-01. Location of seismic profiles and corresponding crustal cross sections in the fore-Sudetic region, southwestern Poland (from Guterch et al., 1986, fig. 1). [Publications of the Institute of Geophysics, Polish Academy of Sciences, A-17 (192), p. 3–83. Reproduced by permission of Instytut Geofizyki Akademii Nauk, Warsaw, Poland.]

A summary was published by Guterch et al. (1986). The location map shows the dense coverage of Poland with DSS lines, consisting of the first lines A, B, and C, accomplished in the early 1960s, the International Profiles V, VII, and VIII, completed by the early 1970s, and the sets of national profiles, the M-lines concentrating on the Sudetic foredeep, and the LT-lines, concentrating on the Tornquist-Teisseyre Zone in central Poland. In 1986, the LT-7 line in northwestern Poland could be added (Guterch et al., 1991b; Appendix A8-1-7), in cooperation with Finnish institutions. This line was both recorded as a seismic-refraction line, with 2 km station spacing and 5 shotpoints with charges between 100 and 900 kg, and as a steep-angle reflection line. This set of observations became the target of a special workshop, held in Warsaw in November 1993 (Guterch et al., 1994).

Also in the fore-Sudetic region, the first near-vertical reflection profiles were observed on profile A (Fig. 8.3.5-01, named GB2 in Fig. 7.2.7-04) in 1987, using 48-channel equipment and 24 10-Hz geophones per channel. Energy was produced by 15–30 kg borehole explosions and recorded at up to 18 s and 4 km maximum distance, and the set of M-profiles of 1966 was reinterpreted (Guterch et al., 1991a).

In Czechoslovakia a 150-km-long deep seismic-reflection transect was observed through the Slovakian West Carpathians. In 1983–1985, three lines were shot consecutively, using dynamite and recording with a 96-channel recording system. The deepest reflector was recorded continuously over 40 km distance from the Central (Apulian) West Carpathians to the Inner (Tethyan) West Carpathians, dipping toward SSE from 6 s TWT to ~9 s (Tomek et al., 1987; Tomek, 1993; for more details, see section 8.3.1.6).

8.4. DEEP SEISMIC SOUNDING PROJECTS IN EASTERN EUROPE AND ADJACENT ASIA (USSR)

The third period of Russian deep seismic sounding (DSS) investigations started at the end of the 1970s and continued through the 1980s. It was a time of stabilization of DSS methods, and an optimal system of observation and data interpretation was developed, including a program for a uniform study of the whole USSR (Benz et al., 1992; Pavlenkova, 1996). Considerable progress was made due to the efforts of the activities of the Special Regional Geophysical Expedition (SRGE; renamed GEON in the early 1990s) of the Ministry of Geology of the USSR (Egorkin and Chernyshov, 1983; Egorkin et al., 1987, 1991). The network of seismic profiles of the SRGE covered almost the whole territory of the USSR (Fig. 8.4-01).

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 (Fig. 8.4-02). Two types of energy sources were used. Chemical explosions with charges up to 5000 kg loaded in a series of boreholes 100–150 m apart allowed recording distances of 300–400 km. For distances up to 3000 km so-called "industrial" (nuclear) explosions were specially arranged for these investigations (later named PNE—peaceful nuclear explosions; dots in Fig. 8.4-02). Two to four of such shots, spaced 1000–1500 km apart, were arranged on several profiles (double lines in Fig. 8.4-01, lines in Fig. 8.4-02).

The long-range profiles allowed in particular the recording of reflections from the transition zone between upper and lower mantle. Most of its data were reprocessed and reinterpreted in the 1990s by several authors (e.g., Egorkin, 1999; Mechie et al., 1993; Morozova et al., 1999; Ryberg et al., 1998). The observation scheme and a data example from the "Quartz" profile are shown in Figures 8.4-03 and 8.4-04.

One of these projects, using large chemical explosions, aimed to investigate the crustal and uppermost mantle structure around the Mirnyi kimberlite field in Siberia (Suvorov et al., 2006). In 1981 and 1983, two profiles of nearly 400 km in length were recorded, perpendicular to each other (Fig. 8.4-05).

Profile 1, 370 km long, crossed the kimberlite pipe in a NNW-SSE direction. It was covered by 41 analogue Taiga seismographs, which recorded 21 explosions along the line including one offset shot. Profile 2, 340 km long, ran in a SW-NE direction and was located ~30 km to the south of the Mirnyi kimberlite field. The profile was covered by 45 seismographs which recorded 22 chemical explosions, including 4 off-end shots. Charges were between 1.5 and 6.0 tons of TNT, which were distributed in 100–200 kg individual charges in shallow water (less than 2 m deep). The resulting data are of high quality with high signal/noise ratio to the farthest offsets (Fig. 8.4-06; Appendix A8-1-8).

The interpretation of Suvorov et al. (2006) showed a normal cratonic crust of 45 km thickness with only slight Moho undulations (Fig. 8.4-07). The average velocity of the upper crust to 25 km depth was 6.3 km/s, but in an ~60-km-wide zone around the kimberlite pipe relatively small seismic velocities were

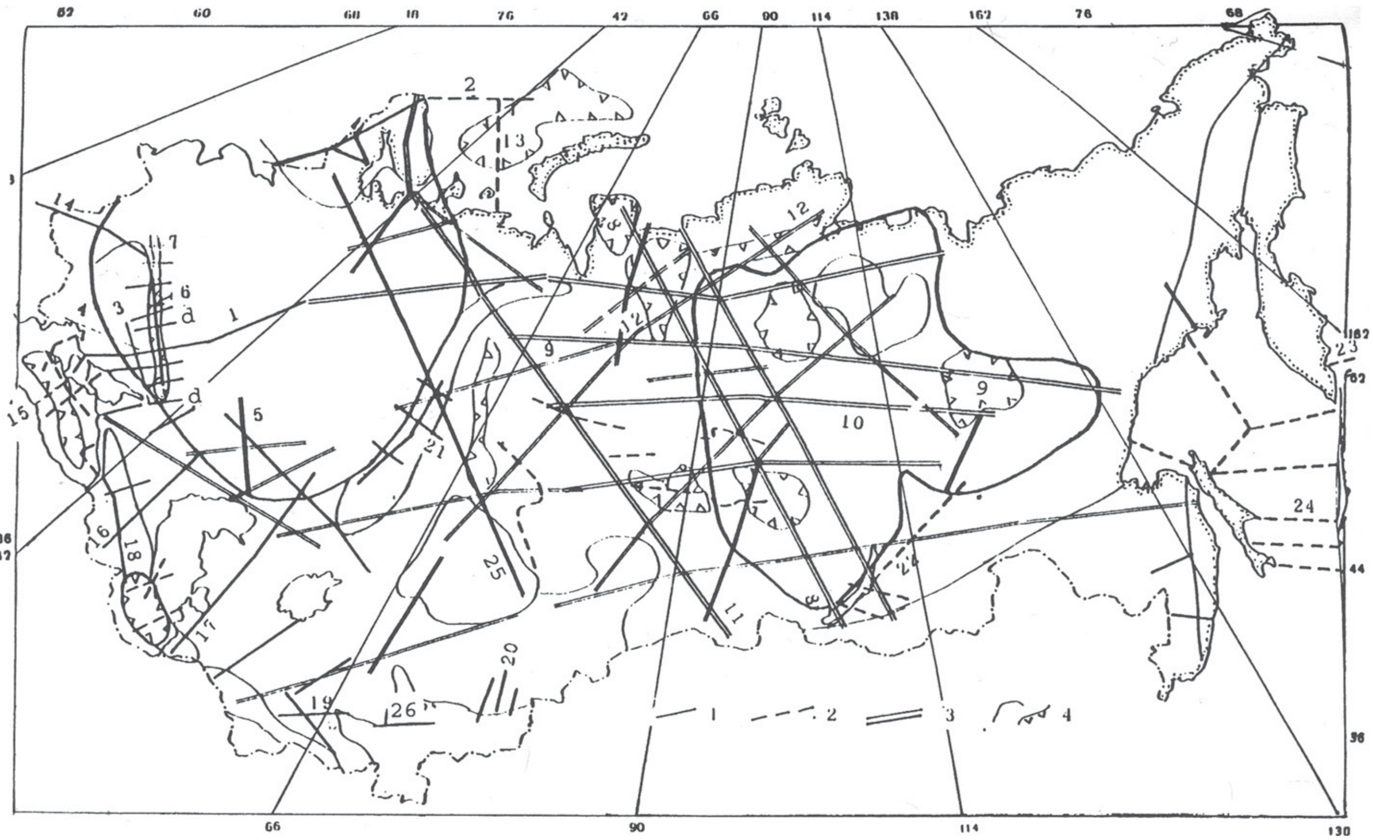

Figure 8.4-01. Location map of deep seismic sounding profiles in the USSR observed by SRGE (Special Regional Geophysical Expedition) in the 1970s and 1980s (from Pavlenkova, 1996, fig. 7). [Advances in Geophysics, v. 37, p. 1–133. Copyright Academic Press, Elsevier.]

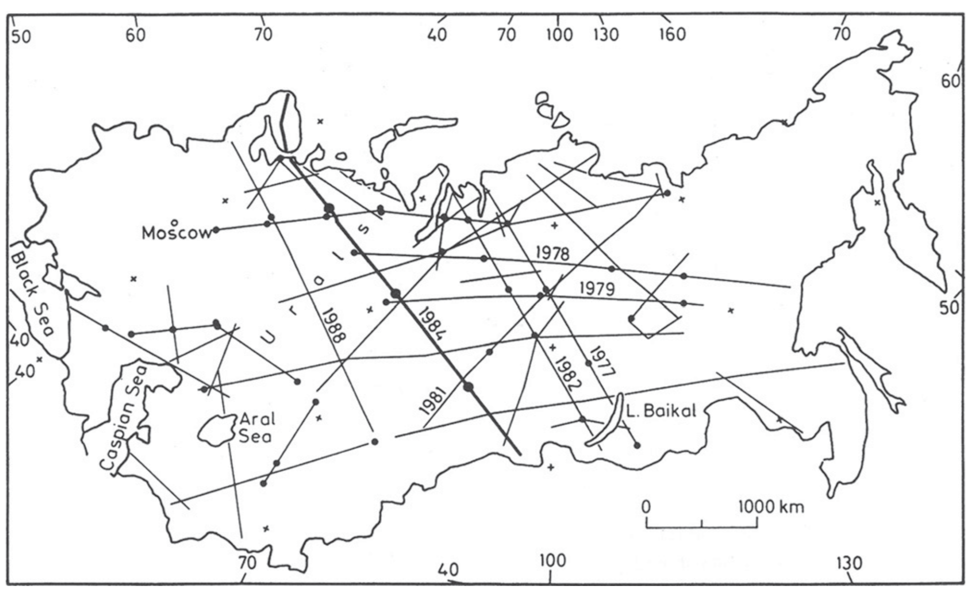

Figure 8.4-02. Location map of long-range deep seismic sounding profiles in the USSR using PNE (dots—peaceful nuclear explosions) as energy sources for distance ranges of several 1000 km (from Mechie et al., 1993, fig. 1). The observation scheme and data example shown in Figs. 8.4-03 and 8.4-04 is from the "Quartz" profile (thick line). [Physics of the Earth and Planetary Interiors, v. 79, p. 269–286. Copyright Elsevier.]

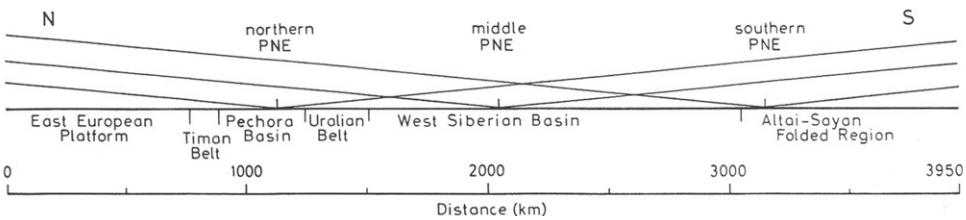

Figure 8.4-03. Observation scheme and tectonic units along the superlong deep seismic sounding profile "Quartz" (from Mechie et al., 1993, fig. 2). [Physics of the Earth and Planetary Interiors, v. 79, p. 269–286. Copyright Elsevier.]

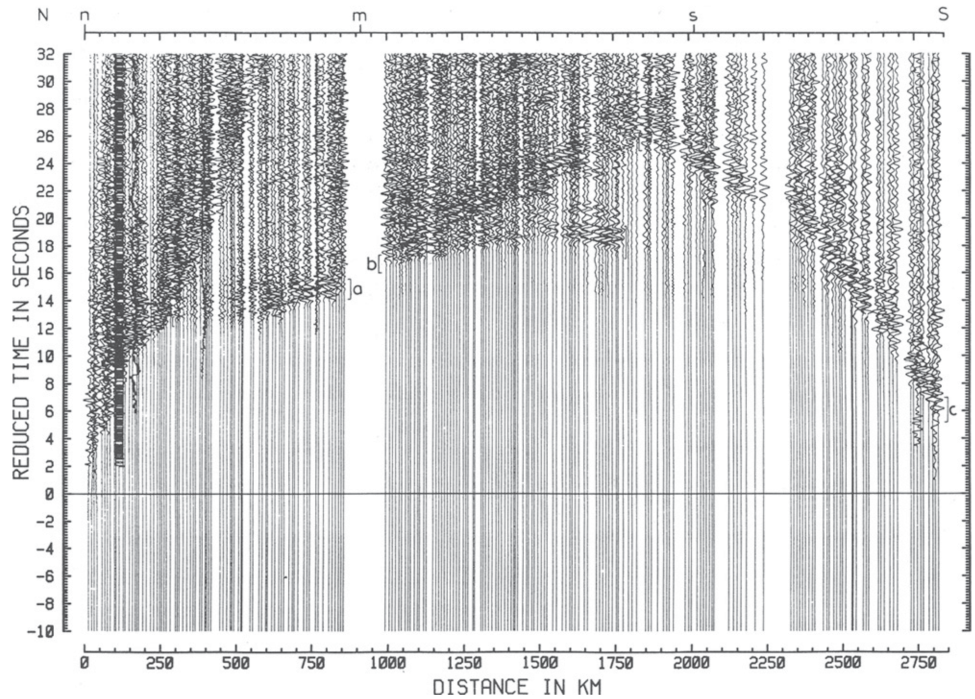

Figure 8.4-04. Data example of the superlong deep seismic sounding profile "Quartz" in the USSR observed in 1984 (from Mechie et al., 1993, fig. 3b). [Physics of the Earth and Planetary Interiors, v. 79, p. 269–286. Copyright Elsevier.]

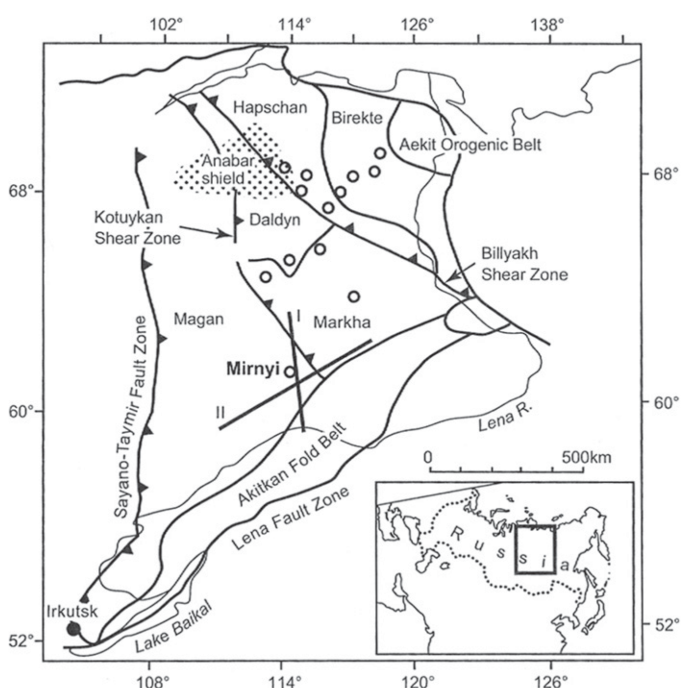

Figure 8.4-05. Location map of deep seismic sounding profiles (thick straight lines I and II) near the Mirnyi kimberlite field in the eastern Siberian craton (from Suvorov et al., 2006, fig. 1). Circles—kimberlite fields. [Tectonophysics, v. 420, p. 49–73. Copyright Elsevier.]

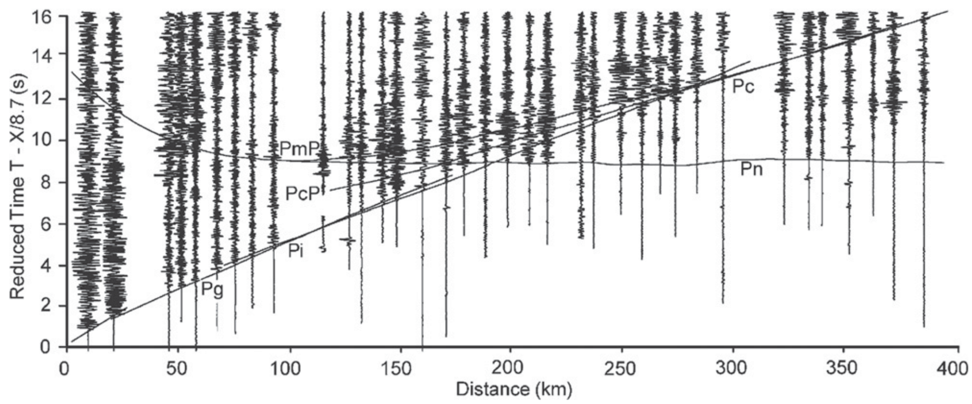

Figure 8.4-06. Data example showing record section of shotpoint 1 of DSS line I across the Mirnyi kimberlite field in the eastern Siberian craton (from Suvorov et al., 2006, fig. 9b). Reduction velocity is 8.7 km/s. [Tectonophysics, v. 420, p. 49–73. Copyright Elsevier.]

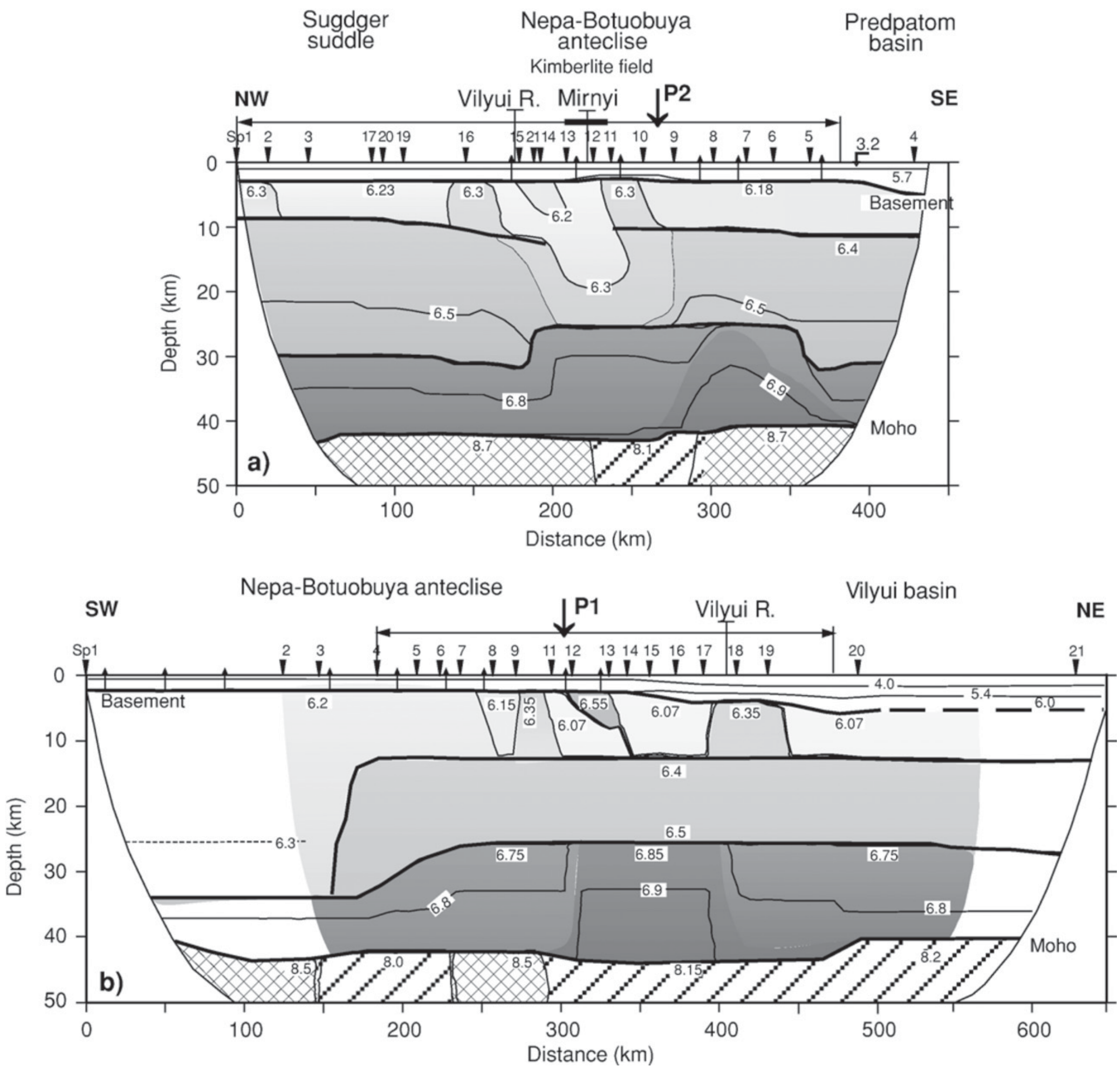

Figure 8.4-07. Velocity-depth cross sections along profile I (a) across and along profile II (b) close to the Mirnyi kimberlite field in the eastern Siberian craton (from Suvorov et al., 2006, fig. 7). [Tectonophysics, v. 420, p. 49–73. Copyright Elsevier.]

detected, surrounded by elevated average velocity of the upper crust (6.3 km/s). The lower crust, in contrast, had constant velocities of 6.8–6.9 km/s and appeared relatively unaffected by the presence of the kimberlite field. Furthermore, along both profiles extremely large sub-Moho mantle P-velocities of greater than 8.5–8.7 km/s were detected, except for a 70-km-wide zone with a "normal" P_n velocity of 8.1 km/s below the kimberlite field on profile 1 and below an ~100-km-wide zone at the southwestern end of profile 2, which again was close to the kimberlite field. The difference in the velocities in the two profile directions indicated anisotropy, but the effect of unusual rock compositions, e.g., from a high concentration of garnet, could not be excluded by the authors.

Near-vertical reflection studies were also performed in the USSR in the 1980s, but at a much smaller scale than in the United States and in western Europe. On the Ukrainian Shield and in the Urals, records were obtained up to 6 s TWT, allowing the study of the upper 15 km of the crust in some detail. In Kazakhstan, deep seismic-reflection records up to 12 s were recorded, and in Belorussia CDP profiles were obtained (Pavlenkova, 1996).

8.5. CONTROLLED-SOURCE SEISMOLOGY IN NORTH AMERICA

8.5.1. Instrumentation

The seismic experiments of the 1980s in North America differed substantially from seismic experiments in earlier decades. In reflection seismic surveys, long lines that were several 100 km in length were being realized. Furthermore, starting in 1978, seismic-refraction projects employing a rapidly growing number of instruments came into use. The requirements in the new development of portable seismic recording instruments had been: the instrument had to be small and available in large quantities (at least 100 pieces); it should be easily be operated by untrained personnel; it should record mostly automatically (i.e., to be switched on and off by a sophisticated clock of high accuracy); it should run unattended for several days; and the playback of the recorded data should be fast and easily gained for field control.

By the beginning of 1978, the U.S. Geological Survey, under the initiative of J.H. Healy, had developed new recording equipment (see Fig. 7.4.2-01), the so-called Seismic Cassette Recorder (SCR), and had built 100 individual units. The instrument was a single-component device consisting of a Mark Products L-4A 2-Hz vertical-component geophone, a set of three parallel amplifier boards with adjustable gain settings, a temperature-compensated oscillator (TCXO) providing the time standard for each unit, a voltage-controlled oscillator (VCO), and a cassette recorder. The three parallel amplifier boards with overlapping dynamic gain ranges allowed a variable total dynamic range. These three data channels and the time code signal were frequency modulated and all four frequencies plus a tape-speed compensation carrier frequency were summed and recorded on cassette tape. During the digitizing process, the cassette tapes were played back and the signals demultiplexed and demodulated (Murphy, 1988; Appendix A7-5-6).

Over the following 10 years, other sets of new instrumentation were being developed and successively introduced into the fieldwork of the North American research groups. In Canada, a digital instrument, the Portable Refraction Seismograph (PRS1), was being developed by the Geological Survey of Canada and afterwards built by EDA Instruments Ltd. By the end of the 1980s, the instrument was ready for use (Asudeh et al., 1992). This unit had been built in large quantities so that by 1989, ~200 individual units were available for seismic fieldwork.

During the second half of the 1980s, digital equipment had also been developed by U.S. companies and was ready for use by the scientific community at the end of the decade, replacing the analogue systems. One of the first experiments where digital equipment came into use was the 1990 TACT survey in Alaska. The first digital U.S. equipment for scientific use was a donation of 200 units of Seismic Group Recorders (SGR) by the oil industry to Stanford University. Another development in the late 1980s ready for use by 1990 was the RefTek 72A-02 instrument which had been developed by RefTec Ltd. and which was being bought by PASSCAL (Program for Array Seismic Studies of the Continental Lithosphere), funded by the U.S. National Science Foundation for the use by North American university groups. For the fieldwork in Alaska in 1990, where all four types of instruments described above were in the field, 35 RefTek's were available (see section 8.5.4; Fuis et al., 1997). Both the SGRs and the RefTeks will be described in more detail in Chapter 9.

8.5.2. Canada

Over ~10 years starting in the late 1970s, a series of long-range seismic-refraction and wide-angle reflection experiments was conducted by a consortium of Canadian university and government crustal seismologists (COCRUST). Figure 8.5.2-01 shows the location of seismic profiles and the main tectonic features of interest (Mereu et al., 1989). In each experiment, between 8 and 23 shots were fired and recorded up to distances between 150 and 400 km, mainly on vertical instruments. In total, 59 inline record sections were obtained. Mereu et al. (1989) describe all COCRUST experiments in some detail, show a series of record sections as data examples (Appendix A8-3-1), and discuss the crustal complexities arising from these data and the nature of the P_MP phase reflected from the Moho.

The first project was carried out in 1977, 1979, and 1981 across southern Saskatchewan and Manitoba and was conducted over the northern part of the Williston Basin and a transition zone between the Churchill Geological Province and the older Superior Province. The north-south and east-west inline profiles of 1977 and 1979 were supplemented in 1981 by three profiles arranged as a triangle which recorded all shots arranged at its edges. The data were interpreted several times (e.g., Hajnal et al., 1984; Kanasewich et al., 1987), indicating in particular a crustal

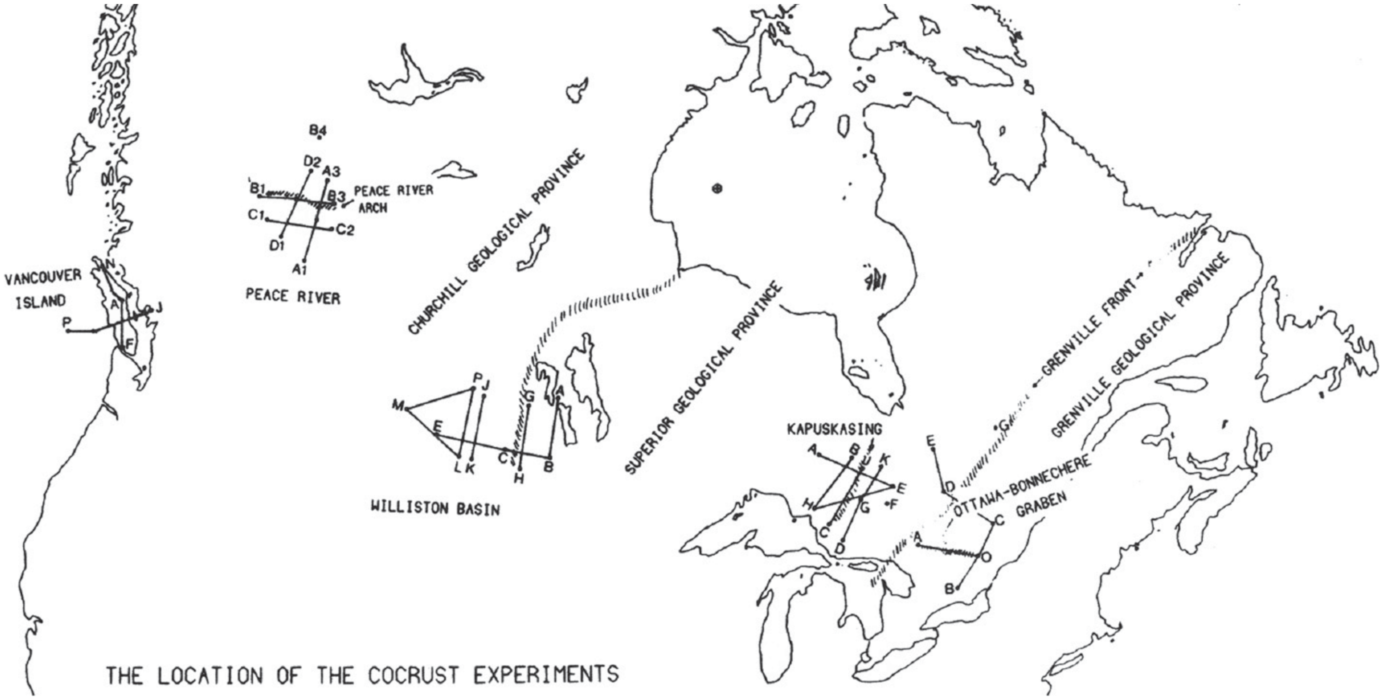

Figure 8.5.2-01. Location of COCRUST seismic refraction surveys in Canada and main tectonic features of interest (from Mereu et al., 1989, fig. 1). [*In* Mereu, R.F., Mueller, St., and Fountain, D.M., eds., Properties and processes of earth's lower crust: American Geophysical Union, Geophysical Monograph 51, p. 103–119. Reproduced by permission of American Geophysical Union.]

thickening from 40 km in the Superior Province to 45–50 km under the Williston Basin.

The second COCRUST experiment was the Vancouver Island project in 1980. These data were later (in 1984) complemented with a series of onshore and offshore near-vertical deep reflection lines, the first project of LITHOPROBE, which will be discussed below (Fig. 8.5.2-02). The main results showed that the continental crust overlying a subducting plate has a very complex crustal structure (e.g., Ellis et al., 1983; Green et al., 1986; Clowes et al., 1987a). Part of the data was used as basic data for a CCSS Workshop, which was discussed in the first section of this chapter (Green et al., 1990a).

The Ottawa-Bonnechere Graben-Grenville Front experiment of 1982 aimed to study the rather complex region of the Canadian Shield in eastern Ontario and western Quebec. The seismic lines were oriented parallel and perpendicular to the strike of the Ottawa-Bonnechere Graben and were interpreted by Mereu et al. (1986). The crust in the region of the graben appeared to be extremely heterogeneous, and a significant thickening of the crust along the

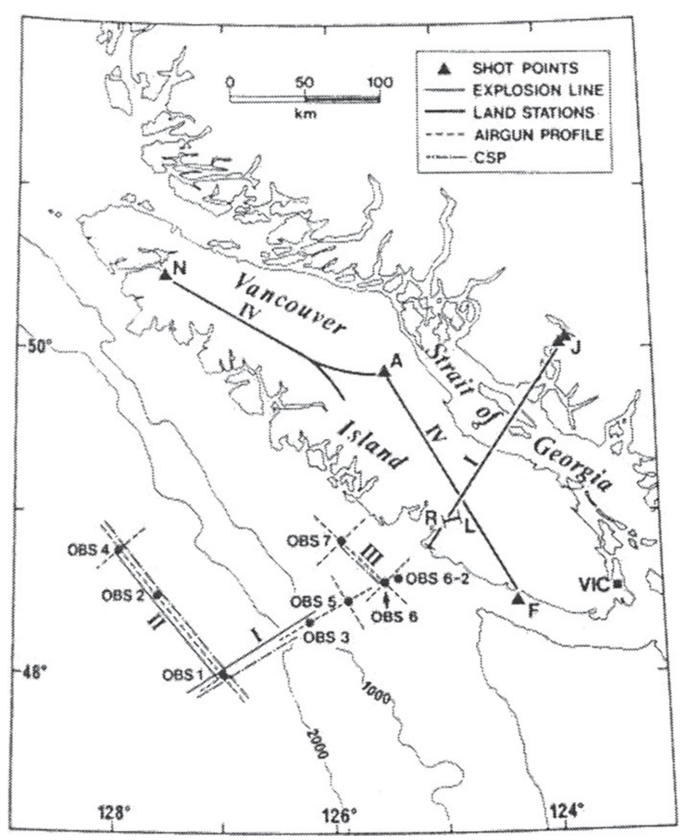

Figure 8.5.2-02. Location map of the COCRUST and LITHOPROBE surveys around Vancouver Island (from Green et al., 1990b, fig. 4). OBS—ocean bottom seismometer locations. [Geological Survey Canada, 89–13. 3–25. Reproduced with the permission of Natural Resources Canada 2009, courtesy of the Geological Survey of Canada.]

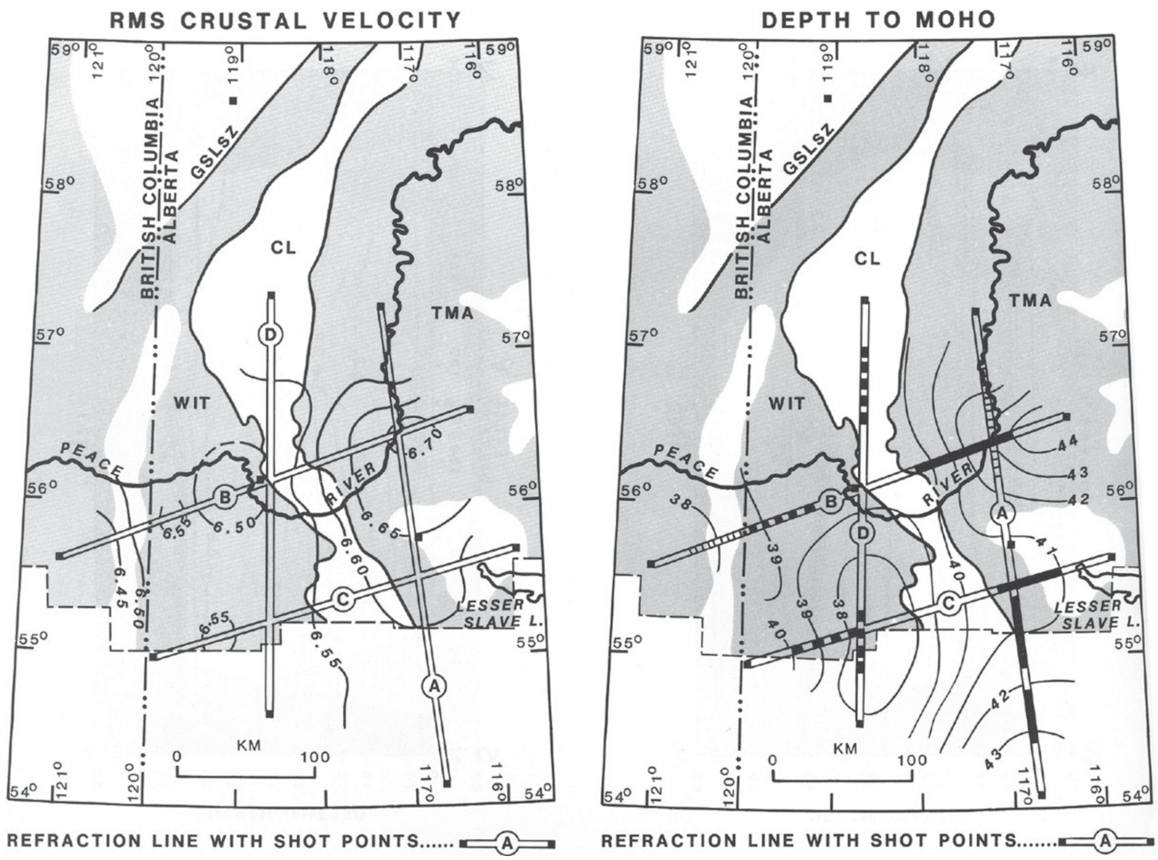

Figure 8.5.2-03. Location of the Peace River Arch experiment (from Stephenson et al., 1989, Figs. 4 and 5) superimposed on major aeromagnetic domains (shaded areas = positive residual magnetic anomalies). Left: Mean crustal velocities. Right: Moho depth contours. [Bulletin of Canadian Petroleum Geology, v. 37, p. 224–235. Permission granted by Bulletin of Canadian Petroleum Geology.]

Grenville front indicated that the front is a deep seated tectonic feature. These data across the Abitibi-Grenville region which later became one of the LITHOPROBE transects (AG in Fig. 8.5.2-05) and the data of the 1988 Ontario–New York refraction experiment (GRAP-88) were discussed and reinterpreted by Mereu (2000a) and White et al. (2000) in the context with new seismic-reflection and refraction data of the 1992 LITHOPROBE experiment (see Fig. 9.4.1-06 and corresponding text in Chapter 9.4.1).

The 1984 Kapuskasing experiment was carried out in northern Ontario over a gravity high, a zone of high-grade metamorphic rocks within the Superior Geological Province, and consisted of five seismic-refraction lines (Fig. 8.5.2-01) sampling the crust both parallel and perpendicular to the structure (Mereu et al, 1989). The investigations continued as the LITHOPROBE Kapuskasing Structural Zone Transect, and in 1987–1988, some 350 km of reflection data were recorded over the uplift (Percival et al., 1991; Leclair et al., 1994). The crust along the axis of this structure is extremely complex with a crust-mantle transition zone occurring from 38 to 48 km depth (Percival et al., 1991; Percival, 1994).

Finally, in 1985, the Peace River arch experiment was carried out in central Alberta consisting of four seismic lines of 290–330 km length, shot parallel and perpendicular to the arch structure (Fig. 8.5.2-03) and interpreted by Stephenson et al. (1989). All profiles were reversed, two of them had 3 km station spacing and an additional mid-point shot, the other two had 5 km station spacing and no mid-point shot. The most significant feature of the data was a very clear P_MP phase reflected from a very sharp Moho at 38–45 km depth. The Moho depth contour map also indicates the character of the observed Moho reflections. Solid black bars indicate a sharp Moho; cross-hatched bars indicate a more diffuse crust-mantle transition.

In 1984, the Geological Survey of Canada established a permanent base camp on the northeastern part of the Canadian Arctic continental shelf on a floating ice island that had broken off an ice shelf on Ellesmere Island in 1983 (Forsyth et al., 1990). In 1985 and 1986, air-supported seismic-refraction surveys were carried out on the adjacent ice pack, and in 1985, 1986, and 1988, the ice island was used as a platform for a floating seismic-reflection array. The refraction lines were up to 40 km long, and shots of 136–653 kg charges were detonated at depths of 100 m below the sea ice. Location of shotpoints and profiles and a velocity model fence diagram are shown in Figure 8.5.2-04.

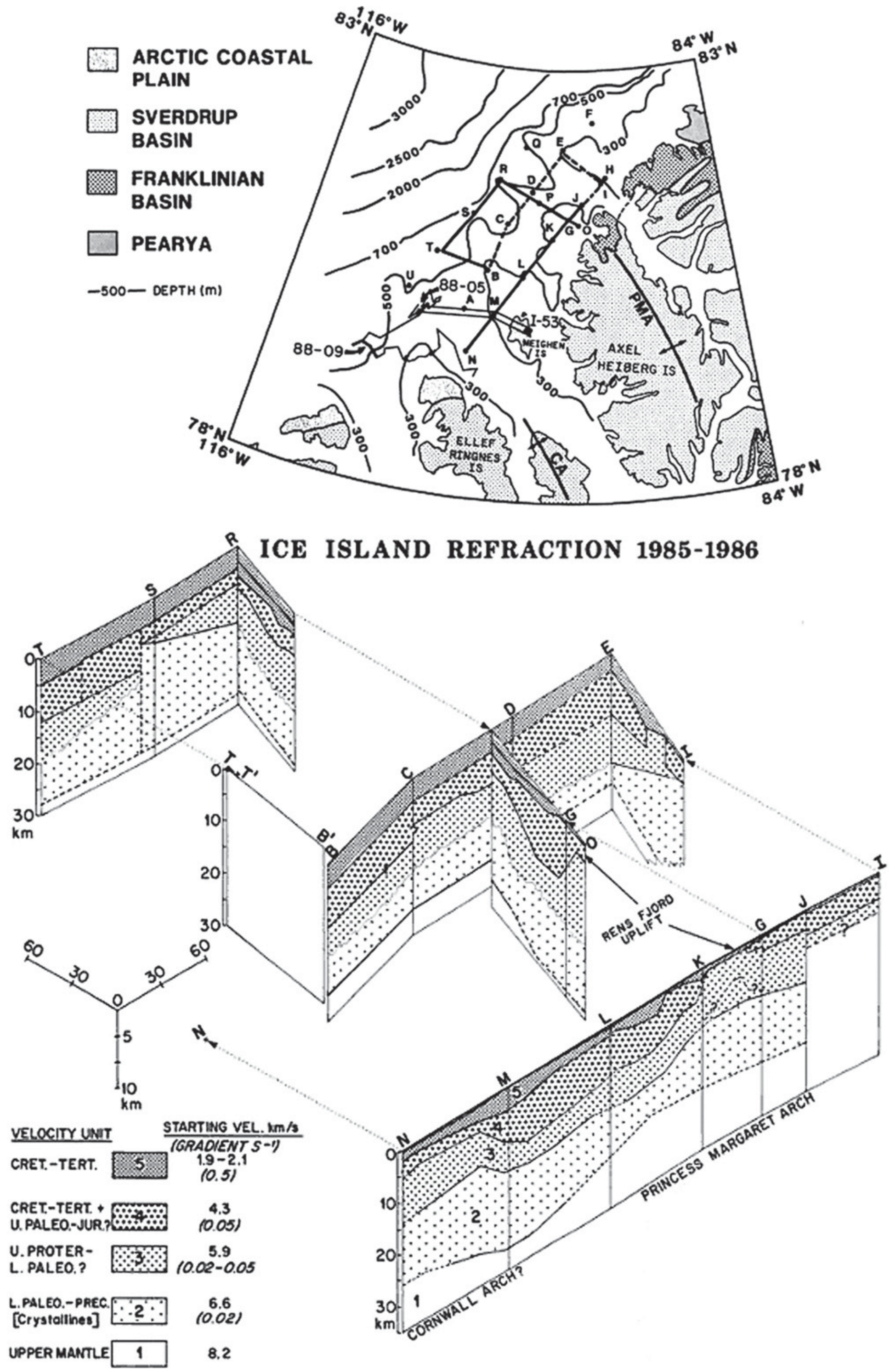

Figure 8.5.2-04. Ice island refraction work on the northeastern part of the Canadian Arctic continental shelf (from Forsyth et al., 1990, fig. 2). Top: location map (Letters: shotpoint locations), Bottom: crustal structure fence diagram. [*In* Pinet, B., and Bois, C., eds., The potential of deep seismic profiling for hydrocarbon exploration: Editions Technip, Paris, p. 225–236. Copyright Editions Technip, Paris.]

On the basis of the successful COCRUST operations and their results, in 1981, first discussions were started to involve the whole earth science spectrum. Soon thereafter, a LITHOPROBE (probing the Earth's lithosphere) steering committee was founded, involving representatives from universities, government agencies and petroleum and mining industries. LITHOPROBE was designed as a coordinated yet highly decentralized research program. Its scientific and operational components were built around a series of transects or study areas (Fig. 8.5.2-05).

Each transect was to represent globally geotectonic processes and addressed the problems of continental evolution by undertaking geological, geochemical, and geophysical surveys and experiments in a variety of tectonic settings representing a wide range of geological time periods. The program was to be spearheaded by the seismic-reflection method, as reflection images provide the most directly applicable information at depth. For this reason, the LITHOPROBE Seismic Processing Facility was established consisting of a central site at the University of Calgary and an associated national network of seismic research nodes at several universities and at the Geological Survey of Canada. In particular, it provided a central facility for storage and rapid access of LITHOPROBE and related digital seismic-reflection and refraction as well as magnetotelluric data (Clowes, 1997; Clowes et al., 1984).

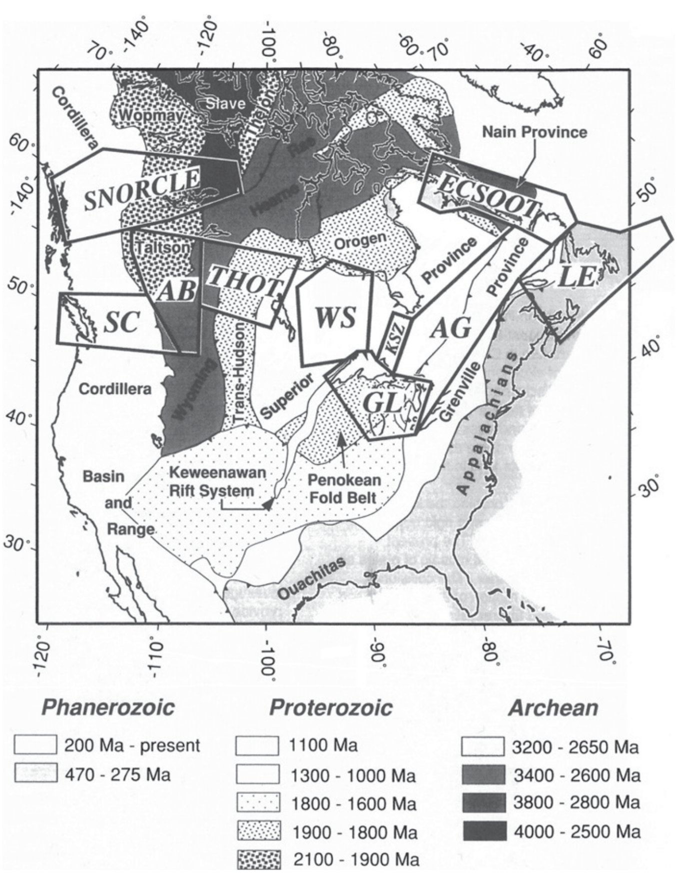

Figure 8.5.2-05. Location of LITHOPROBE transects (study areas) on a simplified tectonic map (from Clowes, 1997, fig. 1.1-1). SC—Southern Cordillera, AB—Alberta Basement, SNORCLE—Slave Northern Cordillera Lithospheric Evolution, THOT—Trans-Hudson Orogen Transect, WS—Western Superior, KSZ—Kapuskasing Structural Zone, GL—Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE), AG—Abitibi-Grenville, LE—LITHOPROBE East, ECSOOT—Eastern Canadian Shield Onshore-Offshore Transect. [LITHOPROBE Phase V proposal—evolution of a continent revealed. LITHOPROBE Secretariat, University of British Columbia, Vancouver, B.C., 292 p. Reproduced by permission of R. Clowes.]

The first project was funded in 1984–1985 for a one-year Phase I preliminary program with primary scientific activity on Vancouver Island including a detailed seismic-refraction and reflection survey (Clowes et al., 1986, 1987a, 1987b), part of the Southern Cordillera Transect, which was continued in Phase II from 1987 to 1990, involving multichannel seismic-reflection acquisition (Kanasewich et al., 1994; O'Leary et al., 1993; Zelt et al., 1992, 1993). In 1985, five marine multichannel seismic-reflection profiles (lines 85-1 and 85-2 are shown on Fig. 8.2-06 in Chapter 8.2) totaling 520 km were recorded across the western Canada convergent margin where the Juan de Fuca plate is subducting beneath North America (Clowes et al., 1987b). The primary objectives were the definition of the offshore accretionary structures and clarification of the convergent interaction between the two plates. The seismic source was a 50 airgun array tuned to concentrate energy in the band below 50 Hz. Signals were recorded by a 3000 m, 120 channel streamer. The top of the subducted crust was clearly resolved and correlated with the lowest-most reflector seen on Vancouver Island on the 1980 COCRUST data described above (Clowes et al., 1987a).

Part of Phase II was SCoRE (Fig. 8.5.2-06), the Southern Cordillera Seismic Refraction Experiment, which was carried out in 1989 and 1990 (Zelt et al., 1992, 1993; Clowes et al., 1995; Spence and McLean, 1998) and which provided seven 350-km-long profiles over the southern Canadian Cordillera. SCoRE 89 included the first six lines and was conducted primarily across the Intermontane and Coast belts, including Vancouver Island, while during SCoRE 90, three lines were recorded from the Intermontane belt to the Foreland belt east of the Cordillera and one line was recorded along strike in the Coast belt. Kanasewich et al. (1994) discussed in detail line 8, which followed the strike direction of the Omineca Belt of the Canadian Cordillera. The corresponding crustal cross section is depicted in Figure 8.5.2-06.

In total, SCoRE comprised more than 50 individual shot gathers (Clowes et al., 1995). Interpreting the longest profile, the 450-km-long SW-NE–directed profile 2, which traversed the southern Cordillera from Vancouver Island through the Coast belt into the Intermontane belt, Spence and McLean (1998) concluded that throughout the crust, seismic velocities were in general high beneath the Insular belt, low beneath the coast and western Intermontane belts, and intermediate beneath the eastern Intermontane belt. The Moho depth increases only slightly along the line from near 33 km in the SW to ~38 km in the NE.

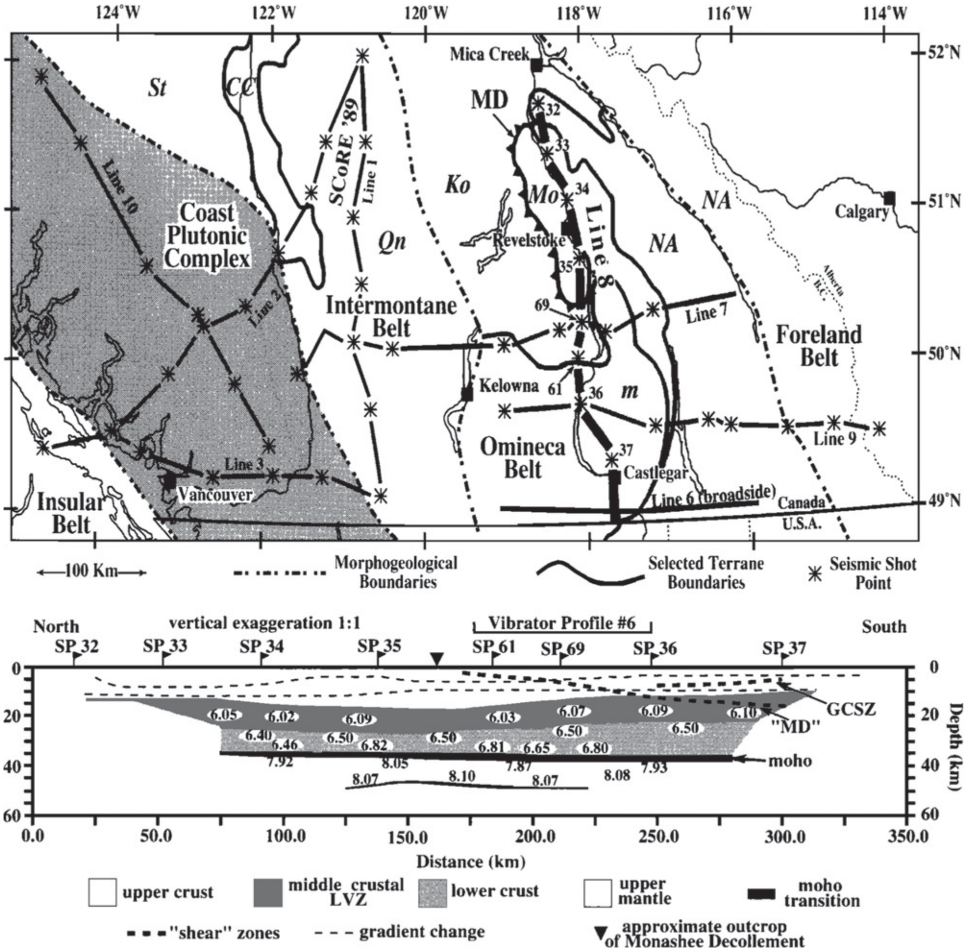

Figure 8.5.2-06. Top: Southern Cordillera Refraction Experiment (SCORE 89–90) shot and receiver lines). Bottom: Crustal cross section of Line 8 (from Kanasewich et al., 1994, figs. 1 and 7b). [Journal of Geophysical Research, v. 99, p. 2653–2670. Reproduced by permission of American Geophysical Union.]

Prior to SCoRE, in 1985 LITHOPROBE had recorded nearly 270 km of crustal seismic-reflection data across the eastern part of the southern Canadian Cordillera (Cook et al., 1987). Reflections near 12 s TWT were interpreted to possibly originate at the crust-mantle boundary which was estimated to lie at ~35 km depth.

In 1984–1985, a marine seismic-reflection survey, to become part of the LITHOPROBE East Transect (LE in Fig. 8.5.2-05), was recorded off the northeast coast of Newfoundland. Further seismic-reflection data were added in 1986, and a seismic-refraction survey was performed in 1988 and interpreted at a later stage together with data of the 1990s (Marillier et al., 1994; see also Fig. 9.4.1-04), which will be discussed in Chapter 9.4.1. Another seismic-reflection survey collected 600 km of data in 1989 in two main corridors, both directed in a NW-SE direction in the southwestern half of Newfoundland, which data were reprocessed and reinterpreted later by Van der Velden et al. (2004).

A fourth transect of LITHOPROBE, where work was started in the 1980s was the Great Lakes zone (GL). Here (Fig. 8.5.2-07) in 1986 the GLIMPCE experiment (Great Lakes International Multidisciplinary Program on Crustal Evolution) was undertaken in a cooperative effort of the Geological Survey of Canada and the U.S. Geological Survey (USGS). The experiment was a combined on-ship seismic-reflection and onshore seismic-refraction experiment to determine the structure of the crust under the Great Lakes, with the main tectonic targets being the Midcontinent Rift System, the Grenville Front, the Penokean and Huronian Fold Belts, and the Michipicoten Greenstone Belt (Green et al., 1989; Behrendt et al., 1989, 1990; Epili and Mereu, 1989; Hall and Quinian, 1994; White et al., 2000).

In total, ~1350 km of multichannel seismic-reflection data and an equivalent amount of seismic-refraction data have been collected across the North American Great Lakes. Across the Midcontinent System in Lake Superior and Lake Michigan alone, 700 km of 120-channel deep seismic-reflection data were collected. Refraction observations were made at the ends of most lines (stars in Fig. 8.5.2-07), and five OBSs recorded wide-angle information at equally spaced intervals along line A. The Moho reflections indicated varying crustal thickness from 37 to 55 km depth along the rift and volcanic and interbedded sediments of the rift to depths as great as 32 km, suggesting the greatest thickness of intracratonic rift deposits ever found on earth.

Taken together, by the end of LITHOPROBE, a series of ten transects, planned to provide a 3-D structure for each of the

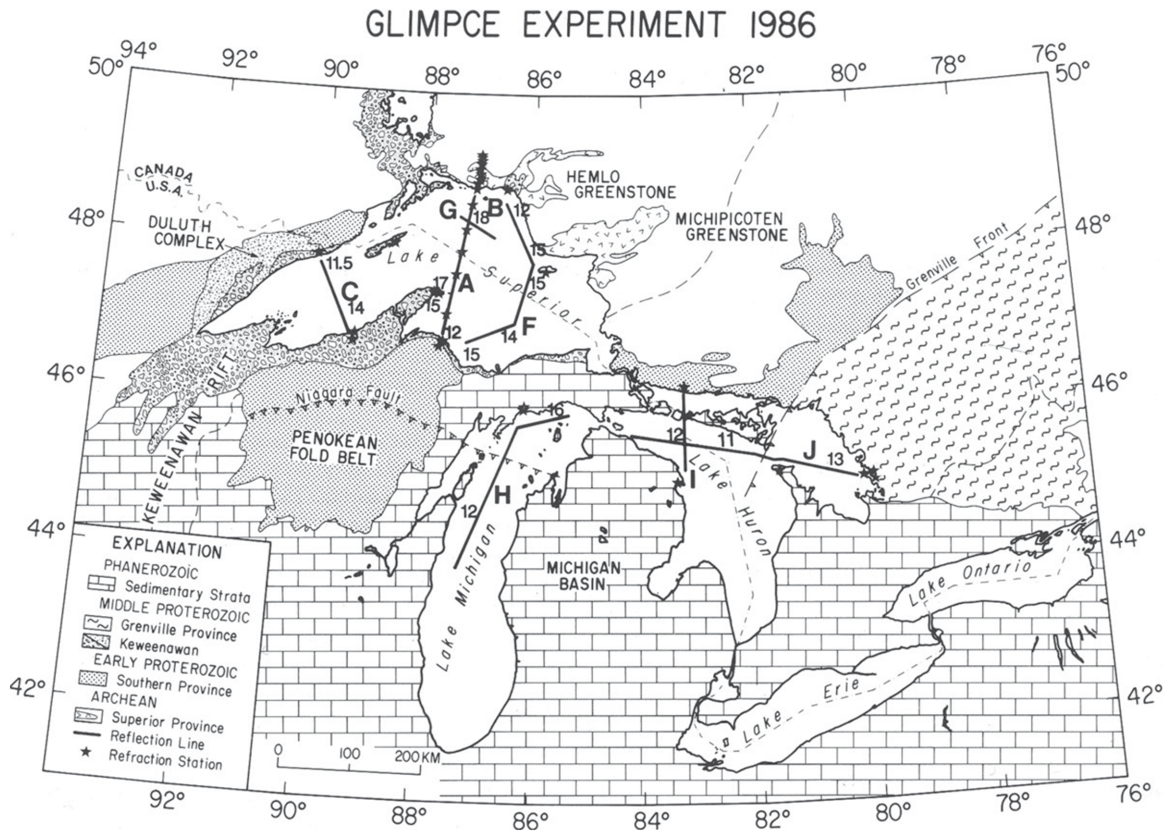

Figure 8.5.2-07. Location of the 1986 GLIMPCE experiment (from Behrendt et al., 1990, fig. 1b). [Tectonophysics, v. 173, p. 595–615. Copyright Elsevier.]

ten key areas (Fig. 8.5.2-05), should provide a nearly continuous coverage of the northern part of the North American continent. Results available up to late 1990 were summarized by Clowes et al. (1992) and Clowes (1993).

8.5.3. Continental United States

8.5.3.1. Seismic-Reflection Surveys

Following the successful start of COCORP in the second half of the 1970s, COCORP surveys continued in the 1980s. Brown et al. (1986) summarized the efforts and published a map showing the location of COCORP surveys completed until 1985 (Fig. 8.5.3-01). Since the beginning of the 1980s, a large amount of new data had been assembled which can best be recognized when comparing Figure 7.4.3-01 and Figure 8.5.3-01. Some of these operations involved some very long lines, such as the traverses through the northwestern Cordillera, through the northern Basin and Range province and through the Appalachians.

In the west, the new data comprised deep seismic-reflection surveys in the northwestern Cordillera from Washington to Idaho (Potter et al., 1986, 1987) along 48.5° latitude; across and east of the Cascades in Oregon; from the Sierra Nevada in northern California to the northwestern Colorado Plateau in western Utah along a 1000-km-long 40°N seismic-reflection transect recorded (see also Fig. 8.5.3-02) in 1982–1984 with its main emphasis on the Basin and Range province (Allmendinger et al., 1987, Klemperer et al., 1986); and in the Mojave desert and in Death Valley in southern California (de Voogd et al., 1988). Also in 1986, COCORP recorded a seismic-reflection line along the PACE lines through Arizona (Hauser et al., 1987a) and in 1989, a COCORP survey in Montana was added (Latham et al., 1988).

The COCORP seismic-reflection traverses of the U.S. Cordillera at 48.5°N and 40°N latitude revealed both fundamental similarities and differences in reflection patterns. On both traverses, autochthonous crust beneath thin-skinned thrust belts of the eastern part of the Cordillera is unreflective, immediately to the west the Cordilleran interior was very reflective above a flat prominent reflection Moho. The prominent reflection Moho was confined to areas which have undergone large Cenozoic post-thrusting extension. The main differences between the two traverses were seen in the reflection patterns of the middle and lower crust in the Cordilleran interior (Potter et al., 1987).

The COCORP 48.5° transect had a total length of 296 km and was acquired in 1984. It formed the initial part of a planned Cordilleran transect at 48–49° latitude, and it consisted of six reflection lines (Washington lines 1–5 and Idaho line 1). The data were collected using Vibroseis technique to produce a correlated record length of 16 s TWT corresponding to a maximum depth

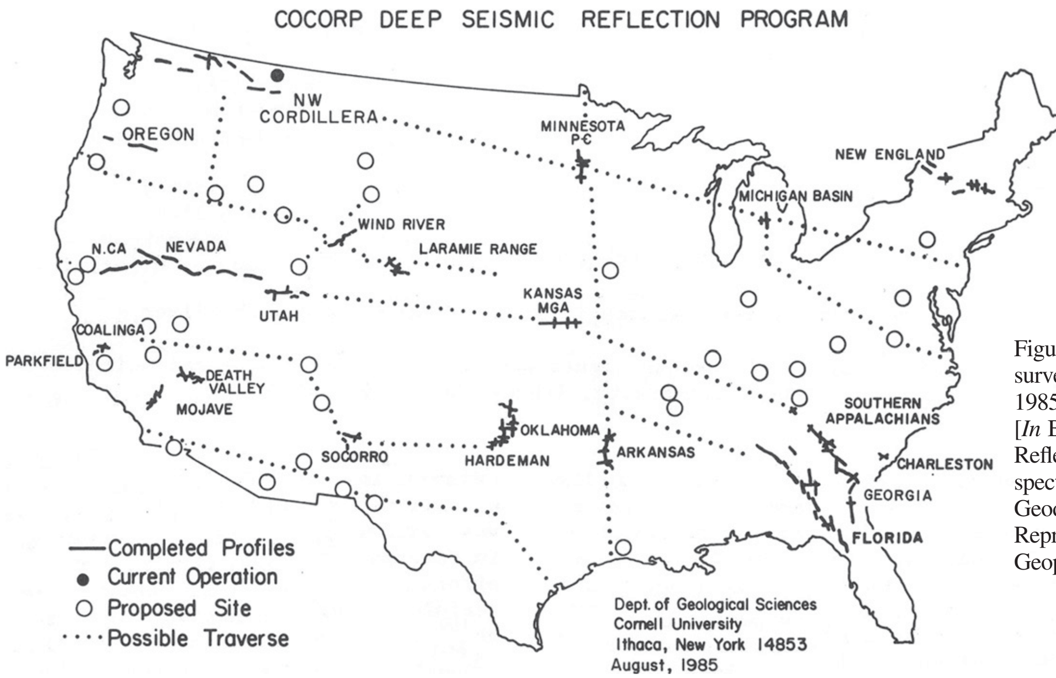

Figure 8.5.3-01. Location of COCORP surveys completed through August 1985 (from Brown et al., 1986, fig. 1). [*In* Barazangi, M., and Brown, L., eds., Reflection seismology: a global perspective: American Geophysical Union, Geodynamics Series, v. 13, p. 107–120. Reproduced by permission of American Geophysical Union.]

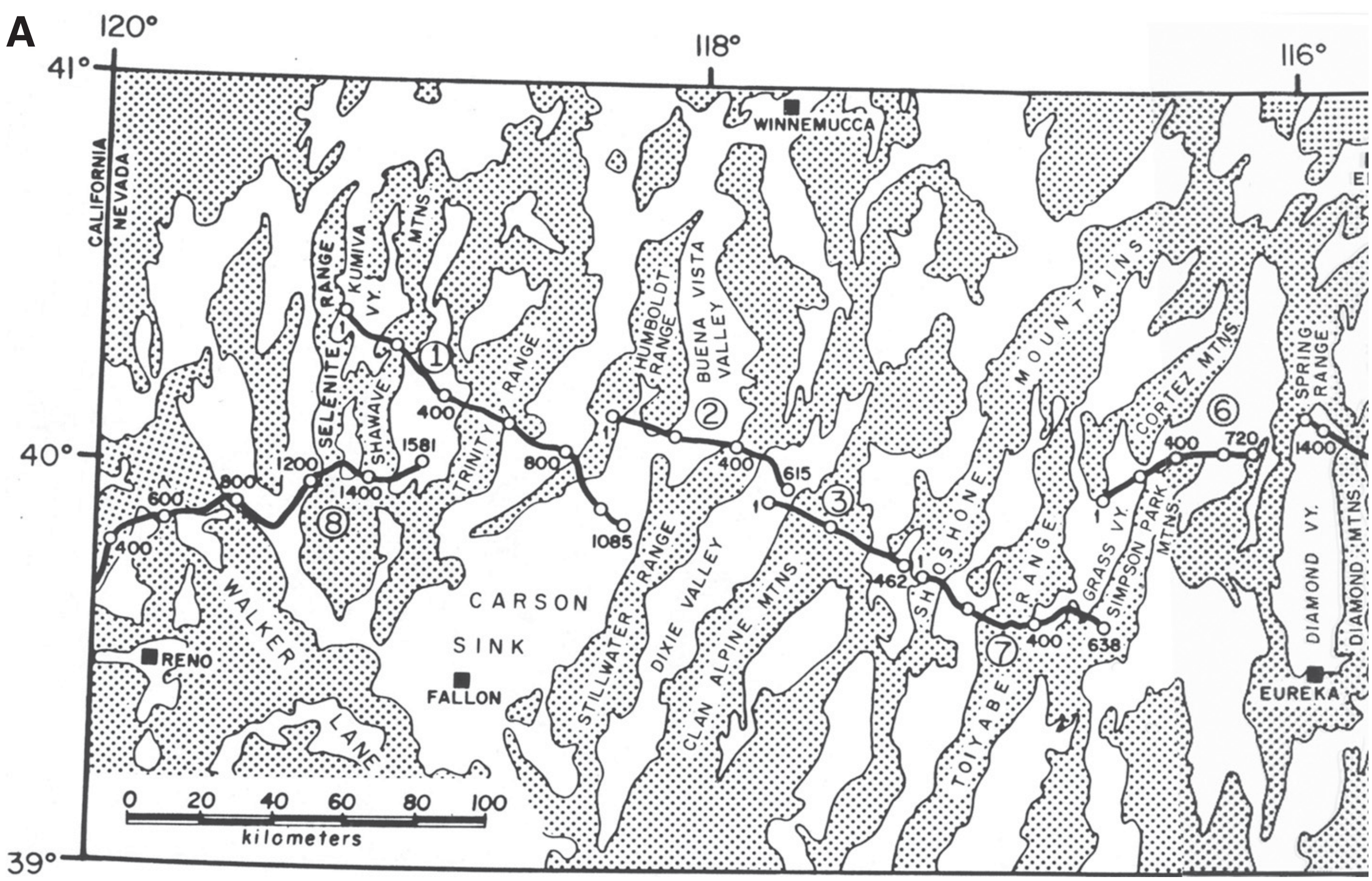

Figure 8.5.3-02 (*on this and following page*). (A) COCORP 40° transect from California to central Nevada (from Klemperer et al., 1986, fig. 1). [Geological Society of America Bulletin, v. 97, p. 603–618. Reproduced by permission of the Geological Society of America.]

of 50 km. The Moho was evident by strong horizontal reflections at 10.5–11.0 s TWT and was recognized as a flat surface underlying a complexly deformed crust, suggesting that it developed in Cenozoic times during widespread magmatism and extension possibly related to the generation of the Columbia River basalts (Potter et al., 1986).

The COCORP 40° transect (Fig. 8.5.3-02) followed the King Survey of the 40° parallel of 1867–1872 which had provided the first systematic reconnaissance traverse of the Cordillera of western North America. It was chosen because a large amount of subsequent research had shown that this transect contained one of the most complete records of Cordilleran evolution in the United States (Allmendinger et al., 1987). It was thus chosen as the site of the first deep seismic-reflection profile across the orogen where it crossed tectonic features ranging in age from Proterozoic to Recent and provided an acoustic cross-section of a complex orogen affected by erosion, compression, magmatism, and terrane accretion.

Allmendinger et al. (1987), for example, described the key features of the 40°N transect as follows The part of the transect traversing the Basin and Range province showed asymmetric seismic fabrics with west-dipping reflections in the east and mainly subhorizontal reflections in the west. The Moho was clearly determined by pronounced reflections at 30 km depth, also at 34 km locally. No clear sub-Moho reflections were seen. In contrast, under the Sierra Nevada and under the Colorado Plateau, complex-dipping reflections and diffractions occurred locally as deep as 48 km depth. The features seen in the eastern part of the transect, which is underlain by Precambrian crystalline basement, were interpreted to be related to the entire geological history of the orogen.

In the western part, in contrast, most reflectors were interpreted to be not older than Mesozoic, indicating a strong Cenozoic overprint which is characterized by asymmetric half-grabens, low-angle normal faults, and a pervasive subhorizontal system of reflections in the lower crust.

The Death Valley COCORP seismic sections also showed a series of subhorizontal events that characterized the lower crust and abruptly ended at 11 s TWT. Between 10 and 11 s, a reflecting horizon was correlated and interpreted as Moho at ~30 km depth. Beneath the reflective lower crust, the upper mantle appeared to be seismically transparent (de Voogd et al., 1988).

The COCORP Arizona transect of 1986 crossed the transition zone between the Basin and Range province and the Colorado Plateau. The Moho reflections under the Basin and Range province contrasted with the non-reflective Moho under the

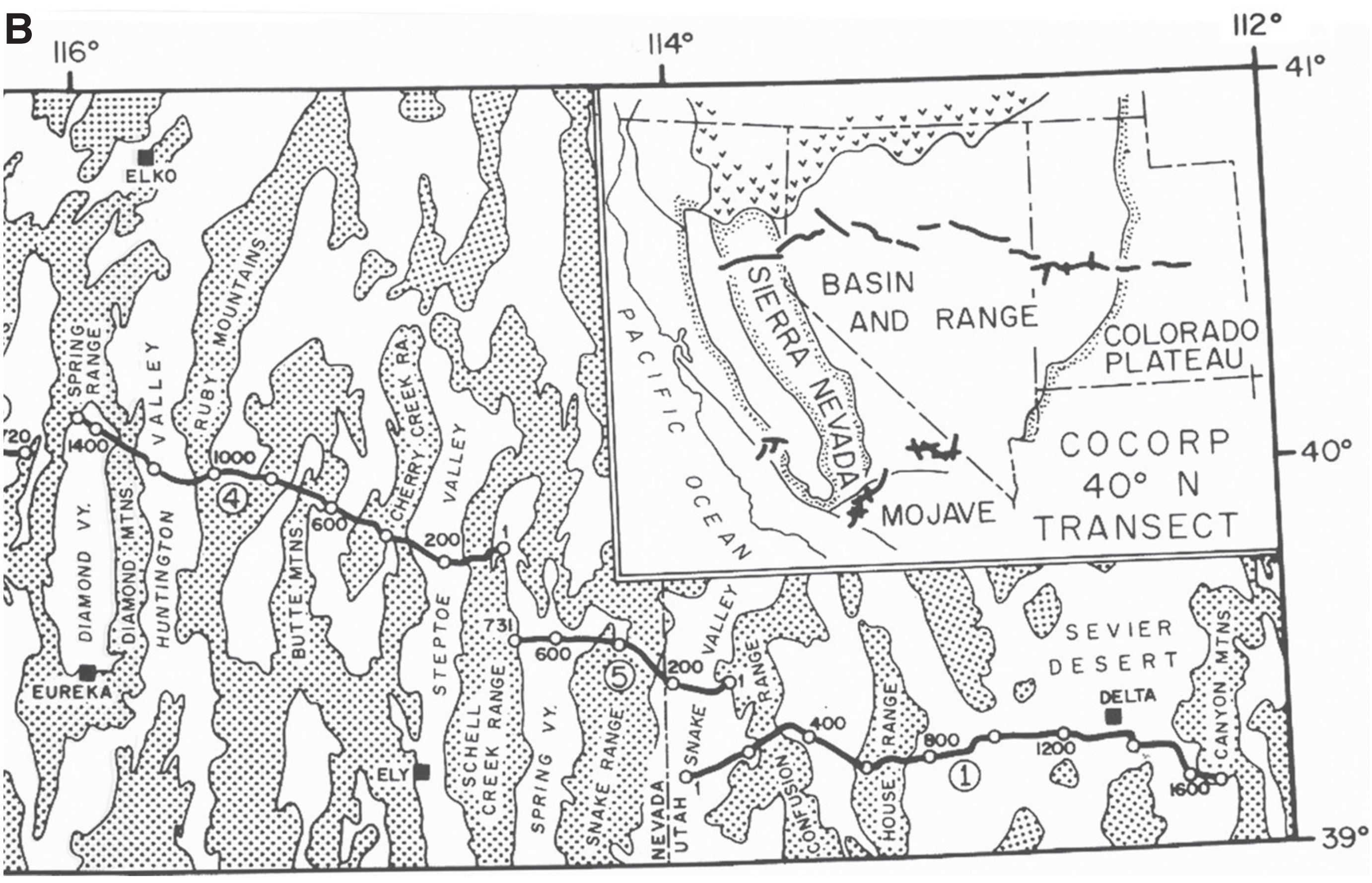

Figure 8.5.3-02 (*continued*). (B) COCORP 40° transect from central Nevada to Utah. The inset shows also the location of the COCORP surveys in southern California: Mojave Desert, Death Valley and San Andreas fault (Parkfield).

Colorado Plateau. This observation was interpreted that the development of reflectors at the Moho was clearly influenced by extension and associated igneous processes (Hauser et al., 1987a).

The seismic-reflection profiles recorded by COCORP in 1987 in the Montana plains between the Rocky Mountains and the Williston basin imaged the crystalline continental basement of the Archean Wyoming cratonic province. The crust appeared to be reflective throughout its entire thickness. West of the Williston basin, the Moho was not marked by the presence of any distinct reflections, but was defined to be located at the base of the reflective crust. The lowermost crust underneath the Williston basin, however, was characterized by a prominent laterally extensive zone of relatively high-amplitude reflections (Latham et al., 1988).

Besides COCORP, the USGS also performed a major study of the Earth's crust by seismic-reflection profiling (for location, see Fig. 8.5.3-24). Already since the early 1970s, a series of multichannel seismic-reflection projects had been supported and organized by the USGS (Hamilton, 1986). They included ~115,000 km of marine multichannel seismic-reflection data in a continuing program to study the geological framework of the U.S. continental margins of the Pacific Ocean off the west coast and Alaska as well as of the Atlantic Ocean off the east coast.

In 1982, the USGS received funds for a new program specifically designed to study the deep structure of the continent primarily by the use of seismic-reflection profiling (Hamilton, 1986). The first project was a study in central California from the Coast Ranges to the Sierra Nevada foothills. In 1984, work began in Alaska to carry out a crustal transect along the pipeline route. In 1985, studies were undertaken along a transect in southern California and southwest Arizona.

In the Midwest (for location, see Fig. 8.5.3-24), COCORP recorded seismic-reflection transects in 1981 both in Kansas and in Arkansas.

The COCORP survey in northeastern Kansas was part of a major east-west traverse across the mid-continent geophysical anomaly (Brown et al., 1983b). The seismic-reflection sections revealed clear indications of complex structure in the mid-to-lower crust which contrasts with the simplicity of the overlying sedimentary cover revealing numerous dipping and arcuate reflections and diffractions in the deeper crust. The basement above shows significantly fewer reflections, which was interpreted as being granitic terrane. The expected Moho at ~36 km depth was less characterized by specific reflections but more by an apparent decrease in the density and number of reflections (Brown et al., 1983b).

The Arkansas transect crossed the Ouachita Mountains in western Arkansas. The data indicated that Carboniferous foreland basin deposits within the Arkoma basin in the north thickened dramatically toward the south reaching more than 12 km thickness. Beneath the Benton uplift in the center of the line a broad antiform could be defined cresting at ~7 km depth. Beneath the southern Ouachitas, south-dipping stratified events were observed to depths in excess of 14 km. At the southern end of the line beneath the northern coastal plain/southern Ouachitas, a prominent gently northward-dipping reflection occurred at ~22 km depth. The major structural features observed on this line were tentatively interpreted as having formed during a "simple" arc/continent collision, in which the subduction zone dipped south (Nelson et al., 1982).

In the eastern United States (for location, see Fig. 8.5.3-24), COCORP recorded the Adirondack–New England transect in 1980–1981, consisting of six lines and traversing the Grenville craton, the Adirondacks, to the west and the New England Appalachians to the east. Across the southern Adirondacks, a striking band of high reflectivity between 6 and 8 s TWT was seen which was interpreted to originate at 18–26 km depth. The Green Mountains to the east were identified as an imbricated thrust slice obducted above the lower crustal penetrating ramp (Brown et al., 1983a). Other intrabasement features were major east-west–dipping reflections, interpreted as possible faults, arched reflections that were interpreted as evidence for folds, a well-defined featureless zone, and possible scattered Moho reflections at times of at least 11 s which, according to Brown et al. (1983a), corresponds to Katz's (1955) estimated Moho depth.

In addition to the southern Appalachian traverse of 1978–1979, in 1983–1984 and 1984–1985, COCORP recorded a second line through the Appalachians and southeastern coastal plains from Georgia to Florida (Nelson et al., 1985). Reflections associated with the Appalachian detachment were the most prominent features of the northwestern portions of both the eastern and western Appalachian COCORP traverses. On both traverses these reflections comprised a prominent, ~0.5 s thick, gently southeast-dipping horizon in the upper crust, which could be traced from the level of detachment within the Valley and Ridge province southeastward for a considerable distance beneath the crystalline interior of the orogen. Beneath the coastal plains of western Georgia, a broad crustal-penetrating zone of dipping reflections was found, probably marking the Alleghanian suture in the southeastern United States. The COCORP data further southeast elucidated the internal structure of the Mesozoic Georgia basin within the Alleghanian orogen showing several large half-grabens separated by intervening highs. Beneath the well-developed Appalachian detachment reflections the Grenville basement exhibited few intracrustal reflections and no obvious reflections from Moho, but under the Georgia and Florida lines, numerous lower crustal reflections and locally prominent reflections at Moho level were evident (Nelson et al., 1987).

In 1983, the USGS shifted part of its seismic-reflection program to the eastern United States, starting with a project in Maine across the northern Appalachian Mountains and continuing in 1984 (QMT in Fig. 8.5.3-24). This project was closely connected with wide-angle profiling and will be described in more detail in subchapter 8.5.3.4. In 1984, a seismic-reflection survey in eastern Pennsylvania was also undertaken to study the seismic-reflection geometry of the Newark basin margin (Ratcliffe et al., 1986).

Another major goal of the USGS program was to study earthquake hazard zones where bedrock is covered by a thousand or more meters of poorly consolidated sediments (Hamilton, 1986), such as the New Madrid, Missouri, zone in the Northern Mississippi Embayment, which was accomplished in the late 1970s (see Chapter 7) and the Charleston, South Carolina, zone in the Atlantic Coastal Plain (Gohn, 1983; Behrendt, 1986), an investigation of which started in 1979 with seismic-reflection lines on land up to 3 s TWT and offshore with lines up to 12 s. The project was continued in 1981 with profiles of 1350 km total length through South Carolina and Georgia recorded to 6–8 s TWT (Hamilton, 1986). The USGS Interstate 64 seismic-reflection line (JRC in Fig. 8.5.3-24) was another relatively long line conducted in 1980 and 1981 that extended from north-central Virginia to near the Virginia coast (Lampshire et al., 1994; Pratt et al., 1987, 1988). The stacked section showed a highly reflective upper crust and also a sequence of reflections at ~9–12 s, indicative of lower crustal layering ~5–10 km in thickness, the base of which coincided with the Moho at 55 km depth under the Valley and Ridge province interpreted from earlier seismic-refraction work (James et al., 1968; Pratt et al., 1988).

As part of the ADCOH (Appalachian Ultradeep Core Hole, line ADC in Fig. 8.5.3-24) project site investigations of 1985, a seismic-reflection Vibroseis survey was carried out along regional lines in North and South Carolina and Georgia that extended for ~180 km across part of the southern Appalachians and, due to the experimental design and careful processing, collected seismic-reflection data of extremely high quality (Coruh et al.,1987; Costain et al., 1989a, 1989b; Hatcher et al., 1987; Hubbard et al., 1991). The ADCOH data were originally recorded with 14–56 Hz bandwith and 8 s length, but an extended Vibroseis correlation was used to produce 17 s data length. The upper crust to 9 km depth could be clearly imaged; below 8 s reflections were weak, but observable to as late as 13 s. However, these Moho reflections were generally short segments (Coruh et al., 1987). During the project, wide-angle and expanding spread data were also recorded (Hatcher, 2010, personal commun.).

Complete overviews of all deep seismic-refraction and reflection programs completed until late 1987 can be found in a summary volume *Geophysical Framework of the Continental United States*, edited by Pakiser and Mooney (1989). In their specific review of seismic-reflection programs in the eastern and central United States, Phinney and Roy-Chowdhury (1989) compiled a table containing the responsible organization, year, and specific references for all programs, which can be found at the end of subchapter 8.5.3.4 (see Fig. 8.5.3-24). Smithson and Johnson (1989) published a similar approach for the western United States.

8.5.3.2. Seismic-Refraction Projects in the Pacific States

The new equipment—100 portable Seismic Cassette Recorders (SCR)—which the USGS had acquired in the late 1970s (Healy et al., 1982; Murphy, 1988; Appendix A7-5-6) enabled a new phase of activity in the 1980s. Following the first projects in the late 1970s (Saudi Arabia, Mississippi embayment, Imperial Valley; for references see Chapter 7), under the leadership of Walter Mooney and Gary Fuis, detailed crustal investigations started in 1981 throughout the United States. Some of the surveys aimed for upper-crustal studies only as, e.g., a detailed investigation of the Long Valley caldera in 1982 and 1983 (Meador and Hill, 1983; Meador et al., 1985; Appendix A8-3-2), and will not be discussed here in more detail, but most projects involved recording distances of 100 km and beyond and allowed study of the whole crust and uppermost mantle.

The beginning of the 1980s saw major activity in California. The western part of the Mojave Desert between the Garlock and San Andreas faults was the goal of a 200-km-long north-south profile with additional lines in 1980 and 1981 involving 12 shotpoints (Harris et al., 1988; Appendix A8-3-3).

From 1980 to 1982, projects followed in the Santa Cruz Mountains and in the Livermore area in the Diablo Range southeast of San Francisco (Meltzer et al., 1987; Williams et al., 1999; Appendix A8-3-3) and in the Great Valley of California (Holbrook and Mooney, 1987; Murphy, 1990; Appendix A8-3-3). The Great Valley project involved six profiles; the three major ones had three shotpoints each, were 180 km long, and were directed parallel to the tectonic strike direction. Furthermore, in 1982, a long line perpendicular to the tectonic strike direction was recorded with 7 shotpoints from Morro Bay at the Pacific coast into the foothills of the Sierra Nevada (Murphy and Walter, 1984; Appendix A8-3-3) across the San Andreas fault zone in the Parkfield-Cholame area and across the Great Valley (line SJ-6 in Figs. 8.5.3-03 and 8.5.3-04).

In 1983, an eighth shotpoint was added and part of the profile reoccupied with a much closer station spacing. The data of this project (see Fig. 8.2-03) together with seismic-reflection data collected by Western Geophysical in 1981 and purchased by the USGS in 1983 (see Fig. 8.2-04) served as basic material for the CCSS Workshop held in Susono, Shizouka, Japan in August 1985 (Walter and Mooney, 1987; Appendix A8-3-3) as was mentioned in the first section of this chapter. In 1986, a northwest-southeast–directed line of 86 km length, centered at San Luis Obispo, was recorded with 120 stations perpendicular to the line SJ-6 with a central shotpoint at the crossing point and two other in-line shots northwest and southeast. The survey was complemented by several fan shots located on land to the northeast and offshore in Morro Bay and farther south. The marine shots were airgun shots (Sharpless and Walter, 1988; Appendix A8-3-3).

Trehu (1991) investigated large-aperture data that had been collected in 1986 by seismometers deployed offshore (OBS) and recording airgun shots spaced ~150 m along a deep crustal seismic profile that was shot off Morro Bay toward southwest across the central California margin. This so-called Pacific Gas and Electric EDGE experiment (Howie et al., 1993) involved two parallel 190-km-long NE-SW onshore-offshore wide-angle reflection/refraction lines (PG&E lines 1 and 3) and three MCS (multichannel seismic) marine reflection lines. Two MCS lines were identical with the wide-angle lines; the third was a tie line. The above-mentioned PG&E-3 transect extended from the San Andreas fault (70 km inland) to

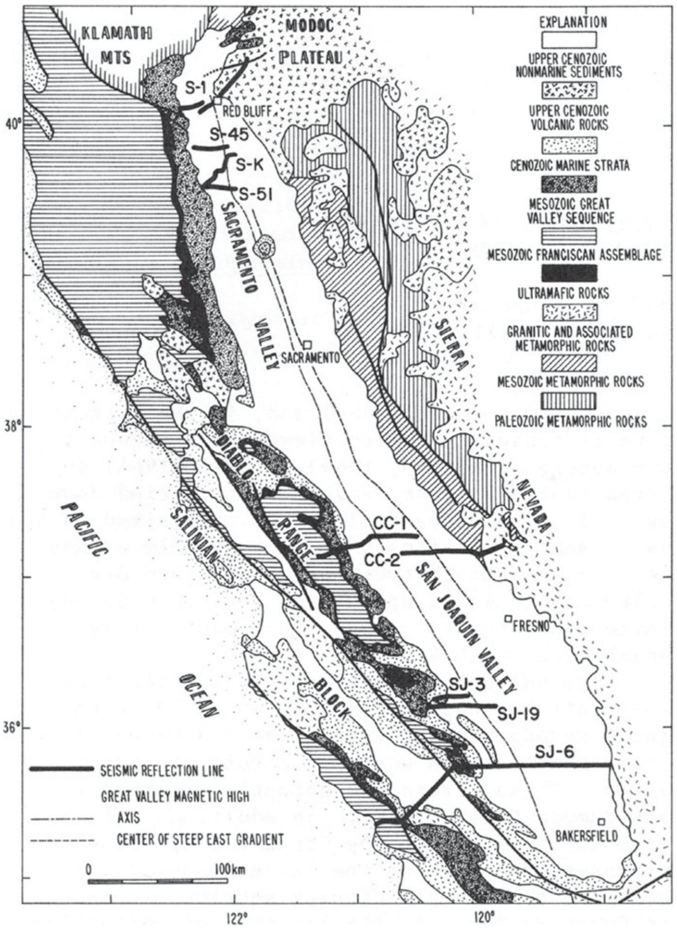

Figure 8.5.3-03. Regional geological map of California showing location of seismic reflection lines (from Zoback and Wentworth, 1986, fig. 1). [*In* Barazangi, M., and Brown, L., eds., Reflection seismology: a global perspective: American Geophysical Union, Geodynamics Series, v. 13, p. 183–196. Reproduced by permission of American Geophysical Union.]

the coast at Pismo Beach and then across the entire continental shelf and slope 120 km offshore.

The occurrence of a M 6.7 earthquake on 2 May 1983, near Coalinga, California, triggered a further detailed seismic investigation of crustal structure (Figs. 8.5.3-03 and 8.5.3-04) across the Mesozoic ocean-continent boundary beneath the California Coast Ranges and Great Valley which involved both seismic-reflection and refraction investigations (Colburn and Walter, 1984; Macgregor-Scott and Walter, 1985, 1988; Walter, 1990; Wentworth et al., 1983, 1984, 1987; Appendix A8-3-3). Some reflection lines were purchased and partly recorrelated from 6 to 12 s (lines SJ). The east-west–directed COCORP line C-1 (Fig. 8.5.3-04) was collected 12 km south of Coalinga.

Farther north, a 15-s reflection line (CC-1 and CC-2 in Fig. 8.5.3-03) was collected under contract. This 170-km-long line extends westward from the Sierran foothills across the northern San Joaquin Valley and into the Diablo Range of the central California Coast Ranges. The interpretation of the seismic-reflection data was coordinated with two seismic-refraction lines (Colburn and Walter, 1984; Walter, 1990) shot after the Coalinga earthquake and crossing each other close to the epicenter area. The east-west line was 83 km long (shotpoints 9–12 in Fig. 8.5.3-04); the northwest-southeast line was 102 km (shotpoints 13–17 in Fig. 8.5.3-04). As the seismic-refraction lines were installed immediately after the 2 May 1983 $M_L = 6.7$ earthquake, the seismic-refraction data were further complemented by aftershock recordings along both lines (Macgregor-Scott and Walter, 1985, 1988).

For the Coalinga east-west profile, only the upper crust was modeled (Fig. 8.5.3-05). The interpretative west-east structural cross section of Wentworth and Zoback (1990) at the bottom of Figure 8.5.3-05 runs parallel to the west-east seismic-refraction line (top of Fig. 8.5.3-05) interpreted by Walter (1990) and follows approximately the reflection line SJ-19. For comparison, a projection of the seismicity superimposed into the west-east line is shown which concentrated on both the Cretaceous Great Valley sequence (Kg) and the Jurassic and Cretaceous Franciscan assemblage (KJf) overlying the basement (B). The model of the NW-SE profile of Macgregor-Scott and Walter (1988) covers the whole crust and shows underneath the 6.6-km/s layer a 6-km-thick lower crust with velocities from 7.1 to 7.4 km/s and the Moho at 27 km depth with a low uppermost mantle velocity of 7.95 km/s. Similar results have been published for the Great Valley profiles (Holbrook and Mooney, 1987) and by most of the CCSS Workshop participants for the Morro Bay–Sierra Nevada line (Walter and Mooney, 1987) mentioned above.

In northeastern California, the USGS conducted seismic-refraction experiments (Fig. 8.5.3-06) in order to characterize the crustal structure of and boundaries between the Klamath Mountains, Cascade Range, Modoc Plateau, and Basin and Range geological provinces (Zucca et al., 1986). The experiments took place in 1979, 1981, 1982, and 1985 (Kohler et al., 1987; Appendix A8-3-3; Zucca et al., 1986; Fuis et al., 1987). A total of 55 shots was detonated at 29 shotpoints; the number of stations varied between 60 and 120, with intervals varying between 0.5 and 1.75 km. The surveys comprised north-south lines both in the Klamath Mountains and the Modoc Plateau; northwest-southeast lines centered on Mount Shasta and Medicine Lake volcanoes, and a west- east line from the Klamath Mountains to the Basin and Range province linking the other profiles. All lines involved a 1 km station spacing and at least three shotpoints over 80 km distance. Along the 300-km-long west-east line (see also Fig. 8.5.3-08, line 9) six shotpoints were placed. One of the northwest-southeast lines across Mount Shasta and Lassen Peak was also 300 km long, had eight shotpoints, and reached to the northern end of the Sierra Nevada. The Medicine Lake Volcano was of particular interest with specially designed recording schemes.

The crustal cross section in Figure 8.5.3-07 by Fuis et al. (1987; Mooney and Weaver, 1989) shows that the Klamath Mountains are underlain by a stack of oceanic layers, while the Modoc Plateau is inferred to be underlain by crystalline igneous and metamorphic rocks beneath volcanic and sedimentary

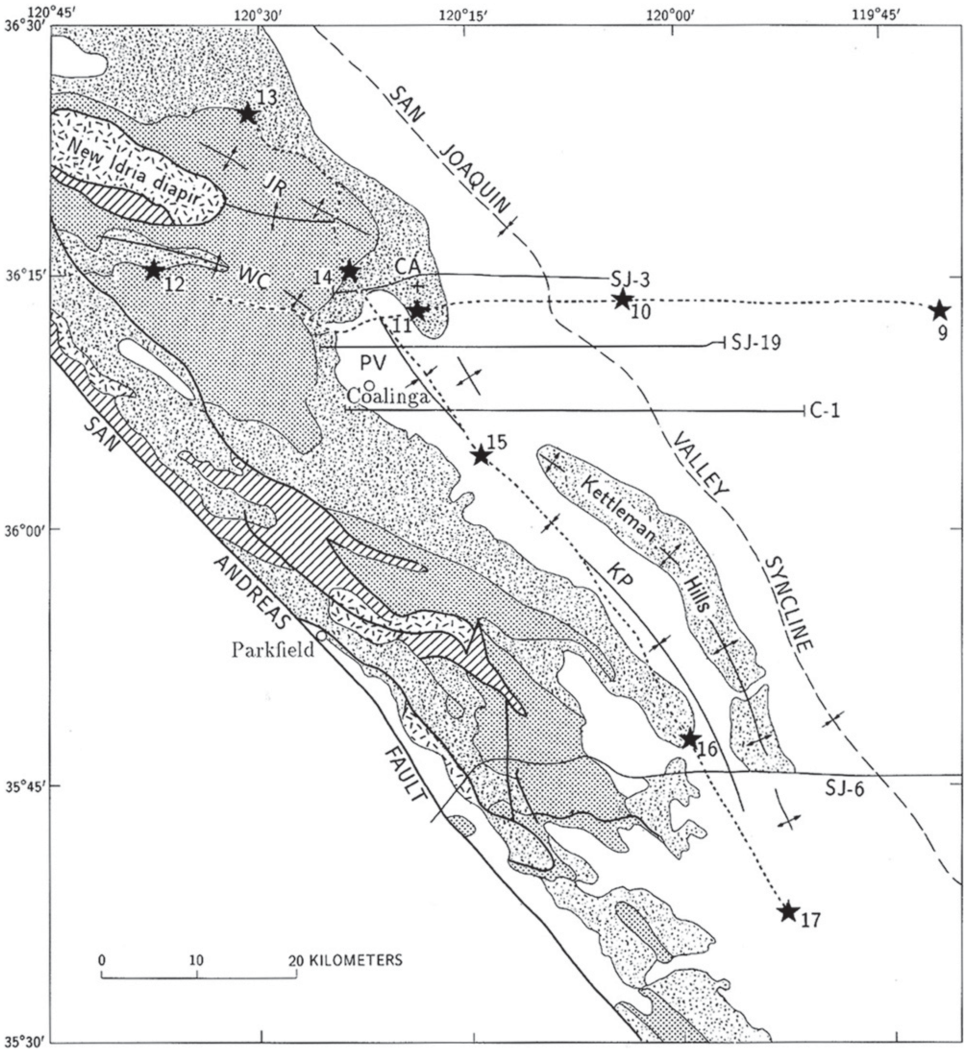

Figure 8.5.3-04. Location of seismic profiles around Coalinga, central California, extending from the southern Diablo Range into San Joaquin Valley (from Walter, 1990, fig. 3.1). +—Main shock (M_L=6.7). Stars—shotpoints, full lines: seismic profiles recorded before 2 May 1983. Dotted lines: seismic profiles after 2 May 1983. SJ—industrial seismic reflection lines; C-1—COCORP line. [U.S. Geological Survey Professional Paper 1487, p. 23–39. Copyright U.S. Geological Survey.]

rocks. The Cascade Range, in between, is a complex suture region currently intruded by magmas. The base of the model in Figure 8.5.3-07 at 14 km consists of a 7.0-km/s layer that extends to unknown depths. The total crustal thickness under the southern Cascades has not reliably been determined; it is estimated to be around 38-40 km. The crustal structure beneath the Modoc Plateau, however, is well known from the seismic-refraction profiles; the Moho lies in ~38 km depth.

Several seismic-refraction investigations were also performed by the USGS farther north in Oregon and Washington (Fig. 8.5.3-08). The Oregon Cascades were the target of a 275-km-long seismic-refraction profile (line 7 in Fig. 8.5.3-08) with three shotpoints and 100 recording stations along the north-south axis of the Cascades from Mount Hood to Crater Lake. The profile was located 20–30 km west of the crest of the High Cascades and nearly coincided with the contact between the High and the Western Cascades. The interpretation of Leaver et al. (1984) includes the observations of three regional earthquakes. Two of the events occurred to the north in southern Washington (Elk Lakes event and Goat Rocks event), and the third event (Stephen's Pass earthquake) occurred in the south in northern California. They had been recorded by local networks of the USGS and the University of Washington and record sections had been prepared. The interpretation of the data resulted in a total crustal thickness of ~45 km underneath the Oregon Cascades, subdivided into a 10-km-thick upper crustal layer and underlain by an intermediate crust with 6.5–6.6 km/s from 10 to 30 km depth and a lower crust with a mean velocity of 7.1 km/s (Leaver et al., 1984).

The investigation of the Oregon Cascades was continued in 1983 by a 180-km-long west-east profile across east-central Oregon (line 8 in Fig. 8.5.3-08) which reached from the High Cascades 30 km west of Newberry crater (triangle on line 8) to the eastern High Lava Plains (Catchings and Mooney, 1988b; Cotton and Catchings, 1989; Appendix A8-3-4). The target was the arc to backarc transition zone between the volcanic Cascade Mountains and the actively extending Basin and Range province. Two-hundred forty recording sites recorded shots from six sites, of which five shotpoints were located in the west around Newberry

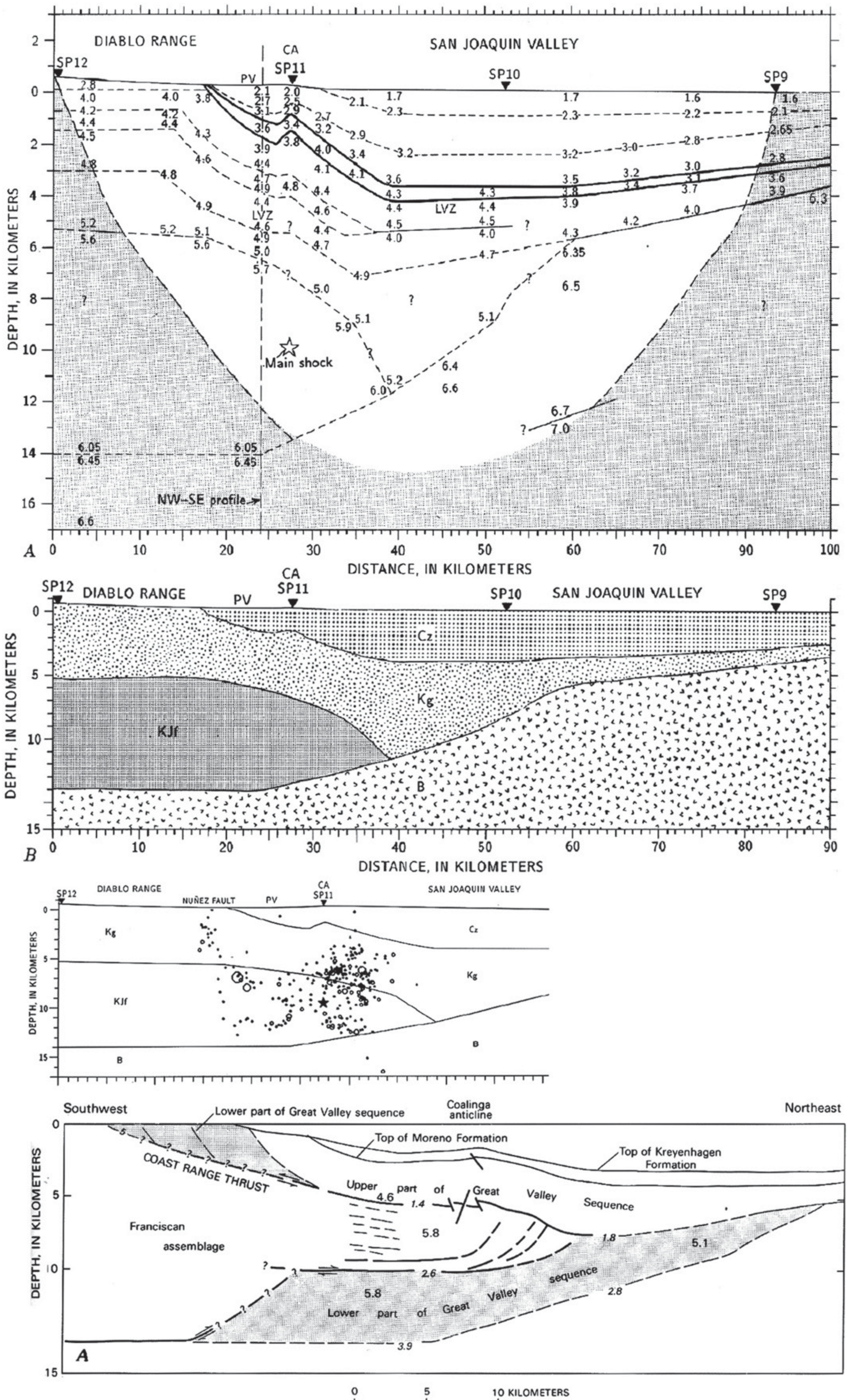

Figure 8.5.3-05. Top and upper center: Upper crustal model of the Coalinga east-west profile (from Walter, 1990, Figs. 3.3). Cz—Cenozoic strata, Kg—Cretaceous Great Valley sequence, KJf—Jurassic and Cretaceous Franciscan assemblage, B—basement. Lower center: Seismicity (from Walter, 1990, fig. 3.9). Bottom: Interpretative west-east structural cross section (from Wentworth and Zoback, 1990, fig. 4.6). [U.S. Geological Survey Professional Paper 1487, p. 23–39. Copyright U.S. Geological Survey.]

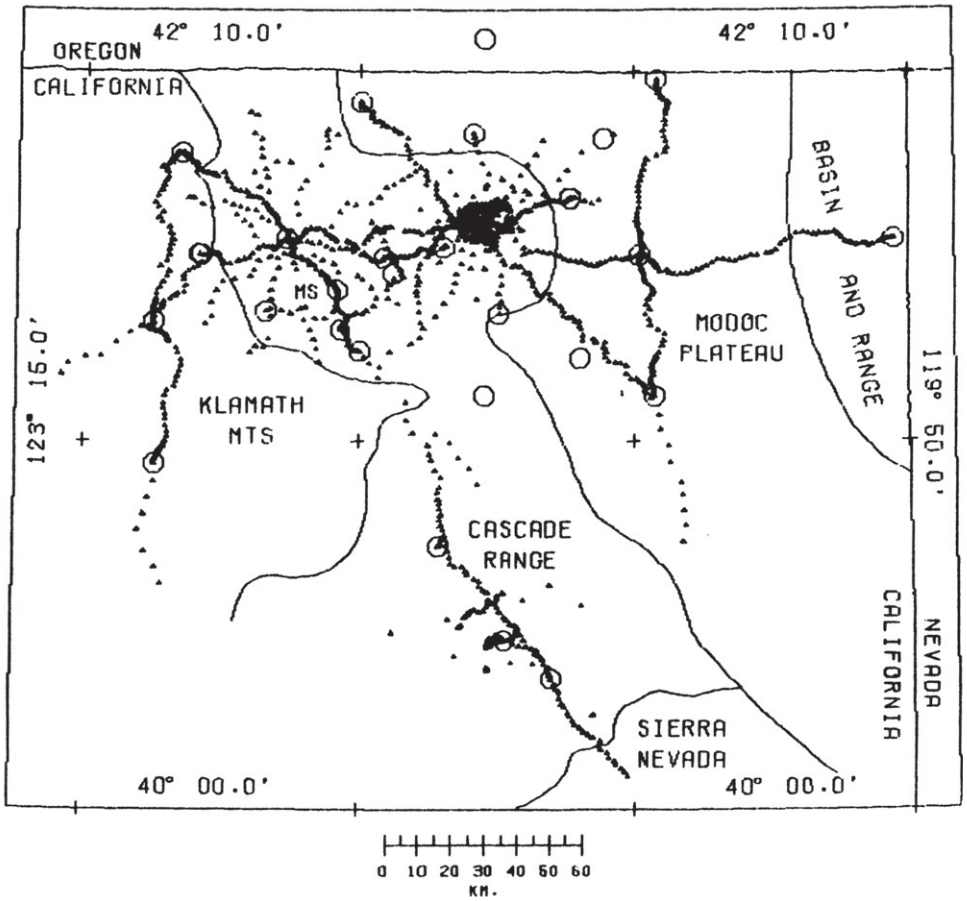

Figure 8.5.3-06. Location of shotpoints and recording sites of the 1979–1985 seismic-refraction surveys in northeastern California (from Kohler et al., 1987, fig. 2). [U.S. Geological Survey Open-File Report 87-625, Menlo Park, California, 99 p.]

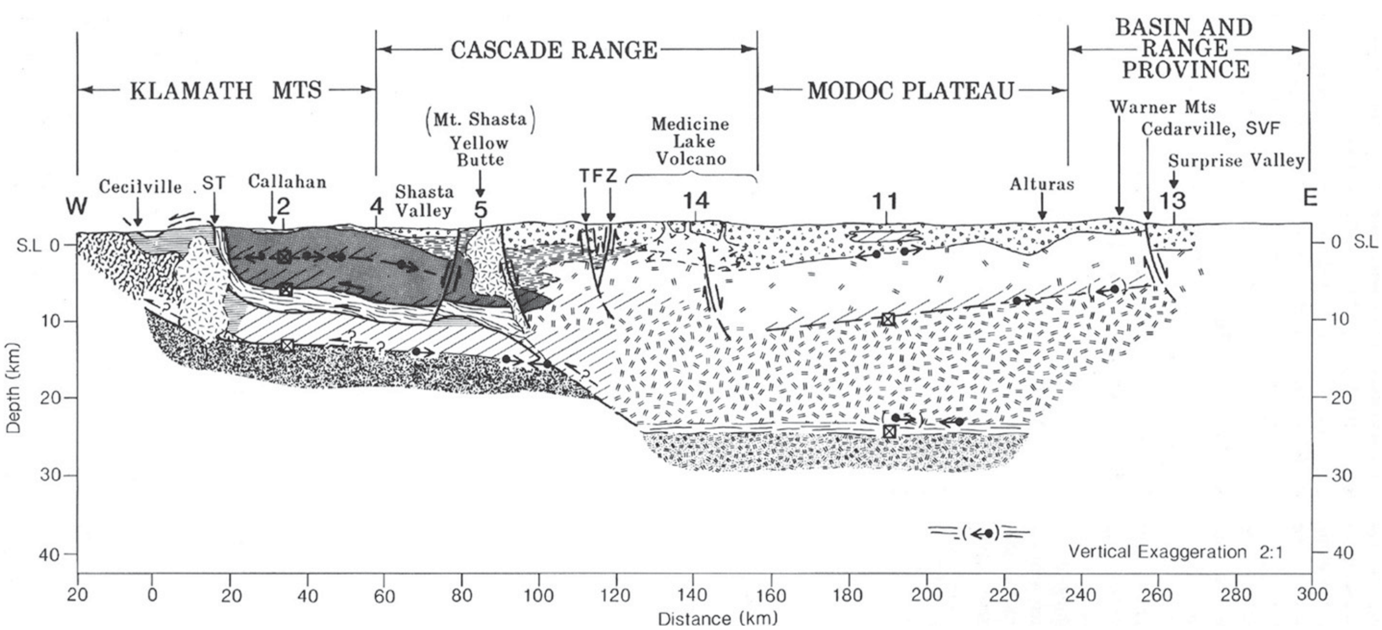

Figure 8.5.3-07. Crustal cross section from the Klamath Mountains to the Modoc Plateau, northern California (from Mooney and Weaver, 1989, fig. 12). [*In* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 129–161. Reproduced by permission of the Geological Society of America.]

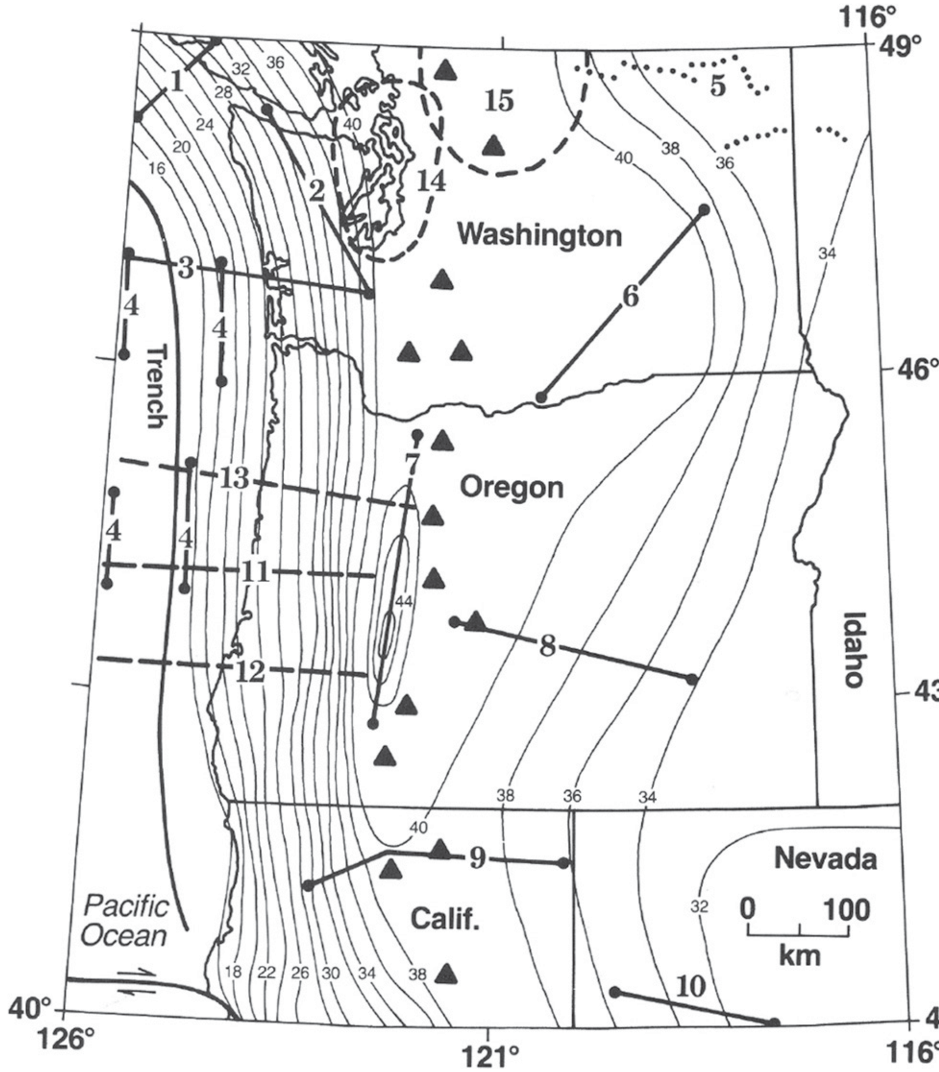

Figure 8.5.3-08. Location map of seismic-refraction (solid lines), seismic-reflection (dotted lines), and other geophysical (dashed lines and circles) surveys in the northwestern United States (from Mooney and Weaver, 1989, fig. 10). 1—Vancouver Island, Canada (Clowes et al., 1986); 2, 3—Washington continental margin (Taber and Lewis, 1986); 4—offshore seismic continental margin studies (Shor et al, 1968); 5—COCORP reflection survey across northwestern Cordillera (Potter et al., 1986); 6—Columbia Plateau (Catchings and Mooney, 1988a); 7—Oregon Cascades (Leaver et al., 1984); 8—Newberry volcano, east-central Oregon (Catchings and Mooney, 1988b); 9—northern California (Zucca et al., 1986); 10—northwestern Basin and Range province (PASSCAL Working Group, 1988; Holbrook, 1990; Catchings and Mooney, 1991); 11–15—other geophysical surveys. Triangles—volcanoes; thin lines—contours of crustal thickness. [*In* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 129–161. Reproduced by permission of the Geological Society of America.]

volcano and spaced ~15 km apart and one shotpoint was located at the eastern end of the line.

To image any extant small silicic magma chambers, the investigation of the upper crust beneath Newberry volcano was continued in 1984 by a dense 13-km-diameter 120-element array of vertical seismographs with average site spacing of 1.07 km and 16 shotpoints. For the interpretation a high-resolution active-source seismic-tomography method was applied (Achauer et al., 1988; Dawson and Stauber, 1986; Appendix A8-3-4). The upper and middle crust (Fig. 8.5.3-09) is similar to that of the Cascade Range but the Moho at the bottom of the lower crust of 7.4 km/s is only 35 km deep (Catchings and Mooney, 1988b).

Mooney and Weaver (1989) compiled a summary of upper crustal structure underneath the most spectacular volcanoes in the Cascade Range (Fig. 8.5.3-09). Seismic velocities of ~6 km/s are found at shallow depths beneath the stratovolcanoes (A, B, C, D, G in Fig. 8.5.3-09), but are not attained until a depth of 8 km for Newberry volcano (E) and 5 km for Medicine Lake Caldera (F) leading to the conclusion that the crustal structure underneath the stratovolcanoes does not differ significantly from that of the overall crustal structure along the axis of the High Cascades.

In 1989, an offshore-onshore seismic experiment was initiated with the aim to investigate the subduction zone underneath the Cascade Mountains in central Oregon (Trehu and Nakamura, 1993; Brocher et al., 1993a) which was followed by the 1991 Pacific Northwest Experiment (Trehu et al., 1993). Both projects are jointly discussed in Chapter 9.4.2.2.

In conjunction with the search of a nuclear waste facility planned in the northwestern United States, in 1984, a 260 km long-range seismic-refraction/wide-angle reflection survey was conducted across the central Columbia Plateau in northeasterly direction from northern Oregon into central Washington (line 6 in Fig. 8.5.3-08) to evaluate its crustal and upper mantle structure and the nature of the Columbia River basalt group (Cotton and Catchings, 1988; Appendix A8-3-4; Catchings and Mooney,

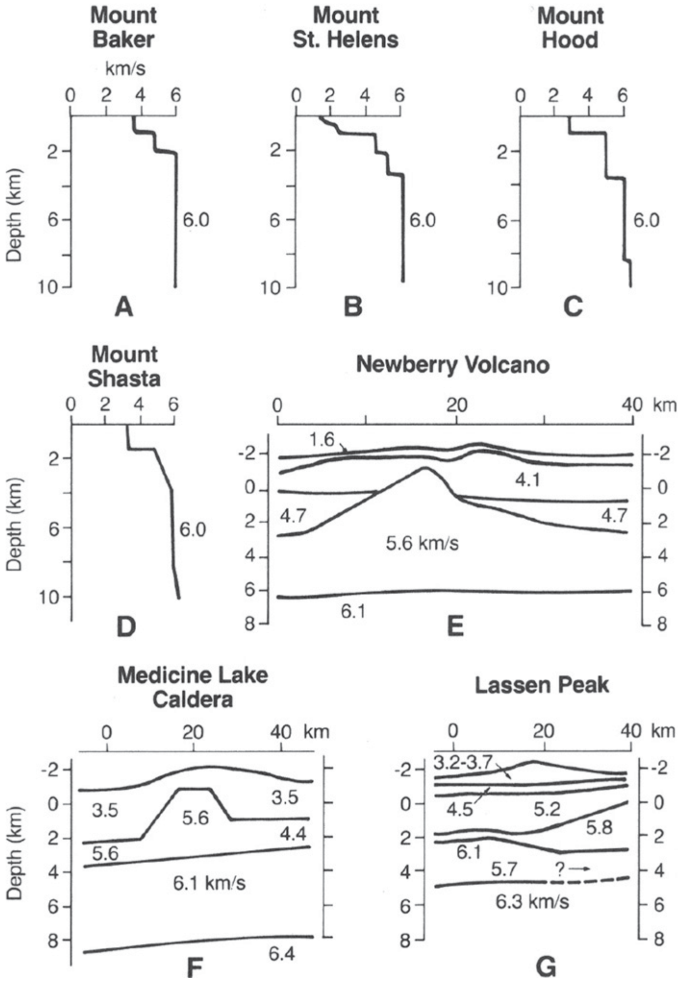

Figure 8.5.3-09. Upper crustal velocity structure of the stratovolcanoes and off-axis basaltic centers Newberry and Medicine Lake volcanoes (from Mooney and Weaver, 1989, fig. 13). [*In* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 129–161. Reproduced by permission of the Geological Society of America.]

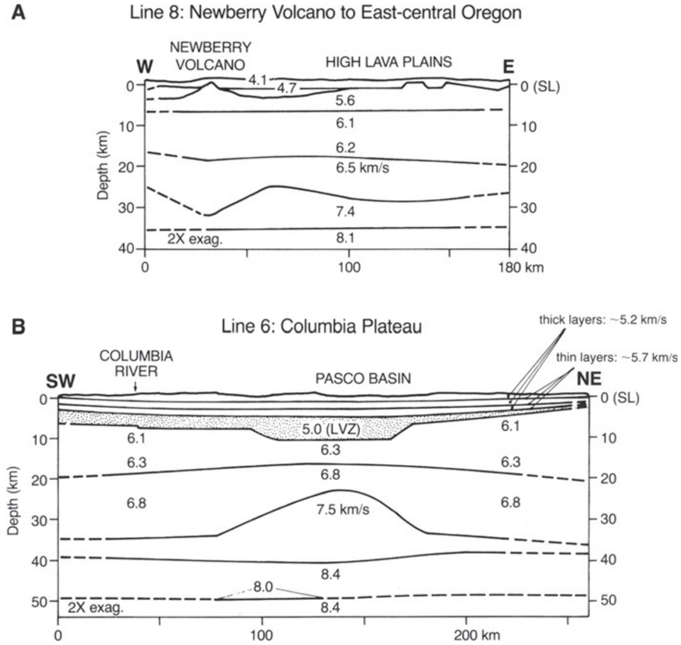

Figure 8.5.3-10. Crustal structure of east-central Oregon and the Columbia Plateau (from Mooney and Weaver, 1989, fig. 14), corresponding to lines 8 and 6 respectively in Figure 8.5.3-08. [*In* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 129–161. Reproduced by permission of the Geological Society of America.]

1988a). The survey was centered on the Hanford site in the Pasco Basin of south-central Washington, a proposed high-level nuclear waste repository and the site of existing nuclear facilities. Four shotpoints were approximately located at profile-kms 60, 115, 160, and 200, and shots of 900–2200 kg sizes were detonated in 50 m deep drillholes. The profile contained 240 recording sites spaced 900 m apart between the shotpoints and 1300 m outside. Though vertical-incidence seismic-reflection profiling has not been successful due to the 3–6-km-thick basalt cover of the area, the wide-angle seismic operation succeeded in obtaining clear seismic signals from the crust and upper mantle beneath the Columbia Plateau.

An interpretation by Catchings and Mooney (1988a) is shown in Figure 8.5.3-10. The crust is 40 km thick, in the center of the line, the lower crust consists of two layers with 6.8 and 7.5 km/s. Beneath the Pasco Basin, the lower basal layer with 7.5 km/s thickens and shows geometry similar to continental rifts. From the seismic-reflection data across the Okanagon Highlands (line 5 in Fig. 8.5.3-08; see also Fig. 8.5.3-01) a highly reflective, complexly deformed crust and a relatively flat Moho at 33–35 km depth have been identified (Potter et al., 1986).

8.5.3.3. Seismic-Refraction Projects in Basin and Range and Rocky Mountains

In 1986, a multi-method seismic experiment was conducted in Nevada (Fig. 8.5.3-11) in the northwestern Basin and Range province (Catchings and PASSCAL Working Group, 1988; Holbrook, 1990; Catchings and Mooney, 1991; Whitman and Catchings, 1987; Appendix A8-3-5) under the auspices of the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL). The aim was to collect and integrate new wide-angle and near-vertical incidence explosion seismic data to gain a detailed picture of the structure and velocity distribution.

The 280-km-long "west-east" line had 7 shotpoints with large shots, 45 km apart, and four smaller shots in the center, and the 200-km-long "north-south" profile had 5 shotpoints, 50 km apart, which shots were all recorded simultaneously on both lines. In total, 28 shots were detonated in boreholes with charges ranging from 230 to 2700 kg which were recorded by three deployments of 120 one-component and 40 three-component stations. Receiver spacing was 900 m for the center 100 km of the west-east line and 1400–1500 m elsewhere. Furthermore, three

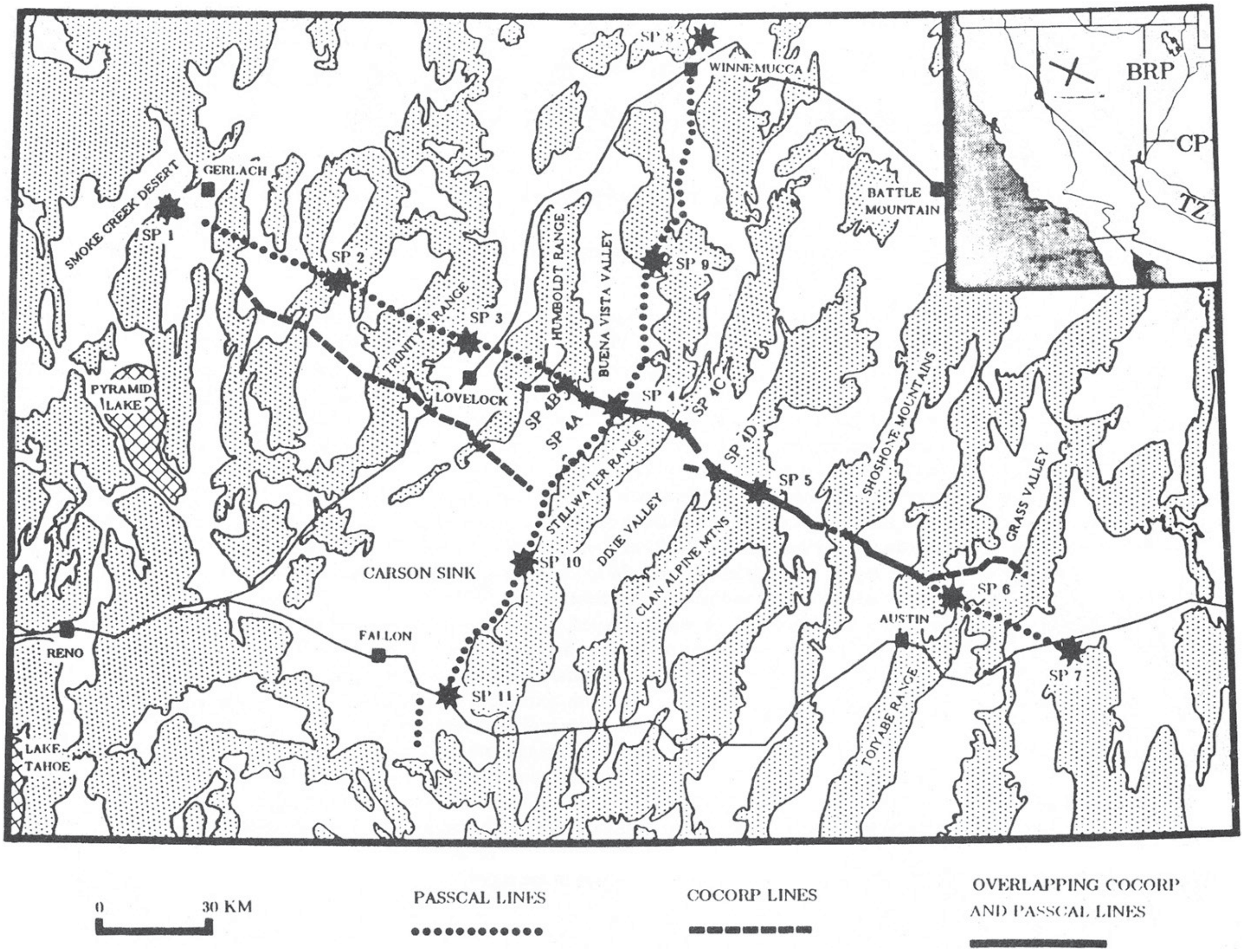

Figure 8.5.3-11. Location of the 1986 PASSCAL Basin and Range lithospheric seismic experiment. Stars—shotpoints (from Holbrook, 1990, fig. 1). Also shown is the COCORP investigation of 1982–1984 (see Fig. 8.5.3-01, western half). [Journal of Geophysical Research, v. 95, p. 21,843–21,869. Reproduced by permission of American Geophysical Union.]

48-channel seismic-reflection recording systems were involved which also were deployed three times.

The seismic-refraction experiment was placed as close as possible at the same position as the western half of the COCORP experiment in 1982–1984 (COCORP 40° transect in Fig. 8.5.3-02, western half). Due to the propagation path of waves to be recorded at wide-angle distance ranges, the seismic-refraction line had to be as straight as possible and therefore the northwestern half and the southeasternmost end deviate from the COCORP reflection lines. The experiment included the objective to compare the entire wavefield recorded coincidently by the "refraction method" with 2-Hz geophones at 1 km spacing and the "reflection method" with 10-Hz geophones and 100 m spacing.

For comparison the main results of the seismic-reflection COCORP 40° transect and the PASSCAL seismic-refraction project are shown (Figs. 8.5.3-12 to 8.5.3-14) and briefly discussed here. In general, the Moho is 30 km thick (Fig. 8.5.3-12). This is also evident in the reflection data where the Moho is identified as the bottom of the highly reflective lower crust (Fig. 8.5.3-13). Middle and lower crust with 6.6 and 7.4 km/s (Fig. 8.5.3-12) more or less agree with the highly reflective lower crust of Figures 8.5.3-13 and 8.5.3-14.

The new data confirm the results of the VELA UNIFORM project in the 1960s, but present a much higher degree of accuracy and details. For example, the interpretation of Catchings and Mooney (1991) contains a lower crustal layer (shaded in Fig. 8.5.3-12) which in an earlier interpretation was identified as crust-mantle transition zone (Prodehl, 1979; see Fig. 6.5.1-09).

More local investigations in the Basin and Range Province of Nevada aimed for detailed crustal studies around Yucca Mountain near Beatty, Nevada. Here the USGS conducted seismic

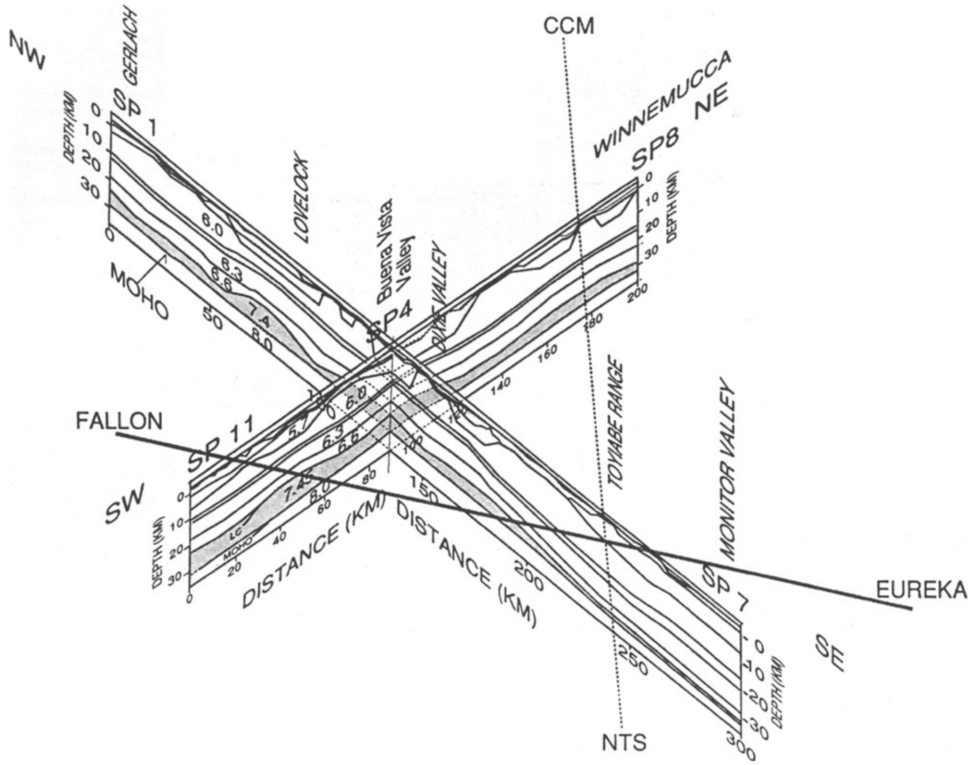

Figure 8.5.3-12. Composite model of the PASSCAL seismic-refraction project (from Catchings and Mooney, 1991, fig. 13). [Journal of Geophysical Research, v. 96, p. 6247–6267. Reproduced by permission of American Geophysical Union.]

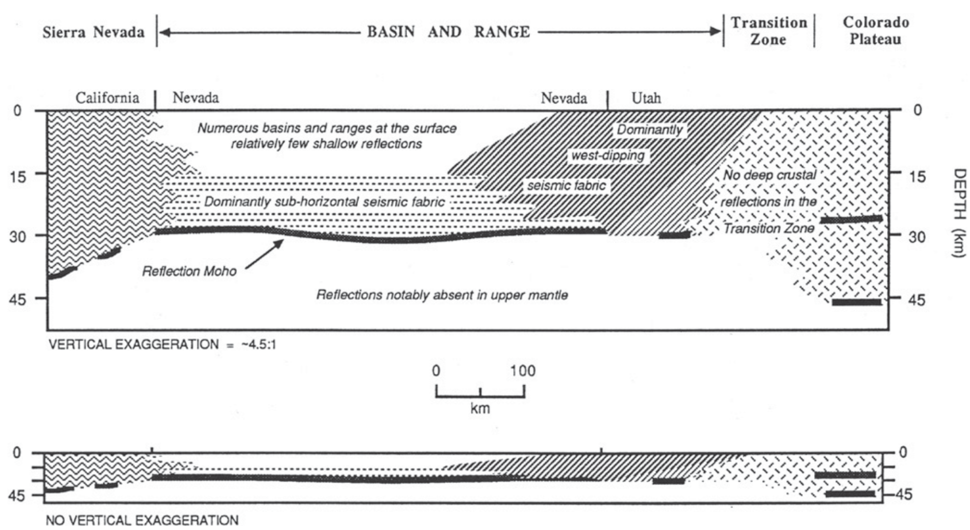

Figure 8.5.3-13. Schematic representation of the seismic fabrics of Figure 8.5.3–14 seen on the COCORP 40°N transect (from Allmendinger et al., 1987, fig. 6). For location see Figures 8.5.3-01 and 8.5.3-02. [Geological Society of America Bulletin, v. 98, p. 308–319. Reproduced by permission of the Geological Society of America.]

studies to aid an investigation of the regional crustal structure at a possible nuclear waste repository site near Yucca Mountain. Initial seismic-refraction studies had already been carried out in 1980 and 1981 (Hoffman and Mooney, 1983), recording three nuclear events at two regional and one N-S profile up to 110 km offsets. Furthermore, an E-W profile had been established in 1982, recording up to 65 km offset from a shotpoint SE of Beatty, Nevada, across Yucca Mountain to the Nevada Test Site area. The data showed prominent reflections from a mid-crustal boundary at 15 km depth, identified other mid-crustal boundaries at 24 and 30 km depth, and revealed a total crustal thickness of 35 km (Hoffman and Mooney, 1983).

In 1988, a test experiment was carried out south of Yucca Mountain, to see if the seismic-reflection method would be feasible for a larger seismic-reflection crustal study in this area (Brocher et al., 1990, 1993b). In this test, both large Vibroseis arrays (more than 72,200 kg) and large chemical explosive sources (charges ranging from 23 to 182 kg) were recorded by a large number (480) of closely spaced (25 m) receiver channels. The recording line was 27 km long and a 60-fold coverage was

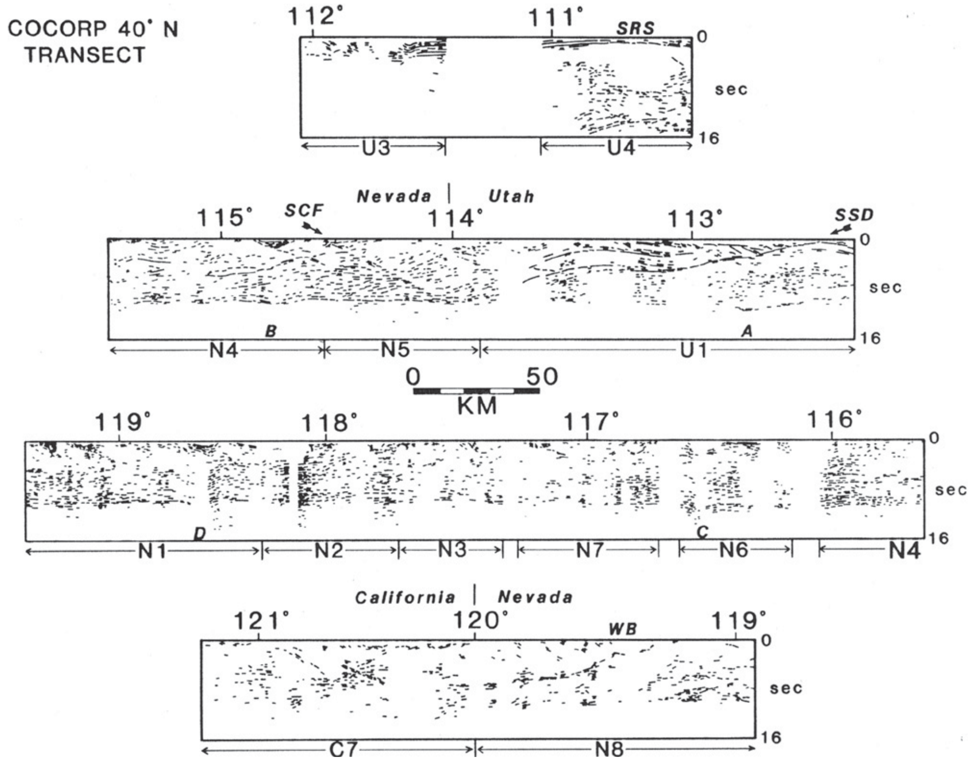

Figure 8.5.3-14. Simplified line drawings of the entire COCORP 40°N transect (from Allmendinger et al., 1987, fig. 5). For location see Figures 8.5.3-01 and 8.5.3-02. [Geological Society of America Bulletin, v. 98, p. 308–319. Reproduced by permission of the Geological Society of America.]

acquired using a 12-km-long symmetric split spread (Brocher et al., 1990). It turned out that the explosive sources produced a higher-quality image of the lower crust (5–10 s). The base of the crust at 35 km depth was estimated from the absence of high-amplitude reflected arrivals below 9–10 s confirming the result obtained already by the 1980–1982 seismic-refraction study described above.

The Long Valley Mono Craters volcanic complex at the western margin of the Basin and Range province in eastern California had already been the target of a major seismic project in the 1970s (Hill, 1976). New seismic-refraction data were obtained in the summers of 1982 and 1983 as part of a study to evaluate the region as a possible site for deep scientific drilling in a thermal regime. One hundred stations in 1982 and 120 in 1983 recorded 1000 kg charges fired in 50–60 m deep boreholes. The profiles sampled the upper 7–10 km of the crust within the western half of the Long Valley caldera, the Mono craters ring fracture system and the "normal" crust north and northeast of Long Valley. At a depth of 2 km beneath the topographic surface, the P-wave velocity is uniformly 5.6 km/s beneath which the velocity increases with a gradient of ~0.1 s^{-1}. Clear secondary arrivals in the western part of the caldera supported evidence from 1972 seismic-refraction profiles for a reflecting boundary at a depth of 7–8 km beneath the west margin of the resurgent dome which may represent the top of a magma chamber (Hill et al., 1985).

A special goal was to study the evolutionary history of metamorphic core complexes of the western Cordillera (Fig. 8.5.3-15). In particular, information on the thickness of the crust, the geometry of the Moho, and the composition of the middle and lower crust that underlie metamorphic core complexes (McCarthy et al., 1991; Wilson et al., 1991) was needed.

For this reason the USGS chose to undertake another multimethod seismic experiment: PACE (Pacific to Arizona Crustal Experiment), a major seismic-refraction/wide-angle reflection study of the core complex belt along the Colorado River in southeastern California and western Arizona. The study of 1985 (profiles 2 and 3) and 1987 (profile 1) was conducted as part of PACE (Fig. 8.5.3-15) and was designed to complement vertical incidence seismic-reflection profiles collected by COCORP (Consortium for Continental Reflection Profiling) and by CALCRUST (California Consortium for Crustal Studies).

The project involved three profiles across the Chemehuevi (A, profile 3), Whipple (B, profile 2), and Buckskin-Rawhide (C, profile 1) mountains metamorphic core complexes. Lines 2 and 3, recorded in 1985 (Wilson and Fuis, 1987; Appendix A8-3-5), were each 130 km long and a total of 30 shots from 20 shotpoints was recorded. Including offset shots, the maximum offsets along profiles 2 and 3 was extended up to 170 km. Profile 1, recorded in 1987 (Larkin et al., 1988; Appendix A8-3-5) with 27 shots from 19 shotpoints, was 180 km long, with maximum offsets extended to 210 km. During both experiments, higher-resolution reflection arrays were deployed within the center of the lines (Henyey et al., 1987).

Crustal thickness is near 30 km and fairly uniform throughout the region. The prominent feature in the model of Figure 8.5.3-16 is a thick midcrustal layer centered beneath or just

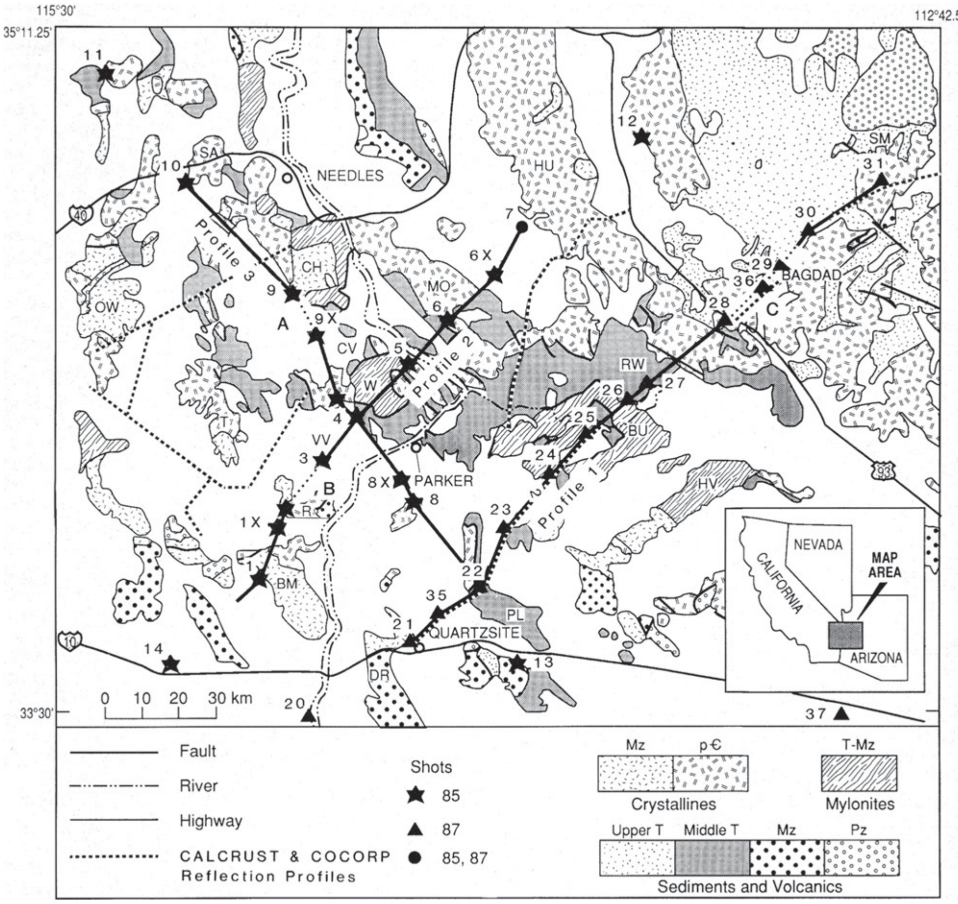

Figure 8.5.3-15. PACE seismic-refraction survey of 1985 and 1987 in southeastern California and western Arizona (from McCarthy et al., 1991, fig. 2). BM—Big Maria Mountains; BU—Buckskin Mountains; CH—Chemehuevi Mountains; DR—Dome Rock Mountains; HU—Hualapai Mountains; HV—Harcuvar Mountains; MO—Mohavi Mountains; OW—Old Woman Mountains; PL—Plomosa Mountains; R—Riverside Mountains; RW—Rawhide Mountains; SA—Sacramento Mountains; T—Turtle Mountains; VV—Vidal Valley; W—Whipple Mountains. [Journal of Geophysical Research, v. 96, p. 12,259–12,291. Reproduced by permission of American Geophysical Union.]

west of the metamorphic core complex (McCarthy et al., 1991; Wilson et al., 1991).

The arch-like shape of its upper boundary was regarded to possibly correlate with the large amount of uplift noted at the surface. For its interpretation the authors offered various explanations, from a magmatically thickened crust composed of diorite or sill-like interfering gabbro and silicic country rock to low-velocity felsic material laterally flowing in from less extended regions and thereby inflating the middle crust (McCarthy et al., 1991).

In 1989, the Pacific to Arizona Crustal Experiment (PACE) was conducted across the northeastern Transition zone and the southwestern margin of the Colorado Plateau. Two profiles were acquired (Fig. 8.5.3-17, McCarthy et al., 1994; Appendix A8-3-5). The PACE Colorado Plateau profile P1 extended 150 km from the northeastern end of the 1987 PACE study (profile 1 in Fig. 8.5.3-15) across Chino Valley to the western edge of the Navajo Indian Reservation near Cameron, Arizona, and had 24 shots with an average spacing of 10 km. The Grand Canyon profile P2 (Wolf and Cipar, 1993) was located entirely within the Colorado Plateau. It was also 150 km long and had inline 10 shots, one of them offset resulting in a maximum recording distance of 225 km. The location map (Fig. 8.5.3-17) also shows the position of earlier seismic-refraction lines obtained in the 1960s (for details and references, see Chapter 6).

The data of profile 1 were inverted together with the 1987 data. Crustal thickness increases from 30 km in the southwest to almost 40 km where profile 1 enters the Colorado Plateau, but decreases to 35 km at the northeastern end of the line (Parsons et al., 1996). Coincident with the thickening of the crust is the thickening of the lower crustal layer (6.5–6.6 km/s). For the Grand Canyon profile a 35-km-thick crust was obtained near Meteor Crater at the southeastern end, but when reaching the Grand Canyon, the crust thickens to almost 50 km (Wolf and Cipar, 19923; Parsons et al., 1996).

In 1986 COCORP (Hauser et al., 1987a; Hauser and Lundy, 1989) recorded 550 km of vertical incidence seismic-reflection data along a transect in Arizona, coincident with the PACE profiles and in areas to the east. The COCORP vertical incidence seismic-reflection data had obtained a gradual increase in reflectivity between 16 and 20 km depth. Moho reflections were generally between 9 and 10 s TWT in the Basin and Range province, corresponding to 27–30 km depth, and were dipping gently eastward beneath the central transition zone, but also showed distinct offsets and reached up to 12 s corresponding to ~36 km depth (Hauser et al., 1987a; Hauser and Lundy, 1989).

Further east, in the area of the Southern Rocky Mountains, two new experiments in 1981 comprised the CARDEX (Caldera

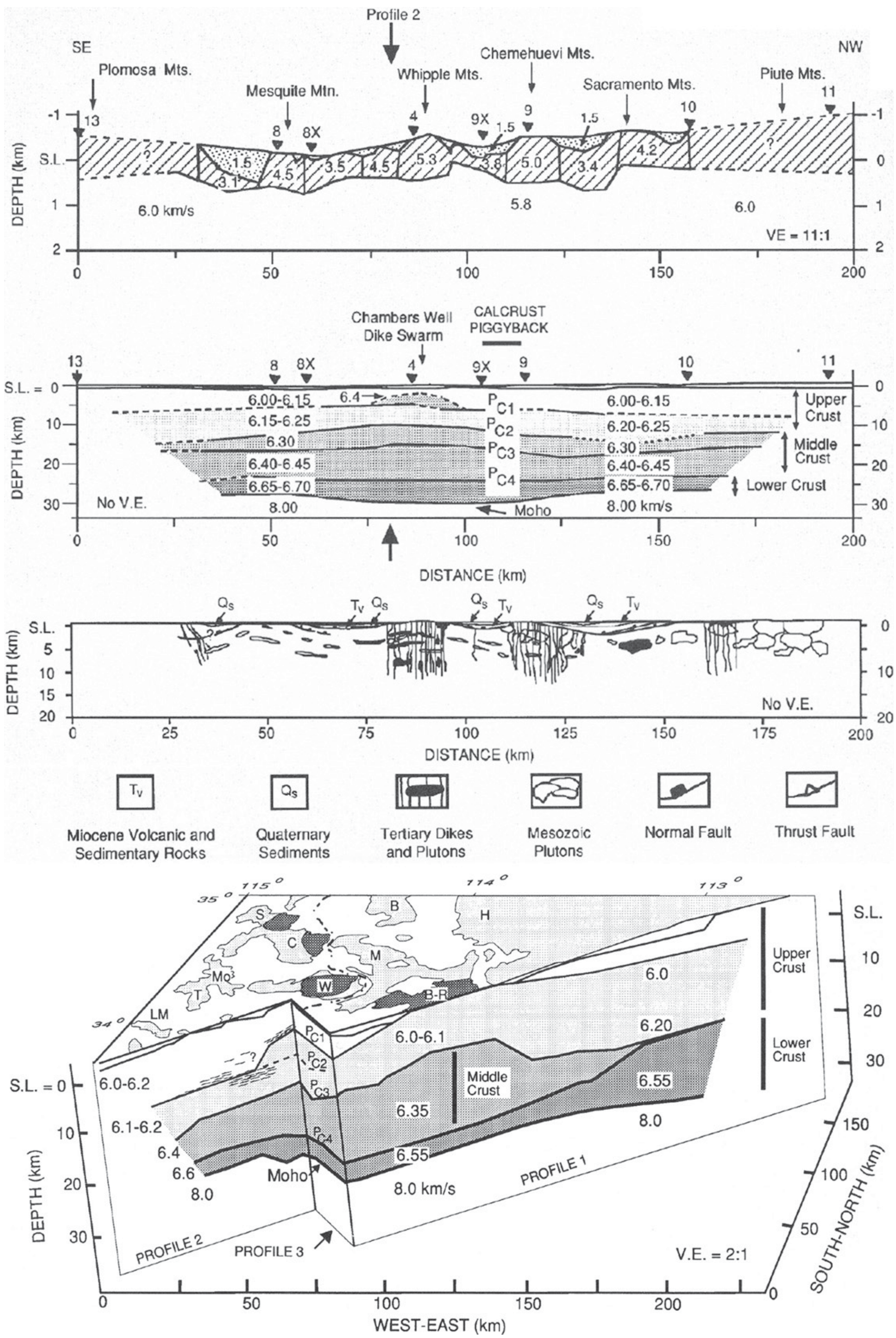

Figure 8.5.3-16. Crustal structure of the Colorado River extensional corridor (from McCarty et al., 1991, figs. 23 and 26, and Wilson et al., 1991, fig. 6). Abbreviations, see Figure 8.5.3-15. [Journal of Geophysical Research, v. 96, p. 12,259–12,291. Reproduced by permission of American Geophysical Union.]

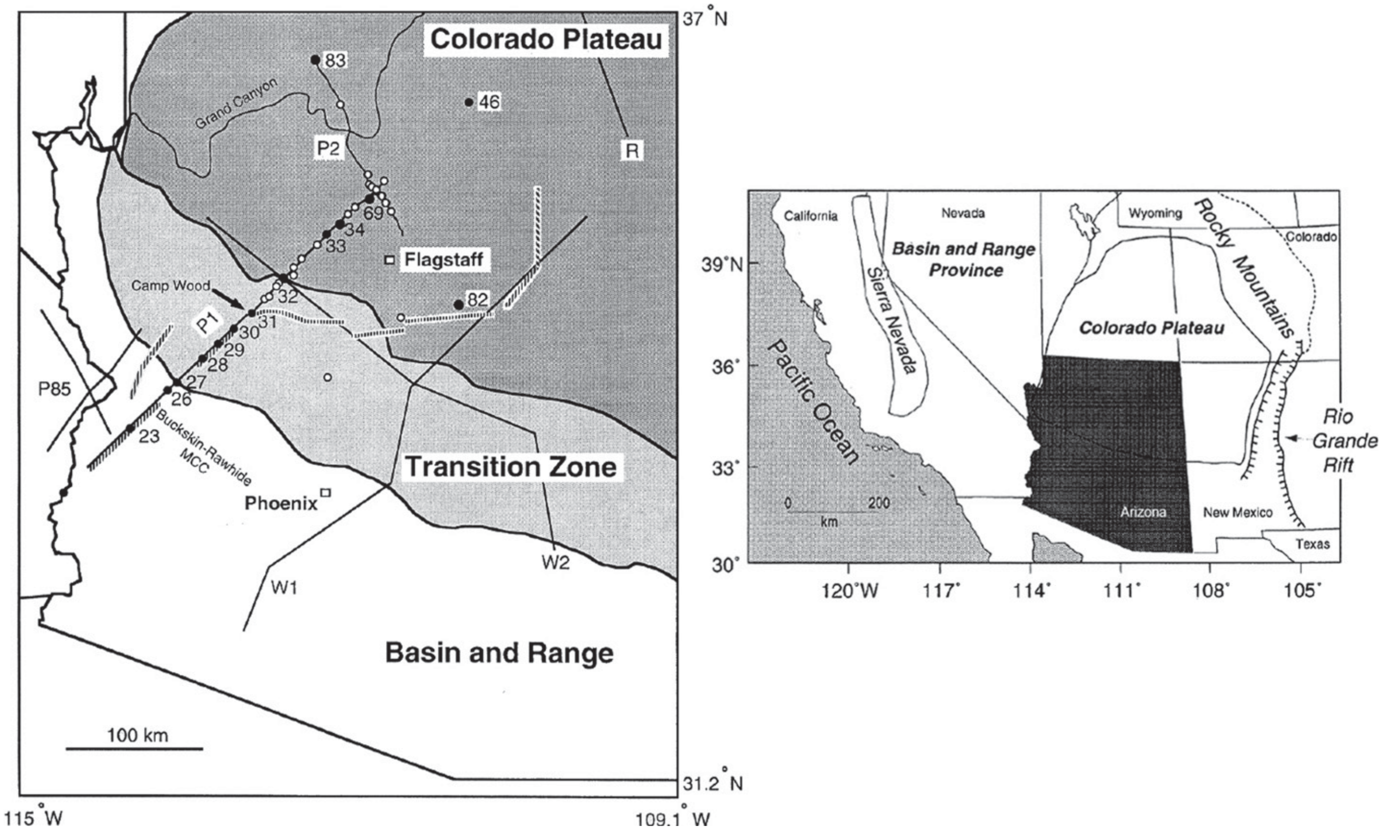

Figure 8.5.3-17. Location of PACE 1989 experiment (from Parson et al., 1996, fig. 1). Circles along P1 (Colorado Plateau profile) and P2 (Grand Canyon profile) are shotpoints. Older lines: R—Hanksville-Chinle profile (Roller, 1965); W1—Gila Bend–Surprise profile (Warren, 1969); W2—Blue Mountain Bylass profile (Warren, 1969). [Journal of Geophysical Research, v. 101, p. 11,173–11,194. Reproduced by permission of American Geophysical Union.]

and Rift Deep Seismic Experiment) project and added to the knowledge of the Rio Grande rift.

In 1981, the Valles caldera within the Jemez Mountain volcanic field at the western flank of the Rio Grande rift in north central New Mexico (Fig. 8.5.3-18; see also Fig. 9.4.2.24 for location of the caldera) was investigated by 72 portable recording units and 10 permanent telemetered stations of the Los Alamos Seismic Network providing radial profile and fan-beam coverage by recording six shots with maximum offsets of 100 km (Olsen et al., 1986). By applying a simultaneous inversion of seismic-refraction and earthquake data, the project elucidated upper crustal structure beneath the caldera providing evidence of a low-velocity body presumed to correlate with the so-called Bandelier magma chamber (Ankeny et al., 1986; see Appendix A8-3-6).

The second experiment targeted the southern Rio Grande rift (Sinno et al., 1986; Appendix A8-3-6), when three interlocking regional profiles were recorded between 1980 and 1983: a 200-km-long reversed SE-NW cross line across the rift, an unreversed 210-km-long axial N-S line, and an unreversed NW-SE line, named Pipeline Road Profile, which was only recorded between offsets of 80 and 195 km (Fig. 8.5.3-19; for data and models see Appendix A8-3-6). The first and second profiles recorded preannounced shots on White Sands Missile Range, while for the second and third profiles quarry blasts from the Tyrone Mine west of the Rio Grande rift were used. The average station spacing on all lines was 4 km.

The reversed SW-NE reversed cross line showed no significant dip of the 32 km deep Moho, while along the axial line a significant dip of Moho indicated a crustal thinning by 4–6 km to the south with respect to the northern rift and thus confirmed a similar upward warping of Moho (see Fig. 7.4.1-07), as sketched earlier by Keller et al. (1979) and as shown by Prodehl and Lipman (1989) in their generalizing NNW-SSE–trending crustal cross section of the Rocky Mountains and adjacent Rio Grande Rift (see Fig. 7.4.1-08).

8.5.3.4. Seismic Projects in the Eastern United States

In 1983, a joint consortium of geoscientists from Canada and the United States arranged a nearly continuous 1000-km-long seismic-reflection survey traversing the northern Appalachians from Quebec to Maine along a line extending from near the edge of the Precambrian Shield in Quebec to the eastern limit of the continental margin bordering the ocean basin (Fig. 8.5.3-20; QMT in Fig. 8.5.3-24).

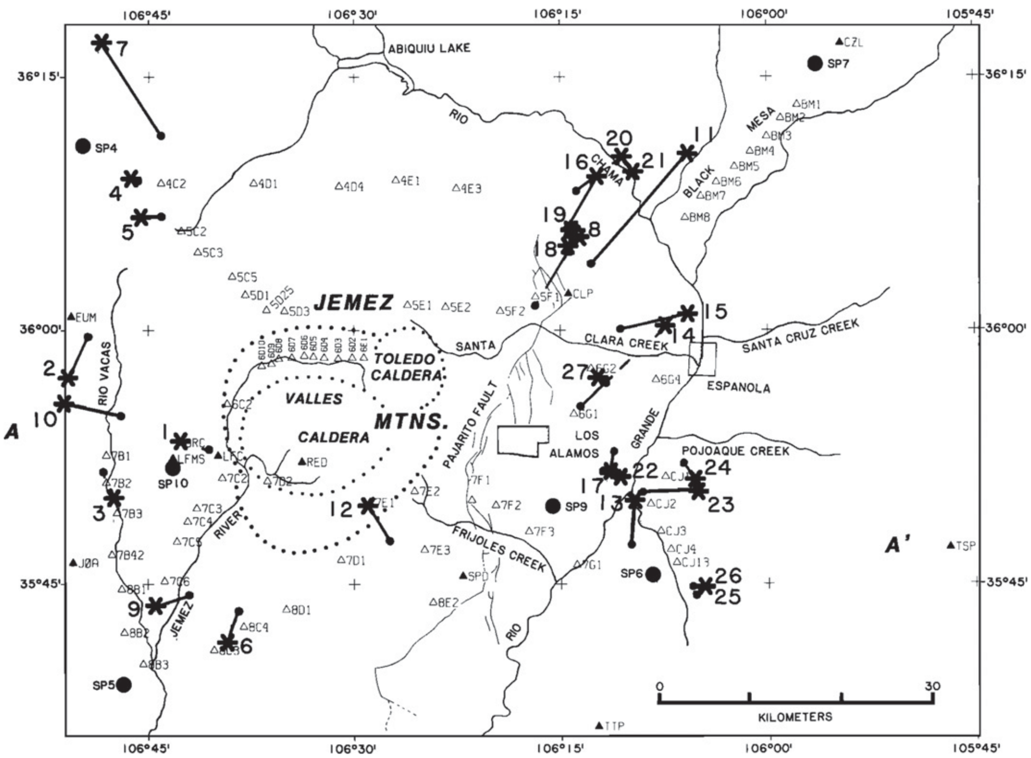

Figure 8.5.3-18. Location of the 1981 CARDEX (Caldera and Rift Deep seismic Experiment) refraction shotpoints (large solid dots), seismograph stations (triangles) and earthquakes (dots and asterisks = initial and relocations) in the Valles caldera within the Jemez Mountain volcanic field (from Ankeny et al., 1986, fig. 1). [Journal of Geophysical Research, v. 91, p. 6188–6198. Reproduced by permission of American Geophysical Union.]

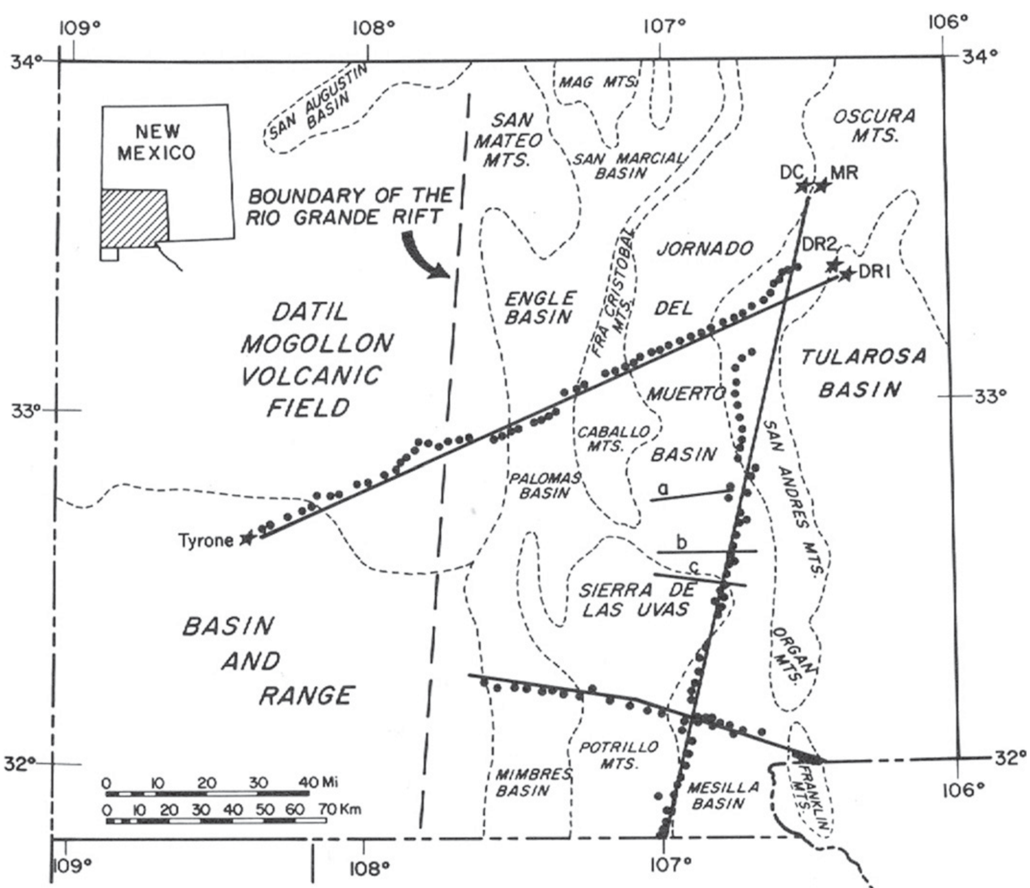

Figure 8.5.3-19. Location of the seismic lines recorded from 1980 to 1983 in the southern Rio Grande Rift in southeastern New Mexico (from Sinno et al., 1986, fig. 2). [Journal of Geophysical Research, v. 91, p. 6143–6156. Reproduced by permission of American American Geophysical Union.]

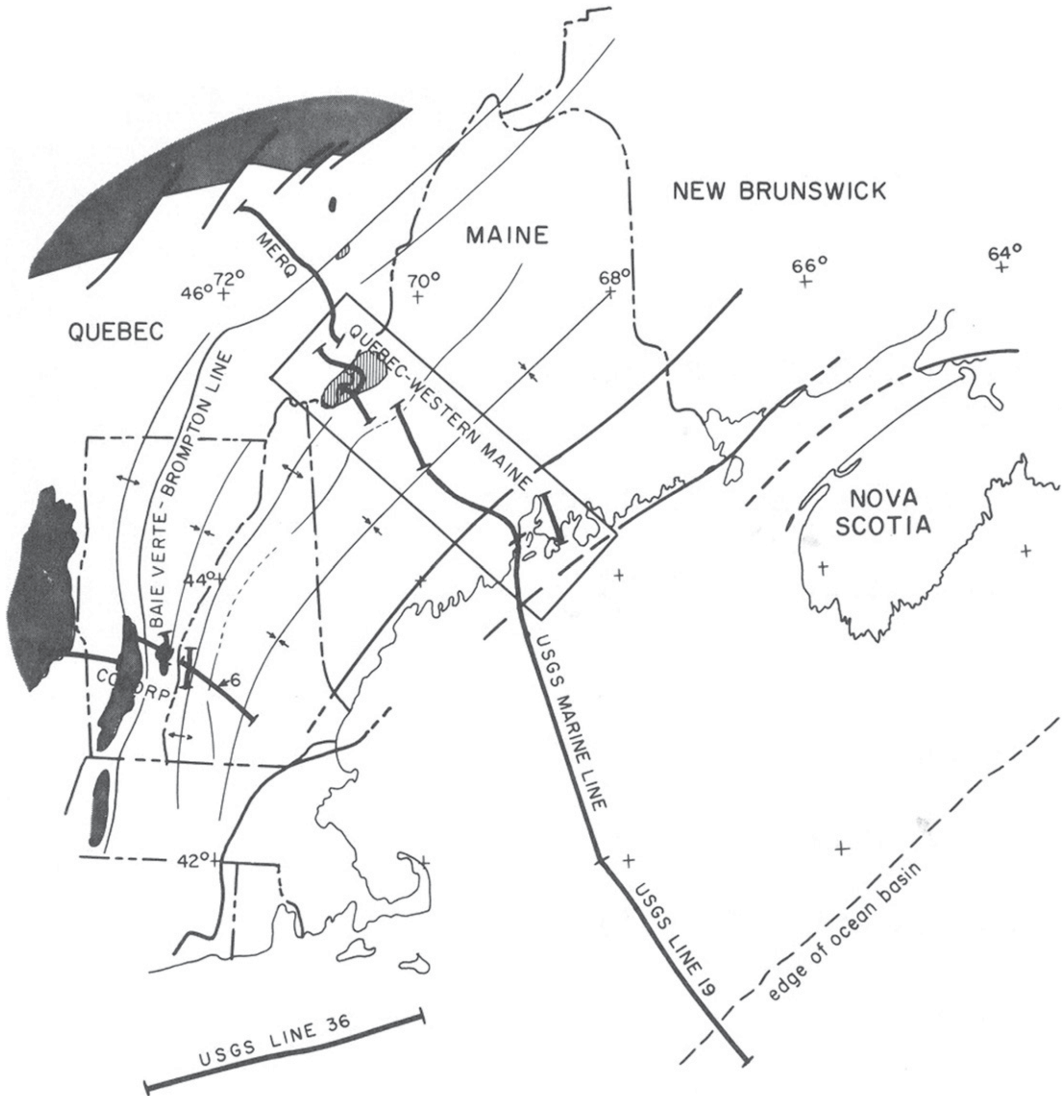

Figure 8.5.3-20. Location of the Quebec-Maine transect through the northern Appalachians (from Stewart et al., 1986, Fig 1). The map also shows a COCORP line through New England (Brown et al., 1986) and one of line 36 of the Long Island platform marine survey obtained in the 1970s (Hutchinson et al., 1986). [*In* Barazangi, M., and Brown, L., eds., Reflection seismology: the continental crust: American Geophysical Union, Geodynamics Series, v. 14, p. 189–199. Reproduced by permission of American Geophysical Union.]

The Canadian section in Quebec was completed in 1983 collecting 219 km of multichannel reflection data for 15 s TWT using Vibroseis sources. Variable upsweeps from 7 to 45 Hz with a 12 km spread, 30 m group intervals, and 90 m vibration points were used (Stewart et al., 1986). It was originally obtained for oil and gas assessment and was recorded to 4–6 s TWT (Green et al., 1986; Stewart et al., 1986). The continuation of this survey into the United States through Maine to the sea coast followed in 1983 and 1984 (Hamilton, 1986) and included a detailed seismic-refraction investigation (Spencer et al., 1987, 1989). The reflection line was extended by a marine profile across the Gulf of Maine to the continental margin (GMM in Fig. 8.5.3-24). Along the marine line in 1984 a 6000 in^3 tuned airgun array was fired every 50 km and recorded by 3 km streamer with 120 channels spaced 25 m apart with a record length of 15 s with a 0.004 s sampling interval, resulting in 30-fold data (Hutchinson et al., 1987).

The seismic-refraction survey was carried out in 1984 and involved eight profile lines, designed to complement the seismic-reflection survey. A 300-km-long traverse consisting of three collinear profiles crossed the Appalachians between Quebec and the Atlantic coast. Three shorter crossing profiles examined individual Appalachian terranes and provided 3-D control for the primary traverse (no. 1 in Fig. 8.5.3-21). A final 145-km-long profile examined the Avalon terrane of southeastern Maine (no. 2 in Fig. 8.5.3-21 and MRP in Fig. 8.5.3-24). (Murphy and Luetgert, 1986, 1987; Appendix A8-3-7; Luetgert

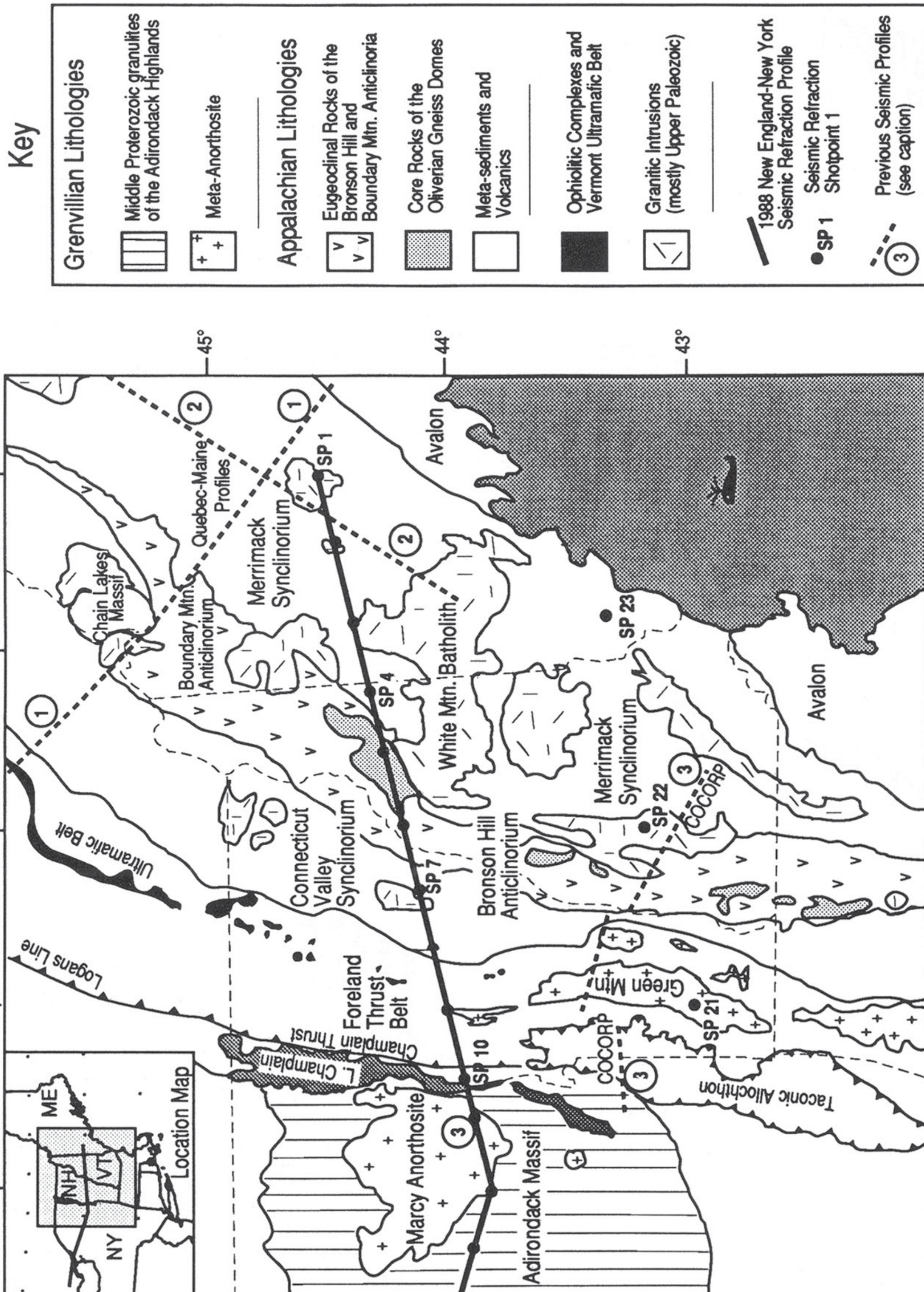

Figure 8.5.3-21. Location of seismic crustal surveys through the northern Appalachians (from Hughes and Luetgert, 1991, fig. 1). [Journal of Geophysical Research, v. 96, p. 16,471–16,494. Reproduced by permission of American Geophysical Union.]

et al., 1987; Spencer et al., 1989; Hughes et al., 1994). A linear array of 120 portable cassette recorders with 2 Hz geophones were deployed at a nominal spacing of 800 m along each profile. A total of 48 shots with an average shot spacing of 30 km was detonated. In addition to the profile data, several shots were fired broadside to the recording arrays and provided detailed wide-angle data. Also shown in the location maps are the New England COCORP lines (Brown et al., 1986; see Fig. 8.5.3-01; no. 3 in Fig. 8.5.3-21; NEC and ADK in Fig. 8.5.3-24) and one of the lines of a marine survey of the USGS investigating the Long Island Platform (LIP in Fig. 8.5.3-24) recorded in 1979 (Hutchinson et al., 1986; Fig. 7.4.3-01).

In 1988, a seismic-refraction/wide-angle reflection experiment crossed the northern Appalachians and the Adirondack Massif in the eastern United States and ended in the Grenville province of the North American craton in Canada (thick line in Fig. 8.5.3-21), leading from New England through upstate New York into southern Ontario (Luetgert et al., 1990; Appendix A8-3-7; Hughes and Luetgert, 1991; Hughes et al., 1994). The main line saw 3 deployments of 300 recording stations and 35 shots at 22 shotpoints, two of them off line.

Furthermore in New England near the Vermont–New Hampshire border a 150-km-long southeastward directed side line and a special high-density wide-angle reflection deployment with 100-m station spacing were added.

The geological interpretation (Fig. 8.5.3-22) of Hughes and Luetgert (1991) shows a midcrustal ramp separating the high-velocity Grenvillian crustal block from the accreted lower-velocity subhorizontally layered Appalachian crust. The lower crust is shown as a continuous layer, but may be divided into discrete Grenville and Appalachian units.

Hughes and Luetgert (1991) compiled a comparison of the main results of the experiments carried out in this region in the 1980s (Fig. 8.5.3-23) which all cross the Appalachian-Grenville boundary. For the Maine-Quebec profile (Fig. 8.5.3-23A), Spencer et al. (1989) have interpreted a "décollement" surface which separates the allochthonous upper crustal units of the Appalachians from the autochthonous Grenvillian crust which underlies much of the western Appalachians. This "décollement" is very similar to the ramp structure seen by Hughes and Luetgert (1991) in the New England–New York seismic experiment (Fig. 8.5.3-23B). For the COCORP New England seismic-reflection line Brown et al. (1983a) have imaged a "thin-skin" detachment near 5 km depth which extends in the form of a steep "steplike" thrust imbricated structure to a depth of 30 km (Fig. 8.5.3-23C).

The New England–New York experiment had not only also produced good P-arrivals, but also excellent S-data from which V_p/V_s ratios Musacchio et al. (1997) inferred the composition of the crust in the Grenville and Appalachian provinces.

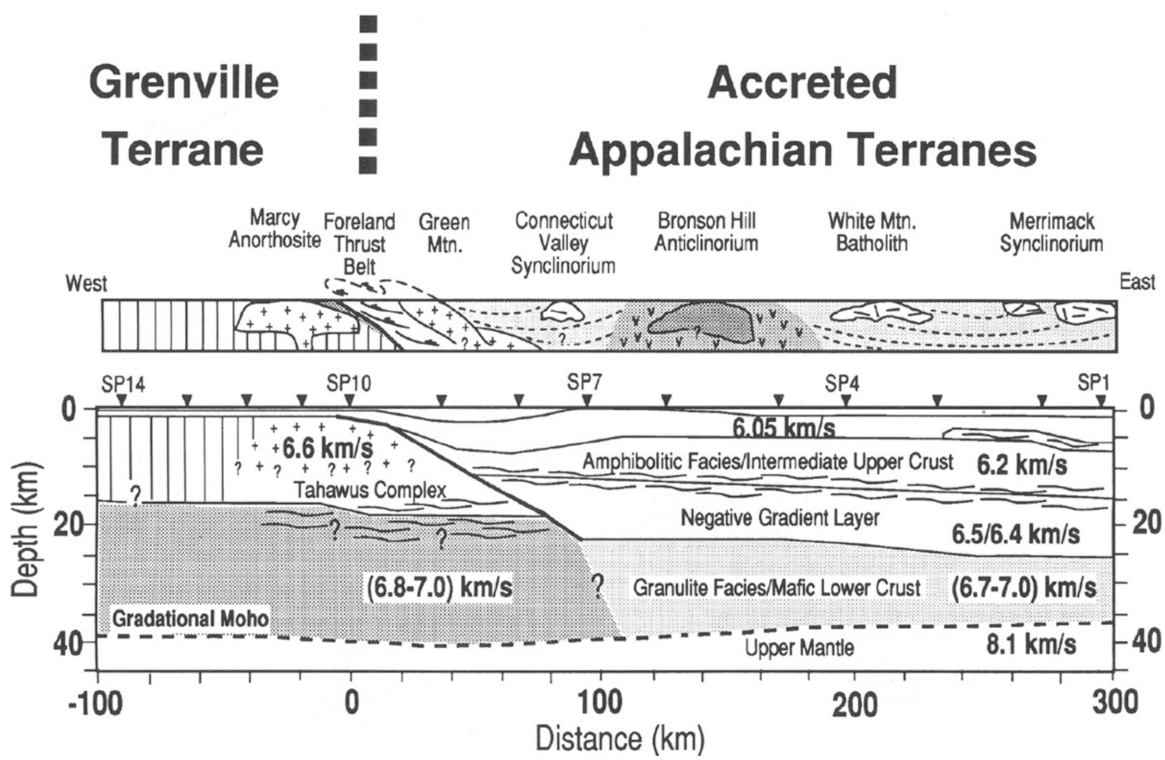

Figure 8.5.3-22. Crustal structure of the 1988 seismic-refraction survey through the northern Appalachians (from Hughes and Luetgert, 1991, fig. 13). [Journal of Geophysical Research, v. 96, p. 16,471–16,494. Reproduced by permission of American Geophysical Union.]

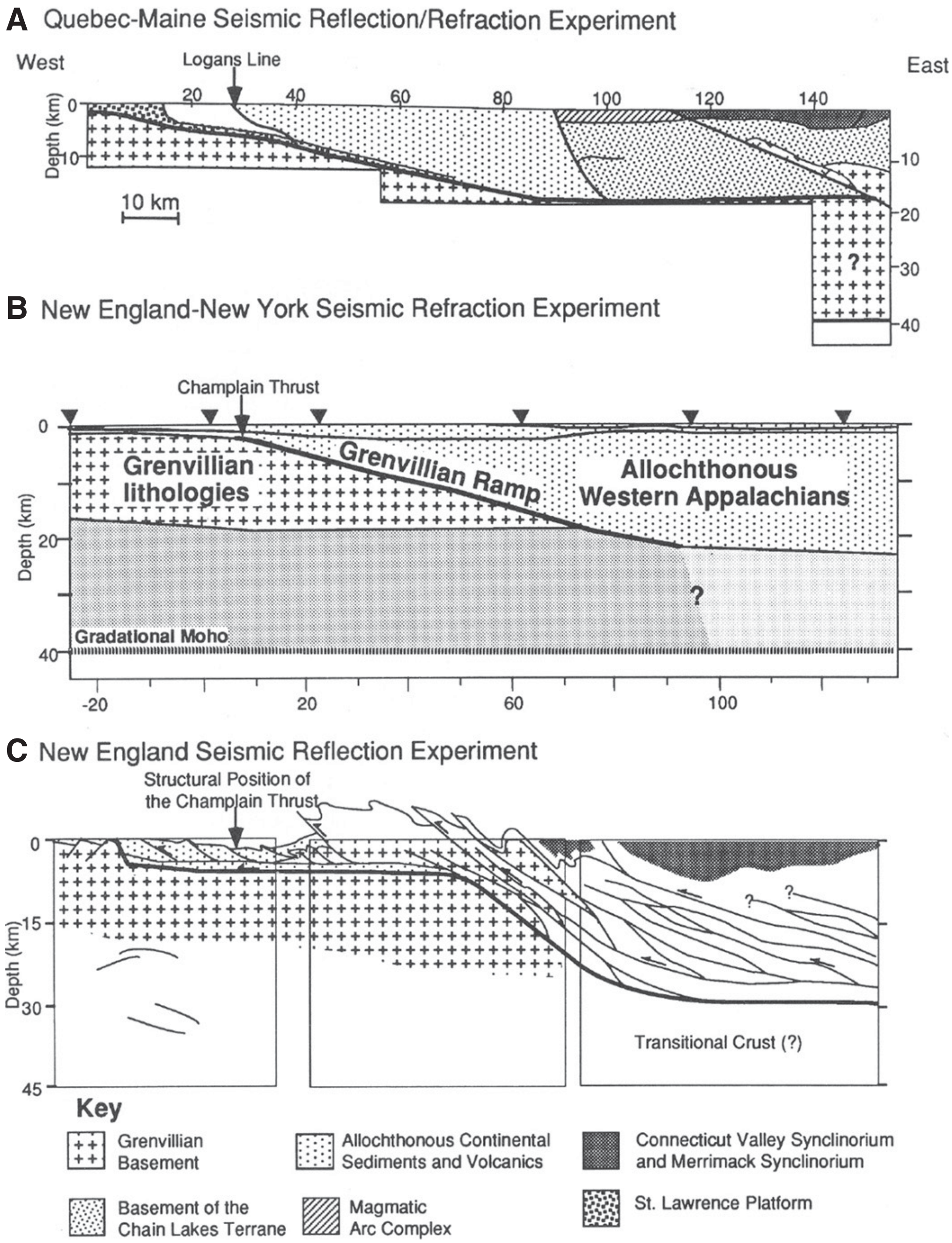

Figure 8.5.3-23. Comparison of the seismic experiments across the Appalachian-Grenville terrane boundary in New England (from Hughes and Luetgert, 1991, fig. 14). [Journal of Geophysical Research, v. 96, p. 16,471–16,494. Reproduced by permission of American Geophysical Union.]

For an overview of all deep seismic-refraction and reflection programs completed until late 1987, the reader is referred to the summary volume *Geophysical Framework of the Continental United States*, edited by Pakiser and Mooney (1989) in which, for the eastern and central United States, Phinney and Roy-Chowdhury (1989) compiled a map (Fig. 8.5.3-24) and a table containing the responsible organization, year, and specific references for all programs, with the exception of the 1988 seismic-refraction project across the northern Appalachians and the Adirondack Massif (Hughes and Luetgert, 1991). For the Appalachians and the adjacent Grenville Province in Canada, Taylor (1989) compiled all available data into a geophysical framework. Smithson and Johnson (1989) published a similar approach for the western United States.

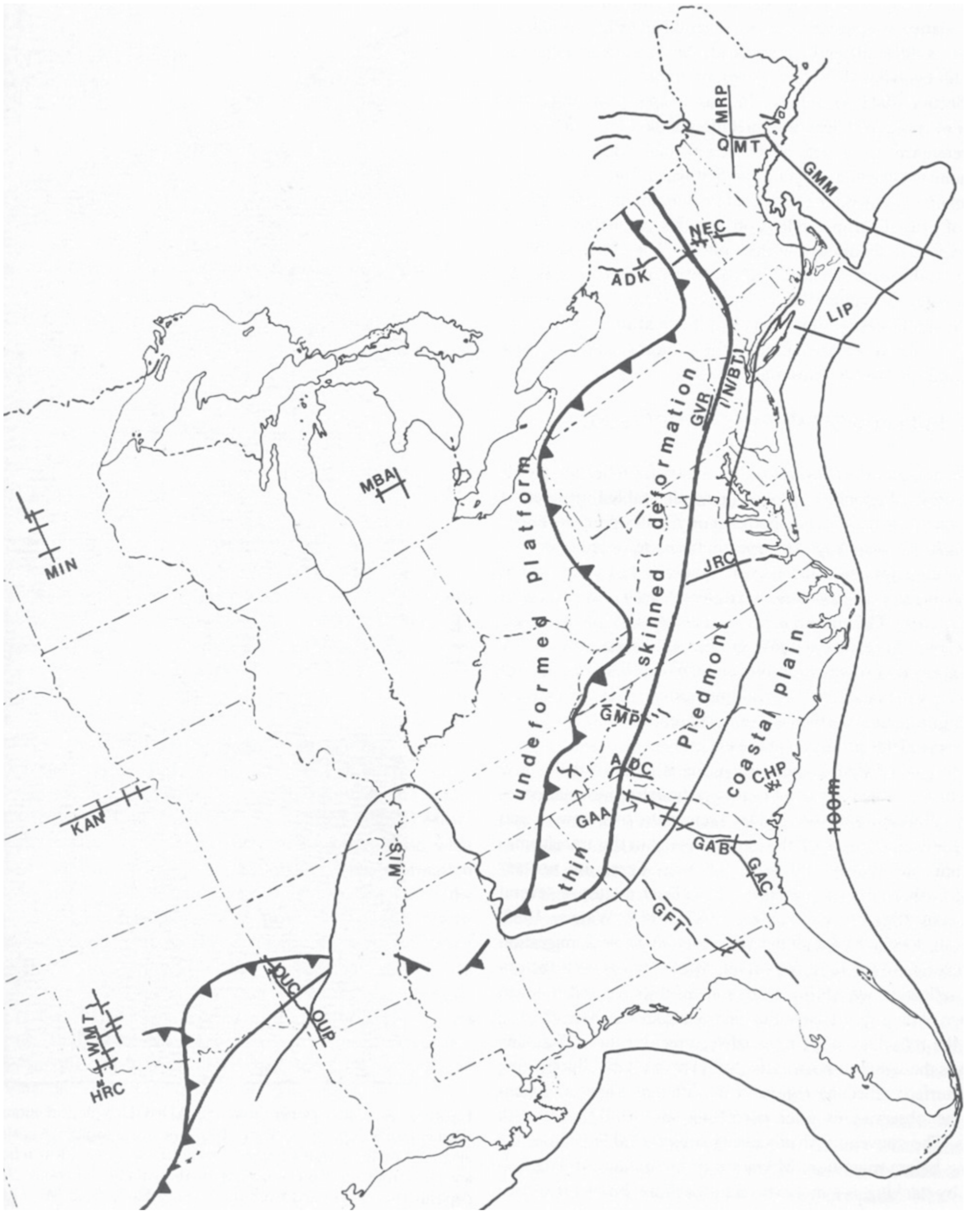

Figure 8.5.3-24. Seismic reflection lines in the eastern United States (from Phinney and Roy-Chowdhury (1989, fig. 1). QMT—Quebec-Maine reflection (USGS 1984–1985), MRP—Maine refraction (USGS 1985), GMM—Gulf of Maine marine reflection (USGS 1985), ADK—Adirondack + NEC-New Hampshire (COCORP 1980–1981), LIP—Long Island Platform marine (USGS 1979), NBT—Newark Basin rift Tectonics (USGS 1984), GVR—Great Valley wide angle (Princeton 1982–1984), JRC—James River Corridor, Virginia (USGS 1980–1981), GMP—Grandfather Mountain, Tennessee–North Carolina (USGS 1979), GAA + GAB + GAC—Southern Appalachians reflection (COCORP, 1978 and 1979, and USGS 1981), CHP—Charleston (COCORP 1978, and USGS 1981), GFT—Georgia-Florida Transect (COCORP 1983–1985), ADC—ADCOH site study (crystalline overthrust belt, 1985), MIS—Mississippi embayment (USGS 1978–1979), OUC + OUP—Ouachita transect (COCORP 1981 reflection and PASSCAL 1986 imaging experiment), HRC—Hardeman Basin (COCORP 1975), WMT—Wichita Mountains (COCORP 1979–1980), KAN—Kansas (COCORP 1981), MIN—Minnesota (COCORP 1979), MBA—Michigan (COCORP 1978). [*In* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 613–653. Reproduced by permission of the Geological Society of America.]

8.5.4. Alaska

In 1984, a major seismic crustal study was launched in Alaska: the Trans-Alaska Crustal Transect project (TACT; Fig. 8.5.4-01). Seismic-refraction work started in 1984 along a 320-km-long transect line in southern Alaska (Fig. 8.5.4-02), crossing the Prince William, Chugach, Peninsular, and Wrangelia terranes (Daley et al., 1985; Flueh et al., 1989; Fuis et al., 1991; Meador et al., 1986; Appendix A8-3-8).

About 500 km of seismic-refraction data were collected. The shots were recorded by four deployments, each ~140 km long and consisting of 120 1-component recording instruments equipped with 2-Hz seismometers, spaced by 1 km. Two north-south segments ran along the Richardson Highway from Valdez in the south to the Denali fault in the north with 13 shotpoints, on average 25 km apart. Four shotpoints were used for both deployments. The two west-east deployments ran roughly parallel to the major geologic structures; the northern one started northeast of Glenallen, extended ~160 km westward along Glenallen Highway and was provided with 5 shotpoints, two of them offset to the east-northeast. The southern line extended 136 km along the trend of the Chugach Mountains from west of Valdez to Lake Bremner in the east and had also 5 shotpoints, one of them offset to the east. Charges ranged from 500 kg to 2730 kg.

In 1985 the seismic-refraction survey in south-central Alaska was continued (Wilson et al., 1987; Appendix A8-3-8). A total of 27 shots with charges ranging in size from 245 to 1850 kg was recorded. The northern west-east line was supple-

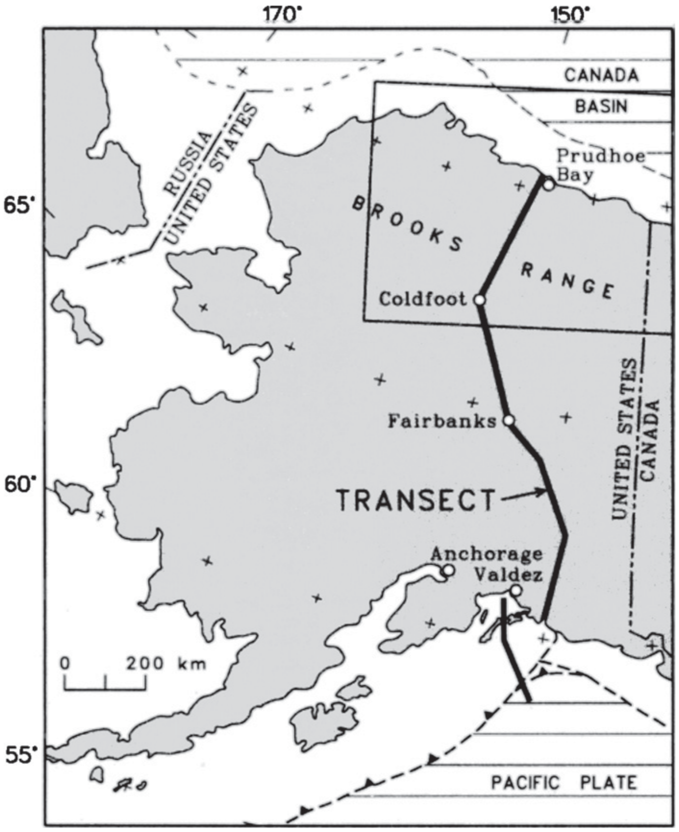

Figure 8.5.4-01. Map of Alaska (from Plafker and Mooney, 1997, fig. 1) showing the location of the Trans-Alaska Crustal Transect project (TACT). [Journal of Geophysical Research, v. 102, p. 20,639–20,643. Reproduced by permission of American Geophysical Union.]

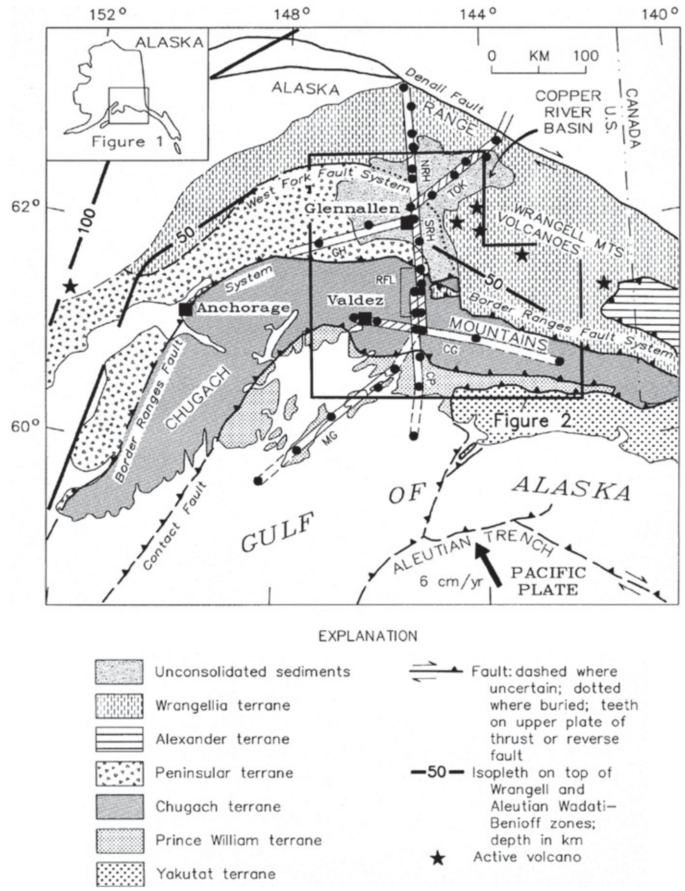

Figure 8.5.4-02. Map of south-central Alaska (from Fuis et al., 1991, fig. 1) showing terranes and TACT seismic-refraction lines with shotpoints (double full lines and dots). Dashed lines indicate directions to offset shots. [Journal of Geophysical Research, v. 96, p. 4187–4227. Reproduced by permission of American Geophysical Union.]

mented for near-surface control west of Glenallen and extended by the so-called Tok Cutoff line to the east-northeast by 170 km with 7 shotpoints east of Glenallen and two offset shots 50 and 100 km off to the west. Furthermore, the 130-km-long southwestern line (Fig. 8.5.4-02), starting at Cordova south of Valdez, was observed with 4 underwater shotpoints along the line and two 50-km offset shots at both ends sampling the deep structure of the Prince William terrane. Finally the Cordova Peak deployment was located in the Chugach Mountains east of Valdez, partly overlapping with the 1984 north-south line and extending it further south. Here 7 shotpoints were used, two of them offset to the north and to the south.

In 1988, the seismic survey of the TACT was extended into the Prince William Sound and the northern Gulf of Alaska (Brocher and Moses, 1990; Appendix A8-3-8) by a marine multichannel seismic-reflection and wide-angle reflection/refraction survey (Fig. 8.5.4-03). Six lines were laid out resulting in a total of 1100 km marine multichannel data acquired by over 65 wide-angle seismic profiles, having either in-line or fan geometry. Airgun signals, provided by a large airgun array (7770 in^3) and generated at 50 m interval, were recorded by a temporary array of 18 seismic recorders along the reflection lines as wide-angle reflections and refractions. Two marine stations designed to reverse the ray coverage were located offshore and used GEOS instruments to record expendable sonobuoys from a nearby ship dedicated to that purpose. Sixteen land stations using three-component five-day recorders (Criley and Eaton, 1978) were deployed in the vicinity of the Prince William Sound and on some islands and continuously recorded the airgun signals.

A third phase of the TACT land-seismic investigation followed in 1987 with three 130-km-long seismic-refraction/wide-angle reflection profiles and a 17-km-long reflection profile (Beaudoin et al., 1989; Goldman et al., 1992; both Appendix A8-3-8), extending the investigation to the north of the Denali fault (Fig. 8.5.4-04).

The southernmost refraction profile, the Alaska Range deployment, followed the Richardson Highway between Paxson and Delta Junction and was centered on the Denali fault, thus overlapping with the 1984 survey. The central profile, the Fairbanks South deployment, started near Delta Junction and extended to Fairbanks, following the Trans-Alaska Oil Pipeline.

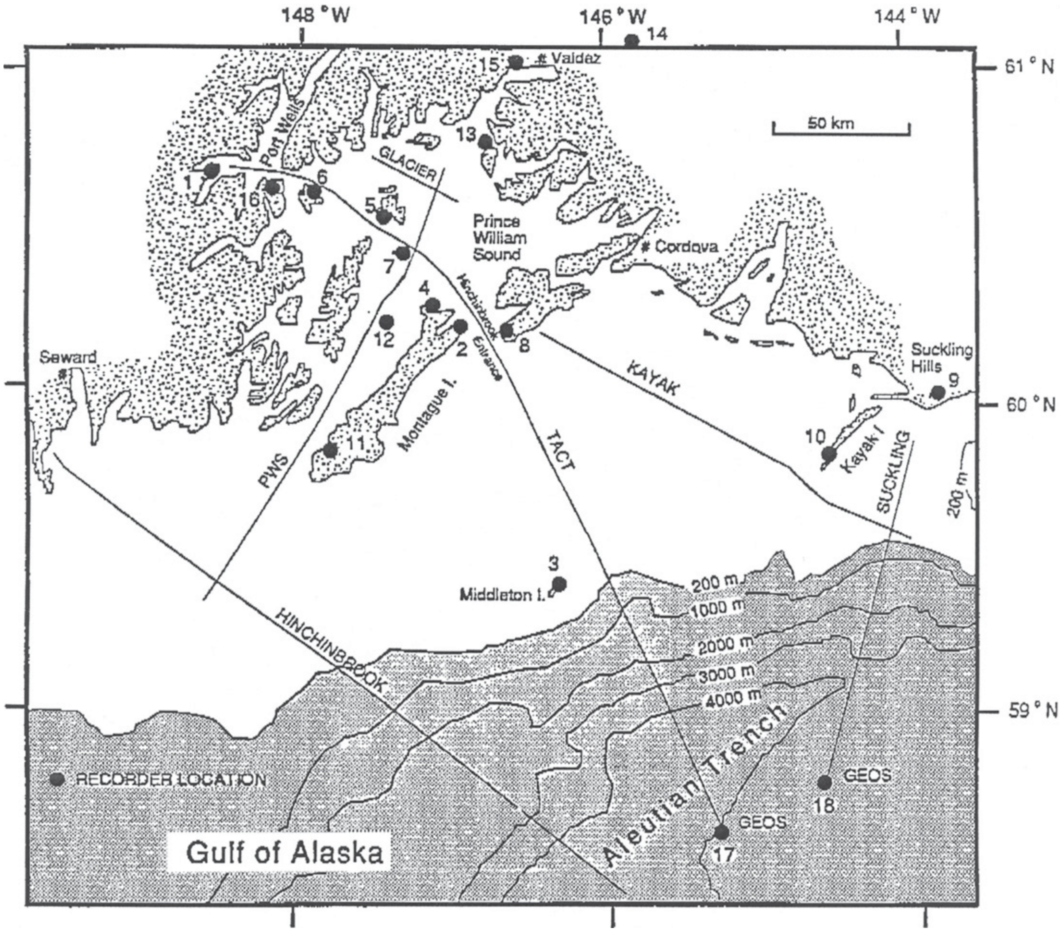

Figure 8.5.4-03. Map of Prince William Sound and the northern Gulf of Alaska showing the locations of the TACT marine reflection lines and temporary seismic recorders (from Brocher and Moses, 1990, fig. 1). [U.S. Geological Survey Open-File Report 90-663, Menlo Park, California, 40 p.]

The northernmost profile, the Fairbanks North deployment, followed the Elliot and Dalton highways and the pipeline to the Yukon River. Each deployment had 140 recording instruments with 1 km spacing. The 17-km Olnes reflection profile had 60 m spacing of the 140 recorders and was coincident with the southern end of the Fairbanks North profile. A total of 48 shots with charges from 227 to 2725 kg was recorded.

The last experiment along the TACT was conducted in 1990 across the Brooks Range, Arctic Alaska (Fig. 8.5.4-05), in a collaboration of the U.S. Geological Survey, Rice University, the Geological Survey of Canada, and IRIS/PASSCAL (Fuis et al., 1997; Levander et al., 1994; Murphy et al., 1993; Appendix A8-3-8). It was the first experiment in which refraction and reflection were simultaneously merged in the TACT investigations. A 700-channel seismograph system recorded 63 shots from 44 shotpoint locations. The instruments were deployed five times (see Fig. 8.5.4-05) in abutting and overlapping arrays, producing a 315-km-long profile with nominally 100 m instrument spacing. Both small (50–300 kg) and large (750–2000 kg) charges were fired to produce a vertical incidence to wide-angle refraction-reflection data set with continuous offset coverage from 0 to 200 km. The project was the first USGS experiment which involved first generations of digital equipment. The instruments used included 35 PASSCAL RefTek 72A-02s, each recording 6 channels, 190 Stanford University Seismic Group Recorders (SGRs), 120 USGS Seismic Cassette Recorders (SCRs) and 180 Geological Survey of Canada Portable Refraction Seismographs (PRS1s).

In the vertical-incidence data of the marine TACT line (Fig. 8.5.4-06) of Brocher et al. (1991a), a prominent mid- to lower-crustal reflector was seen between 6 and 8 s TWT and a landward 9° dip of Moho was indicated in the refraction data. Discontinuous weak reflections might define the top of the subducting oceanic plate to as deep as 10 s TWT. However, the depth to Moho at the northern end of the TACT line was neither constrained in the reflection nor in the refraction data (Brocher et al., 1991a).

Several models have been proposed by Fuis et al. (1991). The preferred model in Figure 8.5.4-07 shows a horizontal velocity discontinuity at 9 km depth underneath the northern Chugach Mountains and southern Copper River basin, overlain by a low-

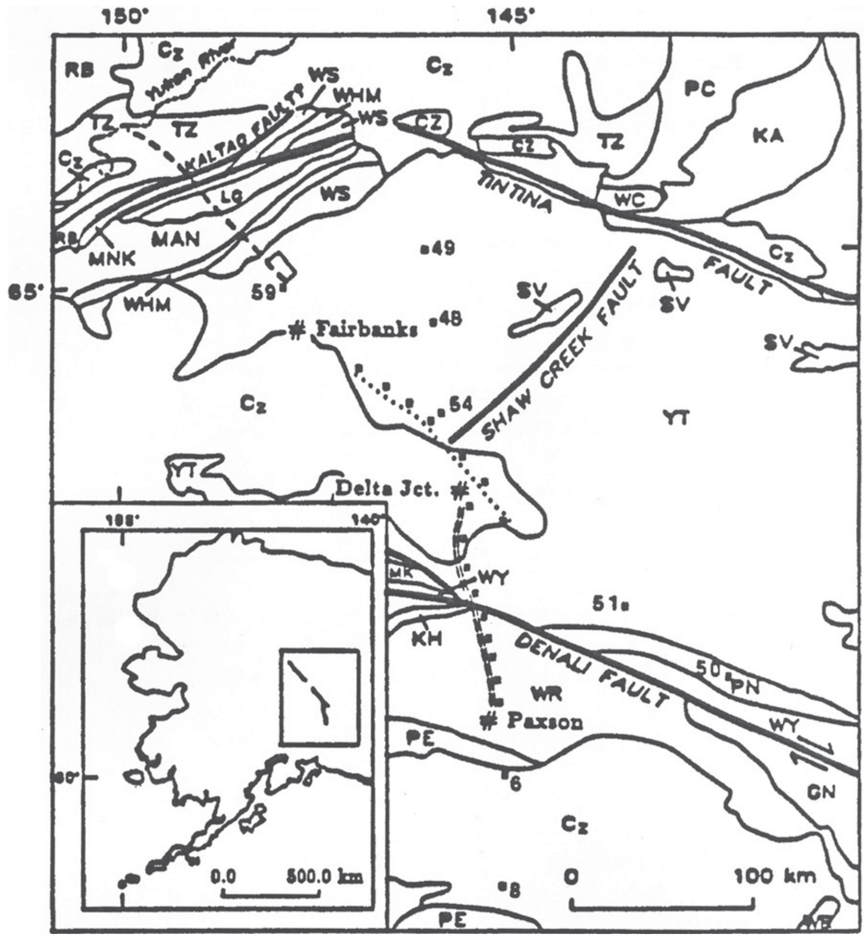

Figure 8.5.4-04. Map of central Alaska (from Beaudoin et al., 1989, fig. 1) showing the location of the 1987 TACT seismic survey. [U.S. Geological Survey Open-File Report 89-321, Menlo Park, California, 114 p.]

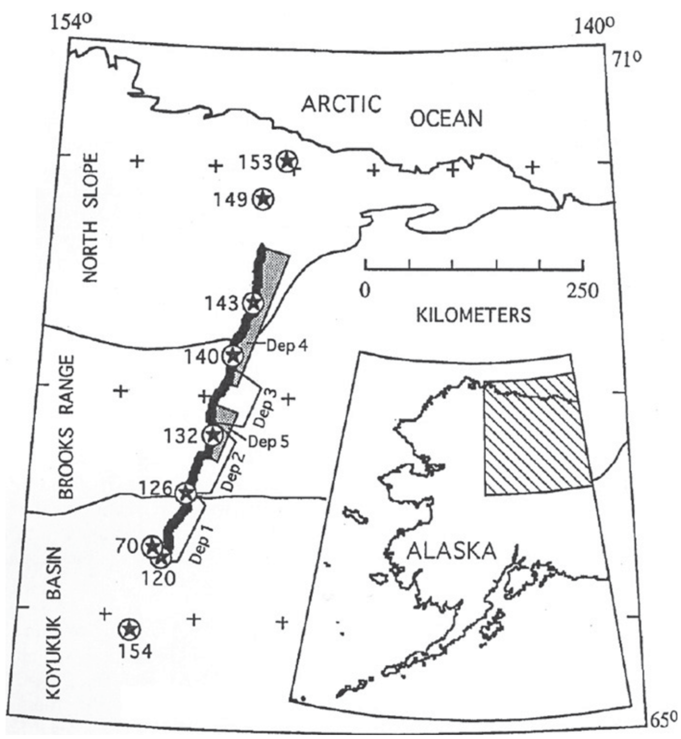

Figure 8.5.4-05. Map of Arctic Alaska (from Murphy et al., 1993, fig. 1) showing the location of the 1990 TACT seismic survey. [U.S. Geological Survey Open-File Report 93-265, Menlo Park, California, 128 p.]

velocity zone, both of which extend across the deep projection of the Border Ranges fault system. To the south the model shows gently north-dipping layers of alternating high and low velocities that seem to be truncated in the south by the contact fault.

At depth, a subducting plate north-dipping from 20 to 25 km to at least 30–35 km is inferred under the Chugach terrane consisting of a 3–6 km lower crust over a clearly defined Moho. Beneath the northern Copper River basin subhorizontal low and high velocity layers in the middle crust appear to extend across the West Fork fault system and a deep Moho is seen rising from more than 55 km northwards to at least 45 km depth. Below 20 km depth, there is a blank region caused by uncertainty

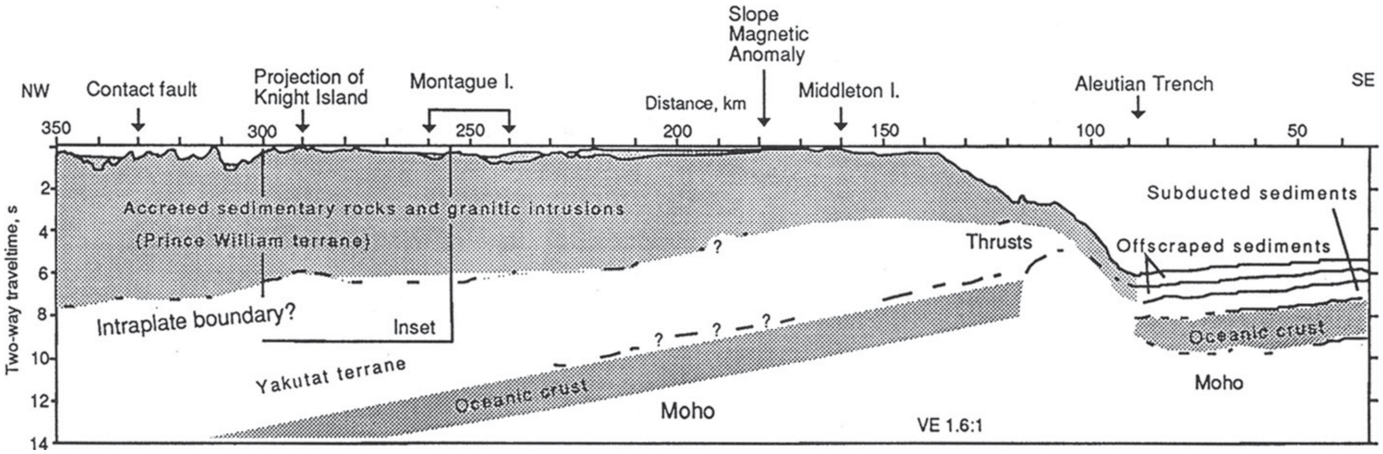

Figure 8.5.4-06. Interpreted line drawing of the unmigrated TACT line (see Fig. 8.5.4-03) showing prominent mid-crustal reflections and reflections from Moho (from Brocher et al., 1991, fig. 2). [*In* Meissner, R., Brown, L., Dürbaum, H.-J., Franke, W., Fuchs, K., and Seifert, F., eds., Continental lithosphere: deep seismic reflections: American Geophysical Union, Geodynamics Series, v. 22, p. 241–246. Reproduced by permission of American Geophysical Union.]

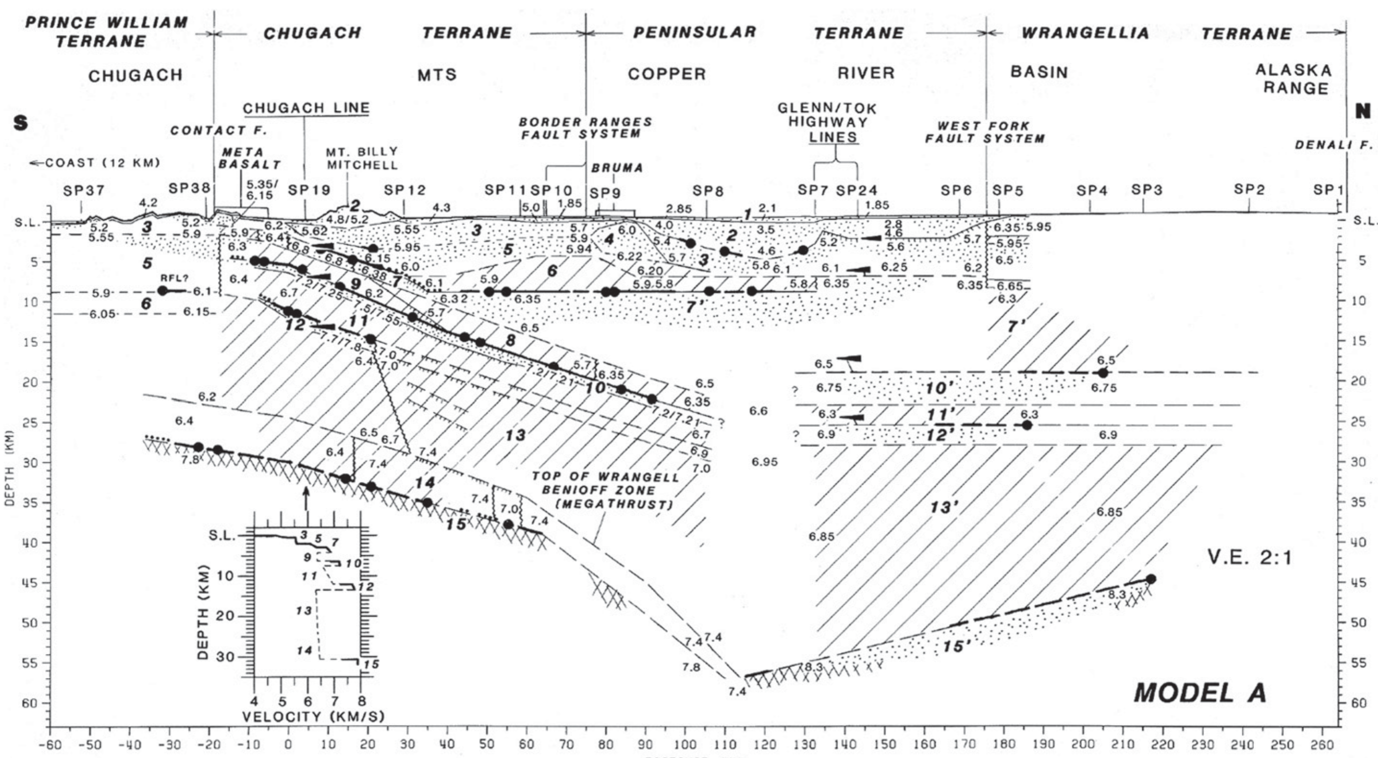

Figure 8.5.4-07. Preferred velocity-depth model for the north-south transect line (from Fuis et al., 1991, fig. 3). Diagonally hatched—low-velocity regions; stippled—regions controlled by bottoming refractions; large dots—subsurface points of critical reflections; cross-hatched—mantle. [Journal of Geophysical Research, v. 96, p. 4187–4227. Reproduced by permission of American Geophysical Union.]

in correlation of features between the south and north halves of the model. A fence diagram shown in Figure 8.5.4-08 shows the inferred structure of the crust for all three lines recorded in south-central Alaska.

The continuation of the seismic observations into central Alaska across the Denali fault toward Fairbanks enabled Brocher et al. (2004a) to study in particular the Denali fault zone in some detail. As a result, the fault zone proper might extend to 30 km depth and, including its nearby associated fault strands, appeared to cause a 5-km-deep low-velocity region, extending up to 40 km width in a north-south direction. From the wide-angle reflection the crustal thickness underneath the Denali fault zone appeared as a transition between the 60-km-thick crust under the Alaska Range to the south and the extended 30-km-thick crust under the Yukon-Tanana terrane to the north. Figure 8.5.4-09 is a compilation of compressional wave velocity models across the Denali fault (Fuis et al., 1991; Beaudoin et al., 1992; Brocher et al., 2004a).

The data of the TACT section recorded northwest of Fairbanks (see Fig. 8.5.4-04) were interpreted by Beaudoin et al.

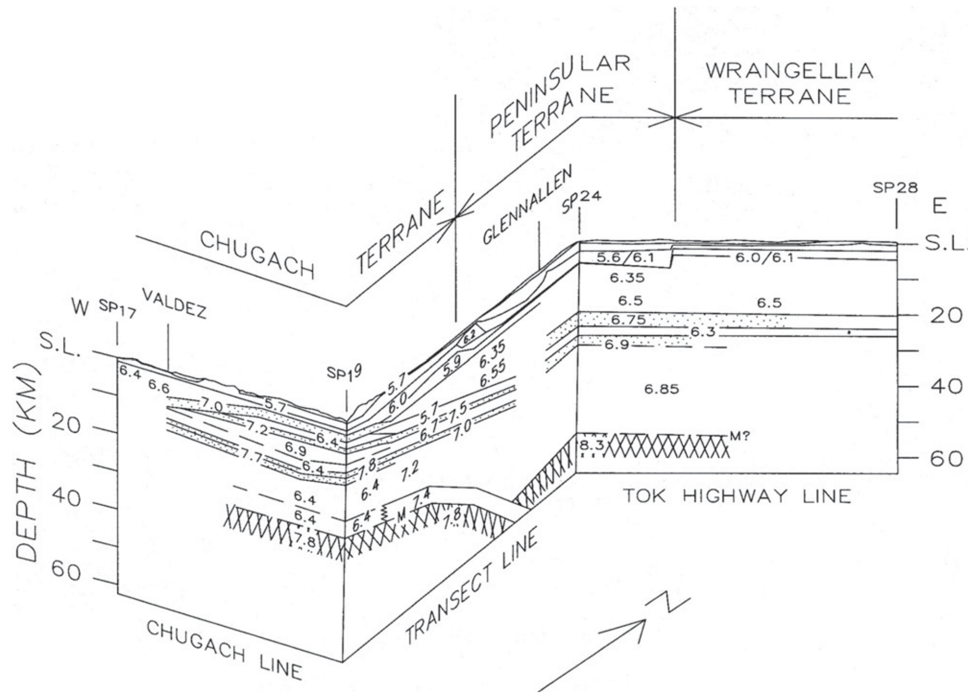

Figure 8.5.4-08. Fence diagram for the Transect, Chugach, and Tok Highway lines (from Fuis et al., 1991, fig. 20). [Journal of Geophysical Research, v. 96, p. 4187–4227. Reproduced by permission of American Geophysical Union.]

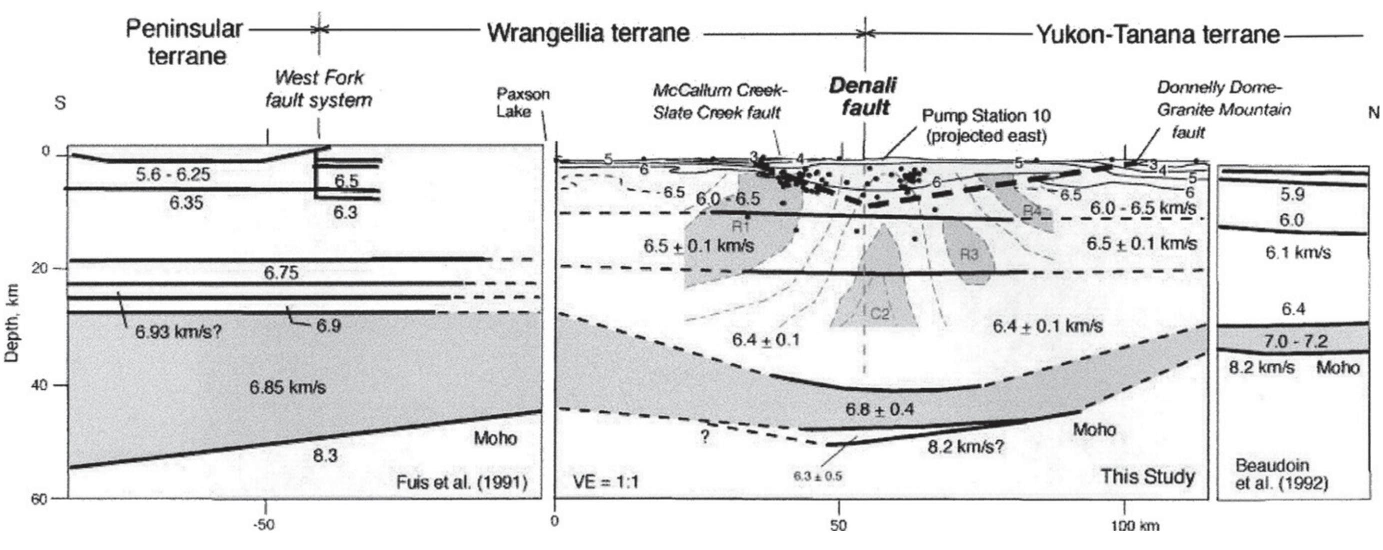

Figure 8.5.4-09. Compilation of crustal models near the Denali fault, central Alaska (from Brocher et al., 2004a, fig. 12). [Bulletin of the Seismological Society of America, v. 94, p. S85-S106. Reproduced by permission of the Seismological Society of America.]

(1994). Their crustal model underneath the Yukon-Tanana upland shows the Moho at ~30–35 km depth (Fig. 8.5.4-10). For the lower crust (layers 2–4) the authors have proposed several tectonic interpretations, one of which is reproduced here.

The seismic-refraction and -reflection data along the transect through the Brooks Range in northern Alaska have been interpreted by Fuis et al. (1997) and Wissinger et al. (1997). Figure 8.5.4-11 shows a velocity-depth interpretation by Wissinger et al. (1997).

According to a tectonic model by Fuis et al. (1997), tectonic wedges are characteristic for the crust under northern Alaska, mostly north-vergent. There is high reflectivity throughout the crust above a basal décollement which deepens southward from 10 km to ~30 km under beneath the Brooks Range. Below this décollement there is low reflectivity which Fuis et al. (1997) interpreted as a southward-verging tectonic wedge (Fig. 8.5.4-12).

8.6. THE AFRO-ARABIAN RIFT SYSTEM

8.6.1. Crustal Studies of the Dead and Red Sea Areas

Following the first deep seismic sounding experiment carried out in 1977 on the west side of the Jordan–Dead Sea rift (see Chapter 7.5.2), a second experiment followed in 1984, this time on the eastern flank of the rift in Jordan, initiated by Zuhair El-Isa of the University of Amman and promoted by scientists of Hamburg (Jannis Makris) and Karlsruhe (Jim Mechie and Claus Prodehl), Germany (El-Isa et al., 1987a, 1987b). The location map of Figure 8.6.1-01 shows both surveys.

Parallel to the rift profile of 1977, a long-range profile was organized in the 1984 experiment in a north-south direction along the eastern flank of the rift passing the cities of Amman and Maán (lines I, III, and IV in Fig. 8.6.1-01) with land shotpoints (1–4)

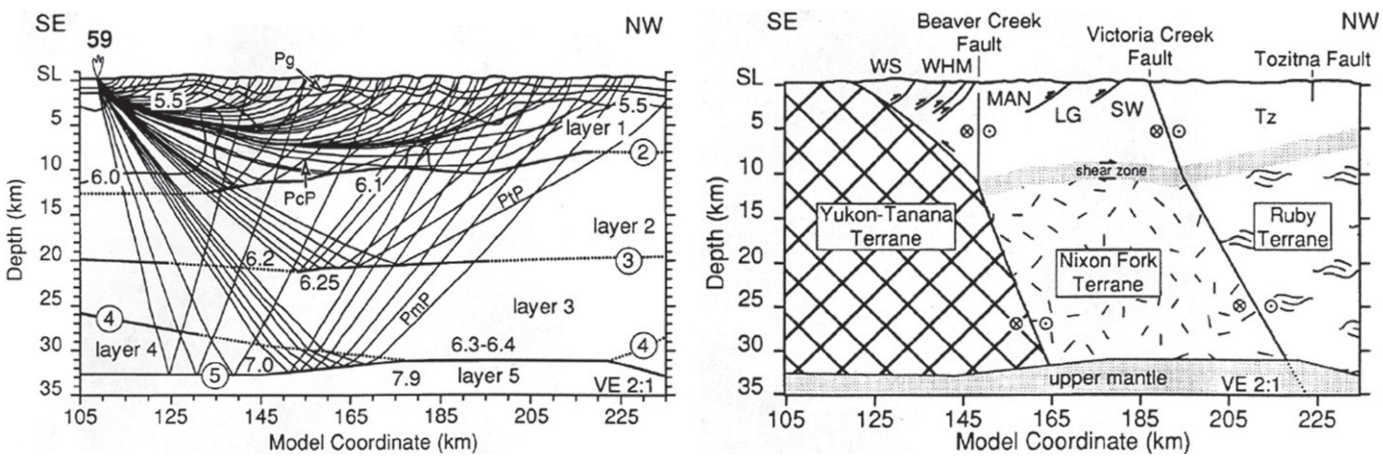

Figure 8.5.4-10. Crustal model of the northern Yukon-Tanana upland, central Alaska: Left: Ray diagram for shotpoint 59. Right: A possible tectonic interpretation (from Beaudoin et al., 1994, figs. 4 and 11). [Geological Society of America Bulletin, v. v. 106, p. 981–1001. Reproduced by permission of the Geological Society of America.]

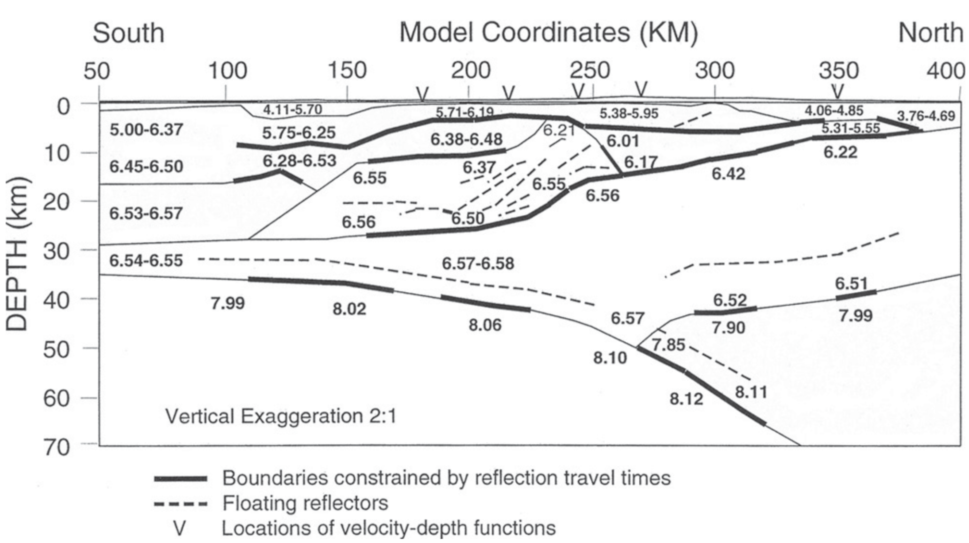

Figure 8.5.4-11. Velocity-depth model for the Brooks Range, Arctic Alaska (from Wissinger et al., 1997, fig. 4a). [Journal of Geophysical Research, v. 102, p. 20,847–20,871. Reproduced by permission of American Geophysical Union.]

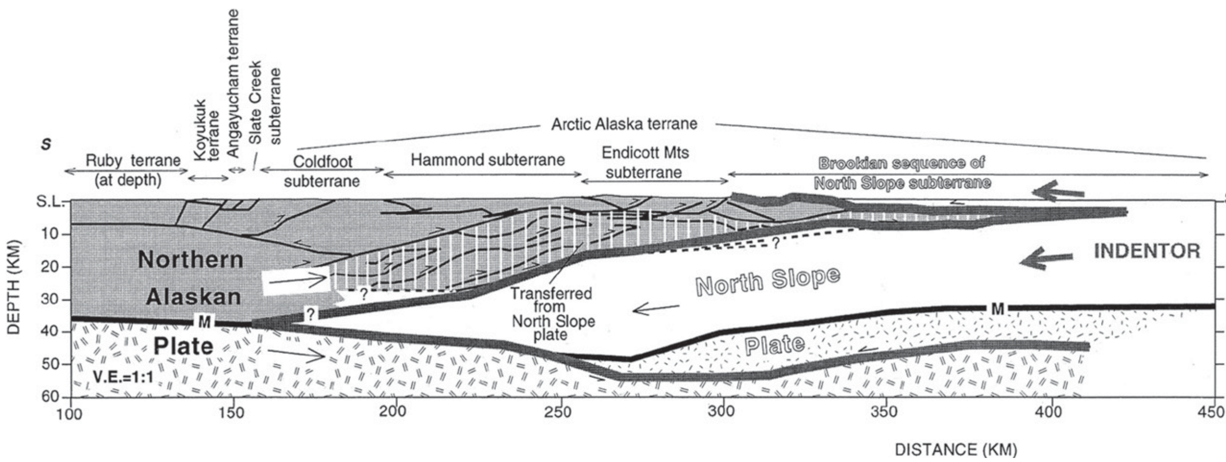

Figure 8.5.4-12. Inferred model for the Brooks Range, Arctic Alaska (from Fuis et al., 1997, fig. 6). Crust is gray (indented plate) or blank (indentor plate); mantle has double-tick pattern (indented plate) or single-tick pattern (indentor plate). Heavy gray line separates indented northern Alaskan plate from North Slope plate. Rock that has been clearly transferred from indentor plate to indented plate is indicated with vertical white lines. [Journal of Geophysical Research, v. 102, p. 20,873–20,896. Reproduced by permission of American Geophysical Union.]

and an underwater shotpoint in the Gulf of Aqaba (no. 5 in Fig. 8.6.1-01) providing energy up to 200 km offsets. A third profile II of 170 km length was recorded to the east of the main line. Here, to obtain information on the near-surface structure, in addition to large shots at shotpoint 3, several small shots (6–10 in Fig. 8.6.1-01) were detonated in shallow drillholes providing energy up to 30 km offset. In total, 28 shots, of which 3 were underwater shots, were recorded by 20 mobile seismic stations of type MARS-66 (for instrument details, see Chapter 6.2.1), recording three components of ground motion and an external time signal of radio Moscow, all frequency modulated, on single-track analogue magnetic tape. Station spacing averaged 5 km along the main lines I, III, and IV and 1–2 km along line II.

All three components were interpreted (Fig. 8.6.1-02) and subsequently published (El-Isa et al., 1987a, 1987b). The upper crust including sediments has a Poisson's ratio of 0.25 except in northwestern Jordan where it gets as high as 0.32. The lower crust has a higher Poisson's ratio of 0.29–0.32 for which the authors have offered two possibilities, either the lower crust possesses high feldspar and low quartz content or fluid phases exist in the form of penny-shaped inclusions. El-Isa et al. (1987a) have also combined their results with those of Ginzburg et al. (1979b) and have compiled a west-east crustal cross section through the Jordan–Dead Sea rift and its flanks (Fig. 8.6.1-03). Under the rift proper crustal thickness is ~30 km. Different from the western flank, the elevated crust under the rift proper extents eastward for at least 40 km away from the rift underneath the eastern flank and only then gradually starts to thicken toward the thick Arabian Shield crust.

In 1984, deep seismic-reflection studies were started in Israel with a SE-NW–directed, 90-km-long line from near the southern end of the Dead Sea to the Mediterranean coast (Rotstein et al., 1987) for a deep crustal study. Two other lines in the Mediterranean coastal area were derived by recorrelation of oil exploration lines. In continental inner Israel a reflective lower crust is apparent between a transparent upper crust and an almost transparent upper mantle, in agreement with the seismic-refraction results. Near the coast, strong reflections from 11 to 12 s TWT characterize the upper mantle, which cannot be associated with the crust-mantle boundary, because the conversion of the Moho

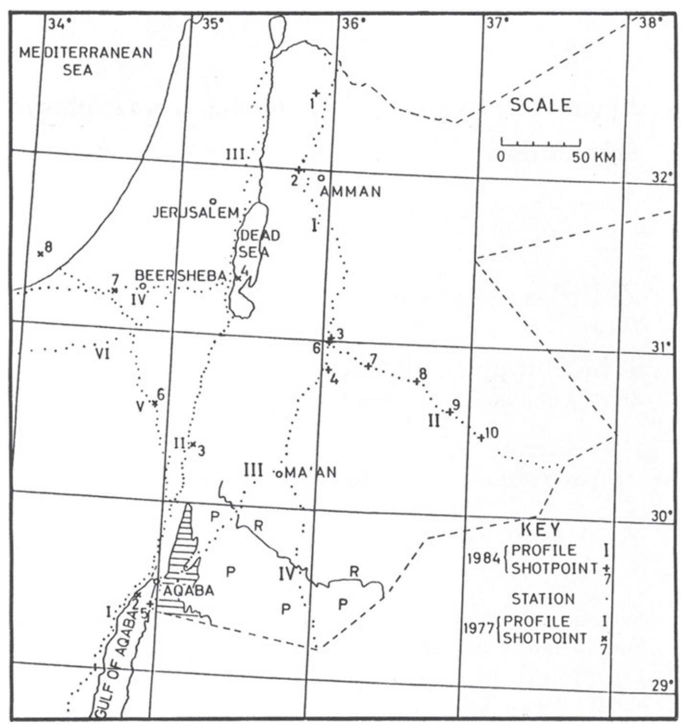

Figure 8.6.1-01. Location map of seismic-refraction lines in the Jordan–Dead Sea rift and on its flanks (from El-Isa et al., 1987b, fig. 1). [Geophysical Journal of the Royal Astronomical Society, v. 90, p. 265–281. Copyright John Wiley & Sons Ltd.]

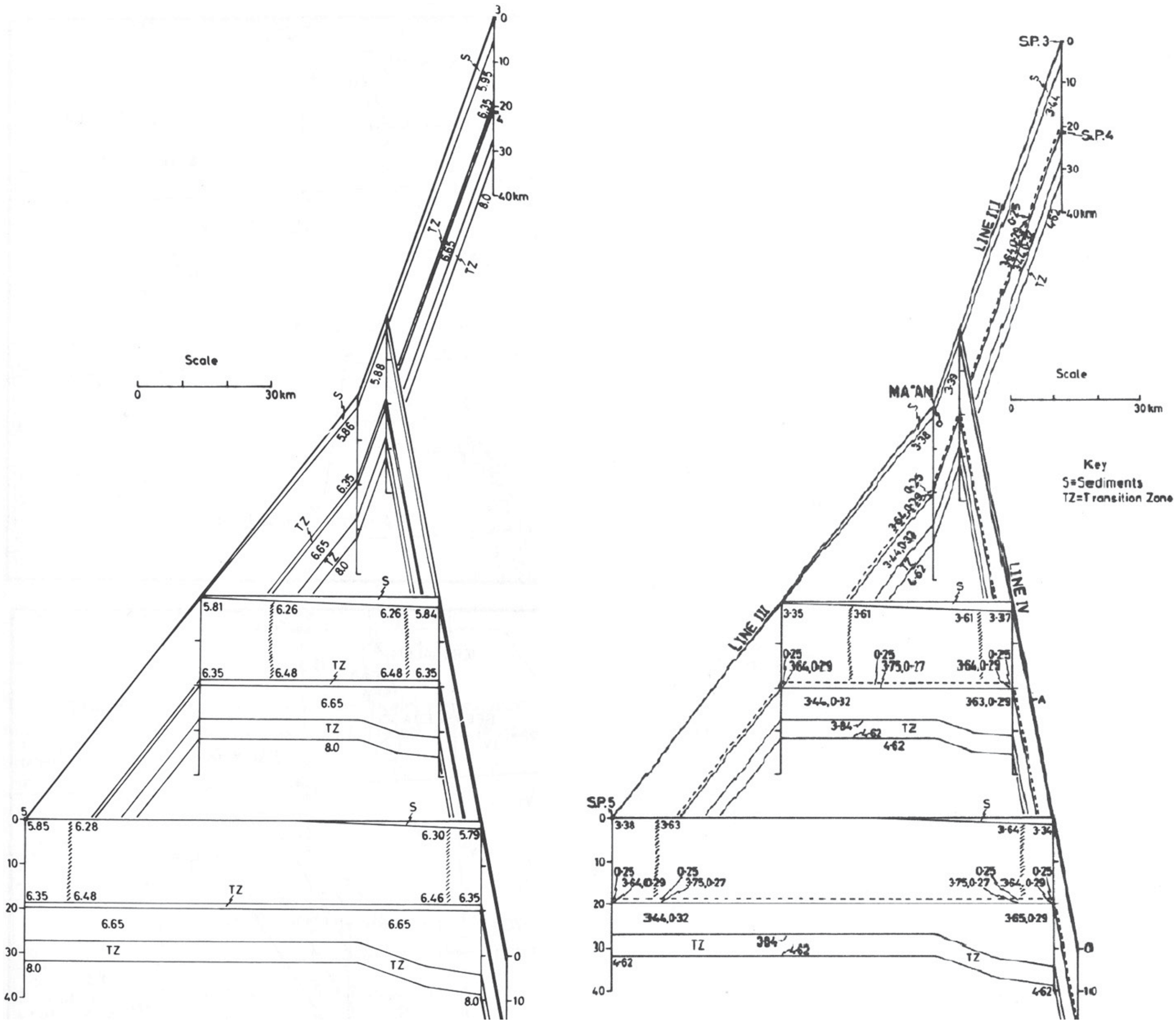

Figure 8.6.1-02. Three-dimensional model of crustal structure beneath southern Jordan (from El-Isa et al., 1987a, 1987b, fig. 6). Left: P-velocities, right: S-velocities and Poisson's ratio. [Tectonophysics, v. 138, p. 235–253; Geophysical Journal of the Royal Astronomical Society, v. 90, p. 265–281. Copyright Elsevier.]

depth derived from seismic-refraction data into TWT results in only approximately 10 s.

In 1986, a French research group investigated the Gulf of Suez and the Egyptian part of the northern Red Sea (Fig. 8.6.1-04) by detailed marine seismic profiling called the "Minos" cruise (Gaulier et al., 1988). Fifteen expanding spread profiles (ESP; see Fig. 8.9.1-01 below) and a seismic wide-angle reflection/refraction line were observed by a two-ship operation using four 16.4 airguns as sound source on one vessel and a 96-channel 2.4-km-long streamer towed by the second vessel.

Three unreversed seismic wide-angle reflection/refraction lines (Avedik et al., 1988) were obtained with a self-contained seismic receiving and recording system, an ocean-bottom vertical seismic array (OBVSA in Fig. 8.6.1-04). In addition, three seismic profiles were recorded on land while the ship shot parallel to the shore.

Most profiles recorded good crustal reflection and refraction arrivals, and Moho arrivals were obtained at offsets of 80–100 km. Crustal thickness decreases from 30 km underneath the shore of Egypt and Sinai to near 10 km in the center of the northern Red Sea (Fig. 8.6.1-05).

Parallel to the French group, the University of Hamburg under the leadership of Jannis Makris was extremely active in the Red Sea area. The location map (Fig. 8.6.1-06) shows all seismic-refraction observations where the University of Hamburg was partner or leader (Rihm et al., 1991). The seismic surveys of the 1970s in Afar and Israel and those of 1978 and 1981 in Egypt, the northern Red Sea, and Saudi Arabia (1979 Egypt and 1981 "Stefan E" in Fig. 8.6.1-06) were already mentioned in Chapter 7. Also shown in Figure 8.6.1-06 is the location of the Jordan 1984 experiment described above in some detail. The 1984 *Conrad* cruise experiment partly overlaps with the French survey of Gaulier et al. (1988). The results for the northern Red Sea and

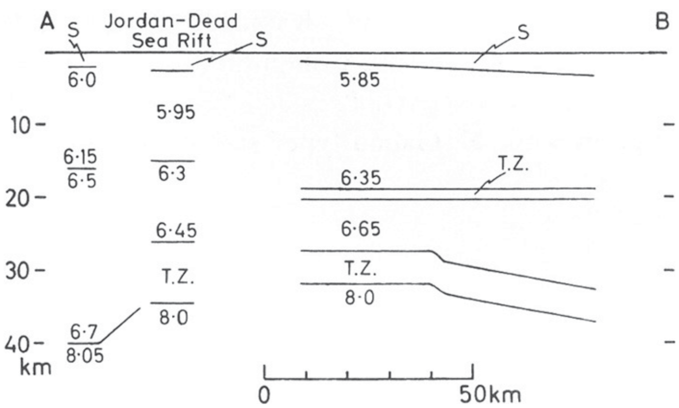

Figure 8.6.1-03. Crustal cross section across the southern Jordan–Dead Sea rift (from El-Isa et al., 1987a, fig. 13). [Tectonophysics, v. 138, p. 235–253. Copyright Elsevier.]

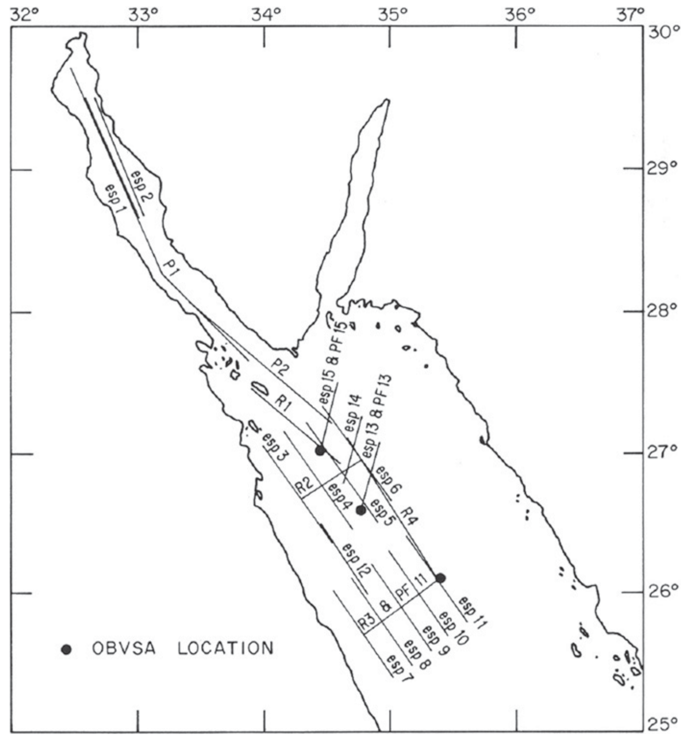

Figure 8.6.1-04. Location map of seismic lines in the Gulf of Suez and northern Red Sea (from Avedik et al., 1988, fig. 1). OBVSA—positions of ocean-bottom seismometer array. [Tectonophysics, v. 153, p. 89–101. Copyright Elsevier.]

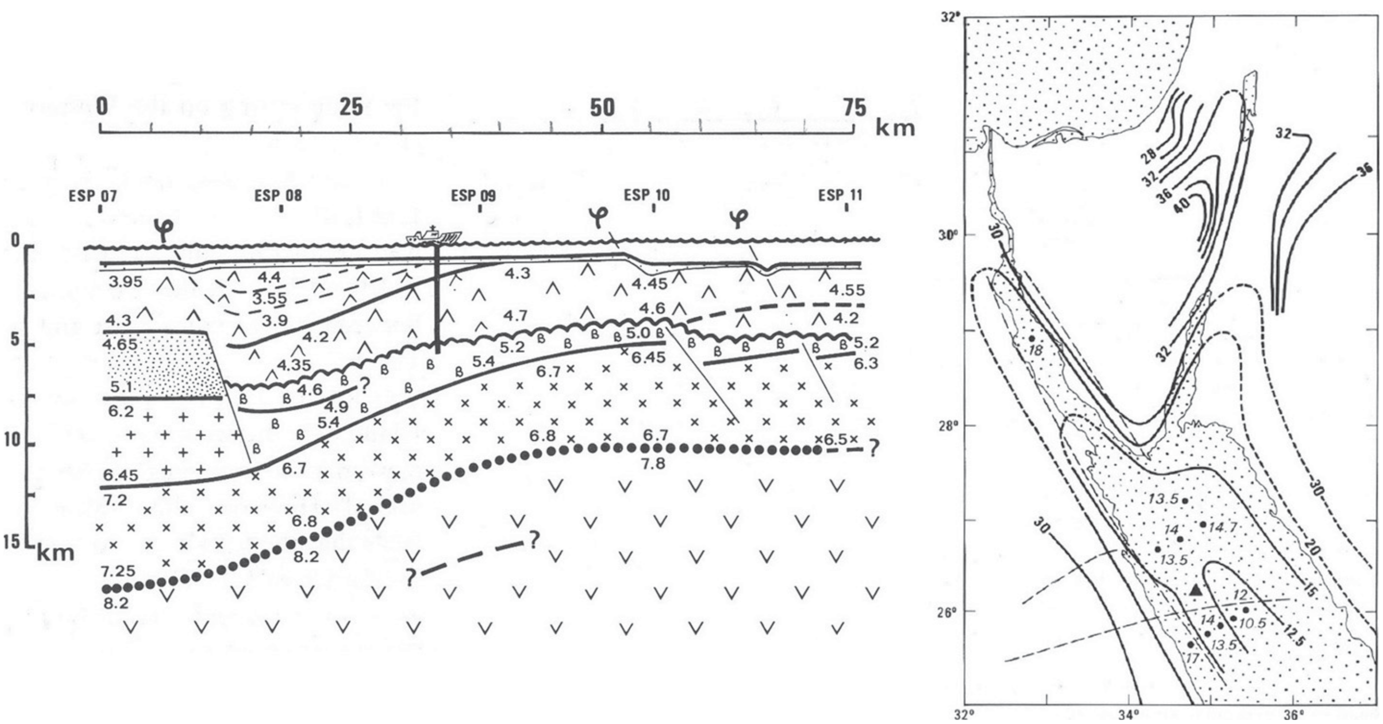

Figure 8.6.1-05. Crustal structure of the northern Red Sea area (from Gaulier et al., 1988, figs. 13 and 17). Left: Crustal cross section through the southern five expanding spread profiles (Figure 8.6.1-04). Right: Moho map. [Tectonophysics, v. 153, p. 55–88. Copyright Elsevier.]

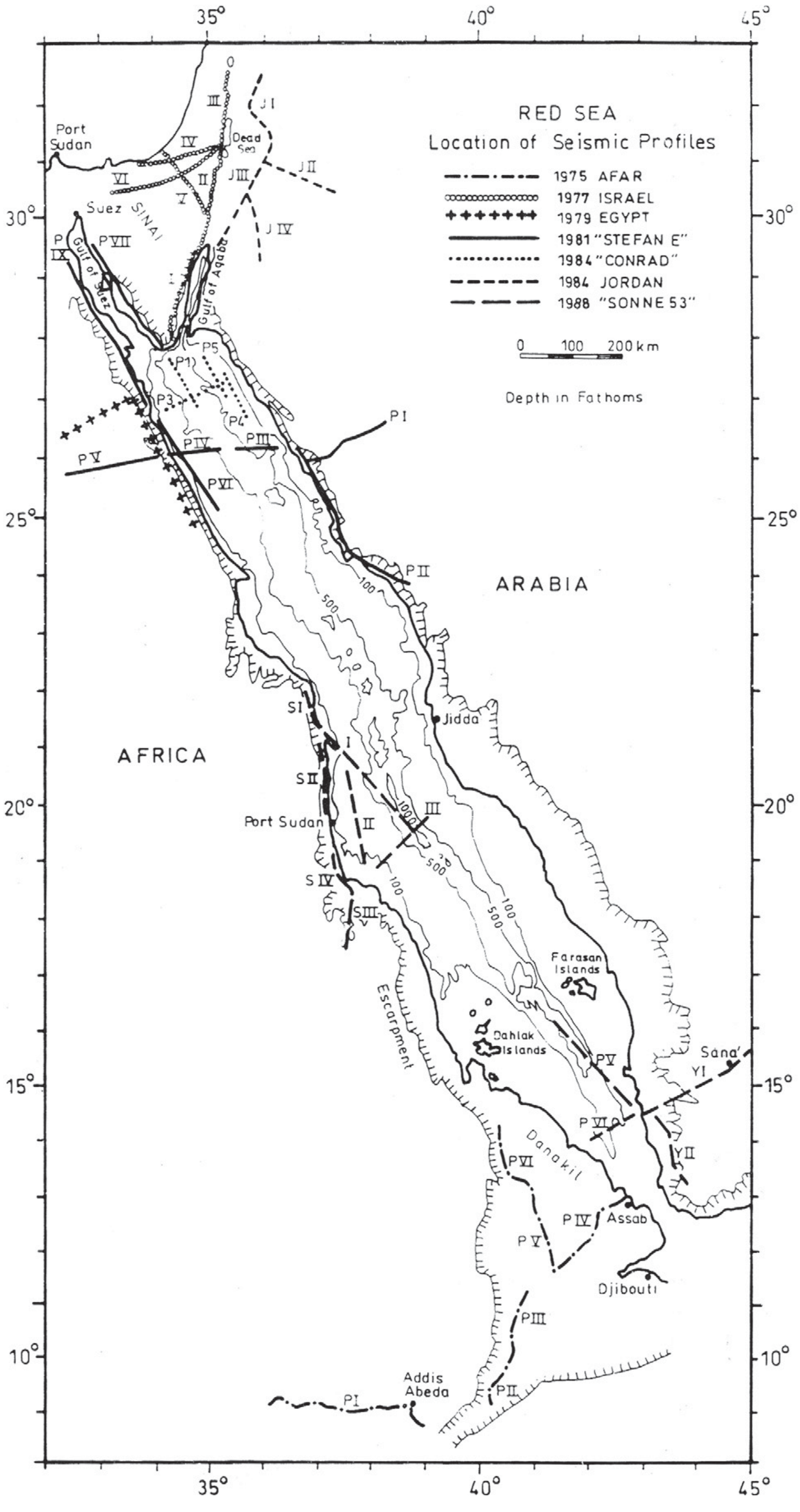

Figure 8.6.1-06. Location map of seismic-refraction lines in the Red Sea in the 1970s and 1980s by or under participation of the University of Hamburg, Germany (from Rihm et al., 1991, fig. 1). [Tectonophysics, v. 198, p. 279–295. Copyright Elsevier.]

the transition toward Egypt are similar to those of the French research group and are incorporated into the Moho map of Gaulier et al. (1988; Fig. 8.6.1-05). Under Egypt, the crustal thickness decreases slightly from 30 km near the coast to 28 km further west.

In 1988 the activities moved into the central and southern Red Sea (Egloff et al., 1991). During the cruise 53 of *Sonne* (Fig. 8.6.1-06) seismic lines were shot in the central Red Sea off the coast of Sudan (lines I to III) and into Sudan (lines SI to SIV) as well as in the southernmost Red Sea (lines PV and PVI) and into Yemen (lines YI and YII). Egloff et al. (1991) have compiled several crustal cross sections from which an example for the Red Sea off Sudan and another one for the line PVI-Y1 from the southern Red Sea into Yemen are reproduced here (Fig. 8.6.1-07). Underneath the axis of the central Red Sea around latitude 19.5°N Moho is found at 5 km depth, while underneath the axis of the southernmost Red Sea near latitude 14°N the Moho depth has increased to 13 km depth. When approaching the coastal waters, the Moho depth increases drastically, but evidently in several steps. At the central Red Sea off Sudan the Moho is at almost 15 km depth, while at the coast off Yemen it is as deep as 20 km, but depth increases further inland to 30 km under the escarpment, and decreases again further to the northeast.

8.6.2. The First Project of Kenya Rift International Seismic Project

In 1985, American, British, German and Kenyan scientists started the first phase of a seismic investigation of the East African rift in Kenya: the Kenya Rift International Seismic Project (KRISP). In Britain the long research tradition in Africa of the University of Leicester with its scientists Don Griffiths, Roy King, Aftab Khan, and Peter Maguire was resumed. In Germany, the University of Karlsruhe with its scientists Karl Fuchs and Claus Prodehl was interested in the Afro-Arabian rift system within the scope of its interdisciplinary collaborative research center "Stress and Stress Release in the Lithosphere" which had already supported the investigations in Jordan. In the United States, it was Randy Keller of the University of Texas at El Paso and Larry Braile of Purdue University at West Lafayette, Indiana, who became the leading U.S. scientists in KRISP because of their major interest in rifts around the world (see, e.g., Keller et al., 1991).

The KRISP project of 1985 was intended as a test phase to explore the propagation of seismic waves within and outside the East African rift in Kenya as a basis for a future major investigation. The project led to the observation of two perpendicularly oriented seismic-refraction profiles (KRISP Working Group, 1987). The north-south line was 300-km-long, extended along the axis of the rift from south of Lake Naivasha to Lake Baringo and was served by five shotpoints, three of them underwater shots in lakes. The second line traversed the rift in east-west direction and had only borehole shots (Fig. 8.6.2-01).

Only half of the data was recorded digitally on U.S. equipment, the rest on frequency-modulated analogue systems (European MARS and UK Geostores). It turned out that, due to the volcanic deposits covering the central section of the rift, only the lake shots were efficient and therefore the east-west line was not successful. However, the north-south profile was a full success.

A data example from shots in Lake Baringo and a preliminary interpretation is shown in Figure 8.6.2-02.

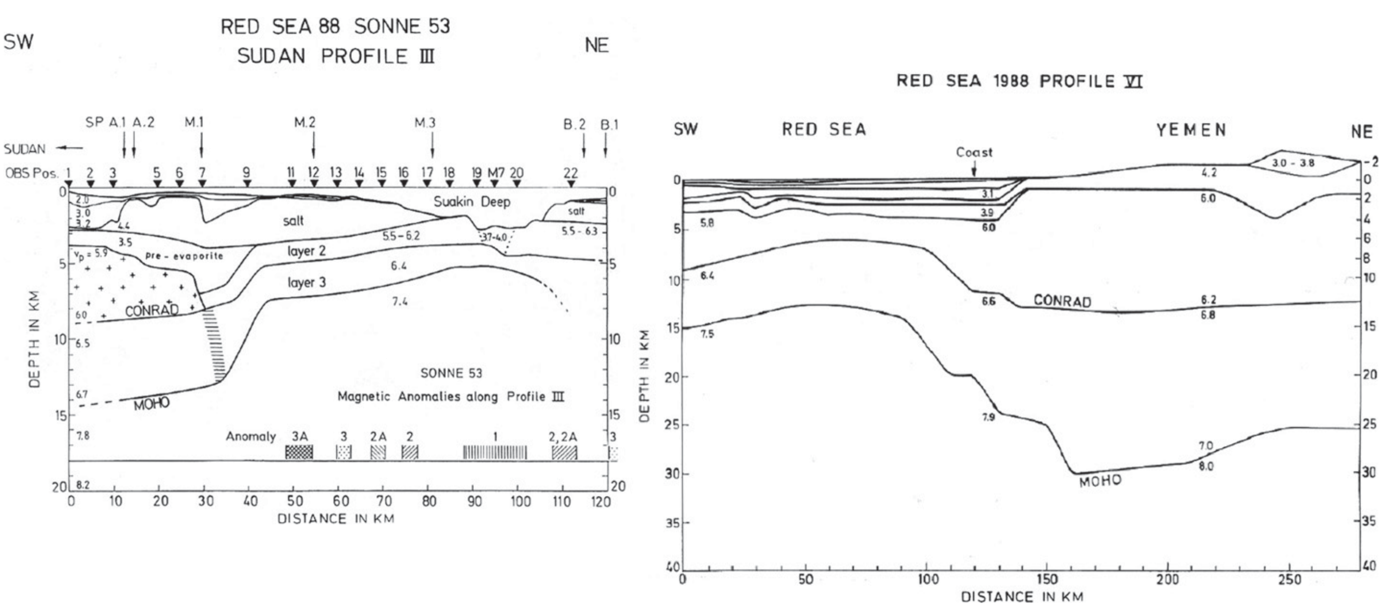

Figure 8.6.1-07. Crustal cross sections through the Red Sea area (from Egloff et al., 1991, figs. 6 and 18). Left: Sudan profile III in the central Red Sea between 19° and 20°N. Right: Profile VI: southern Red Sea into Yemen, passing Sana, between latitudes 14° and 16°N. Note the different scales and different vertical exaggerations! [Tectonophysics, v. 198, p. 329–353. Copyright Elsevier.]

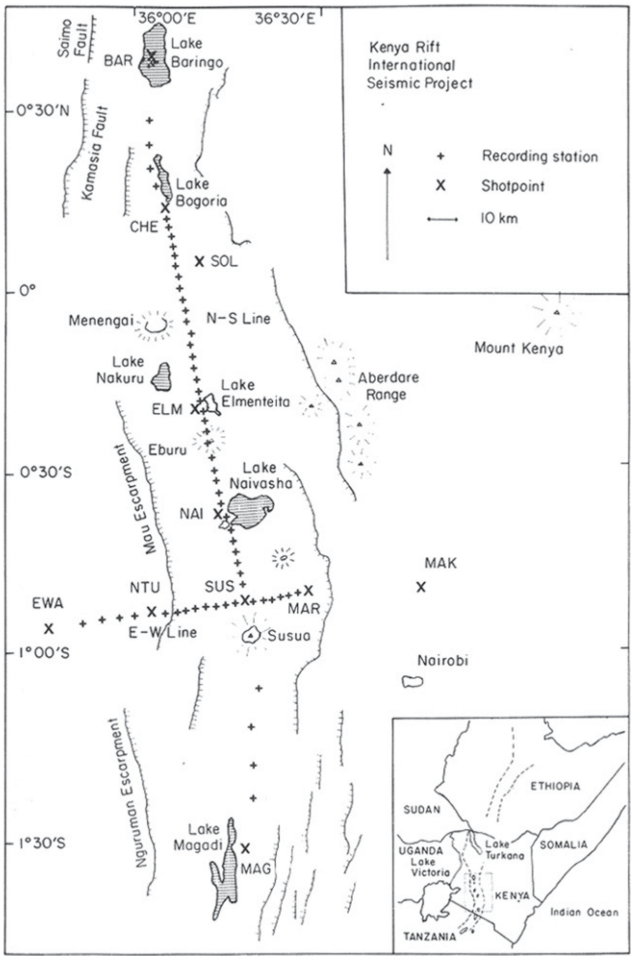

Figure 8.6.2-01. Location of the KRISP85 seismic experiment (from KRISP Working Group, 1987, fig. 1). [Nature, v. 325, no. 6101, p. 239–242. Reprinted by permission from Macmillan Publishers Ltd.]

Surprisingly, Moho depth resulted as deep as 35 km (Henry et al., 1990; Khan et al., 1989). The outcome of this test phase was extremely valuable for the design of the follow-up experiments of KRISP in 1990 and 1994, which is discussed in detail in Chapter 9.5.1. In a review of geophysical experiments and models of the Kenya rift until 1989, the KRISP85 results were discussed in the context with earlier data (Swain et al., 1994).

8.7. DEEP SEISMIC SOUNDING STUDIES IN SOUTHEAST ASIA

8.7.1. India

Since the initiation of the deep seismic sounding technique by an Indo-Soviet collaboration agreement in 1972, as described in Chapter 7.6.1, a great number of seismic-refraction profiles were covered during the 1970s, but extensive deep seismic sounding studies also continued in the 1980s (Mahadevan, 1994), with emphasis placed on basin structures (e.g., Kaila et al., 1987a, 1987b, 1990a, 1990b).

By the end of the 1980s, a total of 6000 km long-range refraction and wide-angle reflection observations had been obtained by deep seismic sounding surveys throughout India along 20 profiles (Fig. 8.7.1-01).

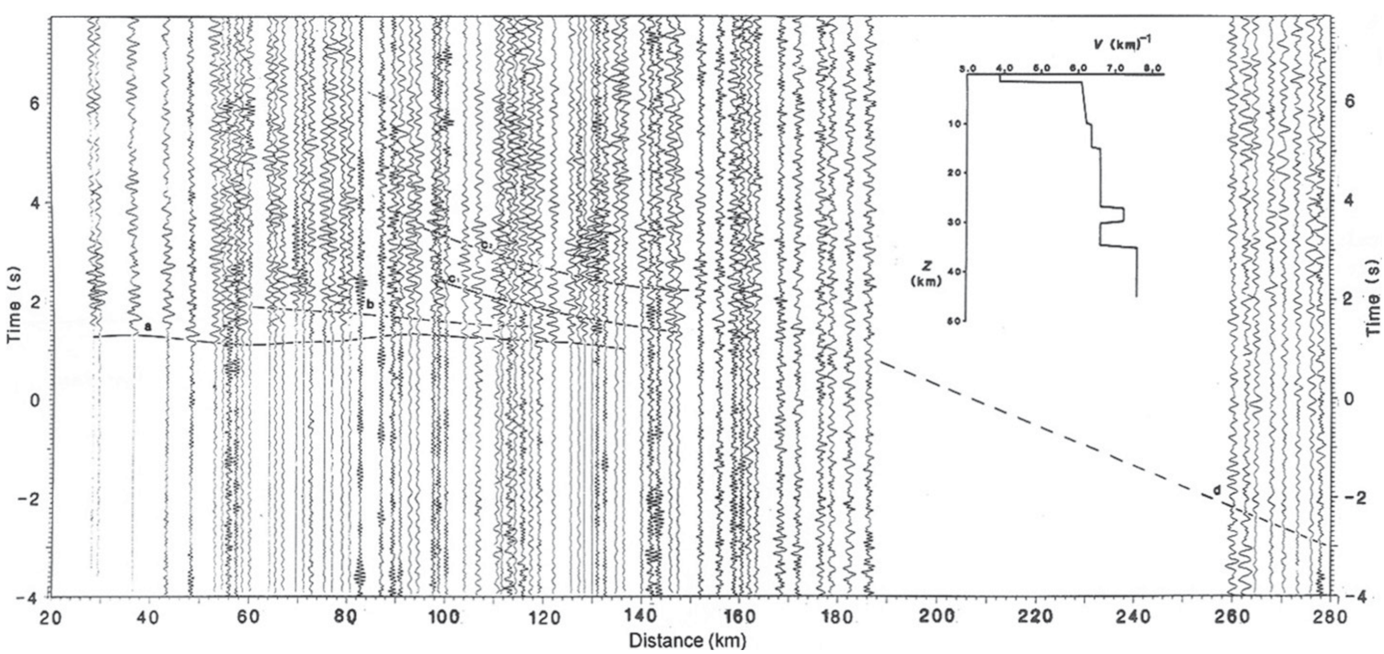

Figure 8.6.2-02. Record section from the Lake Baringo shots with phase correlation and velocity-depth function (from KRISP Working Group, 1987, fig. 2). [Nature, v. 325, no. 6101, p. 239–242. Reprinted by permission from Macmillan Publishers Ltd.]

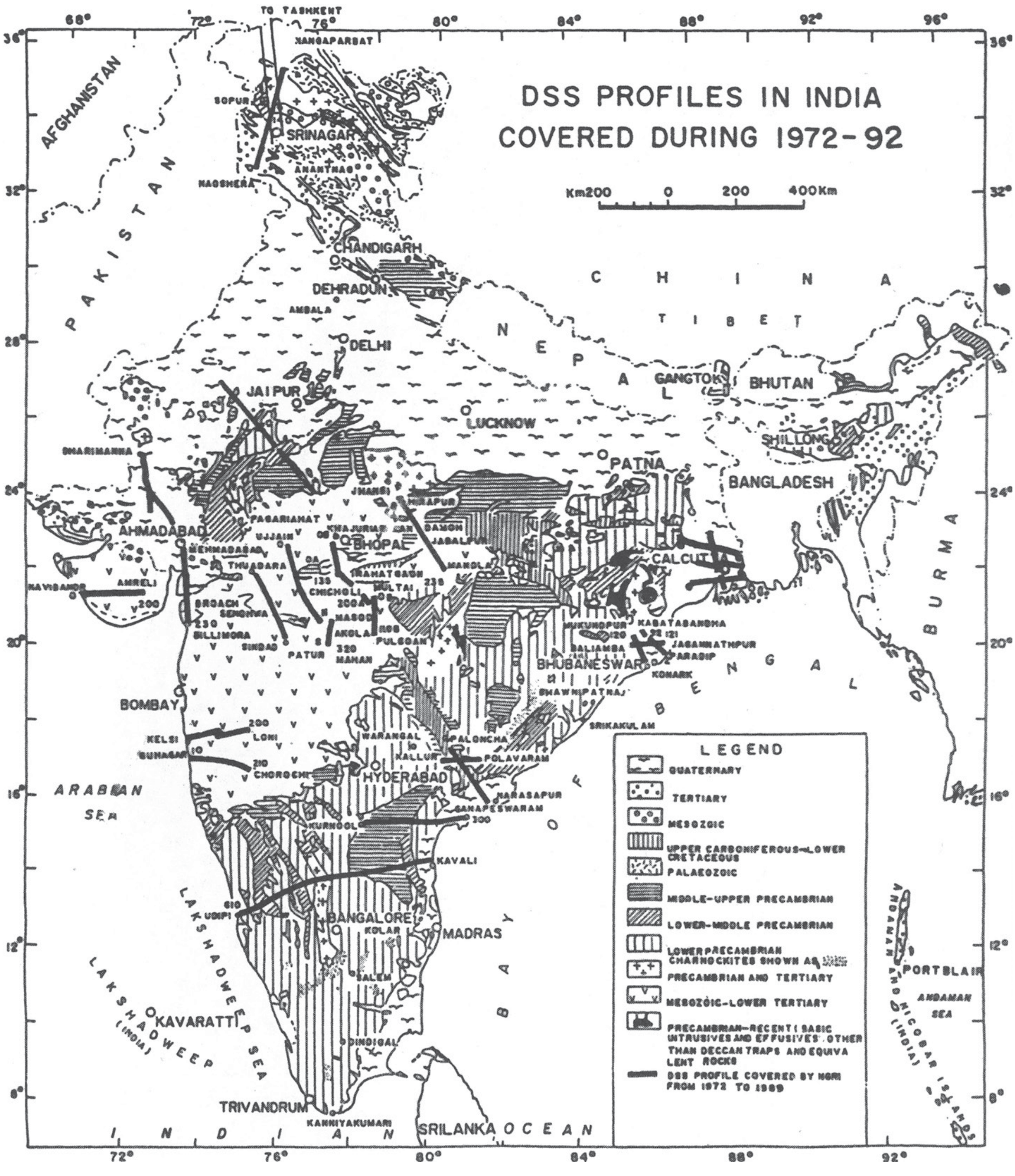

Figure 8.7.1-01. Location map of deep seismic sounding profiles in India observed by NGRI (National Institute of Geophysical Research) between 1972 and 1992 (from Mahadevan, 1994, fig. 2.4). [Geological Society of India, Memoir 28, Bangladore, 569 p. Published by permission of the Geological Society of India.]

For example, to investigate the deep structure of Gondwana basins, three seismic profiles were recorded across the Mahanadi delta 200 km SSW of Calcutta (Kaila et al., 1987b) and another two deep seismic sounding profiles were recorded across the Godavari basin further southwest east of Hyderabad (Kaila et al., 1990a). Another example is the crustal structure study of the Narmada-Son lineament, a continental rift system in the western part of central India.

Here a continuous profiling system was adopted over major portions of four north-south–oriented deep seismic sounding profiles across this lineament (Kaila, 1986; Kaila et al., 1985). The shotpoints were 20–40 km apart and were recorded to maximum distances of 200 km. For this purpose, a multichannel cable of 11.6 km length with geophone groups every 200 m was laid out and connected to two 48 channel magnetic tape systems. The 11.6 km spread was shifted along the line and shots were repeated along the profile until 200 km distance for any shotpoint was reached, shot sizes ranging from 50 to 1000 kg depending on the corresponding recording distance. The interpretation included the data obtained in the Cambay basin to the west described already in Chapter 7. The data allowed a detailed interpretation of the shallow crust, but also revealed a fairly detailed picture of the whole crust. A Moho contour map shows variations of the crustal thickness between 34 and 42 km (Kaila, 1986; Kaila et al., 1985, 1990b).

An example of a crustal cross section along the Paloncha-Narsapur DSS profile running from SE to NW through the Godavari basin and graben in southeastern India is presented (Fig. 8.7.1-02). The data were recorded in the 1980s and their interpretation published by Kaila et al. (1990a).

In the west Bengal basin bordering Bangladesh, in 1987–1988 two wide-angle seismic-refraction lines were recorded in an east-west direction, north (180 km long) and south (140 km long) of Calcutta (Kaila et al., 1992; Fig. 8.7.1-01). Along the two profiles, 1953 line-km of traveltime data were observed from 22 shotpoints at a geophone spacing of 200 m. Moho depths of 32–34 km resulted for the central and western parts of the lines, while to the east and southeast considerable crustal thinning was revealed. In 1988–1990 another east-west line, 120 km long, was added in between, and a 227-km-long north-

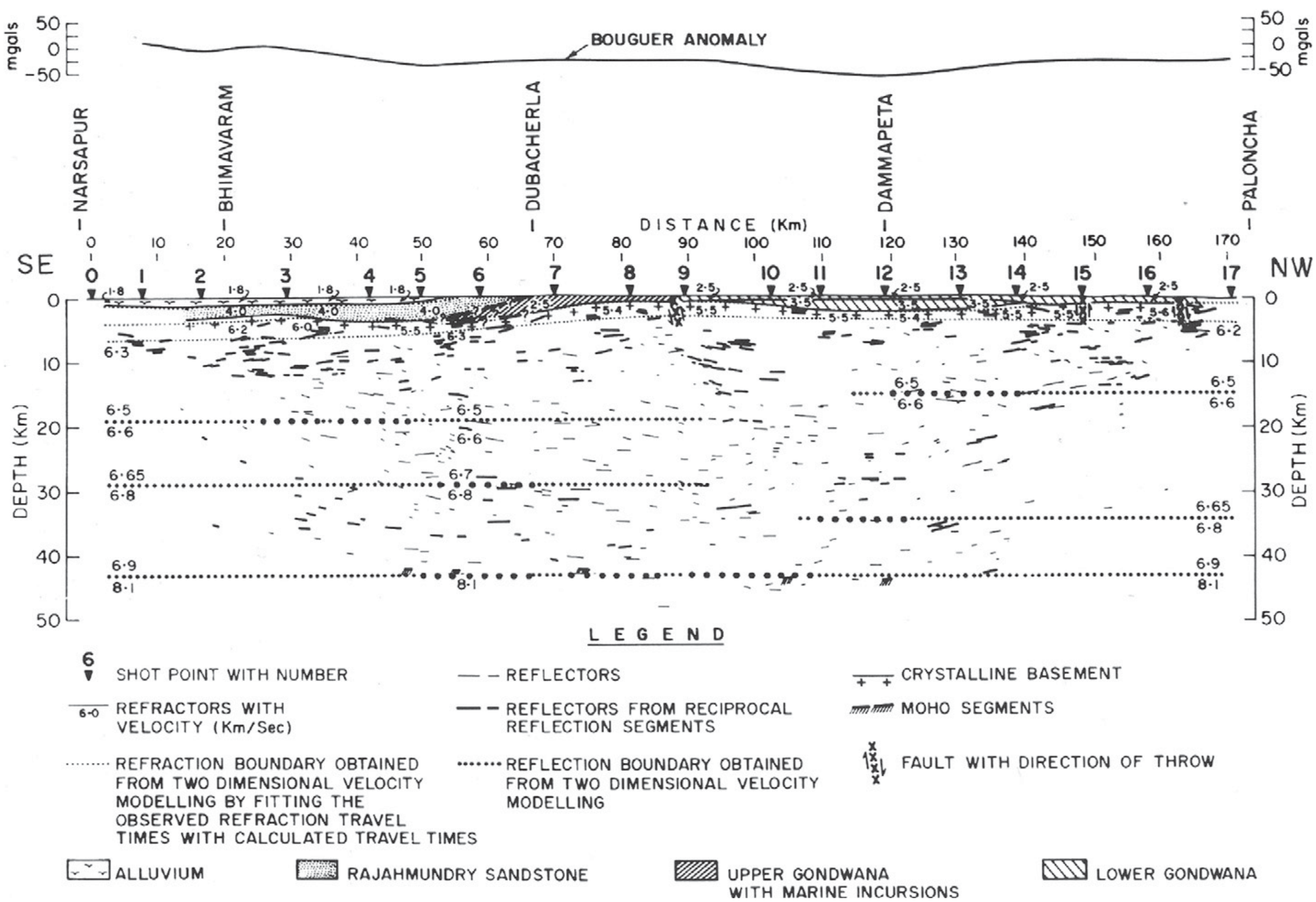

Figure 8.7.1-02. Crustal cross section of a deep seismic sounding profile through the Godavari basin and graben in southeastern India (from Kaila et al., 1990a, fig. 5). [Tectonophysics, v. 173, p. 307–317. Copyright Elsevier.]

south line crossed all the three east-west lines. These new lines, also shown in Figure 8.7.1-01 were recorded digitally with 80 m sensor spacing (Kaila et al., 1996), but only shallow structures were revealed in much detail.

Another line, shot in 1983–1984 between Hirapur and Mandla in central India (Kaila et al., 1987c; Fig. 8.7.1-01; ~500 km to the SSE of Delhi) dealt mainly with the shallow velocity structure and was later interpreted in much detail by Sain et al. (2000).

In 1986–1987, three seismic lines covering 350 km were recorded in the northern Cambay and Sanchor sedimentary basins in western India, north of Mehmadabad (Kaila et al., 1990b; Fig. 8.7.1-01). This project continued the seismic work carried out in the 1970s in the southern Cambay basin (Kaila et al., 1981a).

8.7.2. China

Explosion seismology research in China was considerably increased in the 1980s. The main tectonic provinces are shown in Figure 8.7.2-01.

In 1981 and 1982, a joint Sino-French explosion seismology study was carried out in Tibet investigating the Himalayan border and the adjacent Lhasa block to the north (Hirn and Sapin, 1984; Hirn et al., 1984a, 1984b, 1984c; Teng et al., 1983a; Yuan et al., 1986) which on the French side was organized by Alfred Hirn, University of Paris, France.

In 1981, a 500-km-long east-west line was recorded between the High Himalayas and the Yarlung Zangbo Jiang as part of a French-Chinese geoscientific exploration of southern Tibet (solid line in Fig. 8.7.2-02). A system of reversed and overlapping profiles and some auxiliary profiles were established using 40 portable tape recording seismic stations of type MARS-66 and recorded seven charges ranging from 2000 to 10,000 kg detonated in two lakes and at one drillhole. Spacing of seismographs was 10 km. Twelve additional stations stationed in Nepal tested the energy propagation through the High Himalayas.

Crustal reflections at critical wide-angle distance from the Moho were exceptionally clear and the crust-mantle boundary

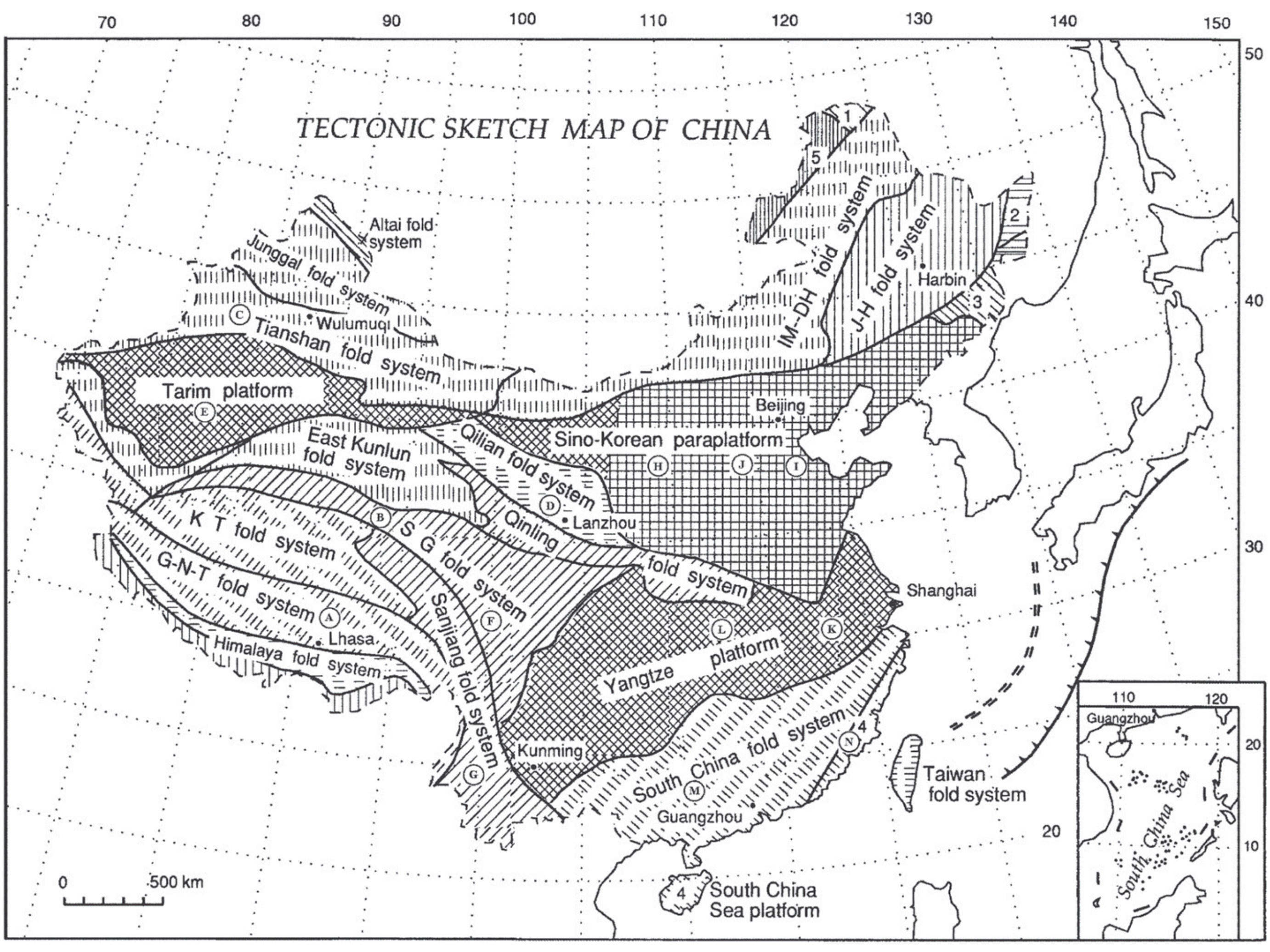

Figure 8.7.2-01. Tectonic sketch map of China (from Li and Mooney, 1998, fig. 1). [Tectonophysics, v. 288, p. 105–113. Copyright Elsevier.]

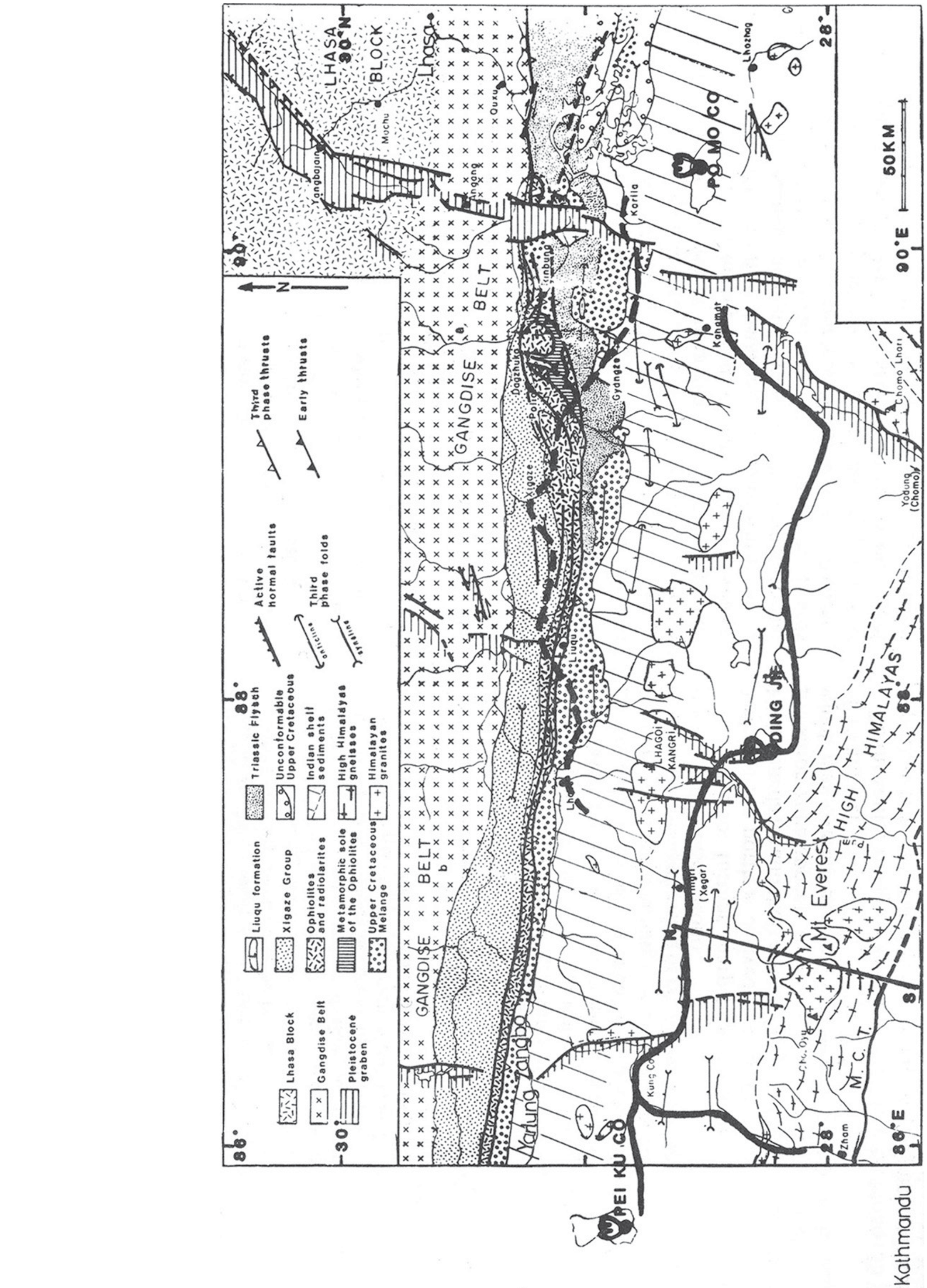

Figure 8.7.2-02. Location map of the deep seismic sounding profiles of 1981 in southern Tibet (from Hirn et al., 1984a, fig. 1). [Annales Geophysicae, v. 2, p. 113–118. Reproduced by permission of the author.]

was modeled as a 12-km-thick transition zone at 75 km depth beneath the present-day surface at 4500 m mean elevation above sea level (see top record section of Fig. 8.7.2-03). The second record section (Fig. 8.7.2-03, lower left) shows the recordings from the center shotpoint Ding Jie along the fan profile running south from the western shotpoint Pei Ku Ko.

The crustal cross section (Fig. 8.7.2-03, lower right) is the result of the fan profile interpretation plotted half way between recording line and shotpoint along the straight line N-S in Figure 8.7.2-02. It shows an intracrustal boundary at 40 km depth and the Moho at 55 km, offset to greater depth up to 70 km and more north of the High Himalayas.

Following this study, in 1982, the fan line was continuously extended toward the north, crossing several fold systems and the eastern part of the Tarim basin and ending in the Junggar basin as can be viewed on the tectonic map (Fig. 8.7.2-01). In this second project in 1982 (Hirn et al., 1984b), a 500-km-long Moho traverse (solid line in Fig. 8.7.2-04) was laid out.

It crossed the Yarlung Zangbo Jiang suture zone, which separates the Lhasa block from the Tibetan part of the Indian continental plate in southernmost Tibet, then traversed the Lhasa block and continued further through the Bangong-Nujiang suture, an earlier suture which limits the Lhasa block 300 km to the north. Most seismograms were obtained at constant distance, 200–250 km from shotpoints; in some parts, however, the seismograms had to be corrected for larger offset distances (Fig. 8.7.2-05). Both sutures appeared as vertical 20-km steps in the Moho and were interpreted by Hirn et al. (1984b) as possible loci for eastward strike-slip motion of the Tibetan lithosphere. Also in the early 1980s, an E-W profile was shot in the Tibetan plateau in the northern part of the Lhasa block (Sapin et al., 1985), south of the Banggong-Nujiang Suture (for location, see Fig. 9.6.2-05A).

Following the French-Chinese investigations, many other seismic-refraction surveys followed. The location of the seismic-refraction/wide-angle reflection profiles in China from 1958 to 1990 is summarized in Figure 8.7.2-06. Some 250 standardized instruments for deep seismic sounding had been distributed within China among various research groups belonging to the State Seismological Bureau. The instruments recorded on two-channel magnetic tape cassettes, one for the seismometer signals, and the other for timing control. The seismic channel was frequency modulation multiplexed at two or three levels to obtain a wide dynamic range. The sensors were

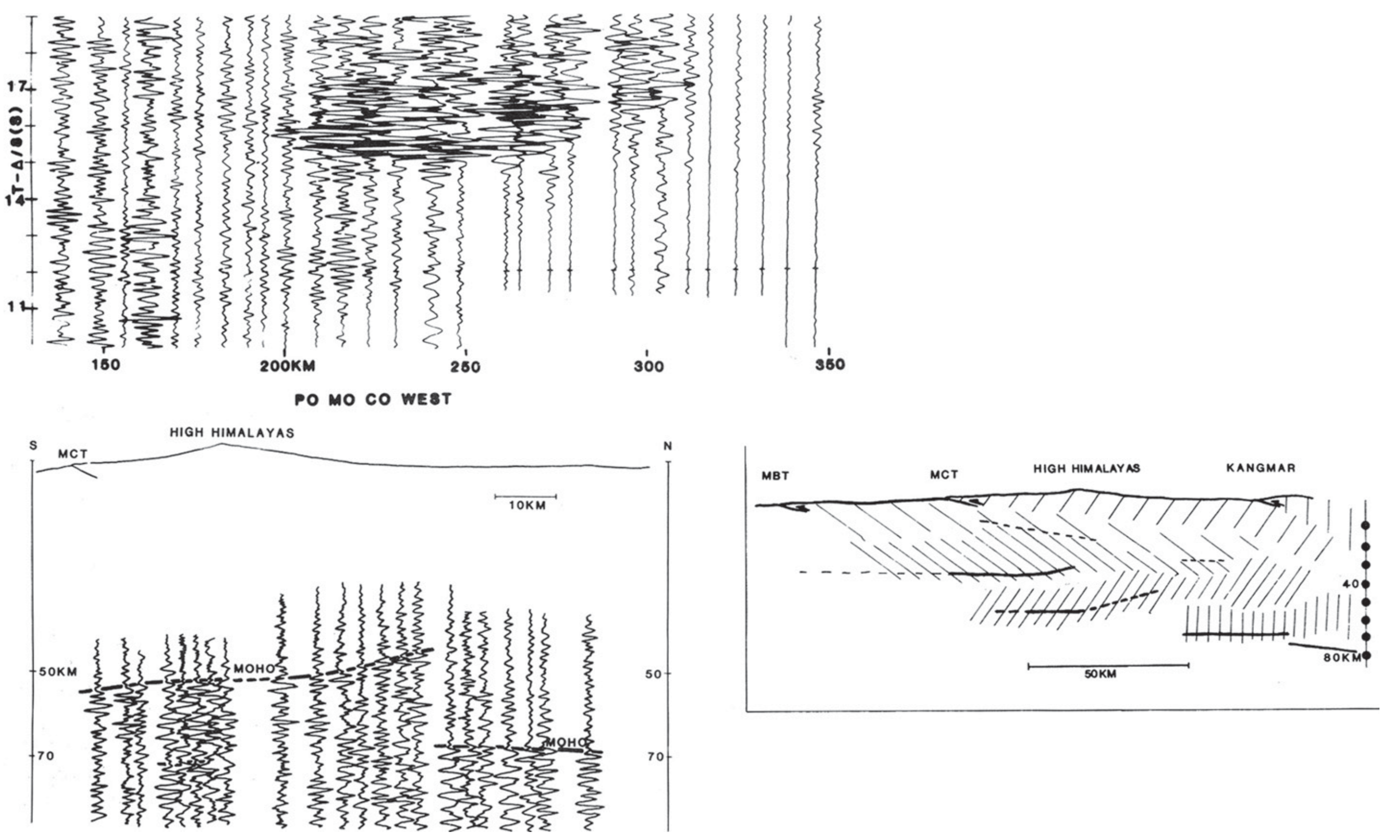

Figure 8.7.2-03. Top: Shots Po Mo Co recorded on the east-west line (from Hirn et al., 1984c, fig. 2). Bottom: Fan profile to the west from shotpoint Ding Jie (left) and seismic structure across the High Himalayas along N-S line of Figure 8.7.2-02 (from Hirn et al., 1984c, figs. 3 and 4). MBT—Main Boundary Thrust, MCT—Main Central Thrust. [Nature, v. 307, no. 5946, p. 25–27. Reprinted by permission from Macmillan Publishers Ltd.]

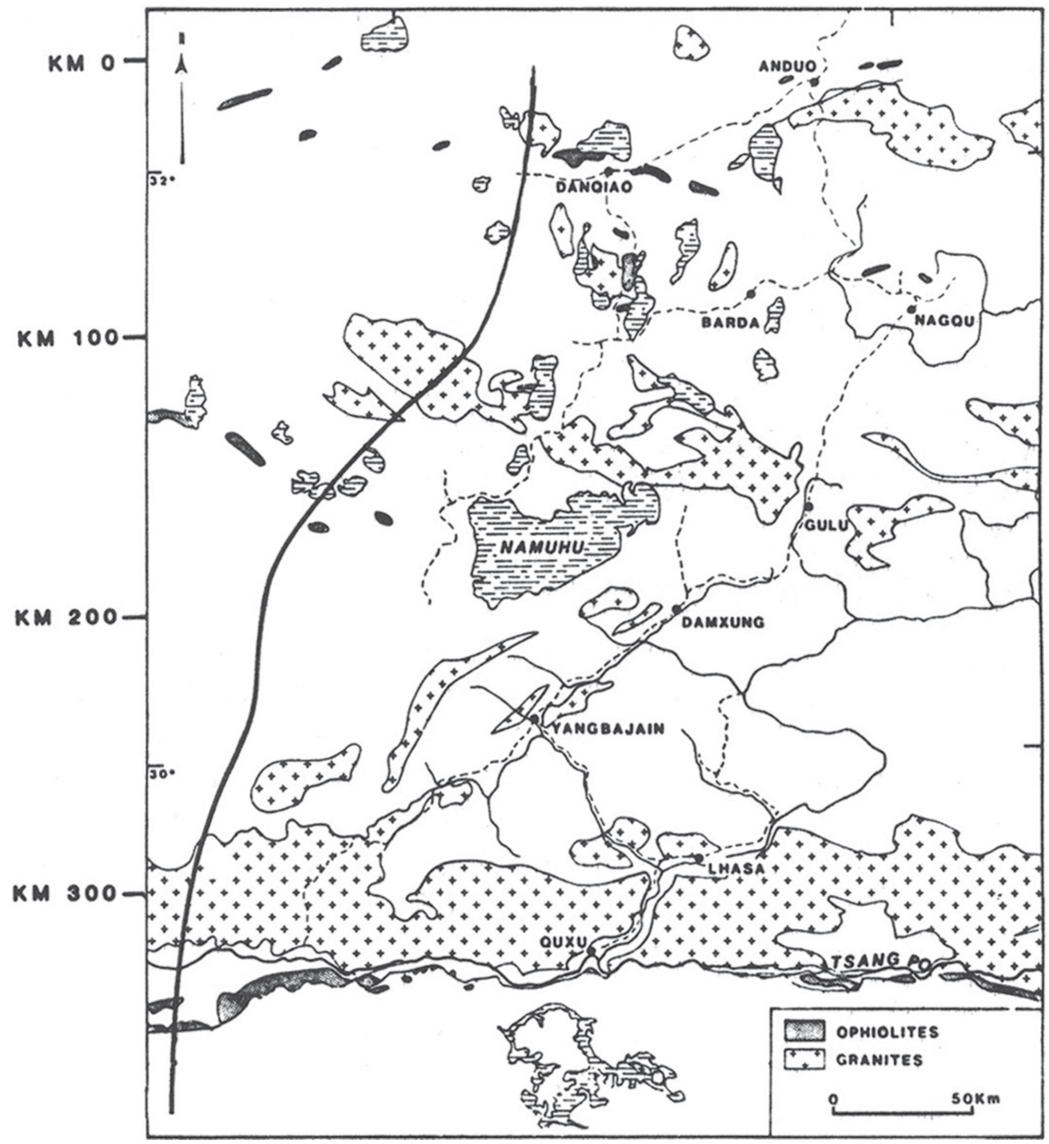

Figure 8.7.2-04. Location map of the 500 km long fan profile of 1982 in Tibet (from Hirn et al., 1984b, fig. 1). [Nature, v. 307, no. 5946, p. 23–25. Reprinted by permission from Macmillan Publishers Ltd.]

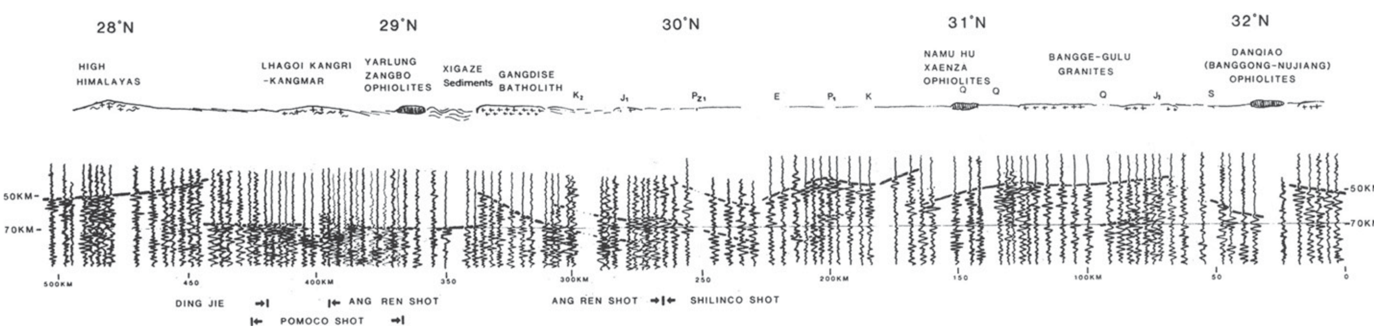

Figure 8.7.2-05. Time section of Moho reflections at constant offset of 250 km (critical to wide-angle range) along the north-south fan profile of 1982 through Tibet (from Hirn et al., 1984b, fig. 2). [Nature, v. 307, no. 5946, p. 23–25. Reprinted by permission from Macmillan Publishers Ltd.]

2-Hz vertical seismometers. Li and Mooney (1998) have published a brief overview of the seismic crustal studies which may have started in 1958, but only in the 1970s was the first modern seismic survey performed (see Chapter 7.6.2). The main activity of seismic research, however, started in the 1980s and continued since then.

An overview of seismic crustal studies in Tibet was published by Teng (1987). He reviewed the explosion seismic studies carried out on the Qinghai-Xizang (Tibet) plateau from 1975 to 1977 and 1981–1982. From shots fired in five lakes and three borehole sites, five seismic profiles had been completed. Moho depths reached 75 km under the Tibetan plateau.

Many seismic-refraction lines were established between longitudes 98° and 106°E from the Qinling fold system in central China (Chen et al., 1988; Zhang et al., 1988) to the Sanjiang fold system in south-central China (Kan et al., 1986, 1988) and the transition into the Yangtse platform where the Moho increases rapidly from 30 to 40 km under the Yangtse platform in the east to more than 70 km depth under the various fold systems in the west (for references see Table 1 of Li and Mooney, 1998, and Table 1 of Zhang et al., 2005).

A dense network of seismic profiles was recorded in the Bejing area in the North China plain and adjacent regions (Sun et al., 1988). To the south a few seismic lines were observed in the eastern part of the Qinling fold belt and adjacent areas of the North China plain and the Yangtse quasi-platform (Hu et al., 1988; Ding et al., 1988; Chen and Gao, 1988). Finally, adding to the observations from the Yongping explosion in the 1970s (United Observing Group of the Yongping Explosion, SSB,, 1988) the South China foldbelt was covered by three more lines (Lhiuzou Explosion Research Group, 1988; Liao et al., 1988). The training of Chinese scientists and their interpretation of seismic data was strongly supported by the USGS under the initiative of Walter Mooney.

One of these projects, which was carried out in cooperation with the USGS, is discussed here in more detail. To define the crustal structure in an area of active tectonics on the southern

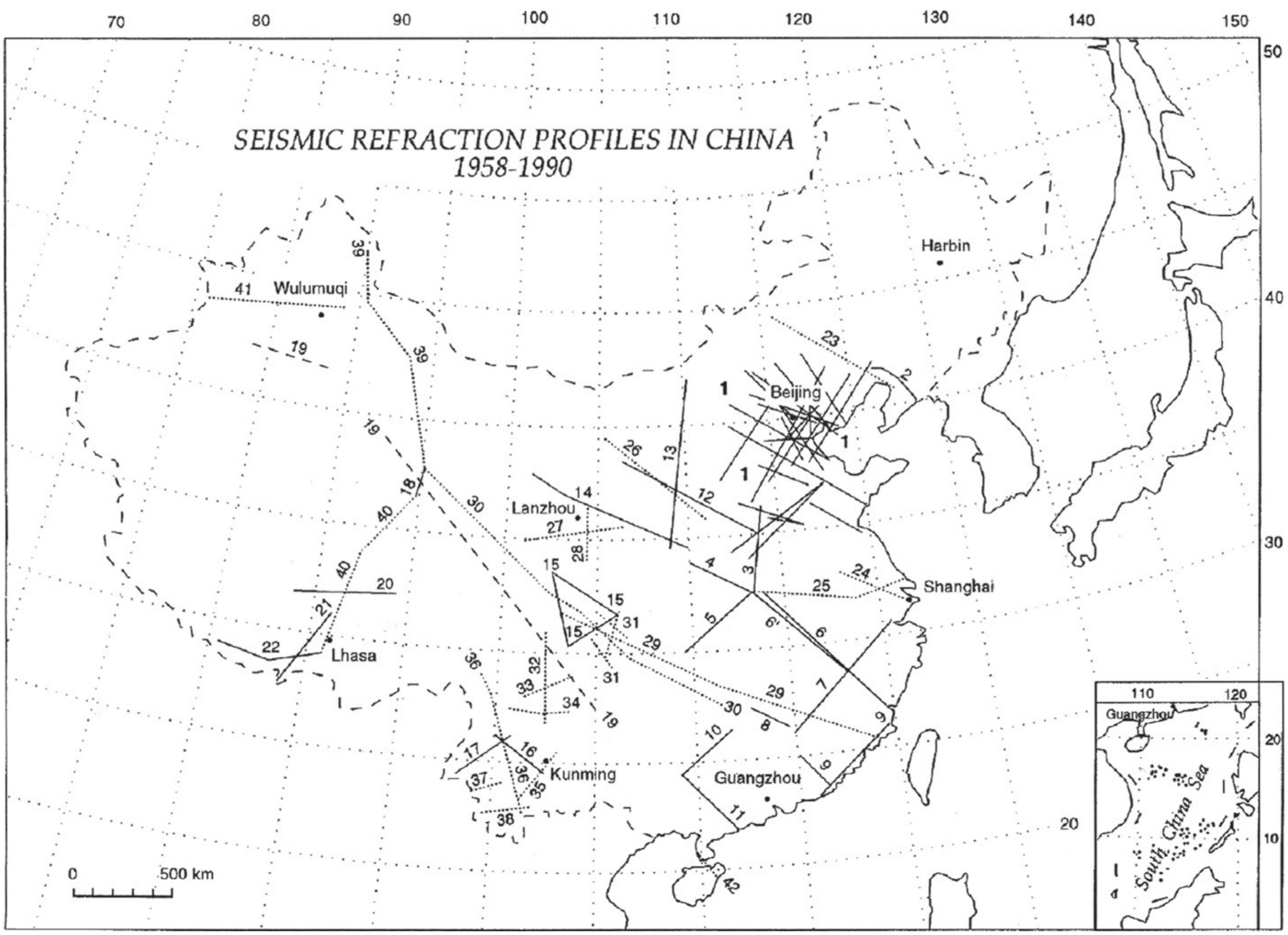

Figure 8.7.2-06. Location map of deep seismic sounding profiles in China observed between 1958 and 1990 (from Li and Mooney, 1998, fig. 2). Solid lines—completed until 1986 and published; dotted lines—completed from 1987 to 1990; dashed line—profile with sparse observational points. [Tectonophysics, v. 288, p. 105–113. Copyright Elsevier.]

end of the Himalaya-Burma arc, in 1982 a seismic project was carried out in the Yunnan province in southwestern China to the southwest of the city of Kunming (Kan et al., 1986, 1988).

It consisted of three 300–400-km-long seismic-refraction profiles with a total length of 1070 km (nos. 16, 17, and 35 in Fig. 8.7.2-06). Four shotpoints were organized along each line and 196 instruments enabled an average spacing of 2 km. The resulting crustal thickness varies from 38 to 46 km. For lines 16 and 17 a fence diagram is displayed in Figure 8.7.2-07 showing some details of the interpreted crustal structure.

Another 1100-km-long seismic-refraction survey was conducted in 1988 across northwest China (Wang et al., 2003). Seismic energy was provided by 12 chemical explosive shots fired in boreholes (Fig. 8.7.2-08). The charges ranged in size from 1500 to 4000 kg provided sufficient energy for first arrivals clearly seen to a maximum distance of 300 km. The spacing between the three-component recording stations was 2–4 km; the spacing between shotpoints was 63–125 km. Both P- and S-wave phases could be well correlated to determine a detailed crustal model (Fig. 8.7.2-09). The data are shown in Appendix A9-4-2, together with other data of western China recorded in the 1990s. The three-layer crust is more than 40 km thick, which was interpreted as being due to subsequent Indo-Asian collision. According to the authors the variation of the average velocity along the line is due to the non-uniform composition of the accreted blocks which comprise continental and oceanic terranes, accretionary prismas, and magmatic arcs.

8.7.3. Japan

Since the early days of seismology, Japanese seismologists continuously exchanged their scientific results with their colleagues worldwide and were actively involved in the foundation of IASPEI (International Association of Seismology and Physics of the Earth's Interior) which provides a platform for communication by its biannual meetings. This concerned also the special field of explosion seismology. For example, as mentioned above, in 1985 they hosted one of the CCSS (Commission on Controlled Source Seismology) workshops where interpretation methods were being discussed and compared.

After intensive investigations of crustal structure underneath the Japanese islands in the 1960s and 1970s, active explosion seismology research in Japan in the 1980s concentrated mainly on offshore research of the adjacent Pacific Ocean. A corresponding offshore investigation by Suyehiro and Nishizawa (1994) will be described below in subchapter 8.9.1. On land most explosion seismic studies were carried out under the national Earthquake Prediction Program and focused on the upper crustal structure, searching particularly for major fault zones and tectonic lines. In effect, every year a seismic-refraction survey was recorded (Ikami et al., 1986; Iwasaki et al., 1998; Matsu'ura et al., 1991; Moriya et al., 1998; Research Group for Explosion Seismology, 1992a, 1992b; Sasatani et al., 1990; Yoshii et al., 1985).

Only two research projects, carried out in 1989 and 1990 within the scope of the Japanese Earthquake Prediction Program,

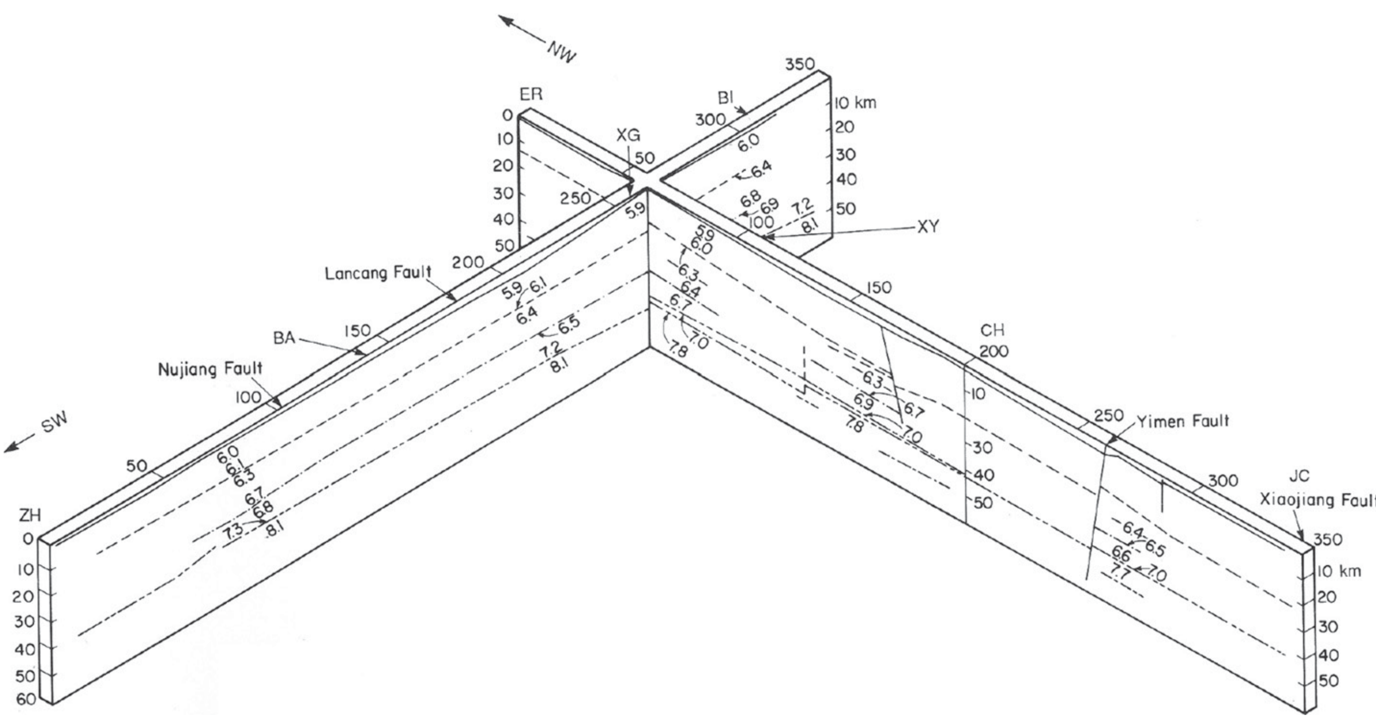

Figure 8.7.2-07. Fence diagram showing crustal structure in the Yunnan province, southwestern China (from Kan et al., 1986, fig. 3). [Science, v. 234, p. 433–437. Reprinted with permission from AAAS.]

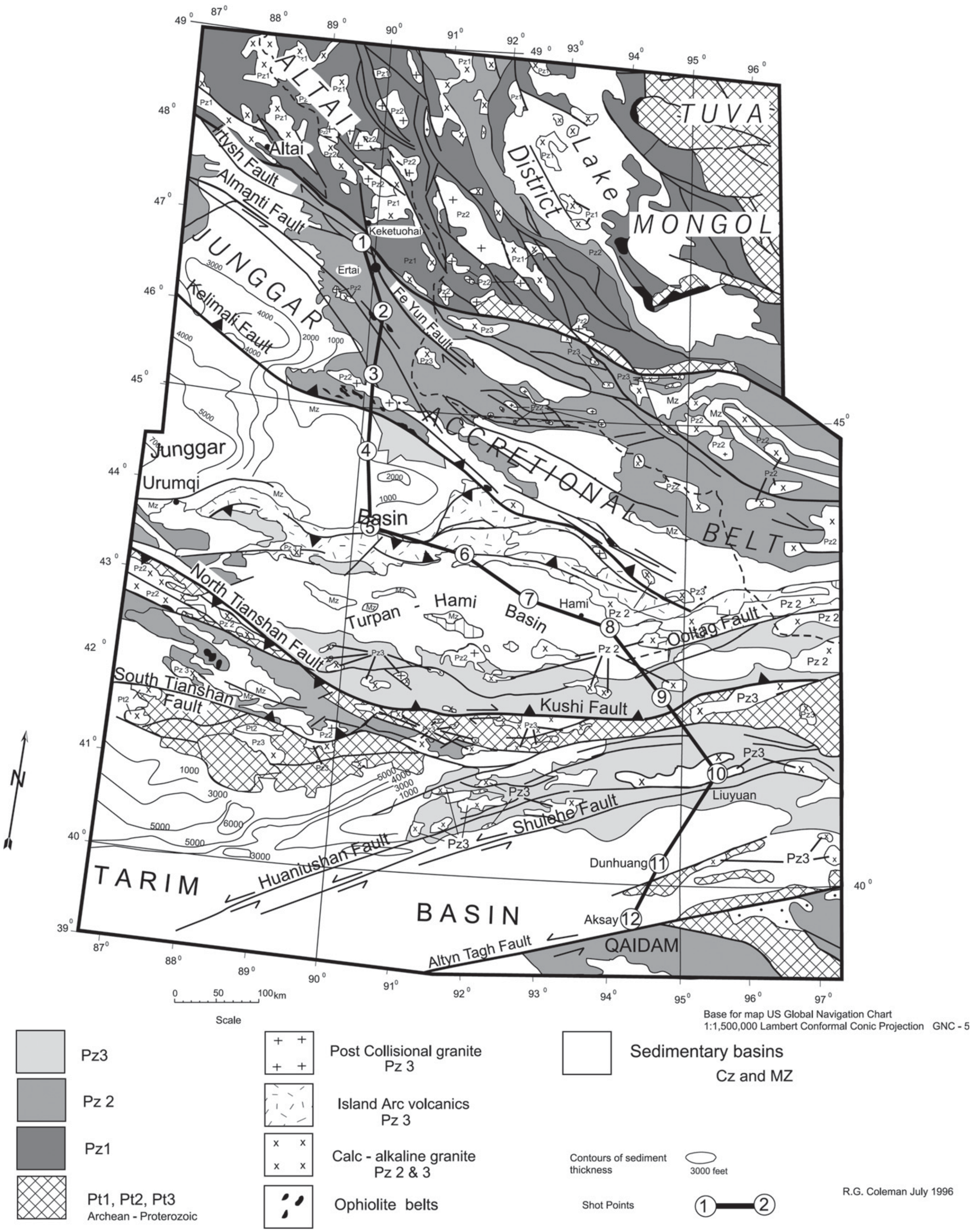

Figure 8.7.2-08. Geologic map of northwestern China showing the seismic refraction survey of 1988 between the Altai Mountains and the Altyn Tagh fault (from Wang et al., 2003, fig. 2). [Journal of Geophysical Research, v. 108, B6, 2322, doi: 10.1029/2001JB000552, ESE 7-1–7-15. Reproduced by permission of American Geophysical Union.]

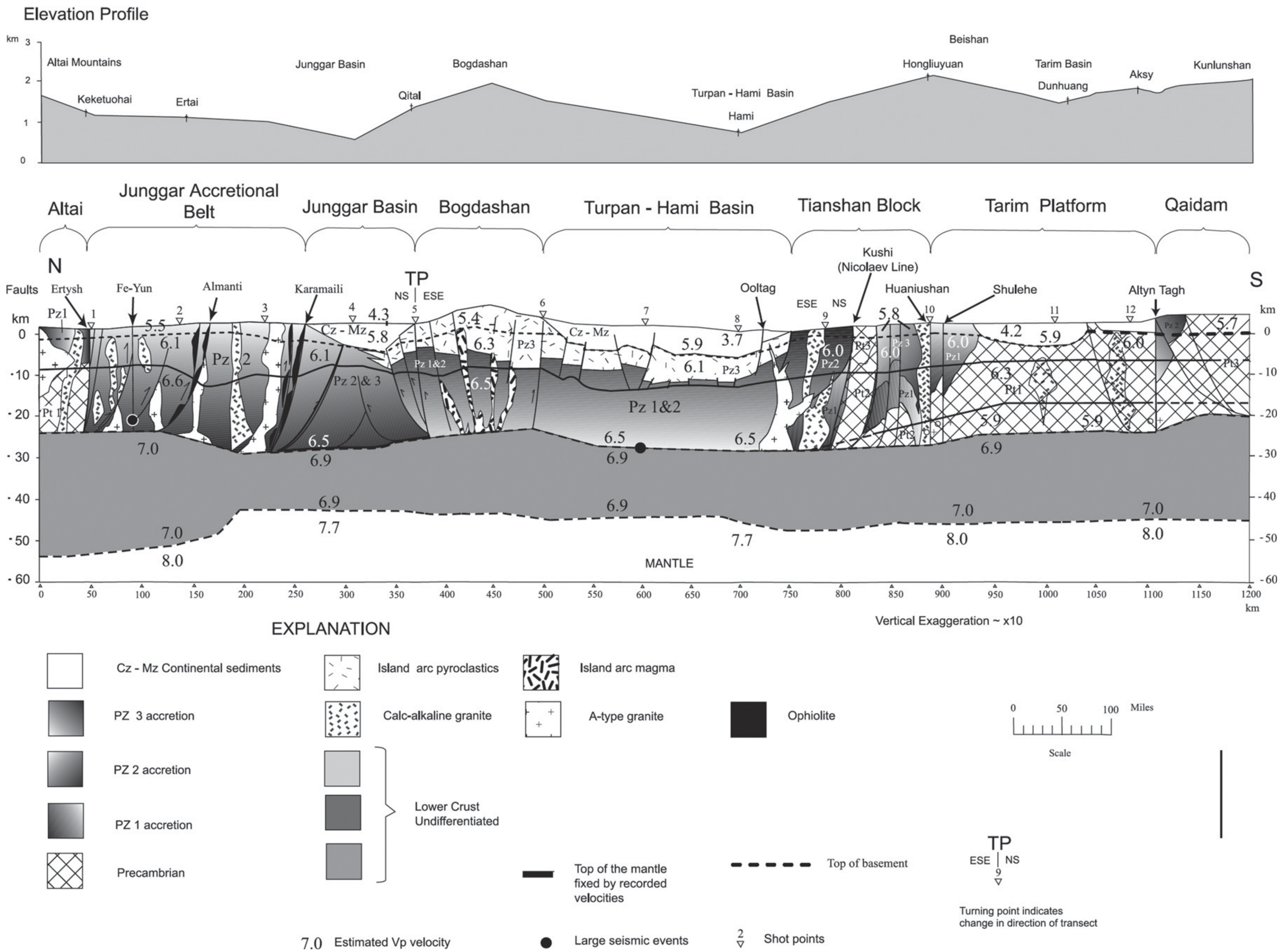

Figure 8.7.2-09. Geologic section through northwestern China showing the crustal structure from the Altai Mountains to the Altyn Tagh fault (from Wang et al., 2003, fig. 10). [Journal of Geophysical Research, v. 108, B6, 2322, doi: 10.1029/2001JB000552, ESE 7-1–7-15. Reproduced by permission of American Geophysical Union.]

both on the island of Honshu, may be mentioned here in more detail. The project of 1989 was a 220-km-long profile between Fujihashi and Kamigori in the western part of Honshu. It involved four shotpoints with charges of 500–800 kg and 137 recording sites (Research Group for Explosion Seismology, 1995).

The second seismic-refraction experiment, again with four explosive sources, was 194 km long and was conducted in 1990 in the Kitakami Massif (Research Group for Explosion Seismology, 1992b). The target area was located in the eastern part of northern Honshu, one of the typical island arcs forming the western rim of the Pacific Ocean, located above the westward subduction zone of the Pacific plate starting beneath the Japan Trench (Fig. 8.7.3-01). The interpretation by Iwasaki et al. (1994) revealed a detailed crustal model with a 32–35-km-thick crust and its P and S velocity structure (Fig. 8.7.3-02) with an upwarping of Moho beneath the Hayachine tectonic belt. The data also allowed studying the corresponding seismic attenuation (Q-structure). Atypically the P/S ratio resulted to be fairly constant throughout the whole crust.

8.8. CONTROLLED-SOURCE SEISMOLOGY IN THE SOUTHERN HEMISPHERE

8.8.1. Australia and New Zealand

In Australia, seismic-reflection recording using digital equipment started in 1976. The positive outcome of experiments of the late 1970s encouraged Australian scientists such

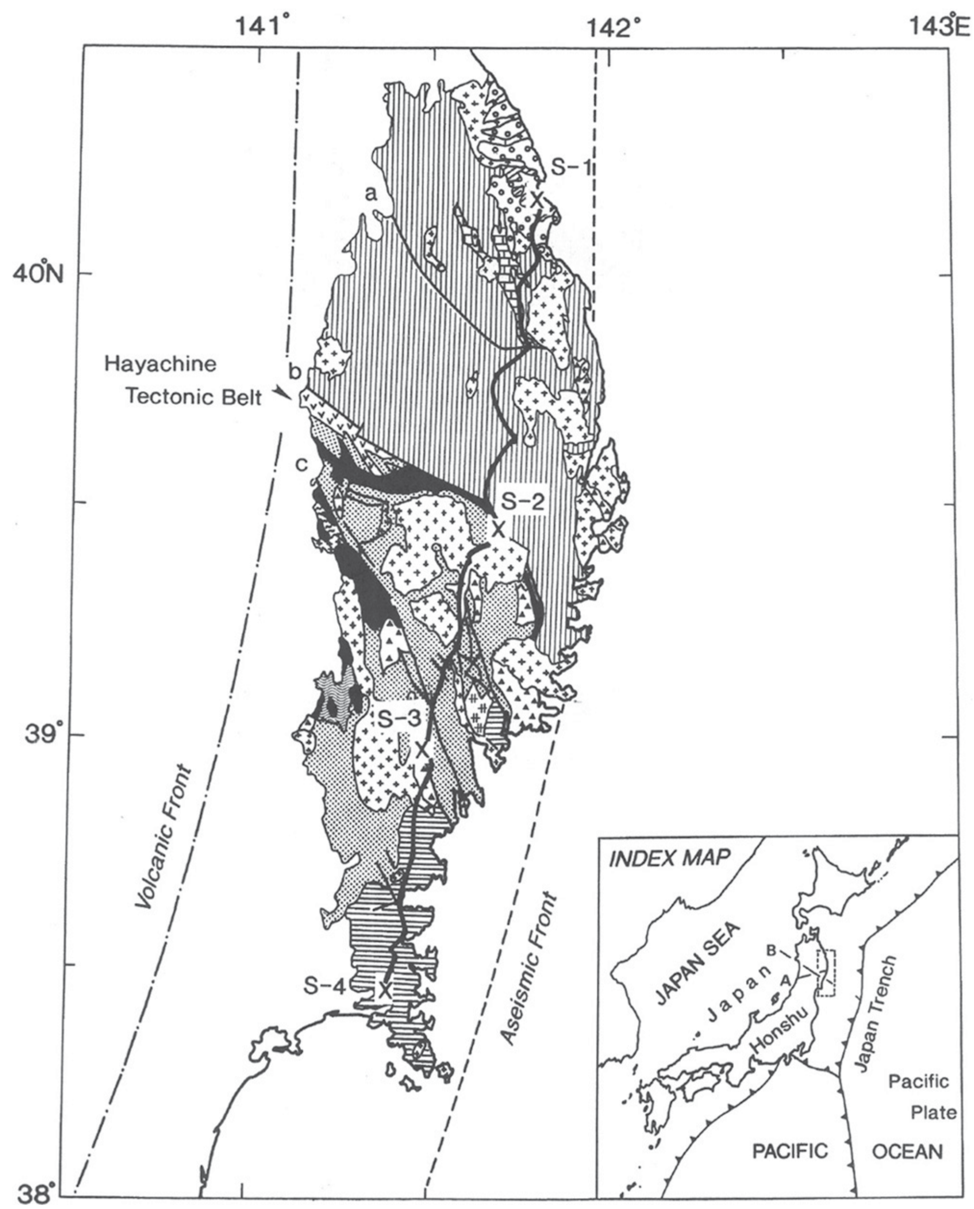

Figure 8.7.3-01. Geological sketch map of the Kitakami region, northern Honshu, Japan, showing the location of the seismic-refraction experiment (from Iwasaki et al., 1994, fig. 1). Refraction line and shotpoints are indicated by a heavy solid line and crosses, respectively. Dashed lines in the index map are earlier seismic refraction lines. A—the Isibuchi-Kamaishi profile (Matsuzawa et al., 1959), B—Oga-Kesennuma profile (Hashizume et al., 1968). [Journal of Geophysical Research, v. 99, p. 22187–22204. Reproduced by permission of American Geophysical Union.]

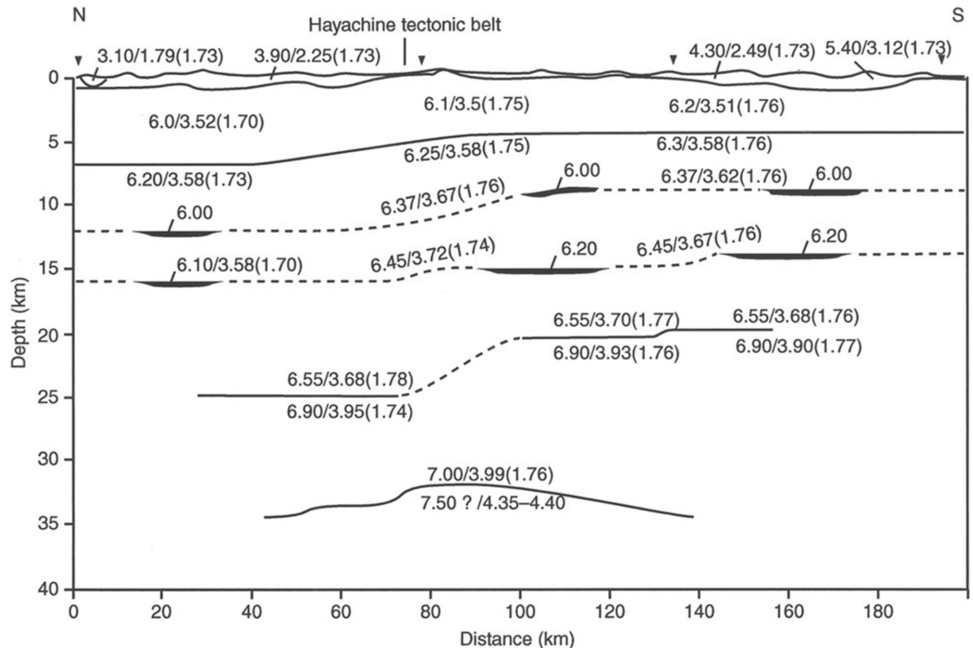

Figure 8.7.3-02. Cross section through the Kitakami region, northern Honshu, Japan (from Mooney et al., 2002, fig. 14, modified from Iwasaki et al., 1994). Indicated are P-velocity/S-velocity, and their ratio. [*In* Lee, W., Kanamori, H., Jennings, P.C., and Kisslinger, C., eds., International Handbook of Earthquake and Engineering Seismology, Part A. Academic Press, Amsterdam, p. 887–910. Copyright Elsevier.]

as Doug Finlayson, Clive Collins, John Moss, Jim Leven, and others to continue with 20 second record length from 1980 onward. Thus, during 1980–1982 good deep seismic-reflection data were obtained in the central Eromanga basin in southwestern Queensland, resulting in 1400 km of traverse in a regional grid on continuous profiles up to 270 km long (Moss and Mathur, 1986; Finlayson et al., 1989). In 1984, a long west-east traverse was added extending from the central Eromanga basin eastward across several basins to near the coast (Fig. 8.8.1-01).

The quality of reflections from the deep crust was generally very good, but the signals from explosive sources had a generally better penetration than the Vibroseis signals. Wide-angle seismic profiling was also conducted along numerous lines coincident with the near-vertical incidence profiles in the Central Eromanga Basin, the Surat Basin, and Clarence-Moreton Basin (e.g., Finlayson and Mathur, 1984; Finlayson 2010; Appendix 2-2).

Overall in the Eromanga basin a highly reflective lower crust between 8 and 12 s TWT was separated from reflective basin sequences in the uppermost crust (1–2 s) by an upper crust with little to no reflectivity. The deep crustal features correlated across a network of traverses at 20–40 km depth were discussed in detail by Finlayson et al. (1989). Figure 8.8.1-02 shows how these lower crustal reflections may be bundled and explained as lower crustal lenticles.

Following these successful studies, a cooperative seismic program with federal and state government surveys and academic institutions was initiated (Fig. 8.8.1-03) in which government and academic institutions were engaged together with industry with the aim to record deep reflection profiling across many parts of Australia (Moss and Mathur, 1986).

Within this program, in 1983 the Australian Geological Survey Organization (AGSO) investigated the southwestern Yilgarn Craton by recording wide-angle seismic profiles along two transects at right angles to each other, both of ~400 km in length. Energy sources were special seismic shots with charges of 800–2800 kg and coal mine shots at the Collie open pit mine. The original two-layer crust of Drummond (1988) was later reinterpreted and a high-velocity layer (7.25–8.10 km/s) in the lower crust added. The resulting Moho depth increases from 35 km in the east to 38 km in the west (Dentith et al., 2000; Finlayson 2010; Appendix 2-2).

In 1984, a wide-angle seismic survey was undertaken across the New England Batholith in eastern Australia. Moho depths were 34–35 km, under the northern part of the batholith a sill-like feature of high velocity was found at 21–24 km depth (Finlayson and Collins, 1993; Finlayson 2010; Appendix 2-2).

In 1985, two major north-south–oriented deep seismic-reflection surveys were conducted in central Australia (Fig. 8.8.1-03) by the Australian Geological Survey Organization (AGSO). Four hundred eighty-six line kilometers were acquired across the Arunta block and the Amadeus basin (Wright et al., 1990; Korsch et al., 1998). The seismic sections were recorded up to 20 s TWT, equivalent to a depth to 60 km assuming an average crustal velocity of 6 km/s. Underneath the Arunta block, the middle to lower crust appeared moderately to strongly reflective, and a series of planar reflections dipping gently to the north were

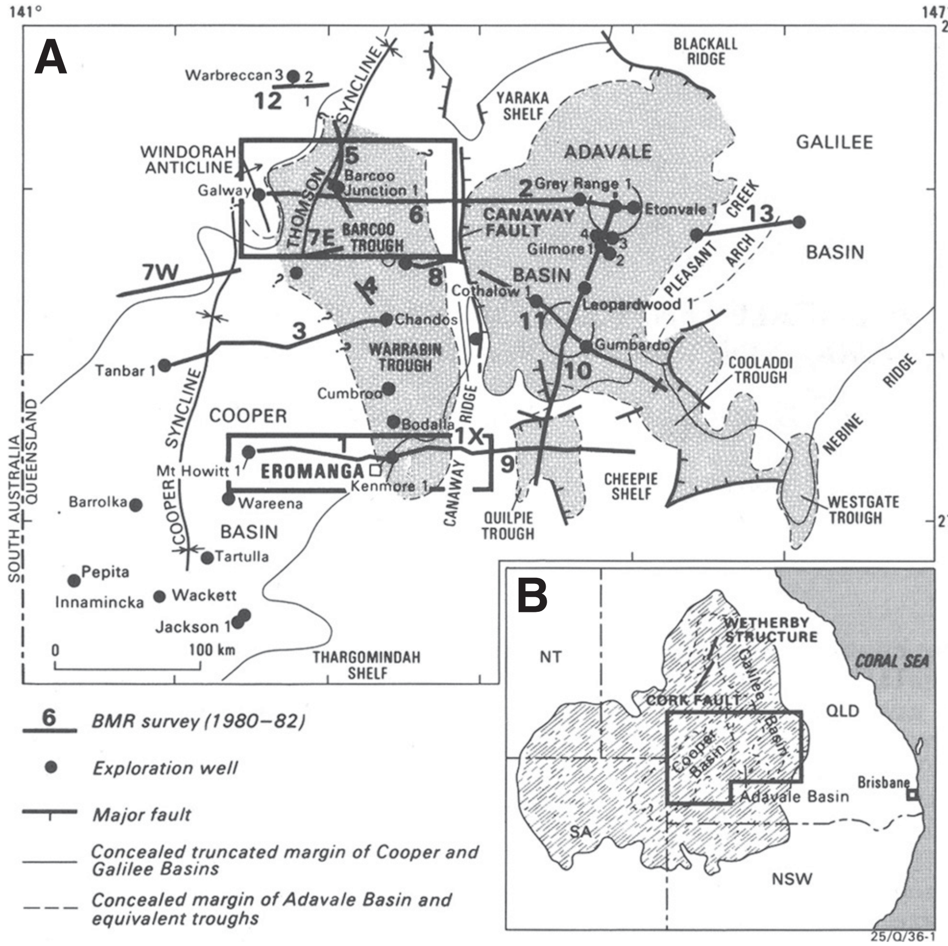

Figure 8.8.1-01. Central Eromanga basin study area, eastern Australia (from Finlayson et al., 1989, fig. 1). (A) Location of Bureau of Mineral Resources (BMR) deep seismic reflection traverses. (B) Outline of the Jurassic-Cretaceous Eromanga basin. [*In* Mereu, R.F., Mueller, St., and Fountain, D.M., eds., Properties and processes of earth's lower crust: American Geophysical Union, Geophysical Monograph 51, p. 3–16. Reproduced by permission of American Geophysical Union.]

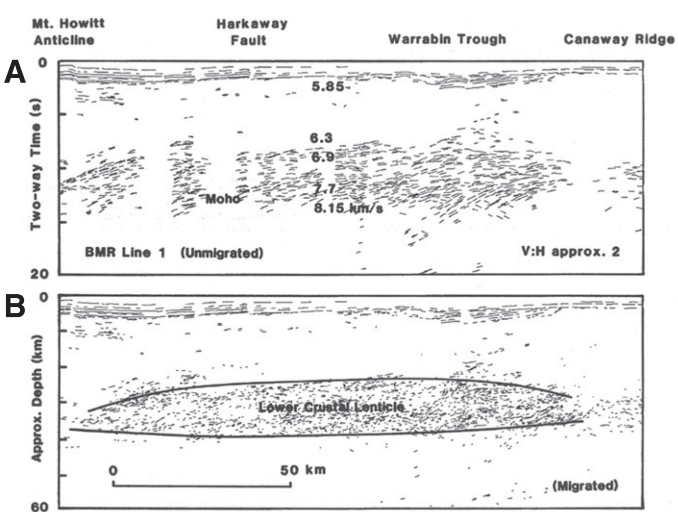

Figure 8.8.1-02. Digitized line diagram of reflectors along BMR line 1 (from Finlayson et al., 1989, fig. 10; for location see Fig. 8.8.1-01). (A) Unmigrated data with velocities derived from coincident seismic refraction data. (B) Migrated data converted to depth using an average crustal velocity of 6 km/s. The migrated data emphasize the reflections in a lower crustal lenticle. [*In* Mereu, R.F., Mueller, St., and Fountain, D.M., eds., Properties and processes of earth's lower crust: American Geophysical Union, Geophysical Monograph 51, p. 3–16. Reproduced by permission of American Geophysical Union.]

interpreted as a series of parallel, planar, north-dipping, thick-skinned thrust faults of which most could be traced at the surface.

In the Amadeus basin beneath the strongly reflective sub-horizontal reflections of the basin sediments, the crust showed low reflectivity in its upper part, but again moderate to strong reflectivity beneath. Only one thrust fault has been recognized in the basin at the southern end of the seismic section (Fig. 8.8.1-04). The crustal thickness across central Australia was interpreted to be between 45 and 50 km and the Mesoproterozoic crustal architecture dominated by planar crustal scale structures were interpreted as ancient thrust faults that had been reactivated by later orogenies.

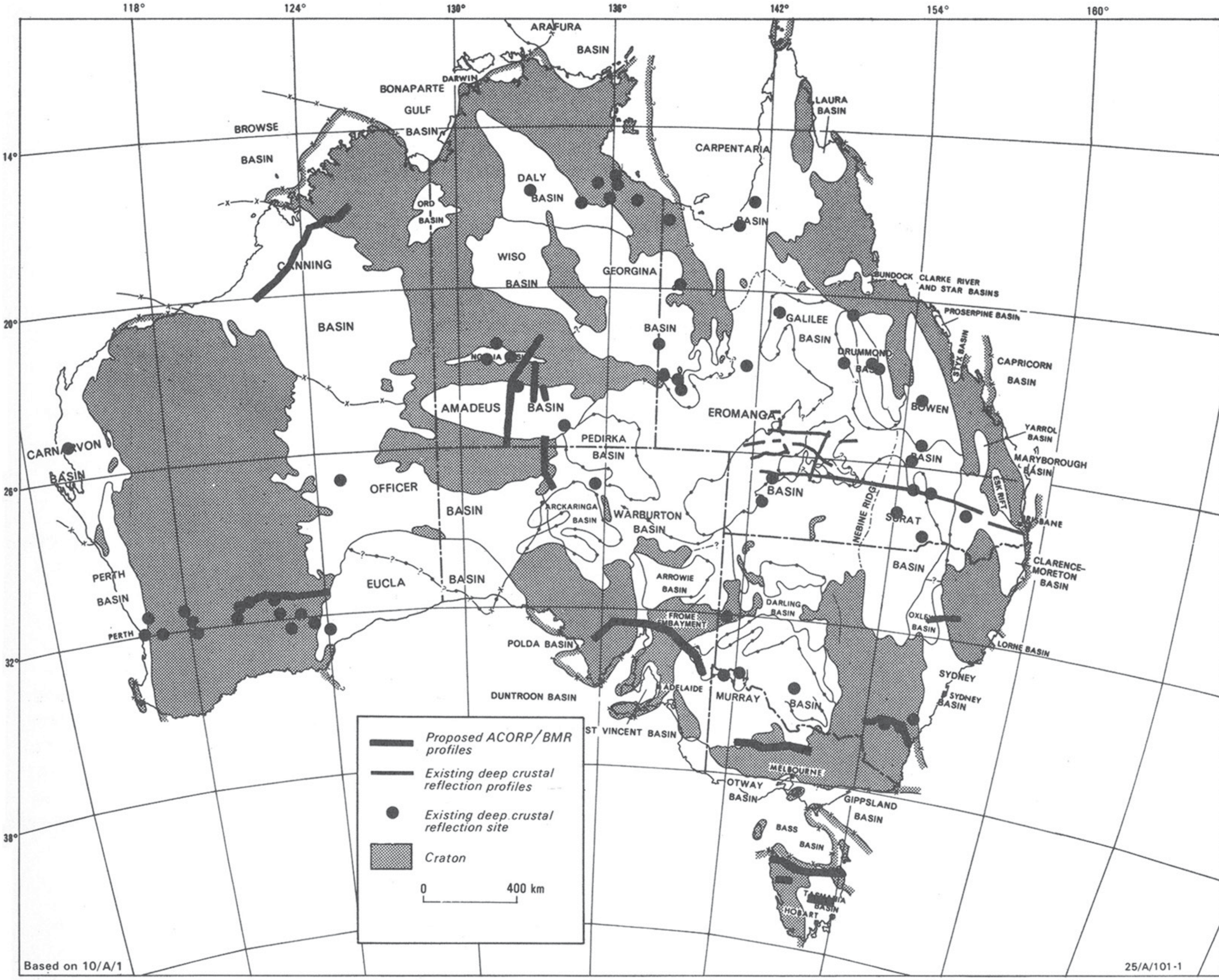

Figure 8.8.1-03. Map of Australia showing locations where deep seismic reflection surveys have been recorded and the planning stage of the Australian Continental Reflection Profiling Program (ACORP) (from Moss and Mathur, 1986, fig. 1). [*In* Barazangi, M., and Brown, L., eds., Reflection seismology: a global perspective: American Geophysical Union, Geodynamics Series, v. 13, p. 67–76. Reproduced by permission of American Geophysical Union.]

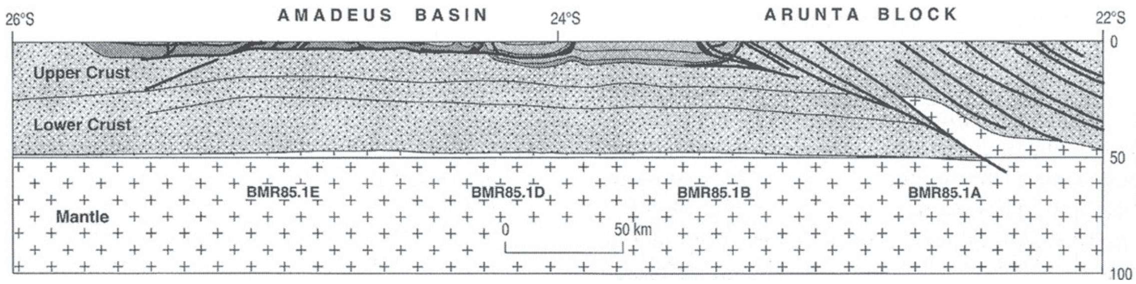

Figure 8.8.1-04. Transect through central Australia showing the crustal architecture based on seismic-reflection, seismic-refraction, and teleseismic investigations (from Korsch et al., 1998, fig. 7b). [Tectonophysics, v. 288, p. 57–69. Copyright Elsevier.]

Finally, from 1987 to 1989, the Australian Geological Survey Organization (AGSO) undertook a number of small deep seismic sounding projects across the Lachlan Orogen in cooperation with various state geology agencies and universities (Finlayson, 2010). In 1989 a seismic traverse involving 294 km of seismic-reflection data was recorded across the northern Bowen basin and the western margin of the New England orogen (e.g., Korsch et al., 1992; Finlayson 2010; Appendix 2-2).

The achievements of seismic and other related studies on the Australian lithosphere were discussed at an interdisciplinary symposium on the Australian lithosphere (Drummond, 1991).

New Zealand is located near the Indian-Pacific plate boundary with a relative motion of oblique convergence. Therefore a wide variety of crustal and upper mantle structures is observed. Beneath the North Island, oceanic lithosphere of the Pacific plate is being subducted, resulting in a configuration of accretionary prism, forearc basin, volcanic arc and backarc spreading basin. In the central South Island there is continental lithosphere on both sides of the plate boundary and mountain building and shear are the mechanisms of deformation (Stern et al., 1986).

The Northland seismic survey of 1982–1983 consisted of marine explosives shots into a 600-km-long line of land stations along the Auckland peninsula. The Central Volcanic Region seismic-refraction profile was recorded through the center of North Island (Fig. 8.8.1-05) with shots in Lake Taupo and in the vicinity of White Island (Stern, 1985). The interpretation of the data along this 200-km-long line resulted in crustal thickness of 14.9 km and an upper-mantle velocity of 7.4 km/s underneath the Central Volcanic Region (Stern, 1985; Stern and Davey, 1987; Stern et al., 1986, 1987).

In 1984 and 1985, a detailed seismic-reflection profile (dashed lines in Fig. 8.8.1-05) was recorded from the Pacific Ocean across Hikurangi Trough up to the east coast of North Island and continued from the west coast of southern North Island across the South Wanganui Basin (Davey et al., 1986; Davey, 1987; Davey and Stern, 1990). The eastern profile of 1984 across the Hikurangi Trough was 250 km long and was recorded up to 20 s TWT. It consisted of a deep-water section of ~100 km length and a slope-shelf segment of ~150 km length.

Its objective was to obtain a crustal cross section across the fore-arc region of the Hikurangi subduction zone. It delineated thrust wedges and back-tilted basins of the accretionary wedge which overlies a detachment zone marking the top of the subducted Pacific plate. No Moho reflections could be identified (Davey et al., 1986). The western profile recorded in 1985 across the South Wanganui Basin defined a broad crustal downwarp in the backarc region of the Pacific-Indian plate boundary overlying the 20–50 km deep subduction zone. The goal was to investigate the region behind the Hikurangi margin, which changes from an extensional backarc basin under the central North Island to a postulated crustal downwarp under the southern North Island. The profile was run across this postulated downwarp.

The data showed discontinuous coherent reflectors dipping westward at the east end of the profile, interpreted as marking the top of the subducting Pacific plate, with overlying east dipping reflectors, which were interpreted as the base of the Australian plate crust, from depths of 9–15 s. Farther to the west a generally transparent middle crust and a reflective lower crust were evident in the reflection section. In 1989 a parallel 110-km-long profile, 150 km north of the western part of the previous profile, was acquired with recording times up to 15 s TWT. The goal was to obtain a crustal cross section across the backarc platform of the Hikurangi subduction zone (Davey, 1987; Davey and Stern, 1990).

The South Island was investigated in 1983. Large marine explosive shots were detonated off each coast and in Lake Tekapo and recorded on 19 seismographs along a 150-km-long profile

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Figure 8.8.1-05. Overview of crustal seismic lines recorded between 1952 and 1985 and some results in New Zealand (from Stern et al., 1986, fig. 2). Wellington profile of 1952 is at southern end of North Island; the Fjordland survey of 1974–1975 is at the SW end of South Island; WHUMP of 1979 is a short line near Wellington across the southern end of North Island; Northland line of 1982–1983 is a 600 km line along Auckland peninsula (northern extension of North Island); Central Volcanic Region profile of 1982–1983 is at center of North Island (Lake Taupo in center and White Island off the north coast); solid line through South Island–Central South Island line of 1983; dashed lines around southern end of North Island mark location of multichannel seismic reflection lines of 1984–1985. [*In* Barazangi, M., and Brown, L. eds.: Reflection seismology: a global perspective: American Geophysical Union, Geodynamics Series, v. 13, p. 121–132. Reproduced by permission of American Geophysical Union.]

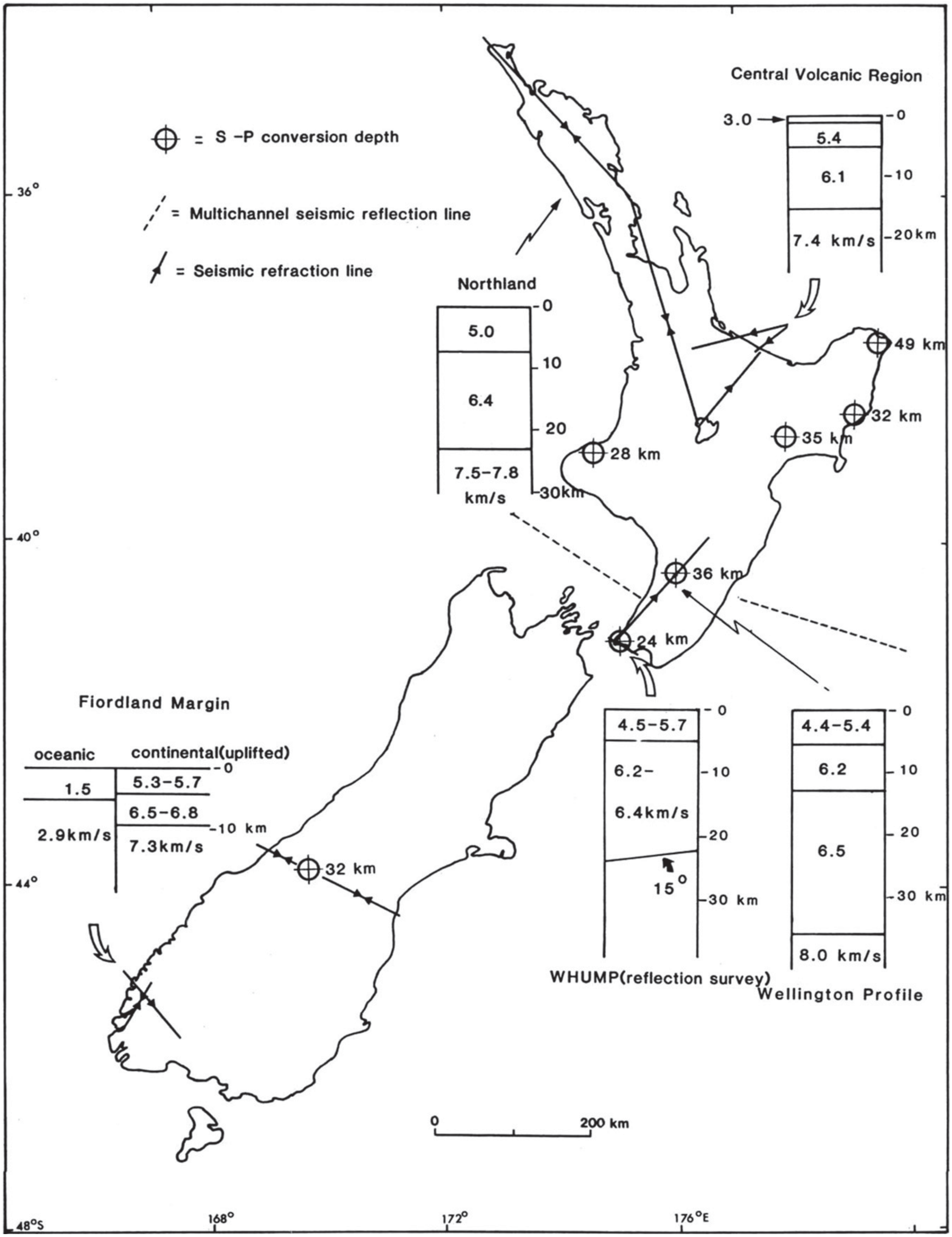


Figure 8.8.1-05.

(Fig. 8.8.1-05), extending across the central South Island from Timaru in the SW to the Pukaku Seismograph Network in the NE (Smith et al., 1995). Strong secondary arrivals were seen from both offshore shots and interpreted by a layer at 24 km depth with a true velocity of 7.2 km/s at the east coast dipping inland at 3.4°. Arrivals from a deeper layer with 8.3 km/s were only evident on the West Coast shot records. Assuming a true velocity of 8.0 km/s as determined from earthquake P_n data, the 7.2 km/s layer would be 11 km thick and its base dip with 2.9°. The extrapolated crustal thickness under the east coast would be 35 km.

8.8.2. South Africa

South Africa has seen some limited controlled-source seismology research in the 1980s. Durrheim (1986) reports on two shallow test seismic-reflection surveys up to 4 s TWT and a short 36-km-long refraction profile in 1982 in the Witwatersrand basin of South Africa that demonstrated successfully that the structure of supracrustal rocks, Proterozoic metamorphosed sediments and lavas, could be mapped and that the boundary between upper and middle crust could also seismically be recognized, being a relatively sharp transition zone (Durrheim, 1986). In 1988, a 112-km-long seismic-reflection profile was recorded across the Witwatersrand Basin that reached from the Ventersdorp dome at the northeastern edge across the Potchefstroom syncline to the center of the Vredefort dome in the center of the basin (Durrheim et al., 1991). The recording time was 16 s TWT. On the basis of contrasting seismic fabrics the crystalline basement could be subdivided into three domains, and it was suggested that a systematic mapping of such basement domains by reflection profiling might provide insights regarding processes responsible for localizing stratified basins. The northwestern portion of the profile showed a change in reflective character at ~12 s TWT, which was interpreted to mark the crust-mantle transition. The absence of a distinct "reflection Moho" suggested a smooth transition from crust to mantle of a depth range of a few kilometers. A seismic-reflection line recorded in 1985 off the Indian Ocean coast (Durrheim, 1987) is described in more detail in Chapter 8.9.3.

In 1987 and 1988, a reconnaissance seismic survey in Botswana (Fig. 8.8.2-01) was carried out by Petro Canada International Corporation on behalf of the government of Botswana (Wright and Hall, 1990). Shots were dynamite charges of 2–4 kg in each hole drilled 6 m deep in a six-hole pattern. Shotpoints

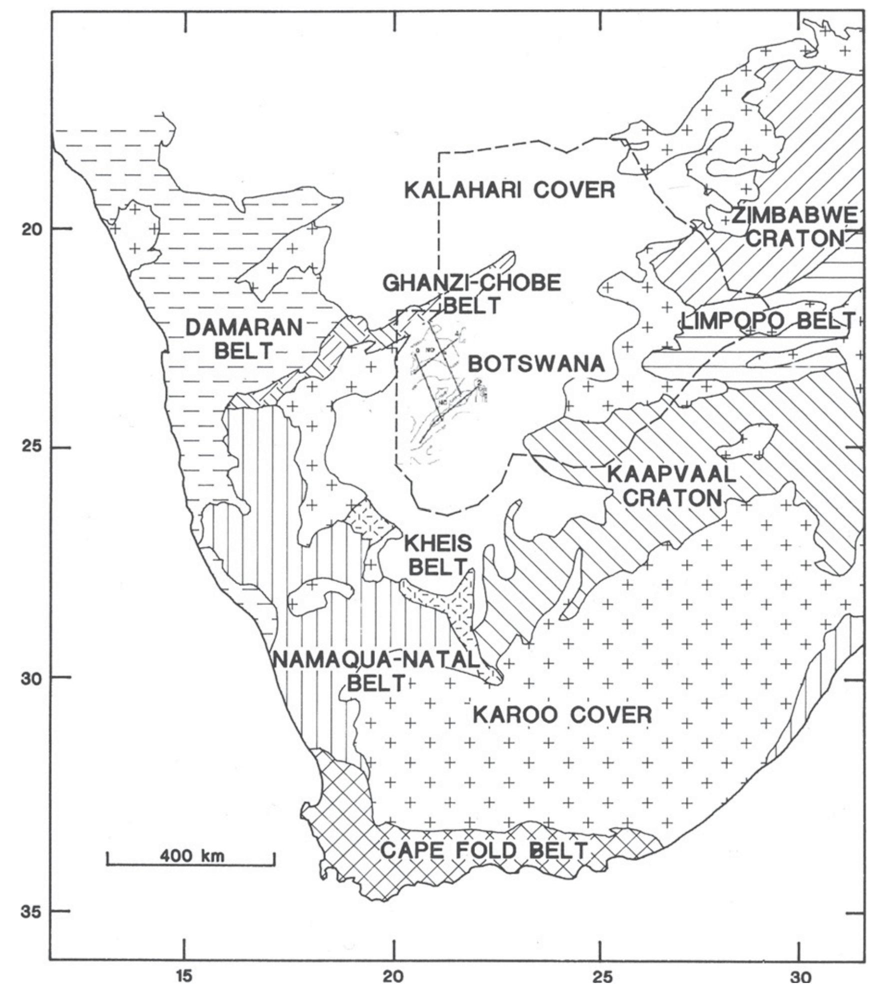


Figure 8.8.2-01. Map of South Africa showing location of deep seismic-reflection survey in the Kalahari desert in western Botswana (compiled from Wright and Hall, 1990, figs. 1 and 2). [Tectonophysics, v. 173, p. 333–343. Copyright Elsevier.]

were spaced such that a 15-fold common mid-point coverage could be obtained. The processed seismic sections covered a time range up to 15 s. In total 600 km of 12 fold data were obtained which showed good-quality reflections between 5 and 15 s TWT. An example is shown in Figure 8.8.2-02. The Moho ("base of crust" in Fig. 8.8.2-02) was tentatively traced piecewise on all lines at ~14 s TWT at the base of a reflective lower crust.

8.8.3. South America

In 1982, crustal research of the Andes in South America received a new impetus. Under the leadership of Peter Giese at the Free University of Berlin, Germany, the geoscientific interdisciplinary research group "Mobility of Active Continental Margins" was established, funded by the German Research Society from 1982 to 1989. This project centered on the Andes of Chile and enabled a variety of onshore and offshore seismic experiments.

The map in Figure 8.8.3-01 shows the location of seismic-refraction lines established in northern Chile and adjacent Bolivia and Argentina in the 1980s. In the first two expeditions in 1982 and 1984, the large explosions in the copper mine Chuquicamata were used as the energy source (Wigger, 1986) and three profiles with recording distances of 240–260 km to SW, S, and SE were successfully recorded in northern Chile. On a fourth profile to the east, reaching into southern Bolivia, seismic energy disappeared beyond 100 km distance.

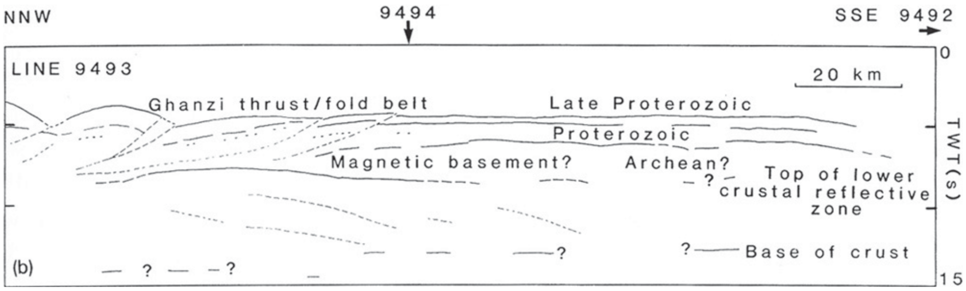


Figure 8.8.2-02. Schematic crustal cross section through the Kalahari Desert in western Botswana (from Wright and Hall, 1990, fig. 6) along line 9493, the eastern NNW-SSE deep seismic-reflection line. Line 9494 is the northern SW-NE line (see Fig. 8.8.2-01). [Tectonophysics, v. 173, p. 333–343. Copyright Elsevier.]

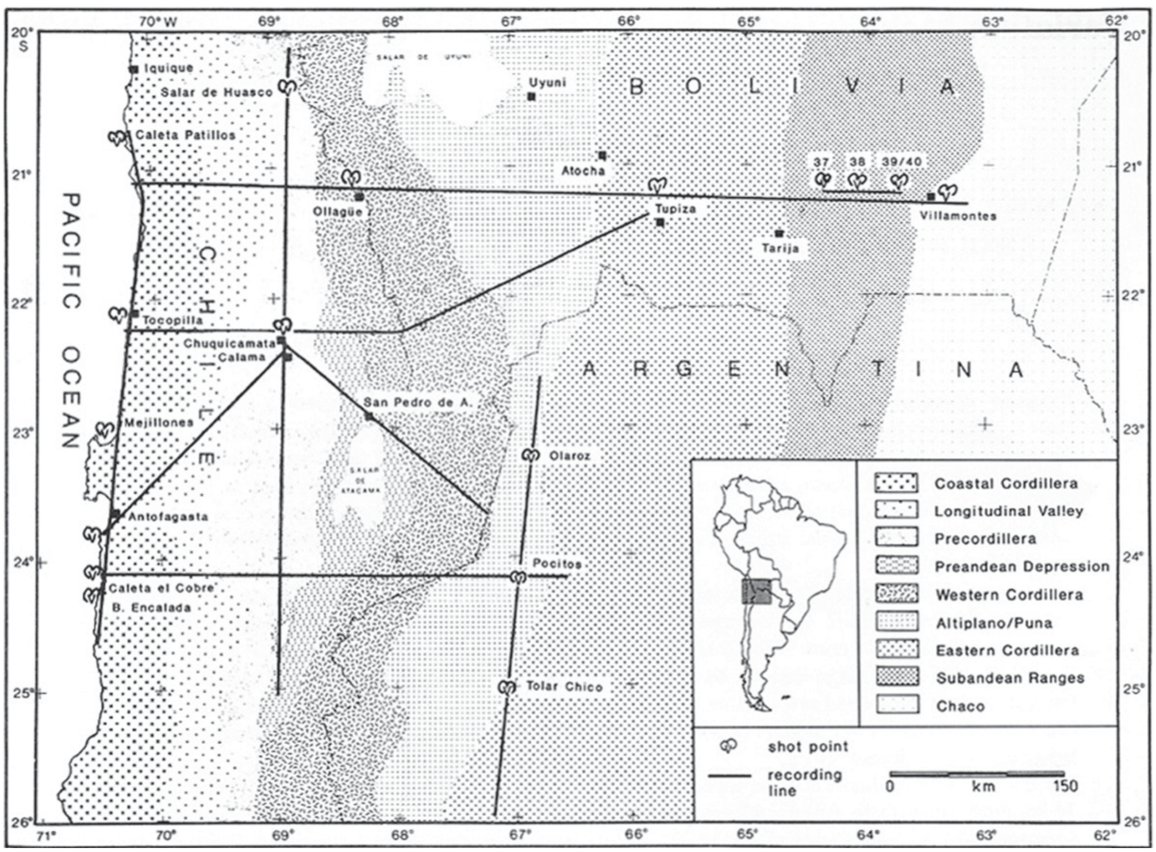


Figure 8.8.3-01. Map of northern Chile and Bolivia showing location of deep seismic refraction surveys from 1982 to 1994 between latitudes 20–25°S and 71–68°W (from Patzwahl, 1998, fig. 2.5). [Berliner Geowissenschaftliche Abhandlungen, Reihe B30: 150 p. Published by permission of Institut für Geologische Wissenschaften, Freie Universität Berlin.]

In 1987 and 1989, additional shotpoints were arranged, and additional profiles were recorded (Wigger et al., 1994). The aim was to obtain as many reversed observations as possible. Energy was primarily obtained by using large quarry blasts from various copper mines, but also some self-organized borehole shots were added. Such land shots, with charges between 500 and 2000 kg, were arranged in Chile as well as in Argentina and were detonated in salt lakes in patterns of shallow boreholes (10–30 m). In Bolivia, borehole shots in the eastern Cordillera and further east were fired.

Furthermore, underwater shots in the Pacific Ocean were arranged, fired by the Chilean navy close to the Chilean coast. The charges, ranging from 50 to 250 kg, were placed on the sea bottom at water depths between 57 and 80 m. The resulting pattern of profiles is shown in Figure 8.8.3-01. In total, 35 recording instruments were available; the average station spacing was between 5 and 10 km.

The data of the various projects carried out from 1982 to 1989 were collectively interpreted (Schmitz, 1993; Wigger et al., 1994). An E-W cross section for the Chuquicamata W-profile (Fig. 8.8.3-02) shows a complicated crustal structure for the forearc region, characterized by a sequence of high- and low-velocity regions, underlain by a dipping Moho from 40 km depth near the coast to more than 70 km depth under the Western Cordillera.

The Central Andean Transect (Wigger et al., 1991, 1994) at latitude 22°10′S displays the crustal and uppermost mantle structure from the Nazca Plate in the southwestern Pacific to the Chaco Plains in northern Argentina (Fig. 8.8.3-03).

8.8.4. Antarctica

With improved technology, extremely hostile areas such as Antarctica also came into reach of extensive seismic research projects. The seismic surveys of the Institute of Geophysics of the Polish Academy of Sciences, which had started in 1979 and 1980 to explore the structure underneath West Antarctica, con-

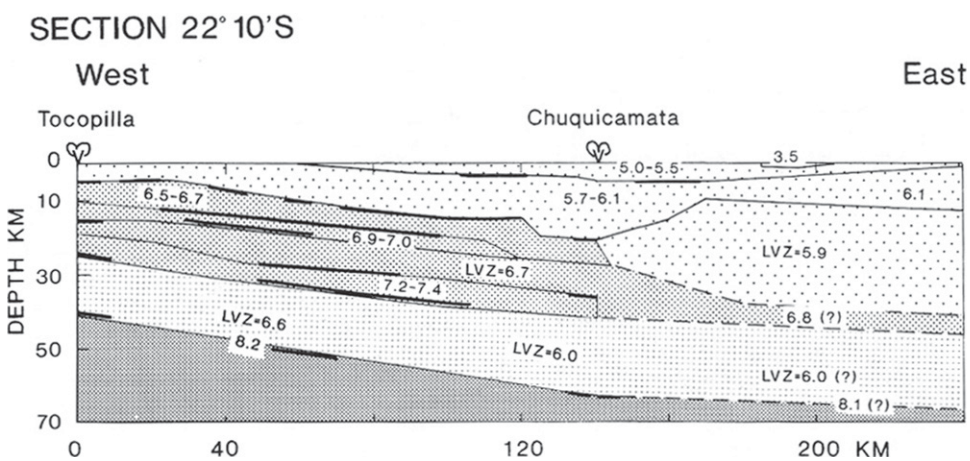


Figure 8.8.3-02. 2-D west-east crustal cross section at latitude 22°10′S of the forearc region in northern Chile (from Wigger et al, 1994, fig. 6). [*In* Reutter, K.-J., Scheuber, E., Wigger, P. eds.: Tectonics of the Southern Central Andes: New York, Springer, p. 23–48. Reproduced with kind permission of Springer Science+Business Media.]

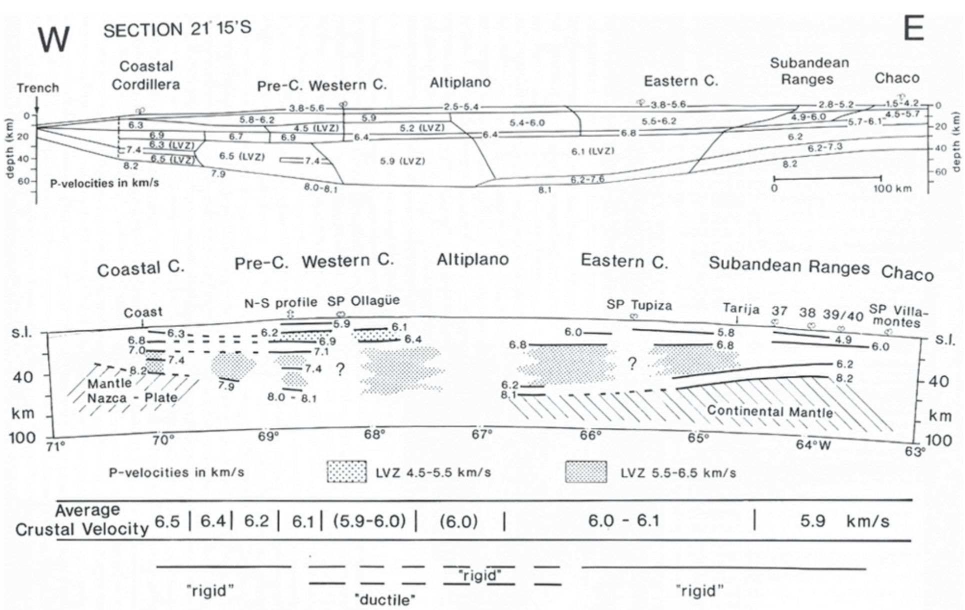


Figure 8.8.3-03. 2-D west-east crustal and upper mantle cross section at latitude 21°15′S from the Pacific Ocean through the Andes to the Chaco in Argentina, showing seismic discontinuities and P-wave velocities (from Wigger et al, 1994, fig. 18). [*In* Reutter, K.-J., Scheuber, E., Wigger, P. eds.: Tectonics of the Southern Central Andes: New York, Springer, p. 23–48. Reproduced with kind permission of Springer Science+Business Media.]

tinued in 1984–1985 and in 1987–1988 (Fig. 8.8.4-01; Janik, 1997). The area of the Bransfield Strait between the South Shetland Islands and the Trinity Peninsula was of particular interest, but a series of profiles was also recorded farther south along the western margin of the Antarctic Peninsula. Land stations on the islands and on the peninsula in the Bransfield Strait recorded shots along various profiles.

The shots, ranging in size from 16 to 144 kg, were detonated at 60 m water depth and were usually 5–7 km apart. Recording stations on land had 3–6 seismometers, spaced by 100–200 m. The resulting modeled velocities were high throughout the crust (Fig. 8.8.4-02). The so-called upper crust yielded already velocities up to 6.8 km/s. A particular result of the interpretation of the data was a high-velocity lower crustal layer with velocities above 7.4 km/s beneath the central subbasin of the Bransfield Strait, which could be separated from the remaining pre-rift mafic lower crust with velocities from 6.8 to 7.3 km/s. Total crustal thickness varied from 36 to 42 km in the coastal area and decreased to ~25–28 km toward the Pacific Ocean (Sroda et al., 1997).

The goal of the U.S. Louisiana State University since the early 1970s was to investigate the east-west boundary of McMurdo Sound at the southern end of the Ross Sea (McGinnis et al., 1985). Following a series of shallow seismic-refraction, magnetic and gravity studies, in 1980 an E-W reversed seismic-refraction profile was recorded between the Antarctica mainland and Ross Island, approximately from 164°30′ to 166°30′E and along latitude 77°45′S parallel to the ice shelf. The observations with maximum shot-to-receiver distances of 40 km provided the velocity distribution in the upper crust. Along this line, a common-depth point reflection profile was also obtained. Layered reflectors in the upper crust dipped and thickened to the east, away from the coast, down to a depth of ~7 s TWT, corresponding to 14–16 km depth. In 1981, a 200-km-long reversed seismic-refraction N-S–directed profile parallel to the coast followed. The interpretation resulted in a 5.0 km/s basement and a 6.5 km/s intracrustal unit, underlain by the mantle at ~21 km depth with a velocity of 8.2 km/s.

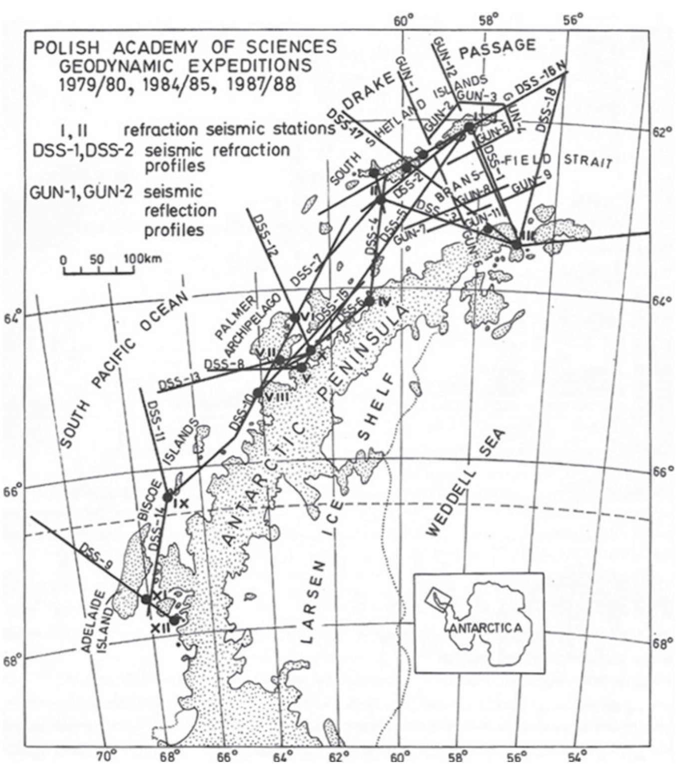


Figure 8.8.4-01. Location of deep seismic sounding lines (DSS), observed in the area of the Antarctic Peninsula from 1979 to 1988 (from Birkenmajer et al., 1990, fig. 2). [Polish Polar Research, v. 11, p. 241–258. Reproduced with permission of Polish Academy of Sciences, Warsaw, Poland.]

8.9. DEEP SEISMIC SOUNDING STUDIES IN THE OCEANS

8.9.1. Introduction

From the early 1980s onward investigation of the crustal structure focused on large dynamic ranges and dense spatial sampling. 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. Possible configurations of sources and receivers to collect offshore seismic data are shown schematically in a sketch (Fig. 8.9.1-01) by Trehu et al. (1989b).

In the 1980s the development of non-explosive sources had become effective enough to be successfully recorded over long ranges of several 100 km at sea and also, in onshore-offshore experiments, on land. In particular, reflection experiments dealing with the sedimentary structure at convergent margins were important for the interpretation concerning sediment subduction, subduction erosion, and the growth of the continental crust (von Huene and Scholl, 1991).

The technique was described in much detail by Jones (1999) in a textbook which corresponds to the technical status available by the end of the 1990s. However, airguns of great power were in use since the early 1980s, in the earlier years possibly with fewer technical refinements than in the 1990s, depending on the actual state of technical development.

Airguns produce a wide range of pulse shapes and source spectra. A most important feature of any energy source is the repeatability of its signature over many firings which turned out to be a major advantage with ongoing progress in data processing. The outputs can be monitored with a deep-towed hydrophone or, more conveniently, with near-field hydrophones, ~1 m from the gun, whose outputs allow the calculation of the far-field waveform. To provide broadband output signals every 10–15 s, airguns of various sizes were grouped in arrays. Typically, two source arrays are towed at depths of 3–10 m and are alternately fired. The gun positions are monitored by hydrophones which receive pulses from a high-frequency transducer (50–100 kHz) close to the ship and/or, later in the 1990s, by a GPS receiver in a head buoy. Several tens of airguns with a total volume of 100 l or more were used for deep seismic profiling, for example, by BIRPS, ECORS, BABEL and CROP (Avedik et al., 1993; BABEL Working Group, 1991; Klemperer and Hobbs, 1991).

Nevertheless, for many marine projects, the use of explosives was not yet out of range. Some projects used both energy sources either to ensure general success or to use the explosive shots to provide enough energy for the larger distance ranges. Also, tests have been made to apply a special technique in which explosives are used with a much less damaging effect. Orcutt (1987) has described new experiments where, e.g., ocean bottom seismometers and seismic sources were placed near the seafloor

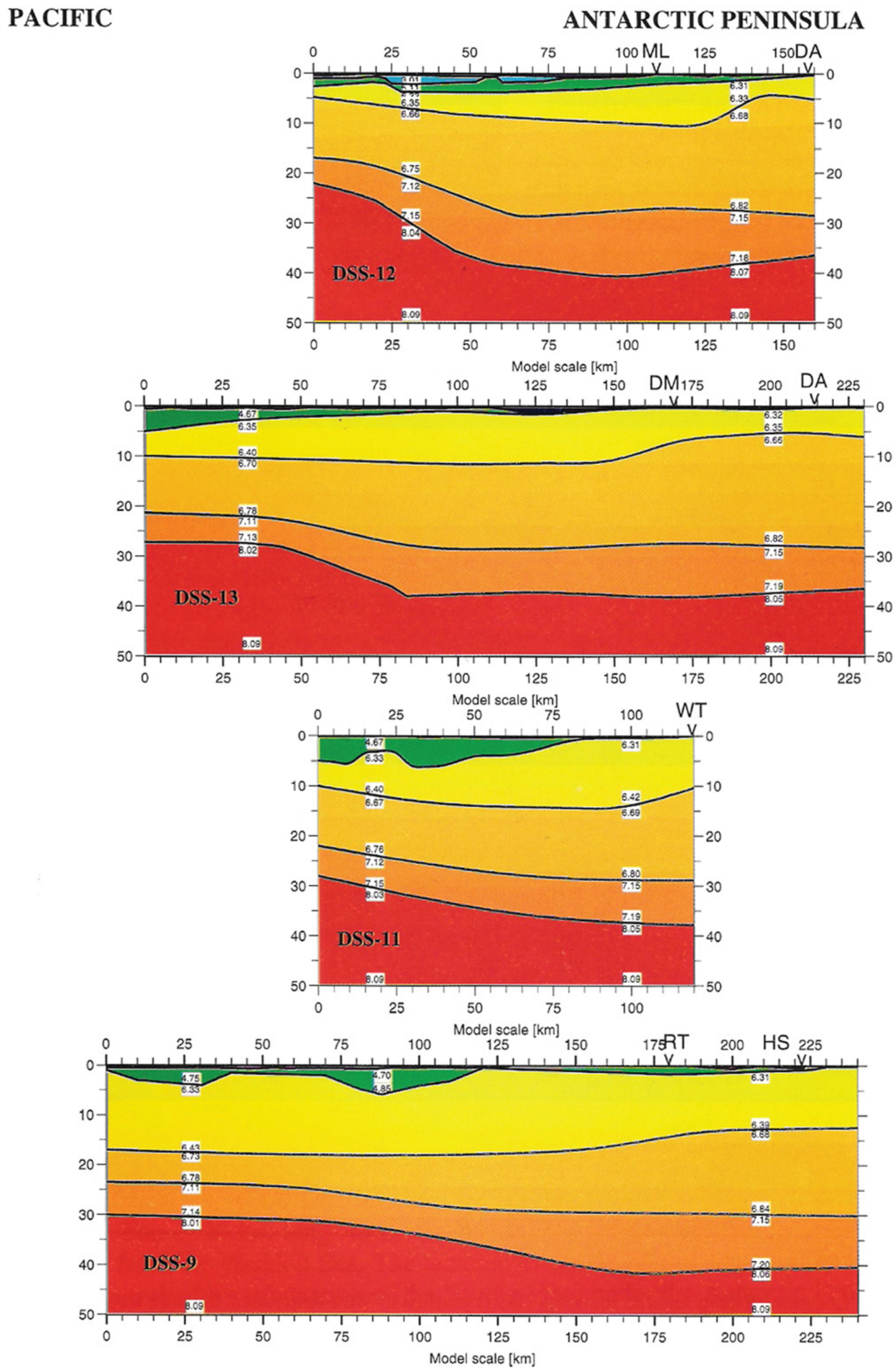


Figure 8.8.4-02. Crustal structure of profiles DSS-12, -13, -11, and -9 crossing the northwestern margin of the Antarctic Peninsula (from Guterch et al., 1998, fig. 6). [Polish Polar Research, v. 19, p. 113–123. Reproduced with permission of Polish Academy of Sciences, Warsaw, Poland.]

(e.g., Purdy, 1986) or multichannel streamers and low frequency sources towed near the seafloor (e.g., Fagot, 1986).

Kirk et al. (1991) have also devised a technique for firing arrays of bottom shots on the ocean bed in depths of 4000 m and more. Ten-kg charges were dropped from the surface while the shooting ship was navigated acoustically. The charges were fired at preset times by an electric timer which initiates an electrical detonator, detonating cord and cast TNT explosives. The ranges to OBS could be calculated from the arrival-time difference of the direct and surface-reflected water waves. Experiments were carried out in 1989 at six sites in the Norwegian Sea at depths of 1500 m and 3900 m. It was possible to obtain regularly spaced traces 200–300 m apart along bottom profiles up to 4 km in length. It was possible to determine the shot-receiver ranges with an accuracy of better than 22 m and shot instants to within 14 msec.

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 with strings of hydrophones which suffered also from the noise produced by the towing ship. While in the 1970s, the use of ocean-bottom seismometers very often was part of the title of a subsequent publication, in the 1980s, ocean-bottom seismographs became practically a standard of deep seismic sounding projects at sea (e.g., Kirk et al., 1982; Whitmarsh and Lilwall, 1983; Duschenes et al., 1985; Nakamura et al., 1987; Moeller and Makris, 1989; Jones, 1999).

Nevertheless, for the exploration of the sedimentary part of the oceanic crust, reflection measurements by a string of towed hydrophones has become the standard practice of any commercial or scientific marine experiment. The hydrophones are packed in streamers or cables and form a hydrophone array. Most towed arrays are multichannel receivers. They are divided into sections which are recorded separately. With developing techniques, the number of channels in a streamer increased, and streamer or cable lengths up to several kilometer lengths could be used to be towed by a ship (Jones, 1999). Techniques were also developed to place multichannel hydrophone arrays on the sea bottom (e.g., Powell et al., 1986).

The Ocean Drilling Project (ODP) continued into the 1980s. The *Challenger* was retired in 1983, and for the succeeding Ocean Drilling Program JOIDES, again with NSF funding, a more advanced drillship was converted from industrial use and rechristened to *JOIDES Resolution*. From 1985 to 2003 this vessel travelled almost nonstop around the world drilling 650 more holes on 110 more legs. By ODP's end the program included more than 20 nations (Alden, 2010).

The theory for the calculation of synthetic seismograms was also developed further. A short overview was published by Chapman and Orcutt (1985). The use of synthetic seismograms in the interpretation of refraction data, also for marine seismic surveys, had been introduced in the 1970s and was well established in the 1980s. Following the pioneering papers of Helmberger (1968) and Fuchs and Müller (1971), the Cagnard-de Hoop-Pekeris and reflectivity methods were widely used to compute synthetic seismograms. Seismic models were iteratively refined to obtain a reasonable fit between the synthetics and the observed data. The procedure was also extremely successful for marine seismic data (Spudich and Orcutt, 1980), but was usually tedious and expensive. Subsequently, attempts were made to automate the inversion process (Chapman and Orcutt, 1980, 1985; Mellman, 1980; Given and Helmberger, 1983; Shaw and Orcutt, 1985). At the same time, the basic theory of the ray method in seismology had been formulated (Červený et al., 1977), and first computer routines to calculate traveltimes and ray paths for lateral inhomogeneous media (e.g., Červený and Horn, 1980; Gebrande, 1976; Will, 1976) as well as to compute ray theoretical seismograms (Červený, 1979; Červený and Pšenčik, 1984a; McMechan and

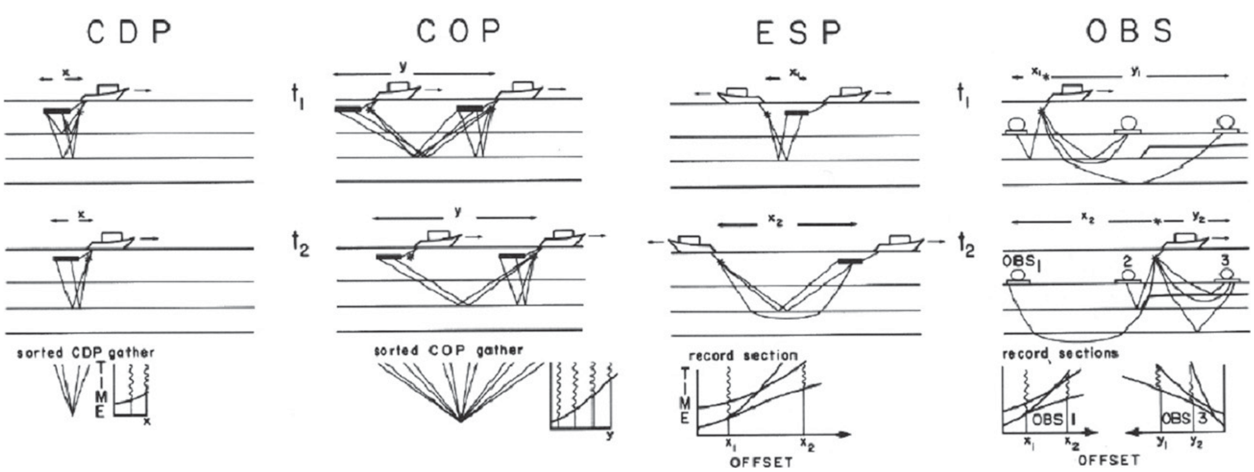


Figure 8.9.1-01. Source-receiver configurations to collect offshore seismic data (from Trehu et al., 1989b, fig. 4). CDP—common depth point, COP—constant offset profile, ESP—expanding spread profile, OBS—ocean bottom seismometer. [*In* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 349–382. Reproduced by permission of the Geological Society of America.]

Mooney, 1980; Spence et al., 1984) had been published. The following decade of the 1980s saw the systematic application of ray tracing methodology for 2-D interpretations of seismic-refraction surveys used for marine seismic data as well.

A similar approach, as was attempted by Kempner and Gettrust (1982a, 1982b) was published by Collins et al. (1986). They calculated 2-D synthetic seismogram profiles of the inferred fossil oceanic crust-mantle transition observed in the Bay of Islands ophiolite complex of western Newfoundland (Salisbury and Christensen, 1978; Christensen and Salisbury, 1982). To simulate a seismic-reflection experiment, they calculated near-vertical incidence seismograms at a horizontal spacing of 500 m for three separate sections of the ophiolite totaling 64 km in length. Multichannel seismic data from both the western Pacific and the western North Atlantic showed Moho traveltimes similar to those observed in the synthetic profiles, suggesting that the structures observed in the inferred fossil crust-mantle transition of the ophiolite were characteristic of oceanic lithosphere.

With advanced techniques, the number of marine seismic experiments carried out in the past three decades since the beginning of the 1980s literally exploded. As we have pointed out in Chapter 1, it is far beyond our ability to aim for a similar completeness of marine seismic projects as we may have achieved for land-based deep seismic crustal projects. Rather, we will restrict ourselves to a selected number of marine seismic projects and will describe them in some detail in the following subchapters.

Furthermore, many marine seismic projects were already described in previous sections of this chapter. This concerns in particular the large national marine seismic-reflection campaigns of BIRPS, ECORS, BABEL, and CROP in subchapter 8.3 which have exclusively investigated continental crust covered by shallow waters. For other marine seismic projects which were carried out in the Mediterranean and in the Red Sea as well as in the North and Baltic Seas, the reader is referred to the corresponding sections. Furthermore, some of the projects which investigated continental margin areas around Africa, Canada, Japan, New Zealand, Australia, South America, or Antarctica, were already described above in the corresponding sections of subchapters 8.3 to 8.8, if they were connected with a strong land component. In the following description of active-source experiments carried out in the 1980s in the Pacific, Indian, and Atlantic Oceans, we will follow again a more or less geographic order.

8.9.2. Pacific Ocean

Besides local investigations in specially defined areas, which will be described further below, Neprochnov (1989) has reported on a bulk of seismic data which were assembled at a worldwide study of the lower crust and upper mantle using OBSs and big airguns, performed by the Shirshov Institute of Oceanology in the period from 1977 to 1984 (Fig. 8.9.2-01). While the first cruises from 1977 to 1979 had concentrated on the central Pacific Ocean (K24, M21 to M23 in Fig. 8.9.2-01), the cruise 29 in 1982 emphasized research in the North Pacific Ocean (M29 in Figs. 8.9.2-01 and 8.9.2-02).

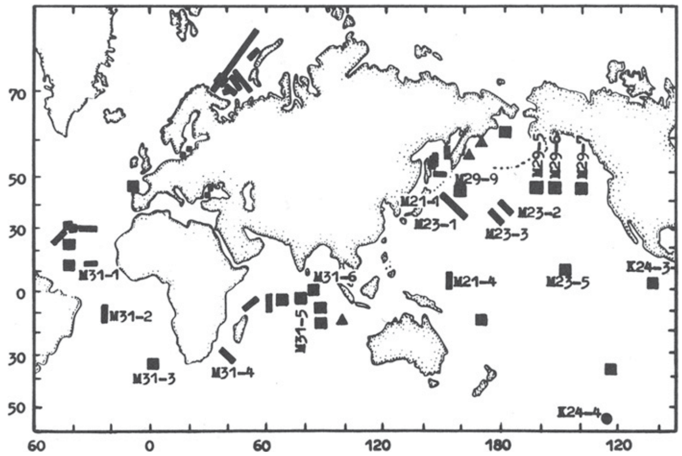


Figure 8.9.2-01. World map showing locations of deep seismic sounding experiments made in expeditions of the Shirshov Institute of Oceanology using OBS and big airguns (from Neprochnov, 1989, fig. 2). Triangles—single OBS, rectangles—several OBS along one profile, square—system of profiles in different directions, long solid lines—geotraverse with a number of OBS. [*In* Mereu, R.F., Mueller, St., and Fountain, D.M., eds., Properties and processes of earth's lower crust: American Geophysical Union, Geophysical Monograph 51, p. 159–168. Reproduced by permission of American Geophysical Union.]

The Juan de Fuca Ridge, located off western North America between latitudes 44° and 52°N and separating the large, modestly sedimented Pacific plate from the small, broken up Juan de Fuca plate, was the subject of several projects in the 1980s.

In 1981, multichannel seismic-reflection profiles were recorded at the southern Juan de Fuca Ridge (Morton et al., 1987). Two profiles perpendicular to the axis crossed the rift at latitudes 44°40′N and 45°05′N. A third line ran along the ridge axis from latitude 45°20′N to south of the intersection with the Blanco Fracture Zone. A weak reflection centered beneath the axis was found at a depth similar to seismically detected magma chambers on the East Pacific Rise (e.g., Detrick et al., 1987).

Later in the 1980s a multichannel seismic-reflection survey (Rohr et al., 1988) collected data by means of a 3000 m long, 120 channel streamer and a 50-l airgun array. As supposed, the deep crustal structure proved to be highly asymmetric. Moho was found to exist at ~6.6 km depth below the sea floor within 4 km of the rift valley on the Pacific plate, in contrast to the Juan de Fuca plate, which showed a reflector at intermediate depths dipping away from the rise to reach Moho depth 12 km from the rift valley.

In 1990, the Juan de Fuca Ridge was investigated by a seismic-refraction experiment conducted with airguns and OBSs at 45°N at the northern Cleft segment and the overlapping rift zone between the Cleft and Vance segments (McDonald et al., 1994). Four OBSs, deployed twice, recorded airgun shots along 700 km of track lines, divided up into three ridge-parallel, one diagonal, and three ridge-perpendicular lines. Seismic velocity anisotropy

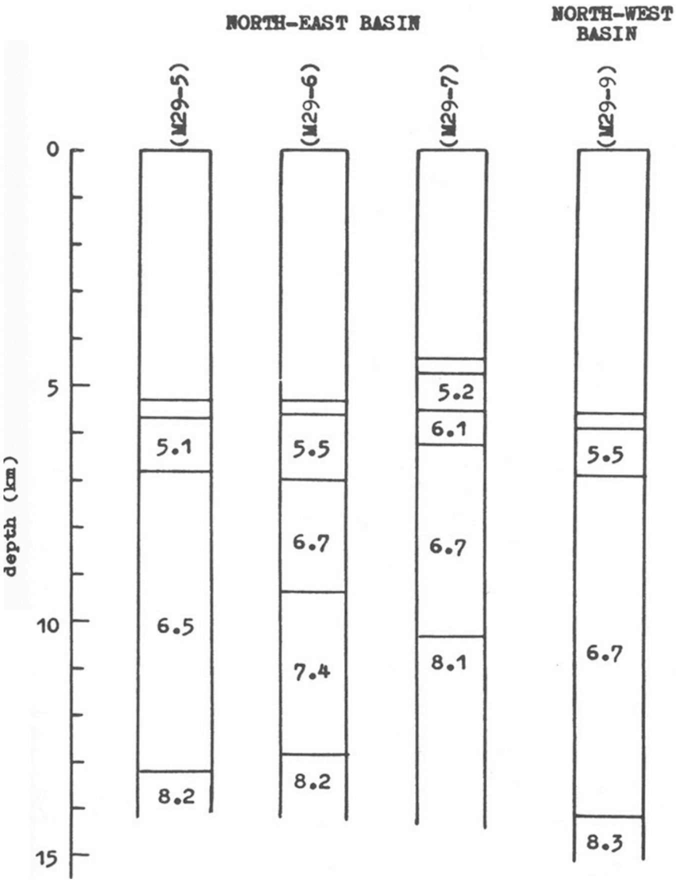


Figure 8.9.2-02. Averaged crustal columns for seismic surveys during the 29th cruise of R/V *Dmitry Mendeleev* (from Neprochnov, 1989, fig. 4). [*In* Mereu, R.F., Mueller, St., and Fountain, D.M., eds., Properties and processes of earth's lower crust: American Geophysical Union, Geophysical Monograph 51, p. 159–168. Reproduced by permission of American Geophysical Union.]

was observed, being confined to the upper 500 m or less of the oceanic crust, the ridge-parallel velocity being ~3.35 km/s and the ridge-perpendicular velocity ~2.25 km/s.

An overview on shallow seismic-reflection surveys performed along the continental margins of California and Baja California as well as in the Gulf of California until the end of the 1980s is contained in the Memoir of Dauphin and Simoneit (1991).

One of the deep sea boreholes, drilled by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP), the Hole 504B on the southern flank of the Costa Rica rift in the eastern equatorial Pacific, provided an opportunity to directly establish the geological nature of the boundary between seismic layers 2 and 3 in the oceanic crust. Since 1979, drilling on seven different DSDP and ODP legs enabled the progressive deepening of hole 504B, to 2111 m below the sea floor and more than 1800 m into the igneous crust, placing it near the expected depth of the layer 2/3 boundary. Seismic experiments were carried out in and around the hole over 15 years since drilling had started. Sonic velocity logs resulted in P-wave velocities from 4 to 6 km/s in the upper 600 m and an increase to more than 6 km/s near 1000 m depth. By 1.3–1.4 km depth velocities reached 6.5 km/s. Based on these observations the top of the seismic layer 3 was placed just above the base of the hole at 1.8 km depth. The available seismic-refraction data from around this hole were reexamined by Detrick et al. (1994). The authors concluded that the seismic layer 2/3 boundary lies within a sheeted-dyke complex and is associated with a gradual downhole change in crustal porosity and alteration and is not a lithological transition from sheeted dykes into gabbro.

Various experiments carried out in the 1970s on the Pacific Rise crest had provided the first geophysical data which could be explained in terms of a crustal magma chamber associated with the genesis of oceanic crust (e.g., Orcutt et al., 1975). Therefore, in order to unambiguously constrain the depth and lateral extent of the crustal magma chamber, in 1982 an extensive seismic-refraction experiment (MAGMA) was conducted on the East Pacific Rise at 12°50′N (Orcutt et al., 1984). The MAGMA experiment utilized OBSs at three sites to record the near-surface explosive sources. The sites were located on the ridge (age = 0), 6 km to the east (age = 0.11 Ma), and 16 km east (age = 0.30 Ma). In a first phase, a grid of short, 15–17-km-long lines were shot using small charges (0.5–1.5 kg) and a shot spacing of ~230 m, to provide a dense areal coverage of the upper crust at the ridge axis and adjacent areas. In a second phase, larger shots (8–150 kg) were placed at 900 m spacing covering an expanded 2-D grid. Investigating the refracted arrivals parallel to the rise crest, Orcutt et al. (1984) attributed the attenuation of seismic arrivals beyond a range of 10–12 km to a shadow zone created by the interaction of seismic waves with a low-velocity zone and interpreted it as evidence for a crustal magma chamber at most 1.5 km below the seafloor.

Detrick et al. (1987) reported on a new experiment in 1985 across the East Pacific Rise near 9°N, based on multichannel seismic imaging of a crustal magma chamber along the East Pacific Rise by Herron et al. (1978), because the shape, longevity, and along-strike variability of ridge-crest magma chambers had remained the subject of considerable controversy. This experiment was a much more extensive two-ship multichannel seismic survey of the East Pacific Rise between 8°50′N and 13°30′N and was designed to provide new information on the shape and dimensions of the axial magma chamber and to investigate how the magma chamber varies along the rise axis over distances of tens to hundreds of kilometers. More than 3500 km of conventional, 48-channel common-depth point (CDP) seismic-reflection data were obtained including 30 new profiles across and a series of CDP reflection lines along the crest of the East Pacific Rise. The seismic velocity structure of the crust and upper mantle in the axial region was obtained using the two-ship expanding spread profiling (ESP) techniques. The ESPs were oriented parallel to the rise and were shot using airguns as well as explosives. In the 9°N area, ESPs were shot on the rise crest as well as 5 km away on either side of the crest. In the 13°N area, ESPs were located within 3.6 km of the rise axis. As a result, a reflection observed on the multichannel profiles along and across the East Pacific Rise was interpreted as to arise from the top of a crustal magma chamber located 1.2–2.4 km below the seafloor. The magma chamber appeared to be quite narrow (less than 4–6 km wide), but could be traced as a nearly continuous feature for tens of kilometers along the rise axis (Detrick et al., 1987). The data were further interpreted in more detail in subsequent papers (Collier and Singh, 1997, 1998; Kent et al., 1993; Vera et al., 1990; Vera and Diebold, 1994). Orcutt (1987) has published a review on experiments in the Pacific Ocean dealing with various aspects of marine crustal research.

Toomey et al. (1990) described a marine seismic survey investigating the 3-D seismic velocity structure of the East Pacific Rise near latitude 9°30′N, encompassing a 12-km-long linear rise segment trending north-south. The project involved 15 ocean-bottom instruments which recorded energy from 480 explosive shots and from several airgun profiles, yielding more than 12,000 seismic records. They found pronounced heterogeneity over distances of a few kilometers. A linear, 1–2-km-wide high-velocity anomaly, centered on the rise axis, was seen to be restricted to the uppermost 1 km of the crust. Consistent with a zone of higher crustal temperatures an axial low velocity zone was found at 1–3 km depth which they interpreted as injections of mantle derived melt.

A two-ship seismic experiment near the Hawaiian islands Oahu and Molokai investigated the lithospheric flexure across the Hawaiian-Emperor seamount chain in 1982 (Watts et al., 1985). The single-ship multichannel reflection profiling techniques was used to determine the configuration of individual crustal layers and the Moho; the two-ship techniques served to obtain the detailed velocity structure of the crust and upper mantle. Both large airgun and explosive shots were fired into the streamers of both ships. The seismic experiment involved normal incidence CDP data, constant offset profiles (COPs), and eleven ESPs obtained across a 600-km-long, 100-km-wide transect of the Hawaiian ridge centered near Oahu. While shooting the COP, the two vessels maintained a constant distance apart of 3.6 km and both ships alternately fired their airguns every minute. During the ESP, the two vessels separated from other, one ship shooting the airgun, the other receiving up to the end of the 65–90-km-long lines and then reversed shooting and receiving when returning along the same profile. During the ESP shooting, at the same time a CDP profile was obtained by one of the ships which was equipped with a 3.6-km-long seismic engineering multichannel streamer with 48 active channels. In a following second part of the experiment a similar sequence of COP/ESPs was completed between the Molokai channel and the arch to the north. The principal result was a total crustal thickening from 6.5 to 6.8 km beneath the Hawaiian arch to 18–19 km beneath the ridge, and that the flexed oceanic crust underneath the Hawaiian Emperor seamount chain is underlain by a 4-km-thick deep crustal body which was interpreted as a deep crustal sill complex associated with the tholeiitic stage of volcano building along the chain (Watts et al., 1985). Some of the ESP record sections were interpreted by Lindwall (1988) in detail to obtain 2-D models of the entire crust of the volcanoes and the underlying oceanic crust near Oahu, of the southeastern submarine flank of Kauai, and of the ridge axis between Oahu and Molokai.

Other experiments dealt with the verification of thin oceanic crust under fracture zones (e.g., Cormier et al., 1984; see subchapter 8.9.4).

Data of the 1983 Ngendei experiment (Orcutt et al., 1983) in the South Pacific (23.82°S, 165.53°W) helped Shearer and Orcutt (1985) investigate the problem of anisotropy in the oceanic crust. The site was ~1000 km east of the Tonga trench and 1500 km WSW of Tahiti. The oceanic lithosphere here is estimated to be ~140 m.y. old, one of the oldest areas in the Pacific. The Scripps Institution of Oceanography shot four split refraction profiles with azimuth spacing of 45° and a circular line of 10 km radius. All of the lines were recorded by at least two ocean-bottom seismometers, and two of the lines were recorded by a borehole seismometer, emplaced 124 m in DSDP Hole 595B by the *Glomar Challenger* on DSDP Leg 91. The analysis of the data indicated anisotropy at two levels in the oceanic lithosphere. In the upper mantle, P-wave velocities varied between 8.0 and 8.5 km/s, with the fast direction at N30°E. Crustal anisotropy was seen within layer 2 with velocity differences of 0.2–04 km/s, with the fast direction at N120°E, orthogonal to the mantle anisotropy.

In 1982 and 1984, a bright midcrustal reflector was seismically imaged beneath an active backarc spreading center, the Valu Fa Ridge, in the Lau Basin of the SW Pacific (Morton and Sleep, 1985), between the Fiji Islands and the Tonga Trench. The data consisted of a grid of seismic normal incidence and wide-angle reflection profiles located at 22°10′–22°30′S, 176°35′–176°50′W. The bright reflector was coincident with a velocity inversion at a depth of 3.2 km below the seafloor and was observed on every one of the 40 across-axis profiles. It was interpreted as the top of a crustal magma chamber. The widest magma chamber reflector occurred beneath the overlapping spreading center, where it extended up to 4 km and was imaged beneath both ridges and the overlap basin (Collier and Sinha, 1992).

A project dealing with the investigation of the Society Islands hotspot in 1989 (Grevemeyer et al., 2001b) is described in the context of follow-up projects in Chapter 9.8.2.

Various projects have dealt with the ocean-continent transition at continental margins. In particular, around Japan various marine projects were carried out. Seismic profiling crossing the trench axis was started in 1983 at the southernmost part of the Kuril trench off Hokkaido, Japan, from which a detailed subduction structure of the Pacific plate was delineated for the first time (Nishizawa and Suyehiro, 1986; Iwasaki et al., 1989). In 1984 and 1988, a German-Japanese cooperative project with refraction profiling was undertaken in the northern part of the Ryukyu trench area. The development of the pop-up type ocean bottom seismographs led to dense receiver spacing (10–20 km) along 190- and 295-km profile lines. This enabled delineation of subduction and accretion structure near the trench axis and also proved that crustal thinning was associated with the backarc spreading of the Okinawa trough (Iwasaki et al., 1990; Kodaira et al., 1996). These results provided the breakthrough for imaging a subducted plate boundary beneath the NE and SW Japan arcs.

In the vicinity of the northern Japan Trench, seismic reflection, two-ship refraction, and OBS refraction data, mostly by airgun shooting, were collected in particular in the 1980s (Fig. 8.9.2-03) and a summary of their interpretation of the seismic velocity structure beneath the forearc of the Tohuku subduction zone was published by Suyehiro and Nishizawa (1994). The area of study extended from the trench axis to the Tohuku coast, ~200 km from the trench. The interpretation revealed that the Pacific crust gradually increases its dip to ~7°, 110 km landward of the trench axis. The basic results are shown in Figure 8.9.2-04. Low-velocity material with 3 km/s is likely to the present-day accretionary prism consisting of unconsolidated sediments. A corresponding onshore investigation by Iwasaki et al. (1994) is described above in the subchapter 8.7.3 (Japan).

The continental margins around Australia became a special target of marine seismic profiling from 1985 to 1989 by the research ship *Rig Seismic*. The vessel had been leased in 1984 by the Australian government to conduct seismic profiling and other geological research of the structure and architecture of the offshore sedimentary basins. At that time *Rig Seismic* was one of a few vessels worldwide which was capable of undertaking a full range of geoscientific data collection including multichannel seismic data (Finlayson 2010; Appendix 2-2).

The first cruise of *Rig Seismic* in 1985 targeted the Lord Howe Rise in the central Tasman Sea, and in cooperation with

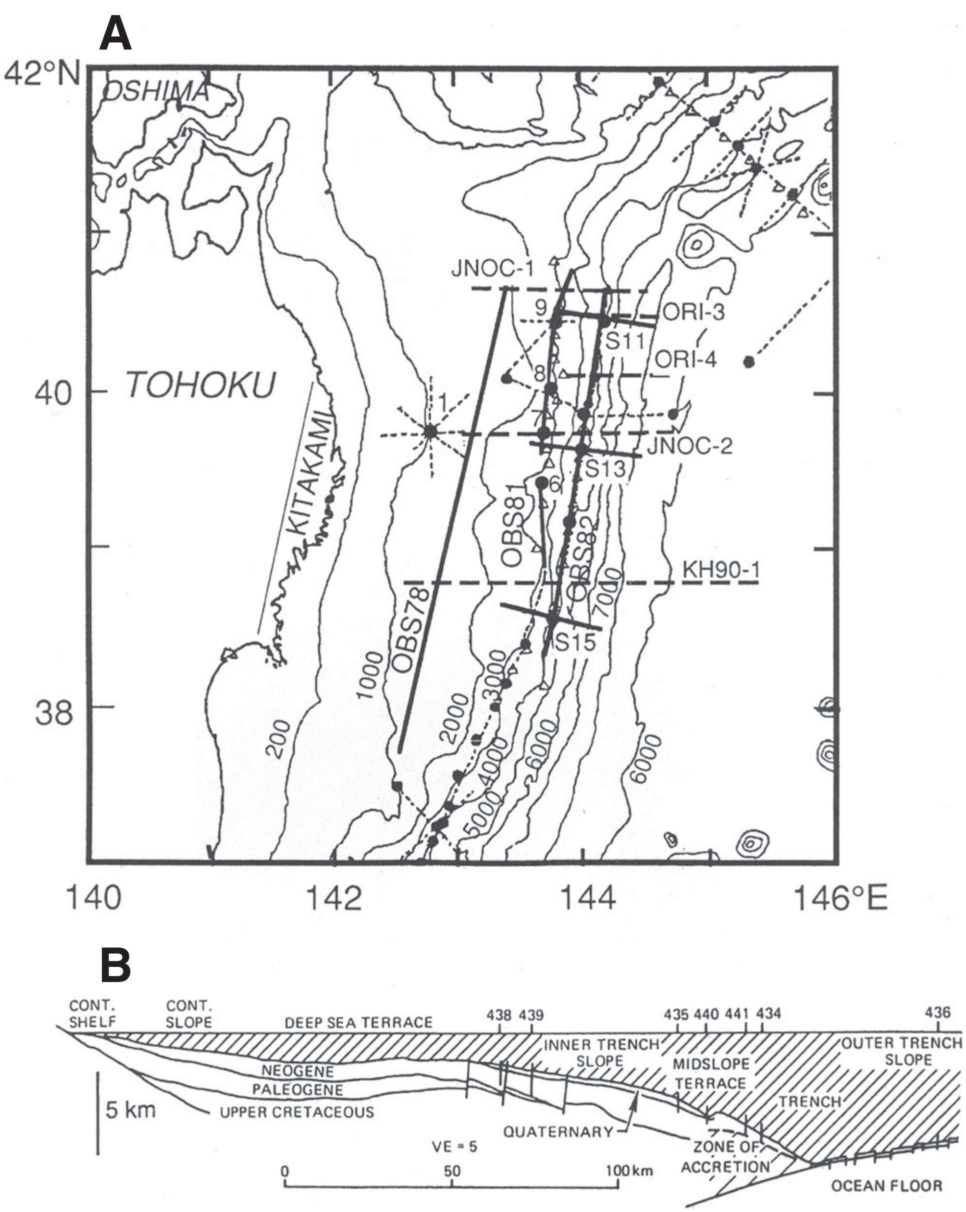


Figure 8.9.2-03. Japan Trench area (from Suyehiro and Nishizawa, 1994 Figure 2). (A) Map showing seismic lines observed from 1978 to 1990. Thick dashed lines—multichannel seismic recording lines, thick solid lines—OBS lines, discussed in detail by the authors, thin dashed lines—other OBS data, solid circles—OBS locations, open triangles—dynamite shotpoints. (B) Schematic explanatory section across northern Japan and adjacent trench. Numbers 436 to 441—DSPD drilling sites. [Journal of Geophysical Research, v. 99, p. 22,331–22,347. Reproduced by permission of American Geophysical Union.]

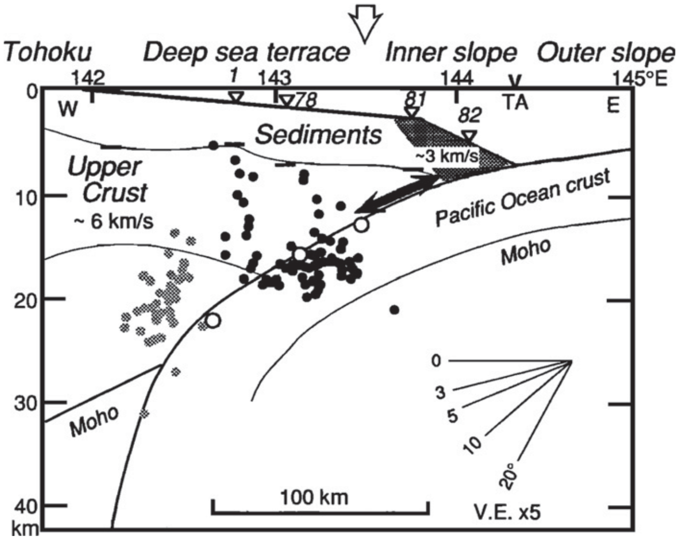


Figure 8.9.2-04. Cross section of the northern Japan Trench area with important structural boundaries and seismicity (from Suyehiro and Nishizawa, 1994, fig. 15). [Journal of Geophysical Research, v. 99, p. 22,331–22,347. Reproduced by permission of American Geophysical Union.]

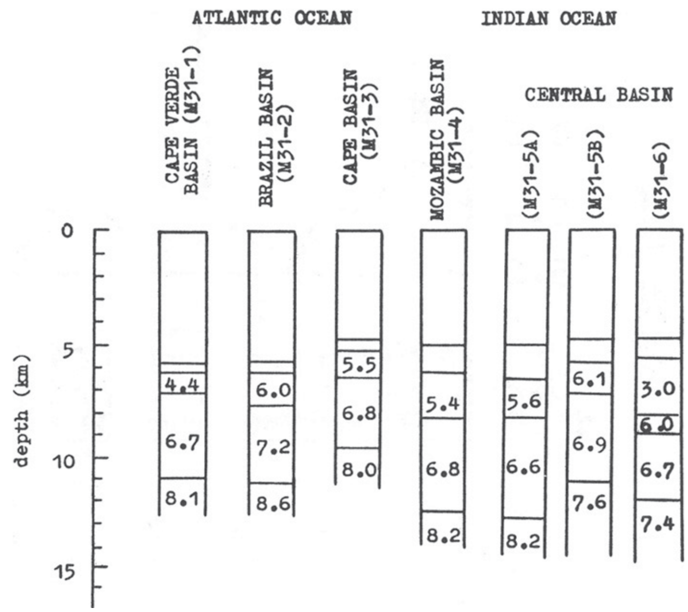


Figure 8.9.3-01. Averaged crustal columns for seismic surveys in the Indian and Atlantic Oceans during the 31st cruise of R/V *Dmitry Mendeleev* (from Neprochnov, 1989, fig. 5). [*In* Mereu, R.F., Mueller, St., and Fountain, D.M., eds., Properties and processes of earth's lower crust: American Geophysical Union, Geophysical Monograph 51, p. 159–168. Reproduced by permission of American Geophysical Union.]

the German R/V *Sonne*, 1250 km of seismic-reflection data were acquired ~200 km southeast of Lord Howe island. In 1985 and 1987, the cooperative two-ship research of *Rig Seismic* and *Sonne* continued in the offshore part of the Otway Basin off southern Victoria, Australia, collecting ~3500 km of multichannel seismic data (e.g., Williamson et al., 1989). In 1986, the Great Australian Bight off Victoria and South Australia was investigated by two cruises, collecting 3500 km of seismic profiling data. Several cruises of *Rig Seismic* targeted the continental margins of northeast Queensland in 1985, 1987, and 1989, and from 1987 to 1989 the Lord Howe Rise was again visited, collecting seismic data over the Gippsland Basin, Lord Howe Rise, and Tasman Basin. In 1988, 1750 km of multichannel seismic data were also collected along a survey targeting the western margin of Tasmania and the deep abyssal plain of the Southern Ocean (Finlayson, 2010; Appendix 2-2). Other cruises of the AGSO vessel *Rig Seismic* investigating the western continental margins of Australia are being discussed in the following subchapter 8.9.3.

8.9.3. Indian Ocean

Rounding South Africa, cruise 31 of R/V *Dmitry Mendeleev* of the Shirshov Institute of Oceanology from 1983 to 1984 covered both the South Atlantic Ocean and the Indian Ocean. In 1984, it had reached the Indian Ocean (Neprochnov (1989). Here, one profile with three OBS was shot in the Mozambique basin and five profiles with 12 OBS deployments in the central basin south of India (see Fig. 8.9.2-01). The results are shown as crustal columns in Figure 8.9.3-01.

East of the Cape on the Agulhas Bank off the Indian Ocean coast of South Africa, in 1985, a 12 s TWT seismic-reflection profile of 46 km length was surveyed (Durrheim, 1987). In contrast to a typical BIRPS profile around the British Isles, the crust underneath the Agulhas Bank off South Africa is characterized by strong upper crustal reflectors ascribed to Proterozoic sediments, while in the lower crust, only a few reflectors were visible. The Moho proper was evident by a zone of strongly reflecting elements at 9.5 s TWT.

Off the coast of Oman, a coincident normal incidence and wide-angle seismic experiment was carried out in 1986 during cruise 18/86 of RRS *Charles Darwin* across the east Oman continental margin (Fig. 8.9.3-02) north of the Masirah Island ophiolite (Barton et al., 1990). The normal incidence reflection profile served to define the upper crustal structure, while the wide-angle reflection profile was obtained with ten digital OBSs recording 110 explosive shots. A steep landward-dipping reflector underneath the continental slope was interpreted by Barton et al. (1990) as Moho (Fig. 8.9.3-03). Beyond the slope, under the deep offshore Masirah basin, the crustal thickness resulted to be as small as 5 km. Depth to Moho increases further out to 14 km under the Masirah ridge, but thins to ~6 km under the oceanic crust beginning 40 km west of Owen Ridge (Fig. 8.9.3-02).

In 1985, the Australian vessel *Rig Seismic* conducted a continental margins cruise to the Kerguelen Plateau in the central Indian Ocean around Heard Island. The cruise included deep seismic profiling to determine the nature and extent of sedimen-

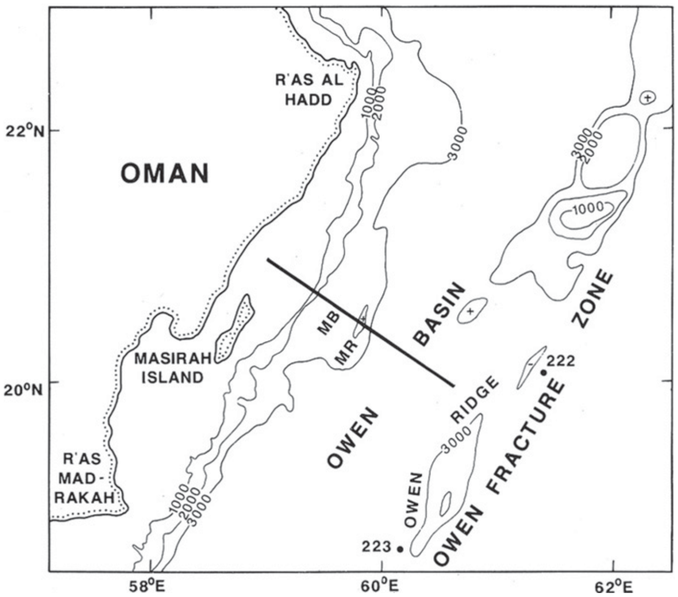


Figure 8.9.3-02. Bathymetric map of the east Oman offshore area with position of wide-angle seismic line (from Barton et al., 1990, fig. 3). MB—Masirah basin, MR—Masirah ridge, 222, 223—DSDP (Deep Sea Drilling Project) holes. [Tectonophysics, v. 173, p. 319–331. Copyright Elsevier.]

tary basins across the region and the underlying crustal architecture. About 5600 km of 48 channel (12-fold) seismic-reflection data were collected (Ramsay et al., 1986; Finlayson 2010; Appendix 2-2).

In another major project, the *Rig Seismic*, in cooperation with the Lamont vessel *Conrad*, investigated in 1986 the margin of offshore northwestern Australia (Mutter et al., 1989; Lorenzo et al., 1991; Finlayson 2010; Appendix 2-2). Here the Exmouth Plateau forms an unusually broad region of continental crust which was deformed during a Jurassic rifting period that preceded Early Cretaceous sea-floor spreading in the adjacent Indian Ocean (e.g., Veevers and Cotterill, 1978). The data included two-ship reflection and refraction measurements. Several ESPs were acquired along each reflection line. Together with velocities obtained by the analysis of CDP gathers, velocity-depth structures were derived and ages assigned to the major tectonic-seismic units using drilling results from near-by ODP Site 763. For some of the lines the whole crust was sampled, for others the upper 5 km of sedimentary section down to an inferred extensional detachment surface was modeled. The refraction data resolved the presence of a 5–10-km-thick 7.3 km/s high-velocity layer in the lower crust beneath a strike-slip deformation zone. The total crustal thickness increased from ~8 km underneath the Cuvier Basin in the southwest, which is overlain by 5 km of water, reached up to 25 km under the transitional strike-slip deformation zone and decreased to ~20 km under the Exmouth Plateau. The crust under the Exmouth Plateau was modeled to be subdivided into a 10-km-thick crystalline crust and 8–10-km-thick detachment complexes. From this result it was inferred that the evolution of the transform was attended by intense magmatism (Lorenzo et al., 1991).

In 1986 and 1988, the North and South Perth Basins were investigated by cruises of the Australian vessel *Rig Seismic*. In the North Perth Basin, 2370 km of 48-channel seismic-reflection profiling data together with sonobuoy data were collected from four traverses in 1986. In the South Perth Basin, a total of 4000 km of multichannel seismic data were acquired in 1988, mostly on the continental shelf but with several lines extending offshore to the deep abyssal plain of the Indian Ocean (Finlayson 2010; Appendix 2-2).

8.9.4. Atlantic Ocean

While the investigations of the Earth's crust in the Pacific and Indian Ocean were carried out exclusively by institutions specializing in marine research work, in the Atlantic Ocean, groups whose expertise had been gained by research work on land were also active.

In the South Atlantic Ocean, the above mentioned cruise 31 of R/V *Dmitry Mendeleev* of the Shirshov Institute of Oceanology had mainly served the purpose of investigating oceanic basins worldwide (Neprochnov (1989). The expedition started in 1983 in the Cape Verde basin with one profile and five OBSs, continued southward to the Brazil basin where again one profile with three OBS was shot, and reached the Cape basin west of southernmost Africa in early 1984 where two profiles with five OBSs were recorded (see Figs. 8.9.2-01 and 8.9.3-01).

The North Atlantic Transect (NAT Study Group, 1985; McCarthy et al., 1988; Mithal and Mutter, 1989) had provided a major improvement on the knowledge of the structure of the oceanic crust and its variability on a large regional scale. In an effort to define the seismic properties of the oceanic crust in detail

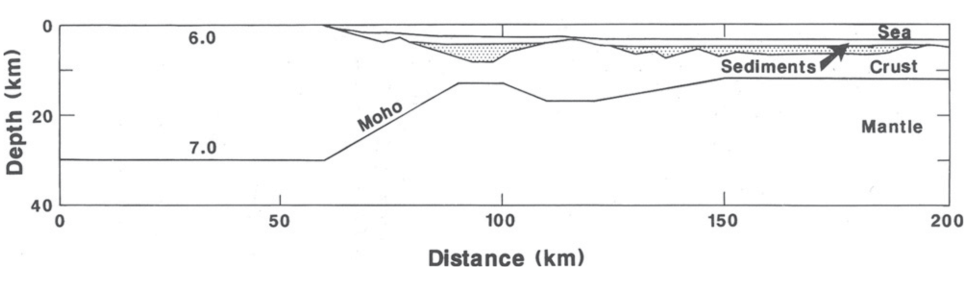


Figure 8.9.3-03. Crustal model of Oman continental margin (from Barton et al., 1990, fig. 11). [Tectonophysics, v. 173, p. 319–331. Copyright Elsevier.]

and on a regional scale, two-ship multichannel seismic data acquisition techniques as described by Stoffa and Buhl (1979) were employed along a transect across the western North Atlantic from the North American continental margin to the Mid-Atlantic Ridge near 23°N. The experiment crossed oceanic crust spanning almost 200 m.y. in age. The two-ship acquisition phase resulted in 3880 km of wide-aperture, CDP data and eleven ESPs at selected intervals (NAT Study Group, 1985).

Other spectacular images of the internal structure of the oceanic crust, showing widespread occurrence of intracrustal reflectivity in the western Central Atlantic Ocean had been published by White et al. (1990). Seismic-reflection studies of the Blake Fracture Zone had provided a complex detailed structure, and crustal thinning underlain by an anomalous upper mantle across this fracture zone had been interpreted by Mutter et al. (1985) which was confirmed later by new seismic data and velocity control from ESPs (see Fig. 8.9.1-01; White et al., 1990).

In 1982, the Kane fracture zone, offsetting the Mid-Atlantic Ridge rift valley near 24°N ~160 km in a left-lateral sense, was studied again by three seismic-refraction experiments (Cormier et al., 1984). They were positioned (Fig. 8.9.4-01) so as to extend and complement the 1977 experiment (Detrick and Purdy, 1980) which had been conducted at ~44°W (dashed line in Fig. 8.9.4-01). The westernmost line was 150 km long and was shot down the median valley of the Mid-Atlantic Ridge south of the Kane fracture zone. The two easternmost lines were shot to investigate whether the anomalously thin crust of only 2–3 km, found in the 1977 experiment along 44°W (Detrick and Purdy, 1980), was present only adjacent to the Kane fracture zone ridge or if it extended also into the older parts of the fracture zone. Shots of 14.5 kg and sometimes 112.6 kg were fired along the lines with a spacing of 1.5 and 4.5 km, respectively. Some of the lines were reshot with an airgun, using a shot spacing of 100 m to improve the resolution of the shallow crust.

The data analysis showed strong lateral variations in crustal thickness and velocities. Along most of the eastern fracture zone trough, upper-mantle velocities were found at depths of only 2–3 km below the seafloor, less than half the typical depth to Moho

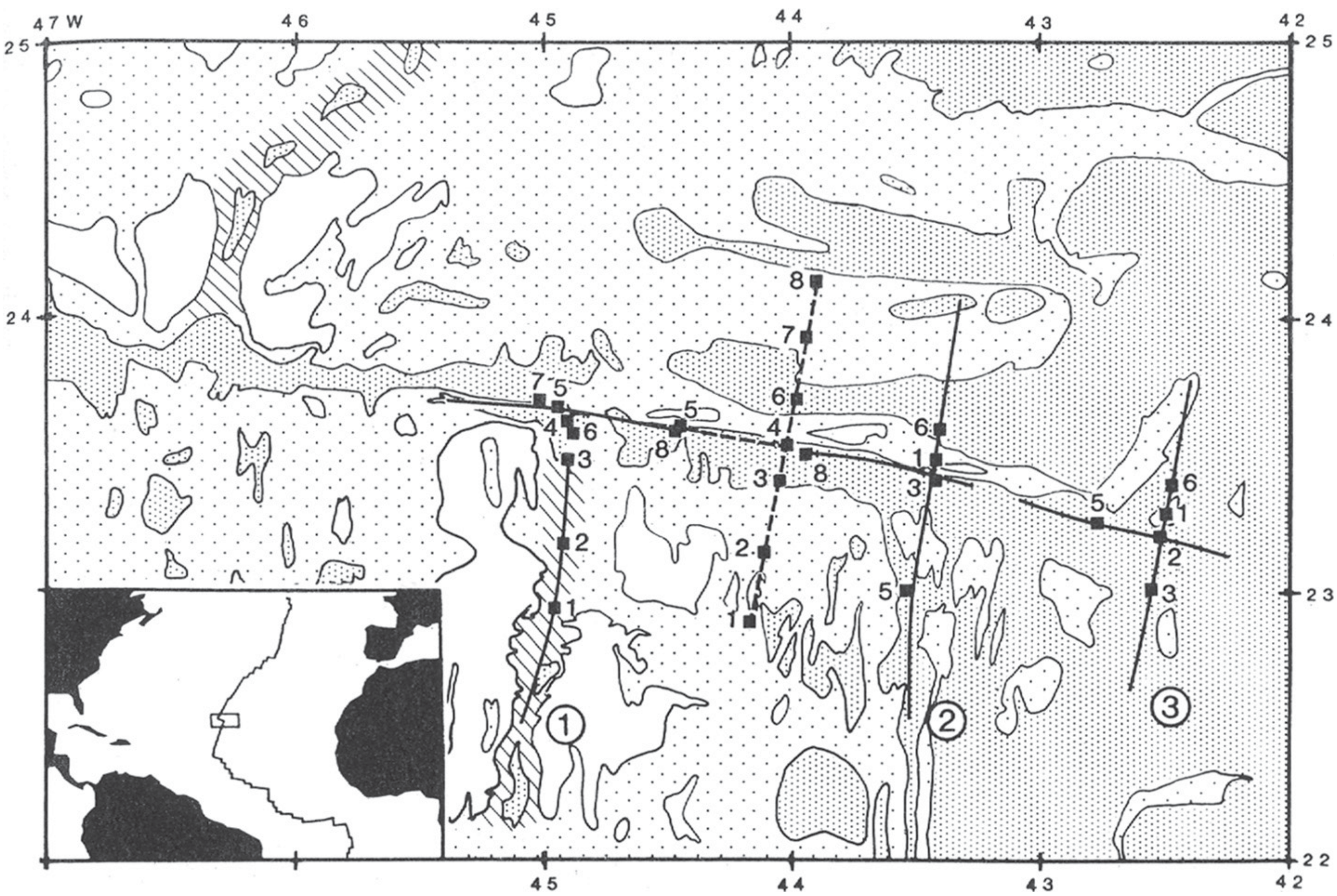


Figure 8.9.4-01. Simplified bathymetric map of the Kane fracture zone and location of the 1977 (dashed line) and 1982 (solid lines) seismic refraction experiments. Black squares—receiver positions; diagonal lining—Mid Atlantic Ridge rift valley; densely stippled areas—depths greater than 4000 m; lightly stippled areas—depths from 3000–4000 m (from Cormier et al., 1984, fig. 1. [Journal of Geophysical Research, v. 89, p. 10,249–10,266. Reproduced by permission of American Geophysical Union.]

in the ocean basins. This anomalous fracture zone crust was generally characterized by low P-wave velocities, relatively high velocity gradients and a distinct crust-mantle boundary. The very thin crust appeared to be confined to the deepest parts of the Kane fracture zone (less than 10 km wide), although a more gradual crustal thinning seemed to extend up to several tens of kilometers from the fracture zone.

Inactive sections of the Tydeman fracture zone at latitude 36°N with approximate crustal ages of 59 Ma and 71 Ma were the target of two separate experiments in 1982 (Calvert and Potts, 1985). The first experiment consisted of two two-ship ESPs located at ~23°30′W. In the second experiment two OBS were laid ~50 km apart in the fracture valley and RRS *Shackleton* fired 24 explosive charges varying in size from 12.5 to 250 kg. The shooting track was centered on 36°N, 26°W, running from west to east along the strike of the fracture zone and passing over the receivers. The resulting crustal velocities were low compared with "normal" oceanic crust; there was a marked absence of an identifiable layer 3, the depth to Moho was shallow and anomalously low velocities of 7.2–7.5 km/s were observed. Using these results and those from other surveys, Calvert and Potts concluded that the seismic velocity in the upper mantle beneath fracture zones systematically decreases with increasing age.

A review of seismic studies on crustal structure of North Atlantic Fracture Zones conducted in the 1970s and 1980s was prepared and published by Detrick et al. (1993b).

A detailed and extensive survey along the Atlantic continental margin of Africa was undertaken by project PROBE, an academia-industry project aimed at understanding the evolution from continental rift to passive rift margin, and from passive continental margin to oceanic crust (Rosendahl et al., 1991). Near the end of the 1980s a grid of multifold seismic-reflection profiles was acquired in the Atlantic Ocean between the Cameroon volcanic line and the coasts of Cameroon, Equatorial Guinea, and Gabon (Fig. 8.9.4-02).

The PROBE lines crossed several major sedimentary basins which all formed as continental rift basins during the early Cretaceous opening of the southern and equatorial Atlantic Ocean. For the data acquisition a 6000 m long cable with a 100–1000 m offset and a tuned airgun array were used. The six-source subarrays had a width of 75 m and a length of up to 100 m. The nominal fold coverage was 60, and common-depth spacing was 25 m. The record lengths were 20 s. Over most of the survey area the reflection Moho was clearly imaged at depths ranging from 7 to 10 s TWT over most of the survey area east of the Cameroon volcanic line. The Moho reflection usually consisted of a 2–4 Hz event and was in many areas the highest amplitude event. On many profiles, the Moho could be continuously traced from oceanic crust to the shoreward ends of the lines, well beyond the assumed transition from oceanic to continental crust. In many cases, the two-way traveltimes remained fairly constant from oceanic to continental crust. The spatial variation in thickness of the igneous component of the oceanic crust was extremely large; even doubling of the crust occurred

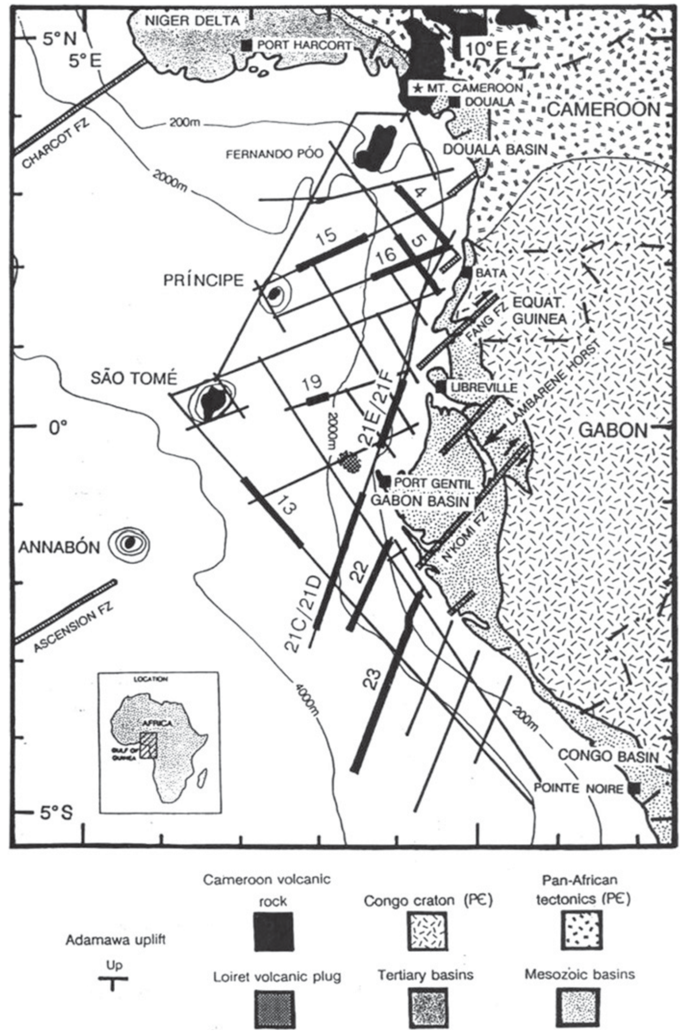


Figure 8.9.4-02. Location of the PROBE survey grid along the African coast between 4°N and 5°S (from Rosendahl et al., 1991, fig. 1). [Geology, v. 19, p. 291–295. Reproduced by permission of the Geological Society of America.]

over distances of a few kilometers. Oceanic basement and the depth to the Moho was greater south of latitude 1°S than north of this latitude. In some profiles, but not on all, the igneous crust appeared to thicken at the transition from continental to oceanic crust (Rosendahl et al., 1991).

The data were later reprocessed and a tectonic model of the continental margin between Cameroon and southern Gabon was developed (Rosendahl and Groschel-Becker, 2000). Under the North Douala Basin, north of the Kribi Fracture Zone, a 75-km-wide transform fault trending NE-SW and intersecting with the coastline at 2–3°N, oceanic crust extended essentially to the coastline. The reflection Moho was relatively weak but continuous here and the oceanic crustal thickness under the North Douala Basin appeared rather uniform, averaging ~1.75 s in TWT. South of the Kribi Fracture Zone, under the Gabon Basin, oceanic crust appeared to be offset ~350 km to the southwest, resulting in a broad rift margin off Gabon. Here, a single continuous event representing the reflection Moho could not be delineated.

Also the *Meteor* (1964) cruise M67 in 1984 under the direction of W. Weigel (University of Hamburg) and K. Hinz (BGR Hannover) provided an extended crustal seismic survey off Northwest Africa (Sarnthein et al., 2008). Banda et al. (1992) had carried out a geophysical study of the oceanic crust in the eastern Central Atlantic Ocean, in the Canary basin west of the Canarian Archipelago (Fig. 8.9.4-03) which is shown here as an example. The crust is ~9–10 km thick, and the multichannel reflection data showed a similar complex internal structure as reported by White et al. (1990) for the western Atlantic Ocean (Fig. 8.9.4-04).

In 1988, an extensive geophysical data set was collected over the Josephine Seamount, located at the NE end of the Madeira-Tore Rise in the eastern North Atlantic. A 275-km-long seismic-refraction line, running in a NW-SE direction between 38°11′N, 14°53′W and 35°57′N, 13°17′W, crossed the Josephine Seamount and the northwestern Horseshoe Abyssal Plain (Peirce and Barton, 1991). Six DOBS (digital ocean-bottom seismometers) were deployed with both 3-component geophone packages and hydrophones and recorded 110 explosive charges (25 and 100 kg) at ~1.8 km intervals. In addition an airgun array fired at 60 s intervals provided a shot spacing of ~150 m. The crust at either side of the seamount was typically oceanic in character. Beneath the seamount, however, a region of anomalously high velocity and crustal thickening to a depth of 17–18 km was found.

Various investigations of fracture zones offsetting slow-spreading ridges, particularly in the North Atlantic Ocean (e.g., Cormier et al., 1984; Fowler, 1976, 1978; Mutter et al., 1985; White and Whitmarsh, 1984) prompted Whitmarsh and Calvert (1986) to conduct in 1982 a seismic experiment in the Charlie-Gibbs Fracture Zone at 52°–53°N which consists of two narrow, deep E-W transform valleys which together offset the median valleys of the Reykjanes and Mid-Atlantic Ridge by 350 km. The objectives of the experiment were to determine the crustal structure within one of the transform valleys and to measure the

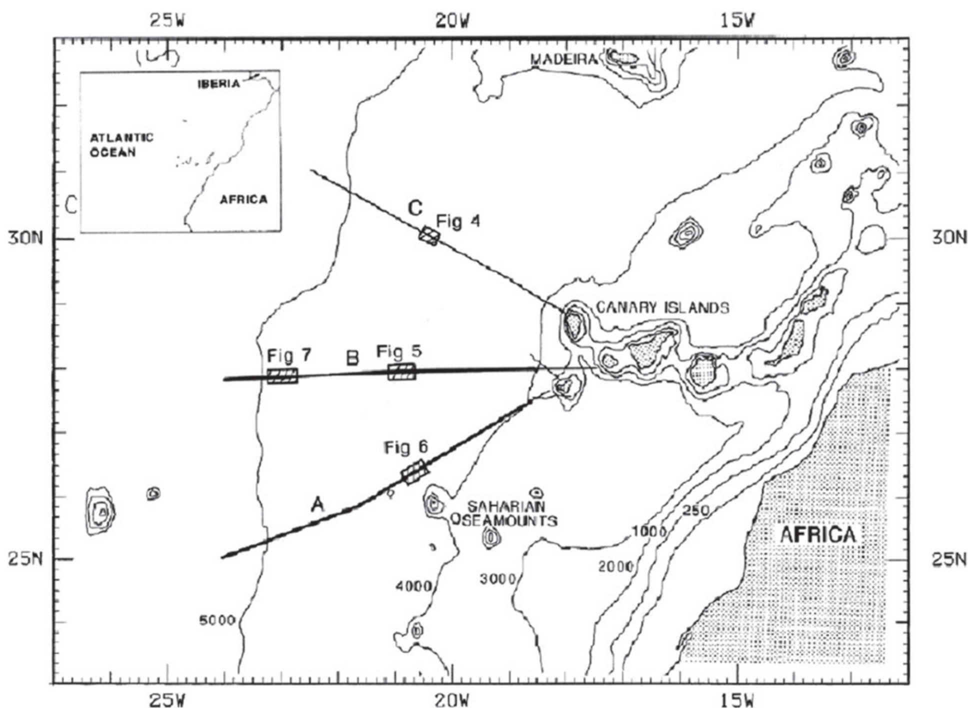


Figure 8.9.4-03. Location of seismic profiles in the Canary basin (from Banda et al., 1992, fig. 1). [Geological Society of America Bulletin, v. 104, p. 1340–1349. Reproduced by permission of the Geological Society of America.]

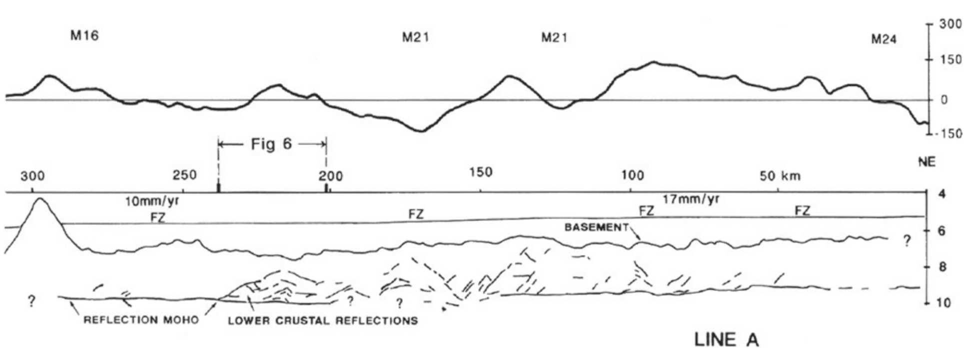


Figure 8.9.4-04. Crustal cross section of the Canary basin along line A, northeastern part (from Banda et al., 1992, fig. 3). [Geological Society of America Bulletin, v. 104, p. 1340–1349. Reproduced by permission of the Geological Society of America.]

rate of crustal thinning normal to the valley axis. Ocean-bottom seismometers recorded airgun shots along two perpendicular profiles, an 84-km-long refraction line along the valley axis and a 94-km-long line N-S profile through the center of the E-W line. A third E-W line, 90 km long, was recorded south of the fracture zone over normal oceanic crust. The crust in the fracture zone appeared to be anomalously thin (4 km); it thinned along the N-S line over a distance of 40 km from 8 to 5 km toward the fracture zone where the belt of anomalous crust was 12 km wide.

Three other groups may be mentioned in particular. In the UK, university research centers and the British Geological Survey connected land and sea crustal research work out of which the BIRPS program developed. In Germany, the University of Hamburg under Jannis Makris had been active both on land and at sea since the early 1970s. In Ireland, it was the Dublin Institute for Advanced Studies at Dublin, Ireland, under Brian Jacob which did major crustal research in continental areas as well as in the surrounding seas.

The 200-km-long Goban Spur continental margin southwest of Britain was investigated in 1985 by the Western Approaches Margin (WAM) deep seismic-reflection profile, recorded jointly by BIRPS and ECORS (Peddy et al., 1989; Pinet et al., 1991). The profile was shot perpendicular to the margin (for location, see Fig. 8.3.1-01) and was aimed to image the structure of the thinned continental crust. Beyond the shelf edge, it was only possible to image the layered lower crust clearly above the first seabed multiple. In 1987, a seismic-refraction experiment was added on the Goban Spur margin to define the crustal structure and the extent of igneous rocks in order to complement the information provided by the deep seismic-reflection data (Horsefield et al., 1994). The project consisted of three seismic-refraction lines, one along the WAM line and two perpendicular to the WAM line, parallel to the margin. Several DOBS were deployed on each line which recorded airgun shots, spaced ~300 m. The project also included 500 km of four-channel normal incidence seismic-reflection profiles to provide control of the sediment structure and depth to the acoustic basement. From traveltime and amplitude modeling of the wide-angle OBS profiles, Horsefield et al. (1994) concluded that the continental crust thins in a seaward direction to ~7 km before it breaks to allow a new oceanic spreading center to develop. They also stated that the thinning was accompanied by only limited igneous intrusion and extrusion of the upper crust and that the adjacent oceanic crust is abnormally thin (5.4 km).

In 1985 a two-ship Synthetic Aperture Profile (SAP-5) was shot from the Rockall Bank into the center of the Rockall Trough (Joppen and White, 1990). The 1985 seismic-reflection operation included a single ship reflection profile N-11 and two expanding spread profiles (ESP 11 and 12) which centered on the intersection of the lines SAP-5 and N-11. In 1990, BIRPS recorded the WESTLINE profile. This line ran parallel to the SAP-5 line and also crossed the Rockall Trough (England and Hobbs, 1995; Snyder and Hobbs, 1999). It was a 450-km-long, normal-incidence, deep seismic-reflection profile which was shot perpendicular to the edges of the trough in order to image its conjugate margins.

The offshore study of the COOLE experiment (for locations, see Fig. 8.3.2-05), a joint project of the Dublin Institute for Advanced Studies and the University of Hamburg, comprised three seismic-refraction profiles offshore southern Ireland (Makris et al., 1988; O'Reilly et al., 1991). Profile COOLE'85-7, along the axis of the North Celtic Sea Basin, comprised ten OBS stations, which were deployed at 15–20 km intervals over a distance of 160 km ~40 km south of the position of the CMRE 1969 profile (CMRE'69 in Fig. 8.3.2-05; lines A in Fig. 6.2.3-01; Bamford, 1971). Sea shots were fired every 2.5 km. The transverse profile COOLE'85-6 comprised eleven OBS stations deployed at 14–16 km intervals over a distance of 140 km, with airguns used as a seismic source. The main objectives were to investigate lithospheric structures related to rifting/stretching during the development of the North Celtic Sea and Porcupine basins. In addition, profiles COOLE'85-3a and -3b were laid out in a NE-SW direction (Makris et al., 1988). Profile COOLE'85-3a (for location, see Fig. 8.3.2-05) served to determine the structure of the transition region between the Porcupine Seabight and SW Ireland. Profile COOLE'85-3b was recorded in the prolongation of COOLE'85-3a farther southwest between longitudes 13°W and 15°W and approximately at latitude 50°N; i.e., it reached from the Porcupine basin (for location, see Fig. 8.9.4-05) into the Porcupine abyssal plain to the west.

Another enterprise of the Dublin Institute for Advanced Studies and the University of Hamburg was the RAPIDS (Rockall and Porcupine Irish Deep Seismic) project, shot in 1988 and 1990 (Figs. 8.3.2-05 and 8.9.4-05). It consisted of two orthogonal wide-angle seismic profiles totaling 1600 km.

Individual lines were typically 200–250 km long. Ocean-bottom seismometers were deployed every 7–10 km and explosive charges of 25 kg were fired at optimum depth of 65 m over intervals of ~1 km. Energy propagated usually farther than 150 km. Data examples are shown in Appendix A8-5-1.

The model along the 1000-km-long east-west profile from Ireland to the Iceland Basin shows the complex structure when crossing the various troughs and basins and intervening banks (Fig. 8.9.4-06). The low-velocity mantle with velocities of 7.5–7.8 km/s underneath the Rockall Trough was interpreted as serpentinized mantle, the still lower velocity of 7.2 km/s west of the Hatton basin as underplated body (Fig. 8.9.4-06). The Moho appeared as a transition zone and is shallow under the basins (with 12–15 km depth, Figs. 8.9.4-06 and 8.9.4-07), but reaches continental dimensions under the Rockall bank (Shannon et al., 1994, 1999; Hauser et al., 1995; O'Reilly et al., 1995, 1996; Vogt et al., 1998).

Prior to the RAPIDS project, in 1985 Cambridge, Durham and Birmingham universities had undertaken a detailed geophysical study of the Hatton bank volcanic margin over a SE-NW–trending line of ~150 km length between the Rockall plateau and the Iceland basin, centered around 59°N and 18.5°W (Morgan and Barton, 1990). The experiment included expanding spread profiles, parallel and synthetic aperture profiles, a wide-angle ocean-bottom seismometer and a multichannel refraction line

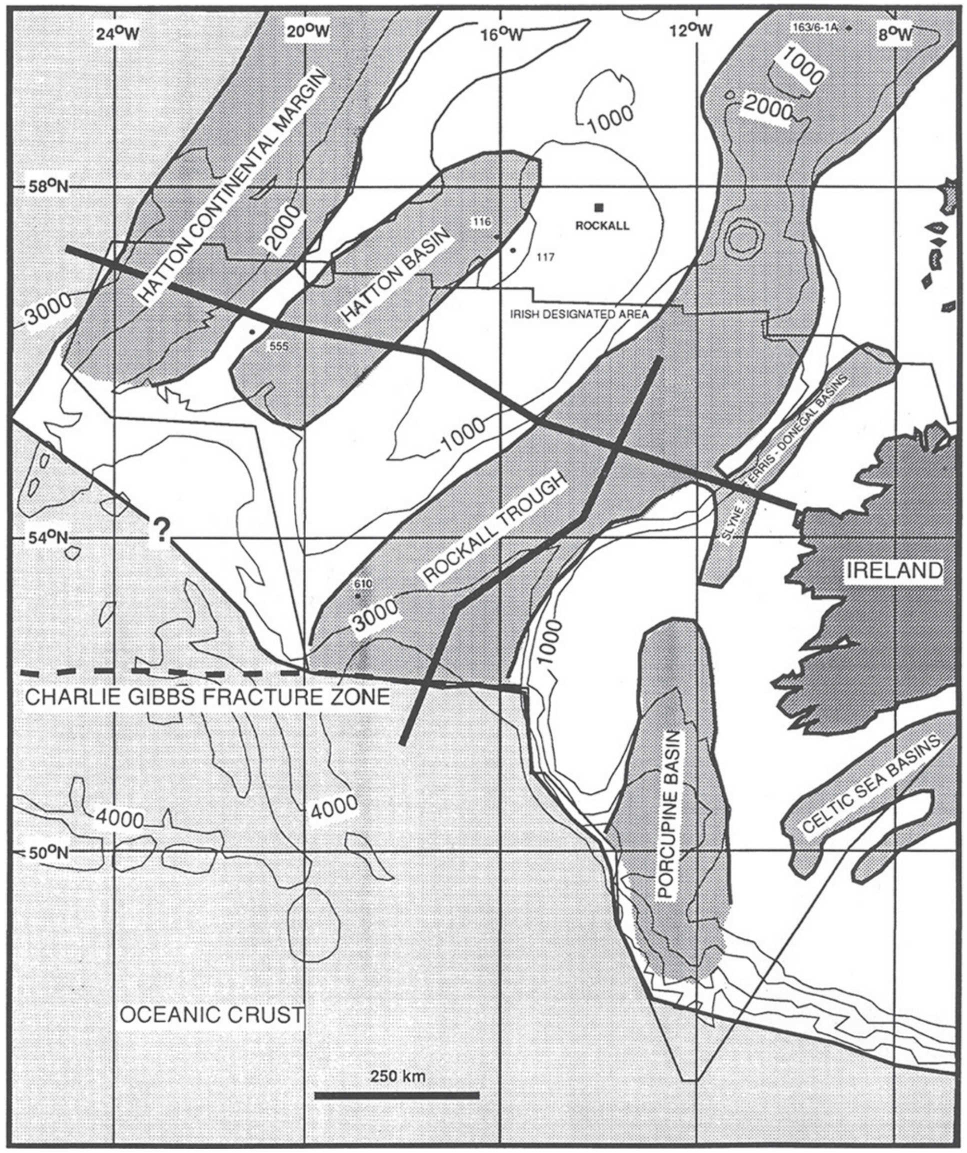


Figure 8.9.4-05. Location of seismic profiles in the Atlantic Ocean west of Ireland (from Shannon et al., 1994, fig. 1). [First Break, v. 12, p. 515–522. Copyright EAGE.]

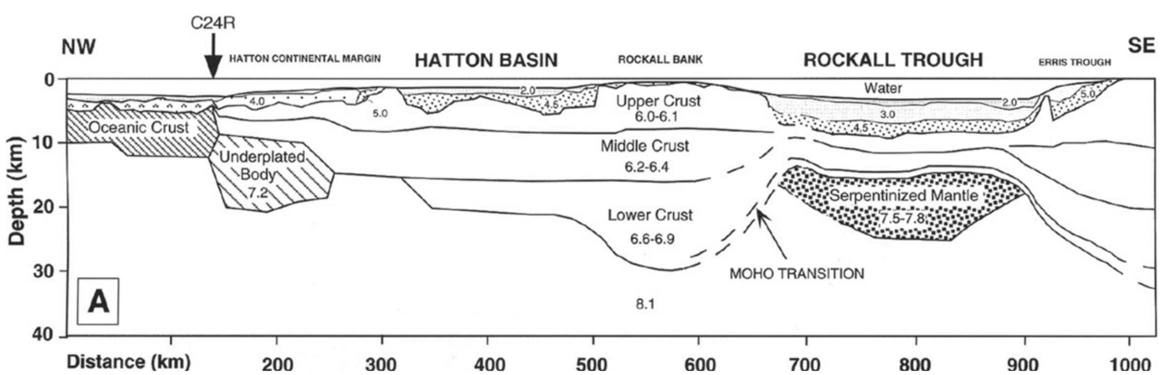


Figure 8.9.4-06. WNW-ESE–directed crustal cross section from Ireland across Rockall Trough, Hatton Basin to the Iceland Basin, Atlantic Ocean (from Shannon et al., 1999, fig. 2A). For location see Fig. 8.9.4-05. [*In* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum Geology of Northwest Europe: Proceedings, 5th Conference, p. 421–431, Petroleum Geology, v. 86, Geological Society of London. Reproduced by permission of Geological Society Publishing House, London, U.K.]

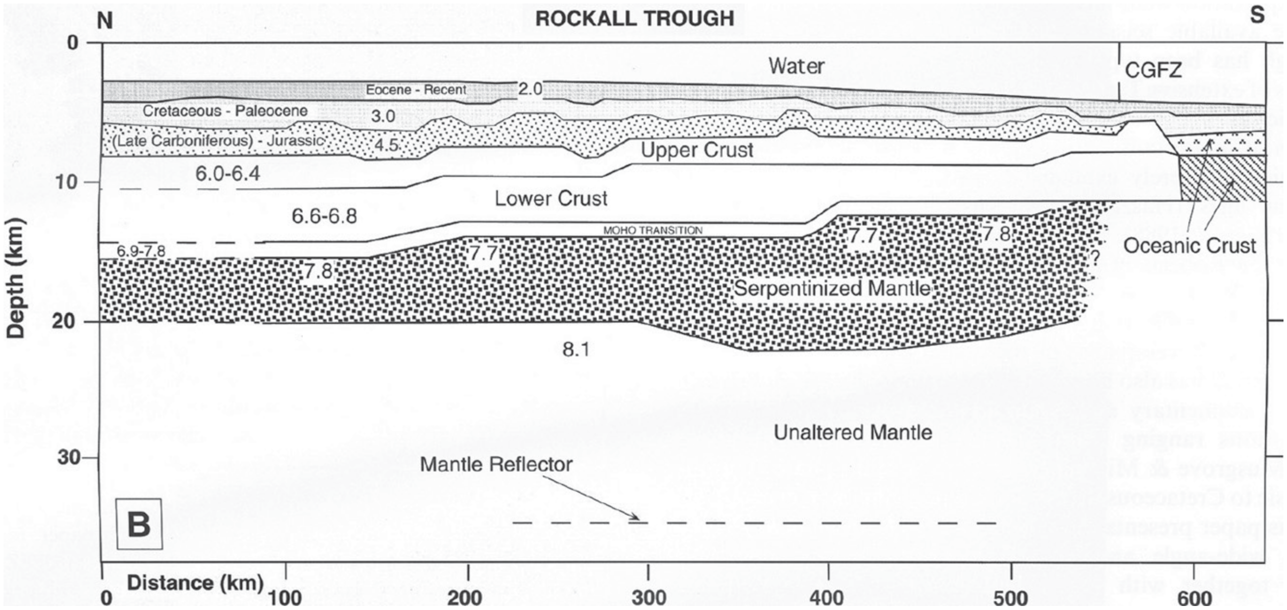


Figure 8.9.4-07. NNE-SSW directed crustal cross section through the Rockall Trough, Atlantic Ocean, west of Ireland (from Shannon et al., 1999, fig. 2A). For location see Fig. 8.9.4-05. [*In* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum Geology of Northwest Europe. Proceed. 5th Conf.: p. 421–431. Petroleum Geology 86, Geological Society of London. Reproduced by permission of Geological Society Publishing House, London, U.K.]

perpendicular to the margin, and a multichannel refraction line through the midpoints of the expanding spread profiles and 1400 km of normal incidence seismic observations. The resulting velocity model showed a gradual depth decrease of Moho from ~27 km under the Rockall plateau to 15 km toward the Iceland basin.

Farther north, off the coast of Norway on the Voering plateau, north of the Jan Mayen fracture zone, a wide-aperture CDP line was recorded across the midpoints of a series of ESP profiles (Fig. 8.9.4-08; see Fig. 8.9.1-01 for definitions of CDP and ESP) using the two-ship multichannel seismic techniques. The crustal structure was determined from a series of expanding spread profiles with midpoints along a wide-aperture CDP transect which also intersected two deep-drilling sites (DSDP) and was plotted by Zehnder et al. (1990) as a velocity contour diagram (Fig. 8.9.4-09). The data were interpreted to imply the presence of a 15–20-km-thick igneous crust that was emplaced along the margin during the initiation of seafloor spreading. Seaward, the igneous crust diminishes in thickness.

At the same time, in 1988, farther northeast a major seismic-reflection/-refraction experiment including long-offset refraction profiles along the Lofoten passive margin was started. It was a cooperative project among Norwegian, German, and Japanese institutes to investigate the detailed structure of the continental breakup. In particular, the OBS method was applied (Mjelde et al., 1992; Goldschmidt-Rokita et al., 1994; Kodaira et al., 1995). The program was continued in the 1990s, also covering the Voering marginal high and amongst other lines also re-shooting the line of Zehnder et al. (1990). In Chapter 9.8.4,

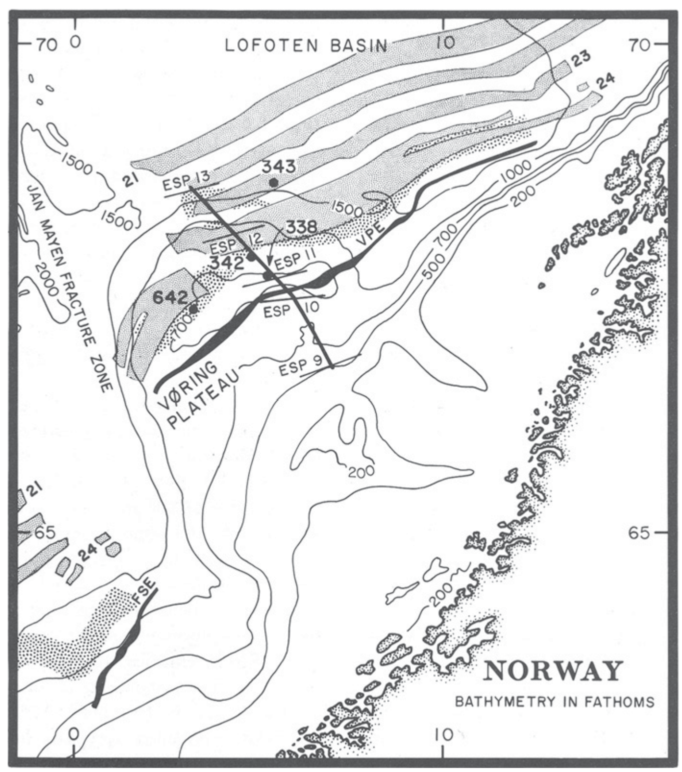


Figure 8.9.4-08. Location map of seismic observations on the Voering plateau off Norway (from Zehnder et al., 1990, fig. 2). VPE is Voering plateau escarpment; dots are deep sea drilling sites; dense dot pattern identifies seafloor magnetic lineations. [Tectonophysics, v. 173, p. 545–565. Copyright Elsevier.]

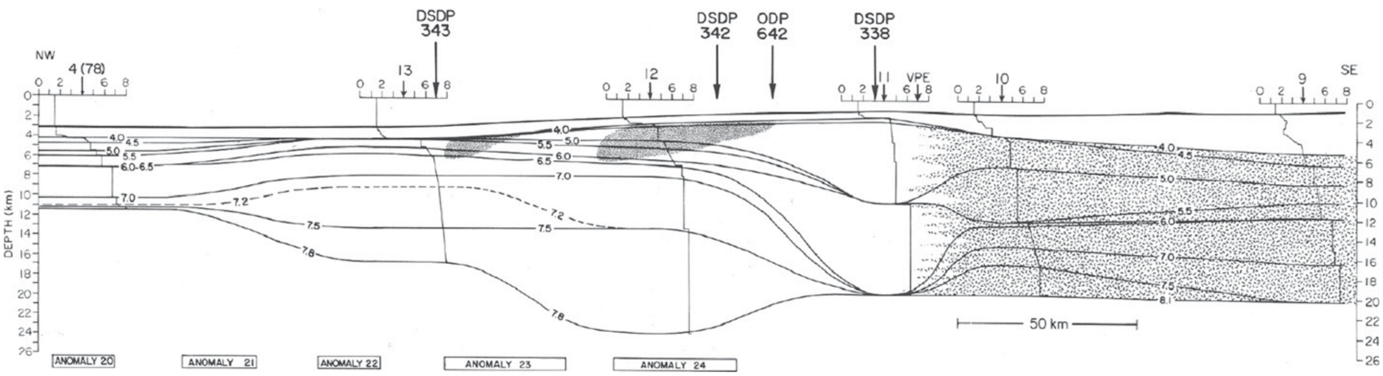


Figure 8.9.4-09. Velocity contours across the Norwegian continental margin (from Zehnder et al., 1990, fig. 6). VPE—Voering plateau escarpment. [Tectonophysics, v. 173, p. 545–565. Copyright Elsevier.]

measurements and results of this survey are summarized (see, e.g., Figs. 9.8.4-18 and 9.8.4-22).

In 1987, the Aegir rift was investigated by two crossing profiles (Grevemeyer et al., 1997). It is located half-way between Norway and Iceland and to the north of the Faeroe Islands at 3°–5°W, 65°–67°N and trends in a SW-NE direction (for location, see Fig. 9.8.4-18). The Aegir rift is a graben structure and centered between the Jan Mayen Ridge and the Faeroe-Shetland Escarpment southwest of Norway and is regarded as an extinct spreading center. Ocean-bottom hydrophones and seismographs were deployed along two reversed lines. One profile of 90 km length with five OBSs was shot along the rift's median valley; the other one was 200 km long and oriented perpendicular to the strike and was occupied with ten OBSs. The shooting interval of the airgun array was 2 min; spacing between the shots ~330 m. In addition, explosives were detonated at 2 km intervals. The crust within the extinct spreading center was found at 10 km depth to be thinner and of lower velocity compared to the crust sampled off-axis at 11 km depth below sea level, water depth being ~3 km. Upper mantle velocities were 8 km/s.

In 1985, deep seismic sounding measurements were performed in the transition zones west and north of Spitsbergen (also named Svalbard) by a Polish expedition (Czuba et al., 1999). The recordings were made by stationary land stations (stars in Fig. 8.9.4-10, upper left), which recorded all 105 underwater shots detonated along five profiles. Two shot profiles were recorded to the west toward the Knipovich Ridge (K1 and K2 in Fig. 8.9.4-10) and two profiles to the north toward the Yermak Plateau (C1 and C2 in Fig. 8.9.4-10). Furthermore a shot profile C1 was recorded along the west coast of Spitsbergen, where in 1976 and 1978 the first experiments had been carried out. For comparison the map shows Moho depths by large numbers in quadrangles as obtained by Czuba et al. (1999) and Moho depths by small numbers in small circles and triangles as had been obtained by the earlier expeditions (Faleide et al., 1991; Sellevoll et al., 1991).

Eastern Greenland and its margin on the western side of the northernmost Atlantic Ocean became the goal of detailed seismic mapping since the end of the 1980s which continued in the 1990s (for locations, see Fig. 9.8.4-30). In 1988 and 1989 deep seismic-reflection data were acquired on Jameson Land in connection with oil exploration activities in eastern Greenland providing the first seismic depth information on the deeper crustal structure (Mandler and Jokat, 1998).

During 1988 the first combined marine-land refraction experiment was carried out in East Greenland (Weigel et al., 1995). The primary goal was to map the continent-ocean transition east of Scoresby Sund, hereby deploying six recording stations on the southern coast of the Sund. The results indicated strong variations in crustal thickness from at least 30 km in the western part of the Scoresby Sund to less than 20 km at its eastern termination (Weigel et al., 1995).

The western side of Greenland also became the goal of a seismic investigation in 1989 (Clement et al., 1994; Gohl et al., 1991; Gohl and Smithson, 1993). The survey was conducted by the University of Wyoming and consisted of a marine airgun array recorded by land-based receivers (Fig. 8.9.4-11). Fifteen PASSCAL RefTek 2-Hz three-component seismometers were placed on 35 locations along the coast, fjords, and farther inland. An array of five airguns (6000 in^3) was fired with 100–150 m shot spacing along a north-south–striking offshore line, covering offsets of up to 350 km, and along the Godthaab and Ameralik fjords to obtain data farther inland (Gohl et al., 1991). An excellent quality of first and secondary-arrival P-phases was obtained, and strong S-phases were recorded. For the P-phases Moho depths between 30 and 40 km resulted (Gohl et al., 1991; Gohl and Smithson, 1993). From the S-wave analysis (Clement et al., 1994), the continental crust appeared to be clearly seismically anisotropic (Fig. 8.9.4-12).

Several projects dealt with the Arctic Ocean. The Canadian expedition CESAR (Canadian Expedition to Study the Alpha Ridge) explored the Alpha Ridge complex in the Amerasia basin in 1983 with a seismic-refraction survey (Asudeh et al., 1988; Forsyth et al., 1986; Jackson et al., 1986; Weber, 1986, 1990). The Amerasia basin is dominated in the north by the Alpha-Mendeleev Ridge complex which is the most prominent and least understood of the Arctic submarine ridges. The ice station

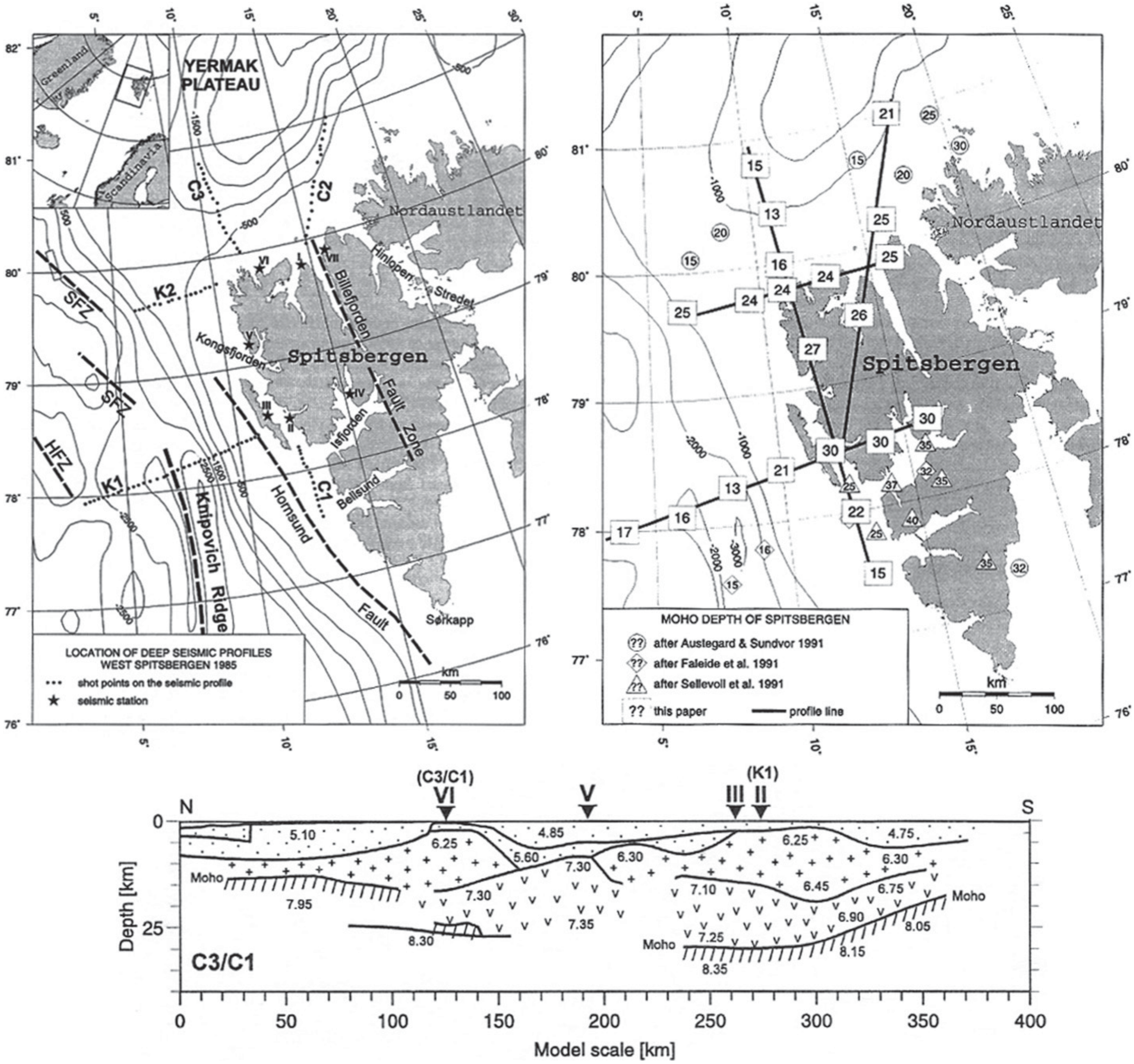


Figure 8.9.4-10. Top: Locations and Moho depths of the 1985 Spitsbergen survey (from Czuba et al., 1999, figs. 1 and 11). Bottom: Crustal cross section along the profiles C1/C3 (from Czuba et al., 1999, fig. 9). [Polish Polar Research, v. 20, p. 131–148. Reproduced with permission of Polish Academy of Sciences, Warsaw, Poland.]

CESAR was set up on the drifting Arctic sea ice in the vicinity of the Alpha Ridge and experiments were conducted from March to May 1983. A refraction line, 210 km long, was shot along the crest of the Ridge. The resulting crustal model showed a nearly 40-km-thick crust. A velocity of 6.45 km/s with a steep gradient was measured below layer-2 at the ends of the line and in the central portion an additional velocity of 6.8 km/s was obtained. Beneath this, a high-velocity layer of 7.3 km/s, 10 and 16 km thick, occurred along the entire line. The layer-2 and -3 velocities appeared typical of oceanic crust but several times thicker than in ocean basins. The model for the Ridge suggested many similarities with the region of Iceland.

In 1989 a seismic-refraction experiment was carried out in the Makarov Basin of the Arctic Ocean (Sorokin et al., 1999). Ten 6-channel analog recorders with array lengths of 200–500 m were placed on drifting ice by helicopter with intervals of 10–

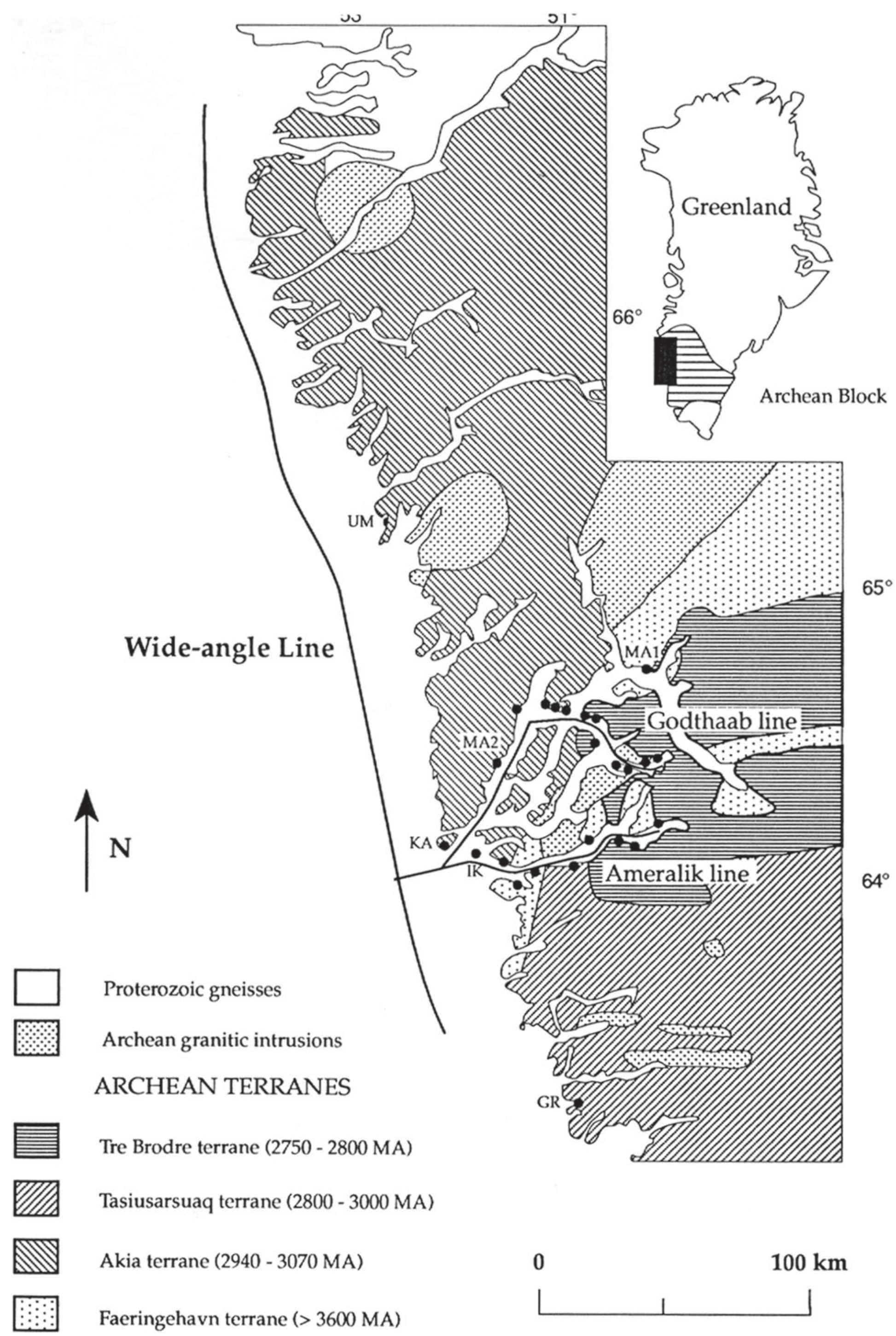


Figure 8.9.4-11. Location of the 1989 survey along the southwest coast of Greenland (from Clement et al., 1994, fig. 1). Solid lines—positions of source array for wide-angle recordings; dots—land-based receiver stations. GR—Graedefjord; IK—Ikaarisat; KA—Kangeq; MA—Manistog; UM—Uman. [Tectonophysics, v. 232, p. 195–210. Copyright Elsevier.]

15 km. Five underwater shots were fired at a depth of ~50 m. Charge sizes varied from 100 to 500 kg. A split spread of 220 km was obtained with a total of 45 seismic traces with a high signal to noise ratio. The sedimentary and upper crustal arrivals were not constrained due to the paucity of shots near the origin; however, the lower crust and M discontinuity were resolved. Velocities of 6.7 km/s were determined for the lower crust and 8.0 km/s for the upper mantle The 6.7 km/s velocity layer was interpreted as oceanic crust layer 3. The well-resolved thickness of this layer of 15 km was substantially greater than the average thickness of 4 km for layer 3.

In 1987–1989 the Soviet ice-station North Pole-28 (NP-28) drifted across the Arctic Ocean (for location, see Fig. 9.8.4-39). It started its crossing above the Podvodnikov Basin at ~81°N.

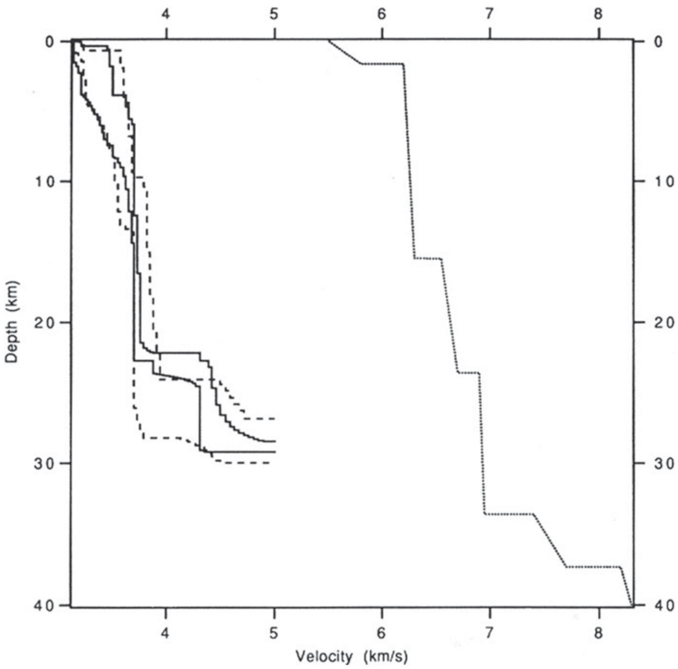


Figure 8.9.4-12. Velocity-depth functions for P-wave (dotted line) and S-wave (radial—solid line; transverse—dashed line) modeling of the 1989 survey along the southwest coast of Greenland (from Clement et al., 1994, fig. 4). [Tectonophysics, v. 232, p. 195–210. Copyright Elsevier.]

It passed near the North Pole and was finally abandoned above the Yermak Plateau (~81°N) north of Spitsbergen. NP-28 crossed the Lomonossov Ridge three times; on the second and third times it also traversed across the Marvin Spur (Lebedeva-Ivanova et al., 2006). The total length of the profile was ~4000 km. The reflection experiment was performed on drifting ice, with an ice-drift of 5–10 km/day, its direction being variable and unpredictable. Seismic receiver arrays were set up along two lines, perpendicular to each other in order to attenuate out-of-plane waves. The arms of the array were 545 m long. Receivers were placed at 50 m interval at each of the two arms. Shots were provided by 3–5 detonators in the vertex of the array at a water depth of 8 m and fired every 2–4 h, resulting in a shot rate of ~0.5 km intervals. Data were recorded for 12 s on magnetic analog tape. For the interpretation, reflection lines of the Alfred-Wegener Institute (Bremerhaven, Germany) were also used, which were recorded in 1990 and 1991 across the Makarov Basin and around site of the ACEX (Arctic Coring Expedition) drillholes, drilled in 2004, coring the first 430 m section on the Lomonossov Ridge near the North Pole. The data provided a basis for correlating a highly reflective sedimentary package and the basement along the Lomonossov Ridge.

In the western North Atlantic Ocean, most deep seismic research projects concentrated on the complex structure of the continent-ocean transition of North America. Large dynamic range and dense spatial sampling were aimed for.

The continental margin of Canada around Newfoundland was investigated from 1983 to 1987. In 1984 and 1986, Hall et al. (1990) investigated dipping shear zones and the base of the marine part of the Appalachian crust west and north of Newfoundland as part of the LITHOPROBE East transect (see Chapter 8.5.2).

In 1985 and 1987 a series of deep seismic-reflection profiles was recorded on the continental shelf to the east of Newfoundland (de Voogd et al., 1990; Keen et al., 1990). The goal was the crustal structure underneath a major transform margin southwest of the Grand Banks, off Newfoundland (Fig. 8.9.4-13). A standard method of data acquisition was applied, but the 127-l airgun source was larger than normally used and the record length was 20 s. Near the edge of the shelf the Moho was well defined near 13 s TWT (de Voogd et al., 1990), converted to ~28 km depth (Keen et al., 1990). A line drawing of the data recorded along line 87-5, i.e., perpendicular to the transform trend, was discussed by Keen et al. (1990) in some detail (Fig. 8.9.4-14). It shows a reflective lower crust near the edge of the shelf (D) overlying the well defined Moho (C). Below a region where a band of reflections (F, G) could be correlated the Moho deepens by 7 km (E), but toward the landward northeastern end of the line it shallows again to 30 km. Under the continental slope to the southwest (I in Fig. 8.9.4-14) the Moho shallows rapidly within the continental shear zone (J). Seaward of the Fogo seamount the top of the oceanic basement is relatively flat (L), and ~6-7 km below the oceanic Moho (M) is found. K in Figure 8.9.4-14 may represent the top of one of the volcanic Fogo seamounts.

The marine database was later enlarged by additional profiles, one of which (line 7) coincided with LITHOPROBE line 85-2 and was discussed by Reid (1994) in some detail. After 2000, the project SCREECH (e.g., Funck et al., 2003; Lau et al., 2006a) added more data to the Flemish Cap margin (see Chapter 9).

A major seismic survey was undertaken across the southern edge of the Grand Banks off eastern Canada, south of Newfoundland (Reid, 1988; Todd et al., 1988). In 1983–1984, a SSW-NNE–directed refraction line was shot as a split spread to a closely spaced array of OBSs along the base of the continental slope at the southwest Newfoundland transform margin, a 900-km-long segment of the ocean-continent boundary south of the Grand Banks between 42 and 44°N, 51°–54°W. A second combined reflection and refraction line was added at right angles, together with some reflection profiles across the margin (Todd et al., 1988).

In 1984, this work was extended to a systematic refraction experiment across the southwest Newfoundland transform margin. Seven OBS were deployed and a pattern of split-spread refraction lines was shot subparallel to structure in order to obtain a detailed coverage of the ocean-continent transition. The seismic source consisted of two 32-l airguns which were fired every 60 s, giving a shot spacing of ~200 m. For the reflection profiles, for which data were acquired by a single-channel streamer, the shot rate was increased and the source reduced. The continental crust with an average P-velocity of 6.2–6.5 km/s with 30 km thickness beneath the southern Grand Banks thinned oceanward to a

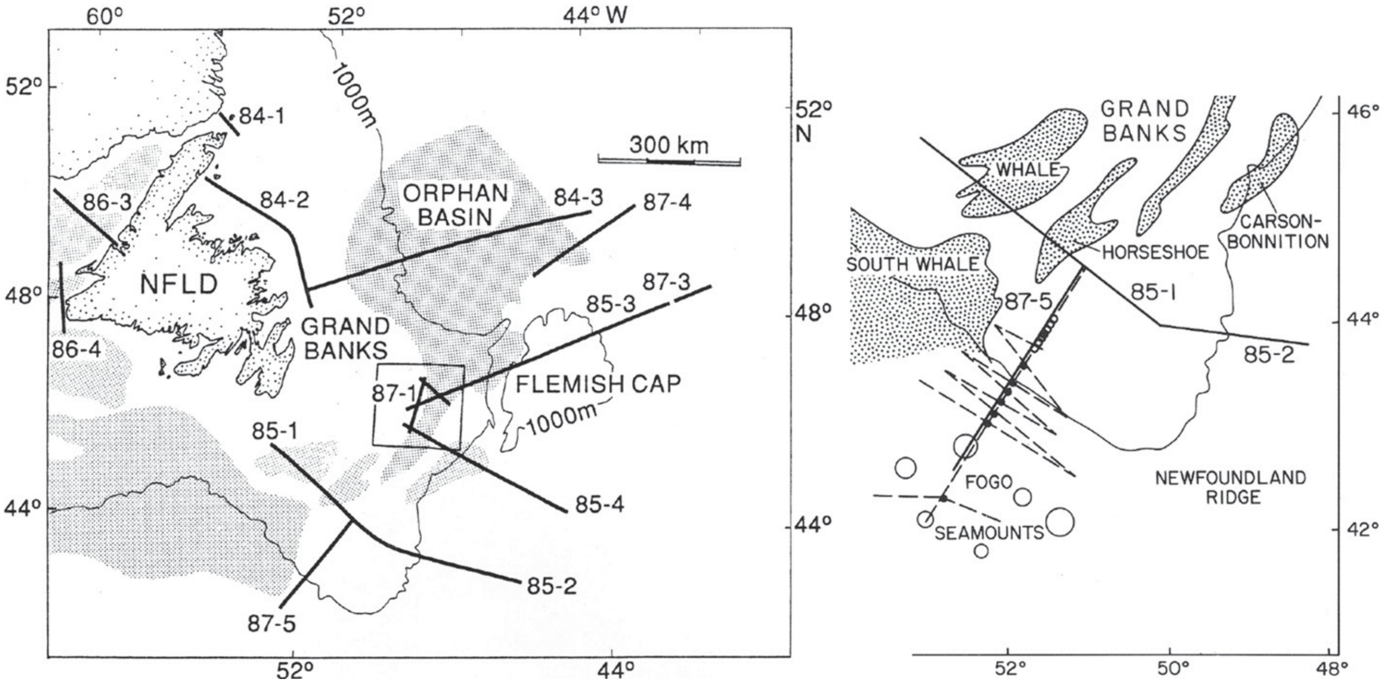
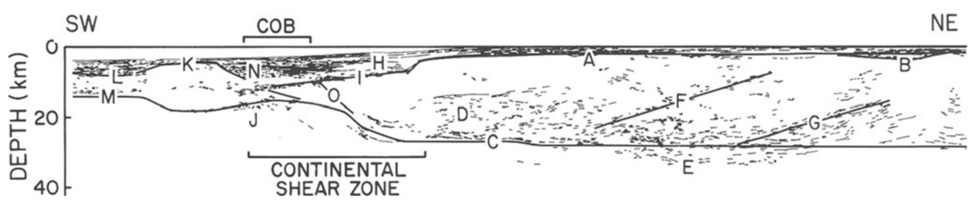


Figure 8.9.4-13. Left: Location of deep seismic reflection profiles off Newfoundland, Canada (from de Voogd et al., 1990, fig. 1). NFLD—Newfoundland. Right: Detailed geography for line 87-5 (from Keen et al., 1990, fig. 1). [Left: Tectonophysics, v. 173, p. 527–544. Copyright Elsevier. Right: Geological Society of America Bulletin, v. 100, p. 1550–1567. Reproduced by permission of the Geological Society of America.]

Figure 8.9.4-14. Line drawing of migrated seismic reflection data recorded along line 87-5 (from Keen et al., 1990, fig. 3) between the Grand Banks and the Fogo seamounts (see Fig. 8.9.4-13 for location). [Tectonophysics, v. 173, p. 527–544. Copyright Elsevier.]



25-km-wide transition zone, where the Paleozoic basement of the Grand Banks (5.5–5.7 km/s) was interpreted to be replaced by a basement of oceanic volcanics and synrift sediments (4.5–5.5 km/s). Seaward of the transition zone the crust appeared oceanic in character, with a velocity gradient from 4.7 to 6.5 km/s and a thickness of 7–8 km. Oceanic layer 3 was not found, and no significant intermediate velocity material (larger than 7 km/s) was seen at the ocean-continent transition which was interpreted to mean that no underplating of continental crust has taken place. The continent-ocean transition across the transform margin appeared much narrower than across rifted margins.

Along the Atlantic continental margin of the United States one of the first of these experiments was the 1981 Large Aperture Seismic Experiment (LASE) during which ESPs and COPs were shot across the Baltimore Canyon (Fig. 8.9.4-15, top section) following approximately line B–B′ in Figure 7.8.4-13 (LASE Study Group, 1986; Diebold et al., 1988; Trehu et al., 1989b).

Another large-aperture experiment in the Gulf of Maine in 1984–1985 (Hutchinson et al., 1987; line GMM on Fig. 8.5.3-24) followed line H–H′ (Fig. 7.8.4-13) and the large-aperture experiment of 1985 followed approximately line E–E′ in Figure 7.8.4-13 in the Carolina Trough (Fig. 8.9.4-15, lower section). Line G–G′ in Figure 7.8.4-13 traversed the Long Island Platform (Trehu et al., 1989a, 1989b). OBS profiles were also laid out, e.g., in 1985, both in the Gulf of Maine and above the Carolina Trough where a series of lines was shot parallel to the structure which complemented the CDP lines (Trehu et al., 1989b). Examples of interpretive cross sections are shown for the Baltimore Canyon Trough and the Carolina Trough (Fig. 8.9.4-15).

In 1988 a deep-penetrating multichannel seismic-reflection (MCS) survey was performed in the Southeast Georgia Embayment on the U.S. Atlantic continental margin consisting of six profiles totaling 1200 km in length (Fig. 8.9.4-16), using a 6-km-long, 240-channnel streamer (Oh et al., 1991). Ocean-bottom seismometers were deployed along the 250-km-long lines BA-3 and BA-6, of which line BA-3 was located entirely on the shelf (Lizarralde et al., 1994), while profile BA-6 aligned across the Carolina trough (Holbrook et al., 1994c). Over 5000

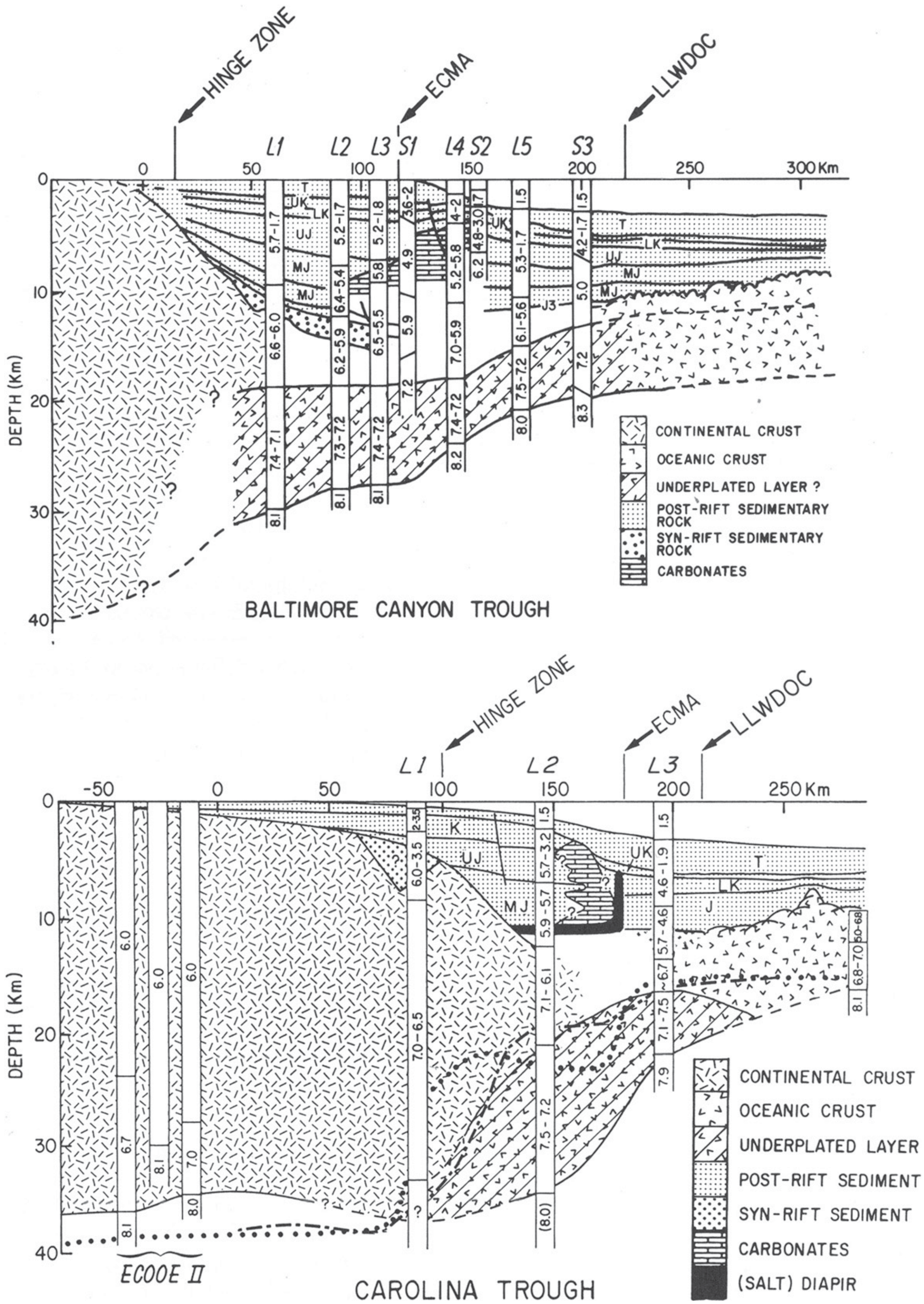


Figure 8.9.4-15. Cross sections through the Atlantic continental margin of the United States (from Trehu et al., 1989b, fig. 18). Top: Baltimore Canyon Trough obtained by LASE Study Group (1986) following line B–B′ in Figure 7.8.4-13. Bottom: Carolina Trough based on data of the 1985 U.S. Geological Survey large-aperture experiment (Trehu et al., 1989a) following line E–E′ in Figure 7.8.4-13. [Journal of Geophysical Research, v. 94, p. 10,585–10,600. Reproduced by permission of American Geophysical Union.]

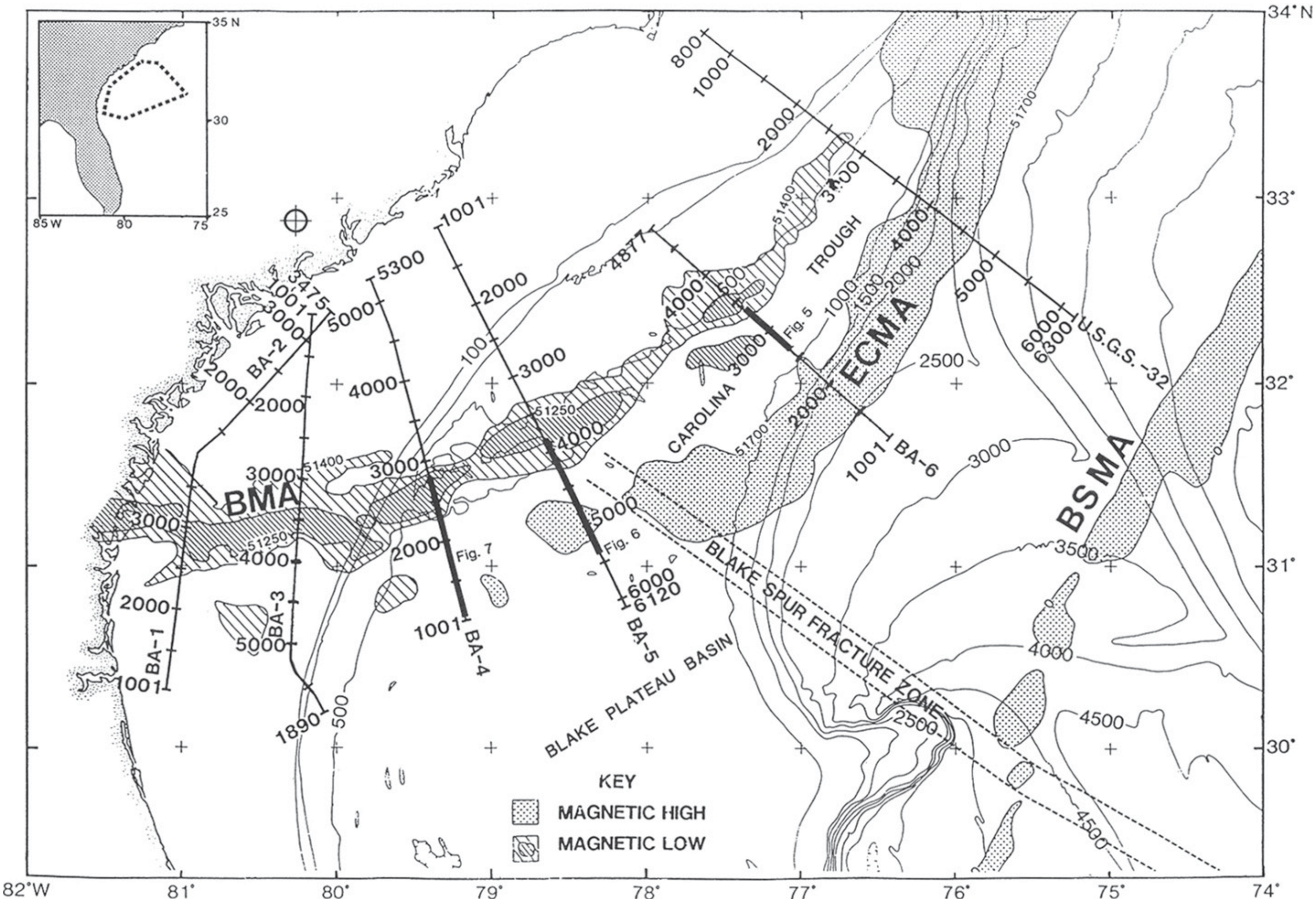


Figure 8.9.4-16. Location of deep-penetrating MCS reflection lines from the Southeast Georgia Embayment (from Oh et al., 1991, fig. 1). Prominent magnetic anomaly trends: BMA—Brunswick; BSMA—Blake Spur; ECMA—East Coast. The USGS line 32 was recorded in the 1970s (see Fig. 7.8.4-13). [*In* Meissner, R., Brown, L., Dürbaum, H.-J., Franke, W., Fuchs, K., and Seifert, F., eds., Continental lithosphere: deep seismic reflections: American Geophysical Union, Geodynamics Series, v. 22, p. 225–240. Reproduced by permission of American Geophysical Union.]

airgun shots were recorded, fired by an airgun array at 50 m intervals. The interpretation of line BA-6 (Fig. 8.9.4-17) shows the structural change from a rifted 34-km-thick continental crust through a 70–80-km-wide transitional zone, where 12 km of postrift sedimentary rocks overlie a 10–24-km-thick subsedimentary crust, to oceanic crust, which comprises 8 km of sedimentary rocks overlying an 8-km-thick crystalline crust (Holbrook et al., 1994c).

The EDGE Mid-Atlantic multichannel seismic experiment was launched to provide more and better images of the deep velocity structure of rifted continental crust on the Atlantic continental shelf of North America (Holbrook et al., 1992b, 1992c). In 1990, data were collected off northern Virginia, United States (Fig. 8.9.4-18). Three marine profiles were recorded, two across the margin (801 and 803) and one parallel to the coast on the continental shelf (802). Shots from a 36-element airgun array were fired at constant distance intervals of 50 m and recorded by a 240-channel, 6-km-long, hydrophone streamer and ten OBS. In addition, shots were recorded by an onshore array of ten RefTeks that extended the aperture of the experiment by ~250 km. Average spacing on line 801 was 13 km on the continental shelf and upper slope and 28 km on the rise.

The crustal cross section of Figure 8.9.4-18 shows the line drawing of the multichannel data along line MA802 (Sheridan et al., 1991) with corresponding crustal velocities from wide-angle data (Holbrook et al., 1992b). The crust appeared to be highly reflective and the Moho was observed between 11 and 12 s TWT corresponding to a depth of ~30 km (Fig. 8.9.4-18).

A preliminary interpretation of line 802 revealed a 34-km-thick crust with four layers beneath the sediments which detailed velocity structure that appeared indistinguishable from the velocity structure found in the 1980s beneath several Appalachian terranes in the northern Appalachians of New England (Holbrook et al., 1992b). Across the margin strong lateral changes in deep-crustal structure were observed. Lower-crustal velocities varied from 6.8 km/s in the rifted continental crust,

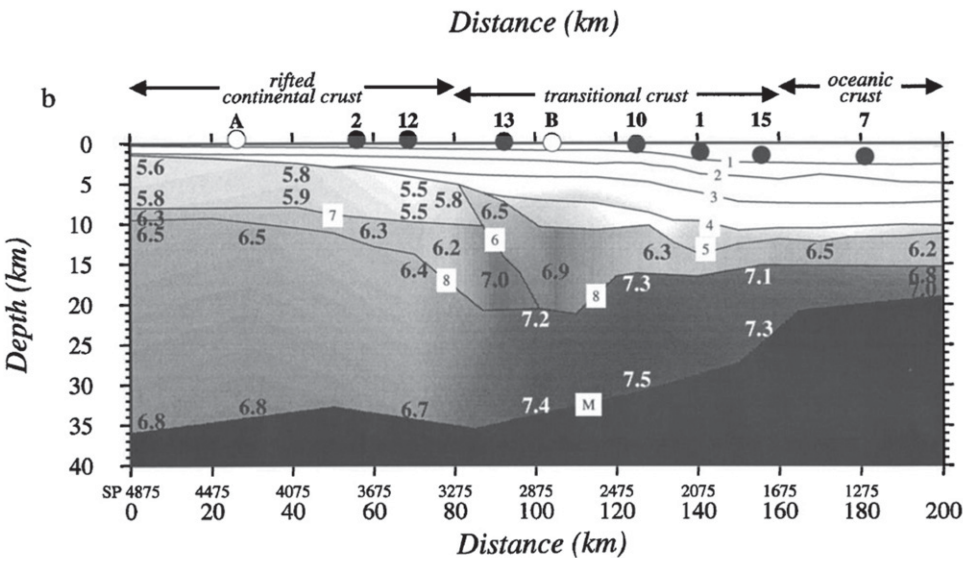


Figure 8.9.4-17. Crustal cross sections through the Carolina Trough of the Atlantic continental margin of the United States (from Holbrook et al., 1994c, fig. 4). [Journal of Geophysical Research, v. 99, p. 9155–9178. Reproduced by permission of American Geophysical Union.]

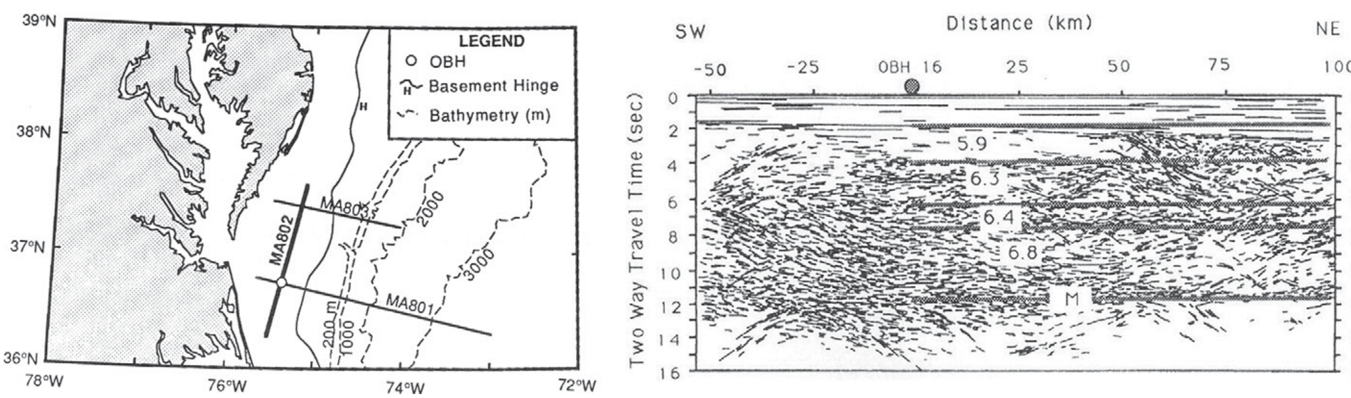


Figure 8.9.4-18. Left: Location of EDGE mid-Atlantic seismic experiment off the coast of northern Virginia (from Holbrook et al., 1992a, fig. 1). Right: Line drawing of multichannel seismic data along line MA802 with corresponding velocities from coincident wide-angle data (from Holbrook et al., 1992a, fig. 5). [Geophysical Research Letters, v. 19, p. 1699–1702. Reproduced by permission of American Geophysical Union.]

to 7.5 km/s beneath the outer continental shelf, to 7.0 km/s in the oceanic crust.

High-velocity lower crust and the seaward-dipping reflections comprised a 100-km-wide, 25-km-thick ocean-continent transition zone. The boundary between rifted continental crust and the seaward thick igneous crust was abrupt, occupying only 20 km of the margin, and the Appalachian intracrustal reflectivity largely disappeared across this boundary as the velocity increased from 5.9 to greater than 7.0 km/s, implying that the reflectivity is disrupted by massive intrusion and that very little continental crust persists seaward of the reflective crust (Holbrook et al., 1994c). The inclusion of the onshore data showed a gradual thickening of the crust from the continental margin westward across the coastal plain, where a uniform thickness of 35 km was observed, to ~45 km under the Blue Ridge section of the southern Appalachians (Lizarralde and Holbrook, 1997).

The Gulf of Mexico also saw increased activities. As an example, the results for a series of experiments carried out after 1983 along the Gulf of Mexico using large airgun sources and dense shot spacing is shown in Figure 8.9.4-19 (Ebeniro et al., 1988; Trehu et al., 1989b).

8.9.5. Summary of Seismic Observations in the Oceans in the 1980s

In the oceans a worldwide study of the lower crust and upper mantle using OBS and big airguns 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

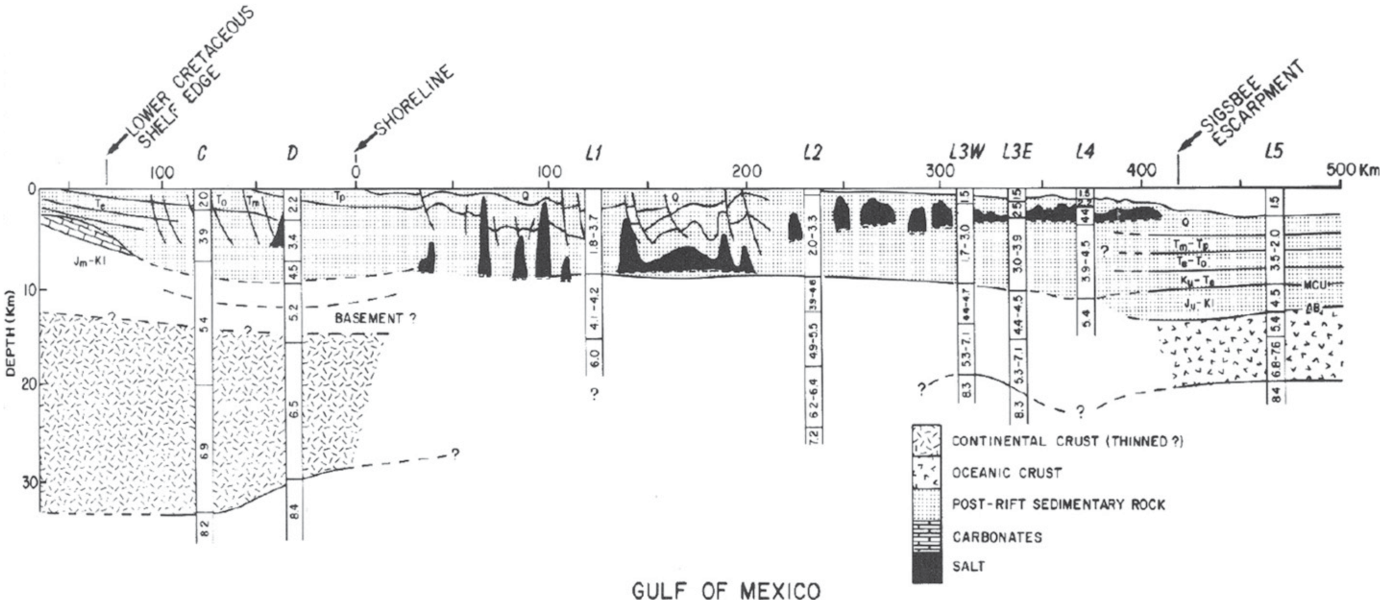


Figure 8.9.4-19. Cross sections through the northern Gulf of Mexico margin (from Trehu et al., 1989b, fig. 18C). [*In* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 349–382. Reproduced by permission of the Geological Society of America.]

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) 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 have 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).

Increased research activity is shown for the Polar Regions, both north and south. The summary map for the 1980s in Figure 8.9.5-01, which lists only data points published until 1989, indicates that apparently less activity happened in the 1980s. This is not quite true. Many projects of the 1980s which were described in Chapter 8.9 do not show up on the map produced from data in the USGS database. None of the marine components of the European large-scale seismic-reflection surveys like BIRPS, ECORS, CROP, or BABEL appear on the map. This is due to the fact that in the database all these surveys were classified as land projects similar to what we have done in this volume. In other cases, as is probably true, for example, for the projects northwest of Ireland on the Rockall Trough, the corresponding publications may have appeared only in the following decade. Finally, few data points do not always mean little activity. Concentration of projects on a specific area may have led to an accumulation of data points and caused them to appear as one data point only. In spite of these discrepancies, which are evident especially for the 1980s, we have included this map in our summary, as it is consistent with the summary maps for the other decades.

8.10. ADVANCES OF INSTRUMENTAL AND INTERPRETATION METHODOLOGY AND THE STATE OF ART AT THE END OF THE 1980s

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). On that basis computer programs for ray tracing and calculating ray-theoretical synthetic seismograms had been developed in the 1970s and early 1980s which allowed interpreting complicated structures in two or three dimensions (e.g., Červený, 1979; Červený and Horn, 1980; Červený and Pšenčik, 1984a, 1984b; Gajewski and Pšenčik, 1987, 1988; McMechan and Mooney, 1980; Sandmeier and Wenzel, 1986; Spence et al., 1984). With

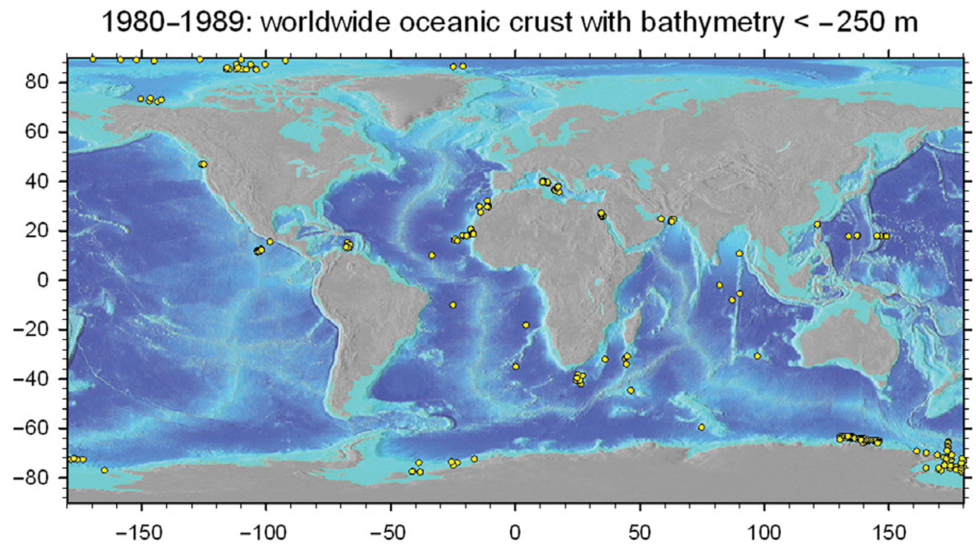


Figure 8.9.5-01. Seismic refraction measurements in the Atlantic, Pacific and Indian Oceans performed between 1980 and 1989 (data points from papers published until 1989 in easily accessible journals and books).

this technique, the requirement to obtain a denser data coverage, in particular in tectonically complicated regions, grew rapidly.

Consequently, the 1980s saw a transition in the development of new instrumentation. It had become clear that the station spacing of 5 km or more for detailed crustal structure studies, which had been regarded as sufficient up to the 1970s, did not provide the resolution required to answer many scientific questions. Rather, smaller shotpoint and station spacing was required. By the end of the 1970s, the development of the cassette recorders at the USGS (Murphy, 1988; for details see Appendix A7-5-6) was the first attempt to fill this gap. A large number of easily maintained instruments with fast play-back facilities became available, which 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, and by the end of the 1980s, both in Canada and in the United States not only a large number of instruments became available, but also the age of digital recorders had started, pushed forward in particular in the United States by the foundation of IRIS in 1984 with its sub-organization PASSCAL (Program for Array Seismic Studies of the Continental Lithosphere).

In Europe, the MARS-66 analogue system experienced a late peak, and by the early 1980s, ~200 units were available in continental Europe. Station spacing also decreased to 2 km in most seismic-refraction experiments in Europe. The search for suitable super-deep drill sites and the idea of the European Geotraverse spanning the whole of Europe added to the activities in crustal research. The development of a new digital generation of seismic instruments, however, was slower than in North America, partly caused by lack of a Europe-wide organization to enable special funding. Only in the first half of the 1990s would the time be ripe for the test and subsequent purchase of newly developed digital equipment. An exception was the University of Hamburg where Jannis Makris had collected sufficient funding to push for an internal development which finally enabled the building of a large quantity of recording instruments. The development of this analogue device was such that the individual units could either be built into ocean-bottom devices (OBS) or be used on land (LOBS) accompanied by a computerized fast play-back facility. In Britain, the Cambridge university group had undertaken another approach. Here a new digital recording system had been developed, named DOBS, especially designed for controlled-source work, both to be used at sea or on land allowing up to six hours total recording duration (Owen and Barton, 1990). The system was successfully tested in a marine survey off Oman.

On the other hand, crustal research in Europe received a new impulse from reflection seismology by the rapid formation of national groups, such as BIRPS, ECORS, DEKORP, and other national groups, favoring vertical-incidence reflection work in a big style and following the ideas developed by COCORP in North America in the late 1970s. In a review paper, Mooney and Meissner (1992) describe the development and the main achievements of reflection seismology on the research of continental lower crust and Moho.

In the beginning of COCORP, 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. On the other hand, in central Europe, close cooperation between the “reflection” and “refraction” groups started from the very beginning. ECORS profiling was always accompanied by simultaneous wide-angle operations (Bois et al., 1986) as were the first long reflection profiles accompanying the search for deep drill sites in southern Germany (e.g., Wenzel et al., 1987). From 1985 onward, the CCSS workshops aimed particularly at a joint interpretation of seismic-reflection and refraction data (Walter and Mooney, 1987; Green et al., 1990a). Mooney and Brocher (1987) have compiled a global review on coincident seismic-reflection/-refraction studies of the continental lithosphere.

Comprehensive reviews of the seismic velocity structure of the deep continental lower crust that represent the state of art by the end of the 1980s were published (e.g., Mooney, 1987). For example, Holbrook et al. (1992a) included a table of lower-crust velocities and corresponding references typical for different tectonic environments (see also Christensen and Mooney, 1995). Mooney and Meissner (1992) discussed the multi-generic origin of crustal reflectivity of the lower crust in various environments. Other compilations concern summaries of crustal and upper mantle structure based on controlled-source seismology observations for different continents or large parts of those continents, e.g., Meissner et al. (1987b) for Europe, Pakiser and Mooney (1989) for North America, Pavlenkova (1996) for the territories of the former Soviet Union, and Mechie and Prodehl (1988) and Prodehl and Mechie (1991) for the Afro-Arabian rift, while in Olsen (1995), e.g., reviews for continental rifts around the world were compiled by different authors based on a series of discussion meetings of experts.