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CHAPTER 10 The Twenty-first Century (2000–2005)

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CHAPTER 10

The Twenty-first Century (2000–2005)

10.1. THE SECOND DECADE OF DIGITAL RECORDING

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

The PASSCAL pool and UTEP in the United States had a total of 840 of the new Texan instruments by 2000. The University of Copenhagen, Denmark, purchased 100 units, the Earth Science Research Institute TUBITAK-MAM in Gebze, Turkey, acquired 60 units, and other groups in Central Europe obtained ~40 units (Guterch et al., 2003a).

In the UK, Leeds University had purchased the Orion system, and in 2000, the universities of Leicester, Cambridge, Leeds, and London Royal Holloway were awarded a grant to acquire large numbers of Guralp 6TDs and 40Ts, together with a number of Guralp 3Ts, bringing the British scientists to the forefront of observational broadband seismology. Following the end of the grant, the equipment was taken over by the NERC Geophysical Equipment Pool, who kept the name SEIS-UK for the seismological component of its structure. A total of 182 Guralp instruments were acquired at the start of SEIS-UK (10x3TD, 20x40TD and 152x6TD). The 2010 inventory included 28x3TD, 15x3T, 20x40TD, 35x3ESPDC (60sec) and 112x6TD.

In Germany in 2000, the GeoScience Center Potsdam started to gradually renew its instrument pool for short-period and broadband seismology and has now replaced the worn-out RefTek and PDAS data loggers with a new system, the Earth Data PR6-24. Up to mid-2007, almost 240 of these new data loggers were acquired and made available for the geophysical community, with an additional 10 broadband GURALP units for special purposes. A major cooperative effort between land and sea investigations promises a new instrumental pool, named DEPAS (Deutscher Pool für Aktive Seismologie). In early 2006, it consisted of 30 OBS and 65 GURALP seismometers plus Earth Data Loggers, which had been enabled by a joint venture of the German institutions GFZ (GeoForschungsZentrum Potsdam) and AWI (Alfred-Wegener-Institut Bremerhaven) for amphibious seismology (Schulze and Weber, 2006; Schmidt-Aursch et al., 2006). When completed, 100 Earth Data Loggers PR6-24 and 100 GURALP CMG-3ESP compact units will be available for the land part of DEPAS. For the offshore part, 68 standard and 12 deep-sea OBS (Guralp CMG-40T seismometers plus hydrophones) and 5 OBH (hydrophones only) will be available.

Large-scale research programs that involved a multitude of cooperating institutions and interdisciplinary cooperation of various geoscientific fields continued to dominate the scene in the early 2000s. With the increasing number of recording devices, the possibility of covering large areas two-dimensionally enabled more and more the application of tomographic methodologies such as teleseismic tomography. Many earth scientists started to prefer long-term deployments using natural events as energy sources instead of short-term projects using expensive controlled sources.

Since the early 1990s, the organization of large controlled-source seismology projects has faced growing difficulties, which is another reason for the decline in controlled-source work. At sea, the use of explosives as a seismic source is now banned due to the impact on marine life from such effects as vibration and chemical contamination. Nowadays, modern marine projects have to rely mostly on powerful airgun sources. For land-based projects, more and more demanding environmental restrictions involving major environmental impact assessments have very nearly led in the recent past to the cancellation of experiments, in spite of the fact that in general, the real impact is pretty small. This and other organizational difficulties dealing with officials or with the problem of needing a lot of people for a short time, for example, are good reasons that scientists plan more and more for passive rather than active seismic-source experiments.

Nevertheless, in many cases, a combination of active- and passive-source experiments is being aimed for. IRIS/PASSCAL in the United States and LITHOPROBE in Canada continued to support large seismic (active) and seismological (passive) projects, occasionally combined with international and interdisciplinary geoscientific priority programs in Europe, dealing with large-scale tectonic topics. EUROPROBE, supported by the European Science Foundation, continued to support programs concerned with the origin and evolution of the continents (Gee and Stephenson, 2006) emphasizing East-Central-West European collaboration and close multinational cooperation of geologists, geophysicists, and geochemists.

Special sessions on large national and international seismic programs became important components of the annual meetings

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of the various national and international geoscientific organizations, such as, e.g., the American Geophysical Union or the European Geophysical Union, but special meetings of earth scientists at regular intervals also continued such as the biannual meetings of the special subcommission of the ESC's (European Seismological Commission) "Structure of the Earth's Interior," the CCSS (Commission on Controlled Source Seismology) workshops on interpretation methods (e.g., Hole et al., 2005), and the series of "International Symposia on Deep Seismic Reflection Profiling of the Continental Lithosphere" which continued into the twenty-first century with meetings at Ulvik, Norway, in 2000 (Thybo, 2002), in Taupo, New Zealand, in 2003 (Davey and Jones, 2004), in Mont-Tremblant, Quebec, Canada, in 2004 (Snyder et al., 2006), in Hayama, Japan, in 2006 (Ito et al., 2009a), in Saariselkä, Finland, in 2008, and in Cairns, Queensland, Australia, in 2010.

In particular, the Working Group on Seismic Imaging of the Lithosphere played and plays an important role for the development and improvement of seismic interpretation methods. Since 1968 the IASPEI CCSS had sponsored a series of "Deep Seismic Methods" workshops (see, e.g., Chapter 7.9—Ansorge et al., 1982; Mooney and Prodehl, 1984; Chapter 8.2—Finlayson and Ansorge, 1984; Walter and Mooney, 1987; Green et al., 1990a; and Chapter 9.1—Pavlenkova et al., 1993; Snyder et al., 1997; Jacob et al., 1997, 2000). The workshops focused on the methodological aspects of reflection and refraction seismology as applied to the crust and lithosphere, and the goal was to develop and assess improved acquisition, processing, modeling, inversion, and integration procedures. Prior to the workshops, data had been distributed to the participants with the request to interpret them with the available methodologies and discuss methods and results at the subsequent workshops. The CCSS Working Group was recently reorganized as the Working Group on Seismic Imaging of the Lithosphere, continuing the series of international CCSS workshops on interpretation methods (Hole et al., 2005). Just as in the workshop held at Einsiedeln, Switzerland, in 1983 (Finlayson and Ansorge, 1984), before the 2005 workshop, synthetic seismograms were computed from a given model, this time using a 2-D viscoelastic finite difference algorithm (Robertsson et al., 1994). Fifty sources were fired into the model and recorded by 2800 receivers to create a crustal-scale refraction survey geometry. For the interpretation without knowing the model, the current standard methodology was applied. The interpretation of the synthetic data with a first-arrival traveltime tomography gave a high resolution for the upper crust and a correct depth and long-wavelength structure for the Moho, but the resolution deteriorated in the lower crust. The model was subsequently improved by using refraction and reflection traveltimes from the Moho to invert for a discrete Moho and velocity structure below 15 km (Hole et al., 2005; Zelt et al., 2003).

The following description of major seismic projects undertaken between 2001 and the beginning of 2006 cannot be complete and will be rather limited. Due to the large number of available instruments and the resulting huge amount of data, the completion of large seismic projects, with major publications on the results available in print, usually takes at least 5 years. For many projects undertaken since 2001, only abstracts or short outlines have become available up to the end of 2005. In the following, we have concentrated in particular on those projects for which reasonable information has already been published. Nevertheless, we will also mention some other major projects which were undertaken in the first five years after 2000, for which either abstracts or internal reports at scientific meetings have become available to us.

10.2. CONTROLLED-SOURCE SEISMOLOGY IN EUROPE

10.2.1. Western and Southern Europe

The fruitful cooperation of the Dublin Institute for Advanced Sciences with German partners continued in 2002. During the recording windows set for the controlled-source seismic experiment of VARNET96 (see Chapter 9), some earthquakes and a nuclear event had been recorded. These data had been used to model the probable trace of the Iapetus suture in the upper mantle just south of the Shannon river estuary at between 30 and 110 km depth (Masson et al., 1999). In 2002 and 2003, a specially designed Irish Seismological Lithospheric Experiment (ISLE) was undertaken to investigate the nature and tectonic history of the deep lithospheric and asthenospheric structure of the Iapetus Suture Zone (Landes et al., 2004c, 2005).

On the Iberian peninsula in 2001, the IBERSEIS deep seismic-reflection transect across the SW Iberian Massif (Carbonell et al., 2004; Flecha et al., 2009; Palomeras et al., 2009) crossed three major geological zones. The Vibroseis data set provided a crustal image that revealed the geometry of the structures and average physical properties of the shallow crust, but not for deep crust and upper mantle. One of the most relevant results of the Vibroseis study was a high-amplitude, strongly reflective structure named the IBERSEIS Reflective Body, which is ~140 km long and located at mid-crustal level at ~12–14 km depth. However, due to the fact that the Variscan belt of SW Iberia is a transpressive orogen in which large strike-slip movements have been suggested, the two-dimensional view provided by the deep normal incidence transect IBERSEIS might not be sufficient, and some kind of 3-D control appeared to be needed for a reasonable structural interpretation. Therefore, also in 2001, two wide-angle seismic transects were acquired (Palomeras et al., 2009). The project aimed to provide velocity constraints on the lithosphere and to complement the previously acquired normal incidence seismic profile IBERSEIS (Carbonell et al., 2004). The wide-angle reflection lines were ~300 km long. They had up to 6 shotpoints with an approximate interval of 60 km, with charge sizes between 500 and 1000 kg. A total of 690 digital seismic recording instruments (650 1-component Texans and 40 RefTek 3-component units) from the IRIS/PASSCAL were used. With 400 m spacing along one line and 150 m on the other one, the acquisition parameters provided closely spaced seismic

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images of the lithosphere. The combined data sets indicated rocks of mafic composition in the middle crust and revealed new aspects related to the lithospheric evolution of this transpressive orogen (Palomeras et al., 2009).

The IBERSEIS line was extended by another 300 km to the northeast by the ALCUDIA project in 2007, providing a complete transect from the Gulf of Cadiz to the Hercynian domain of the Spanish Meseta (Díaz and Gallart, 2009).

A detailed review on crustal structure of the Iberian Peninsula was published by Díaz and Gallart (2009). Their location map shows all seismic profiles observed since the 1970s to present, both on land and in the surrounding waters. Several cross sections reaching from coast to coast, and a Moho depth contour map, accompanied by a topographic map showing the individual data points, demonstrate the gradual crustal thickening from near 10 km under the Atlantic margin areas to 30 km under the Variscan Iberian Massif. Maximum crustal thicknesses are reached with 50 km under the Pyrenees and with 40 km under both the Iberian Chain in eastern Spain and the Betic Chain in Southern Spain. Toward the east and south, the crust thins rapidly to 15 km under the Valencia Trough and the Alboran Sea. Under the Balearic Islands, Moho depth increases locally to ~25 km.

10.2.2. Northern Europe

In Denmark in 2004 and 2005, the project ESTRID (Explosion Seismic Transects around a Rift in Denmark) was launched to investigate primarily the lower crust and Moho around the Silkeborg gravity high in central Denmark underneath the Mesozoic sedimentary Danish Basin (Nielsen et al., 2006; Thybo et al., 2006; Sandrin and Thybo, 2008). This is located close to the margin of the Precambrian Baltic Shield within the former Baltica plate. Two seismic profiles in central Jutland were recorded. The first one in 2004 was a refraction/wide-angle survey in an E-W direction across the peninsula and of 160 km length, the other one was a 185-km-long combined reflection/refraction survey oriented in a N-S direction and performed in 2005 (Sandrin and Thybo, 2008). The reflection part of the 2005 line had 4 × 760 recording sites over 110 km profile length and used 94 shots of 15–25 kg. The data confirmed the presence of a high-velocity body with velocities greater than 6.5 km/s and a N-S width of 30–40 km extending from 10 to 12 km depth into the lower crust underneath Silkeborg. Along the E-W profile, the Moho showed a substantial relief, with its depth varying between 27 and 34 km (Thybo et al., 2006).

On the Baltic Shield, new seismic-reflection studies were added to the existing seismic observations. In Finland from 2001 to 2003, a large deep seismic-reflection survey consisting of four sections, FIRE 1–4, was performed throughout Finland to study the structural architecture and evolution of the Fennoscandian Shield. The profiles had a total length of 2165 km and transected all major tectonic units and boundaries of the Fennoscandian Shield in Finland. The data and an interpretation have not yet been published (FIRE consortium, 2006).

On the Kola Peninsula in 2000–2002, Spetsgeofisika conducted a Vibroseis common mid-point experiment across the western and central Mezen Basin and along a line across the Timan Range which was already mentioned in Chapter 9 and discussed in context with the data obtained from 1998 to 2000 (Kostyuchenko et al., 2006, see dotted lines 3 and 4 in Fig. 9.3-03).

10.2.3. Central and Eastern Europe

After the successful completion of TRANSALP from 1998 to 2001 (e.g., Lueschen et al., 2006; Gebrande et al., 2006), in 2002 an additional large-scale seismic-refraction experiment, ALP 2002, was carried out in the Eastern Alps (ALP 2002 Working Group, 2003; Brueckl et al., 2003, 2010, Fig. 10.2.3-01; Sumanovac et al., 2009). Its realization developed out of a large international cooperation, headed and initiated by the Polish scientists M. Grad and A. Guterch, who, in 1997 and 2000, had successfully completed the two large-scale seismic-refraction campaigns POLONAISE'97 and CELEBRATION 2000, which were described in more detail in Chapter 9.2.4. On the basis of these projects, they had initiated the third international campaign, ALP 2002, this time centered on the Carpathians and adjacent Alps (Fig. 10.2.3-01).

ALP 2002 was designed to meet the following criteria: the whole area of investigation should be covered by a 3D geometry of profiles, the CELEBRATION 2000 technique would be applied, and the outline of the survey would connect with the

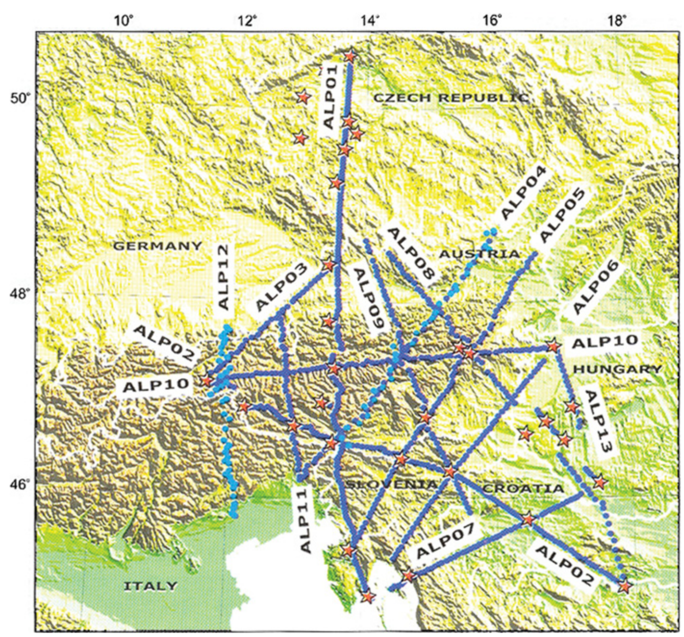

Figure 10.2.3-01. Location map of ALP 2002. Red stars—shotpoints; blue lines—seismic refraction profiles (from Brueckl et al., 2003, fig. 1). [Studia Geophysica et Geodaetica, Academy of Science, Czech Republic, Prague, v. 47, p. 671–679. Permission granted by Studia Geophysica et Geodaetica, Prague, Czech Republic.]

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CELEBRATION profiles as well as with the TRANSALP profile. In total 40 shots were set off, 32 of them "strong" shots with 300 kg charges, distributed in 5–6 boreholes of 40–50 m depth. The remaining 8 shots had less than 100 kg and were shot in Hungary. Thirteen seismic-refraction lines were set up, using a total number of 926 Texan instruments (RefTek-1-component stations with 4.5 Hz geophones). Of these lines, line ALP04 overlapped with and extended the CELEBRATION 2000 line CEL10, and ALP12 followed the TRANSALP profile. In total, 4300 profile-km were covered. In addition a reflection recording spread was deployed in Austria and a dense local 3D-deployment was accomplished in Hungary. Furthermore, 70 stations were deployed along lines ALP04 and ALP12 for passive seismic monitoring. The ALP 2002 Working Group comprised scientists from Austria, Canada, Croatia, Czech Republic, Denmark, Finland, Germany, Hungary, Poland, Slovenia, and the United States (ALP 2002 Working Group, 2003; Brueckl et al., 2003). Recent interpretations were published in 2006, 2007, and 2010 (Bleibinhaus et al., 2006; Brueckl et al., 2007, 2010).

The large-scale seismic-refraction experiment ALP 2002 (ALP 2002 Working Group, 2003; Brueckl et al., 2003) also covered major parts of Eastern Europe outside the Alps. Some of the profiles, ALP01, ALP04, and ALP05 traversed the Bohemian Massif in the Czech Republic, while profiles ALP13, ALP02, and ALP07 were centered in the Pannonian basin of Hungary, also touching the Dinarides of Slovenia and Croatia (Sumanovac et al., 2009; Figs. 10.2.3-01 and 10.2.3-02).

In 2003, the project SUDETES 2003, a 3-D seismic-reflection experiment with the aim to contribute to the investigation of deep crustal structure and geodynamics of the northern part of the Bohemian Massif, the largest outcropping part of the Late Paleozoic Variscan orogen in Central Europe, was launched. An overview of all long-range controlled-source seismic experiments in central and Eastern Europe from 1997 to 2003 was published by Guterch et al. (2007).

The layout of the field part of the project consisted of a network of profiles (Fig. 10.2.3-02), where besides in-line observations also off-line recordings were planned to obtain dense ray coverage for 3-D modeling (Guterch et al., 2003a; Majdanski et al., 2006).

Fifty-three shots with charges ranging from 50 to 1000 kg were fired into a network of six profiles, S01 to S06, which, with an average station spacing of 3–4 km, covered a total of 3450 km. The longest line, S04, ran from Germany in a NW-SE direction through the Czech Republic and Slovakia into the Pannonian Basin in Hungary, and was located ~100 km further north of and

Figure 10.2.3-02. Map of Central-East Europe, showing location of major seismic refraction experiments (from Guterch et al., 2003a, fig. 1): CELEBRATION 2000 (red lines), ALP 2002 (light blue lines), and SUDETES 2003 (dark blue lines). [Studia Geophysica et Geodaetica, Academy of Science, Czech Republic, Prague, v. 47, p. 659–669. Permission granted by Studia Geophysica et Geodaetica, Prague, Czech Republic.]

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parallel to line CEL09, described above. The second-longest line, S01, ran in a SW-NE direction through Czech territory parallel to the German MVE 90 line, south of the Erzgebirge, into Poland and ended on the East European craton.

Lines S02, S03, and S06 were jointly interpreted by Majdansky e al. (2006). The lines S02 and S03 ran almost parallel in an approximately N-S direction from Poland into the Czech Republic, and line S06 was a short, east-west–oriented cross line near latitude 52°N. As a result of the interpretation of the lines S02, S03, and S06 (Fig. 10.2.3-03; for more data examples see Appendix A10-1-1), the crust of the Bohemian Massif with a thickness of 33–35 km appeared slightly thicker than that of the Polish fore-Sudetic area further north (Majdanski et al., 2006; Fig. 10.2.3-04). The lithospheric structure of the Bohemian Massif and adjacent Variscan belt in central Europe based on Profile S01 was interpreted by Grad et al. (2008).

Within the framework of the SUDETES 2003 project, the GRUNDY 2003 was performed with the aim of investigating the extent of the Variscan deformation front, which is one of the key problems of the regional geology of the Central European Permian Basin system, particularly in its Polish part (Malinowski et al., 2007), because conventional reflection seismics usually fail to produce a satisfactory image of the pre-Permian strata due to the shielding effect of Zechstein (Upper Permian) evaporites.

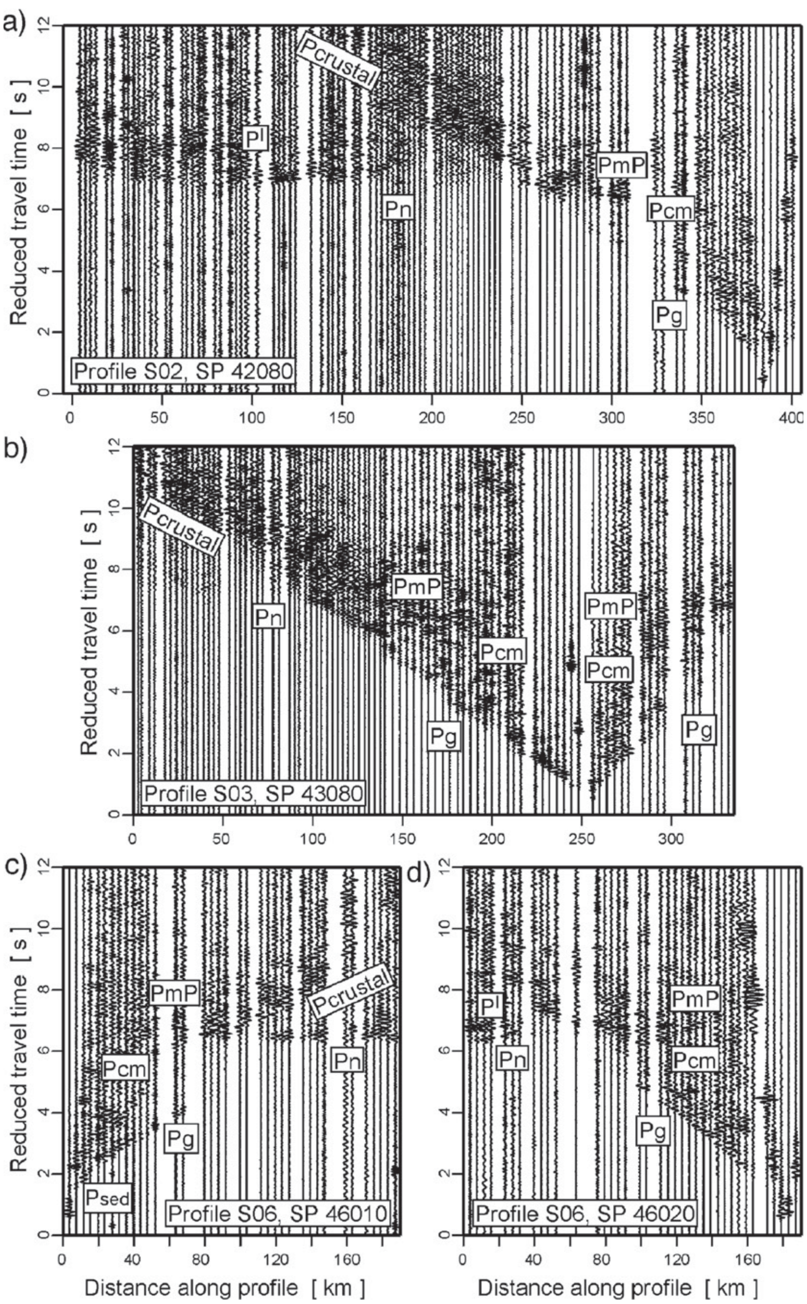

Figure 10.2.3-03. Examples of record sections for profiles S02, S03, and S06 of the SUDETES 2003 seismic project (from Majdanski et al., 2006, fig. 3). [Tectonophysics, v. 413, p. 249–269. Copyright Elsevier.]

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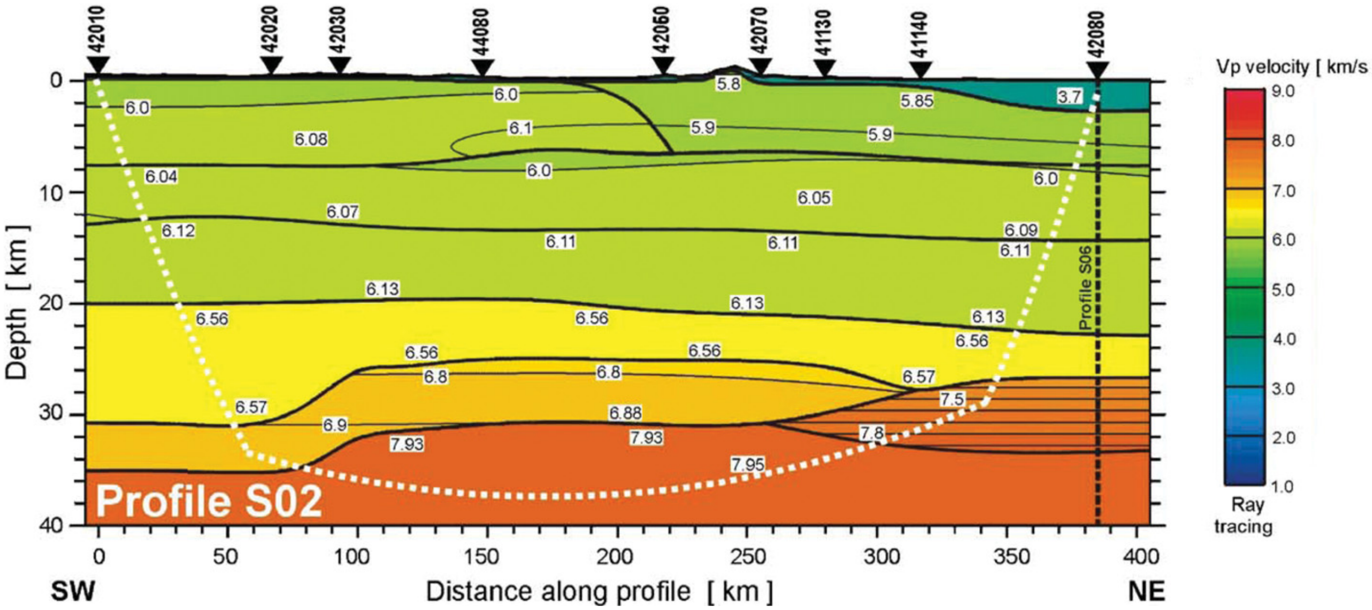

Figure 10.2.3-04. Crustal velocity-depth cross section for profile S02 of the SUDETES 2003 seismic project (from Majdanski et al., 2006, fig. 5). [Tectonophysics, v. 413, p. 249–269. Copyright Elsevier.]

Thus, Malinowski et al. (2007) used a novel seismic acquisition technique to study the base of the Permian complex and its Variscan basement. In the GRUNDY 2003 experiment, wide-angle reflection-refraction measurements were combined with the near-vertical reflection seismics by the use of the constant geophone array with dense (100 m) receiver spacing occupying a 50-km-long profile. The 3-D design of the experiment, covering a 50 × 10 km area, helped in eliminating the effect of out-of-plane propagations and local inhomogeneities. In the 50 × 10 km rectangular area, a total number of 786 single channel RefTek 125 "Texan" seismic stations equipped with 4.5 Hz geophones were deployed, forming a high-density central line (receiver spacing 100 m, 50 km long, referred to as G01 line) and additional 4 parallel profiles (G12–G15) with similar length but with mean receiver spacing of 600 m. Thirty shots were fired along the G01 profile, and 7 shotpoints were put in the side profiles. The mean charge of the shots was 50 kg of TNT explosives located in 2 drill holes 30–40 m deep. The data were recorded both inline and crossline, which allowed for 3D tomographic modeling of the whole target area and 2D reflection processing along G01 line. An effective integration of traveltime tomography, common-depth-point reflection processing, and prestack depth migration of wide-angle reflections applied to the data, allowed for a model in which the contact zone of the Variscan overthrust structure (Variscan front), with its molasse-filled foredeep, was deduced.

From 2001 to 2003, a passive teleseismic tomography project, BOHEMA, was added to the crustal and uppermost mantle investigations of the Bohemian Massif by controlled-source seismic experiments with the aim to develop a 3-D geodynamic model of the whole lithosphere-asthenosphere system (Babuska et al., 2003).

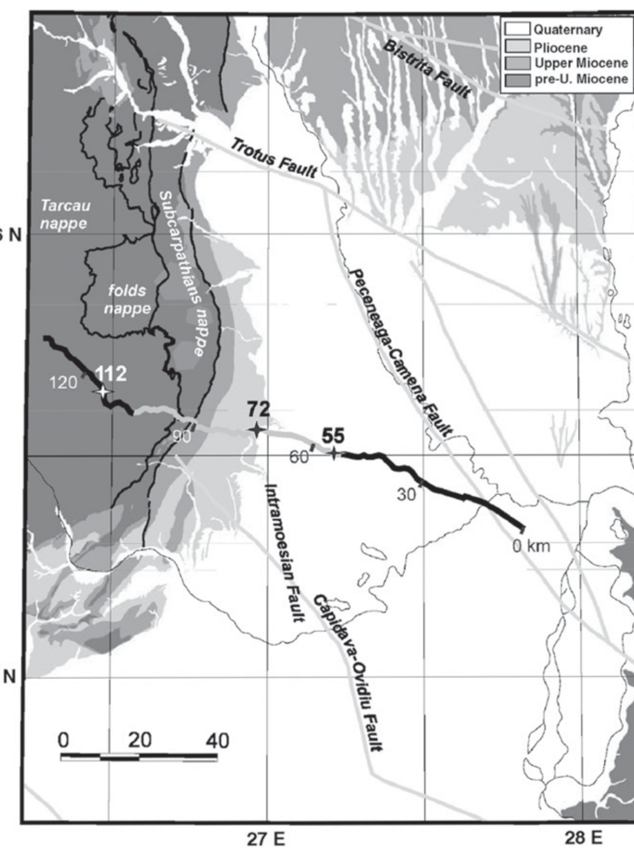

Figure 10.2.3-05. Map of southeastern Romania, showing the location of the DACIA PLAN seismic survey with the separate recorder deployments 1–3 (black-grey-black) indicated (from Panea et al., 2005, fig. 3). [Tectonophysics, v. 410, p. 293–310. Copyright Elsevier.]

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In Romania in 2001, the second experiment across the Vrancea zone, VRANCEA 2001, was recorded. It was a 700-km-long WNW-ESE–trending seismic-refraction line and was carried out in August and September 2001 in Romania with a short extension into Hungary (Hauser et al., 2002, 2007a). The main part (for location see Fig. 9.2.4-11) ran from the Transylvanian Basin to the Black Sea coast, across the East Carpathian Orogen, the Vrancea seismic region, the foreland areas with the very deep Neogene Focsani Basin and the North Dobrogea Orogen. Landes et al. (2004b) have compiled data and other technical details in a data report. Due to its close relation to the VRANCEA'99 experiment, this project and its main results (see Fig. 9.2.4-15) have already been described in more detail in Chapter 9.

The VRANCEA 2001 project (Hauser et al., 2002, 2007a) also included a near-vertical incidence seismic-reflection part. Between shotpoints T and U the geophones had been deployed at a spacing of 100 m. Immediately following the seismic-refraction work of VRANCEA 2001, two more deployments, using all available 640 one-component geophones (Texan type), were again laid out at 100 m spacing along the VRANCEA 2001 refraction line to the east of shotpoint T, traversing most of the Focsani basin, and shots were fired every 1 km (Fig. 10.2.3-05). This additional seismic-reflection program was enabled by the project DACIA PLAN (Danube and Carpathian Integrated Action on Process in the Lithosphere and Neotectonics). Panea et al. (2005) processed the data and published a first interpretation (Fig. 10.2.3-06).

In order to study in more detail a possible connection between crustal structure and the intermediate-depth seismicity of the Vrancea Seismogenic Zone (V in Fig. 9.2.4-11) with epi-

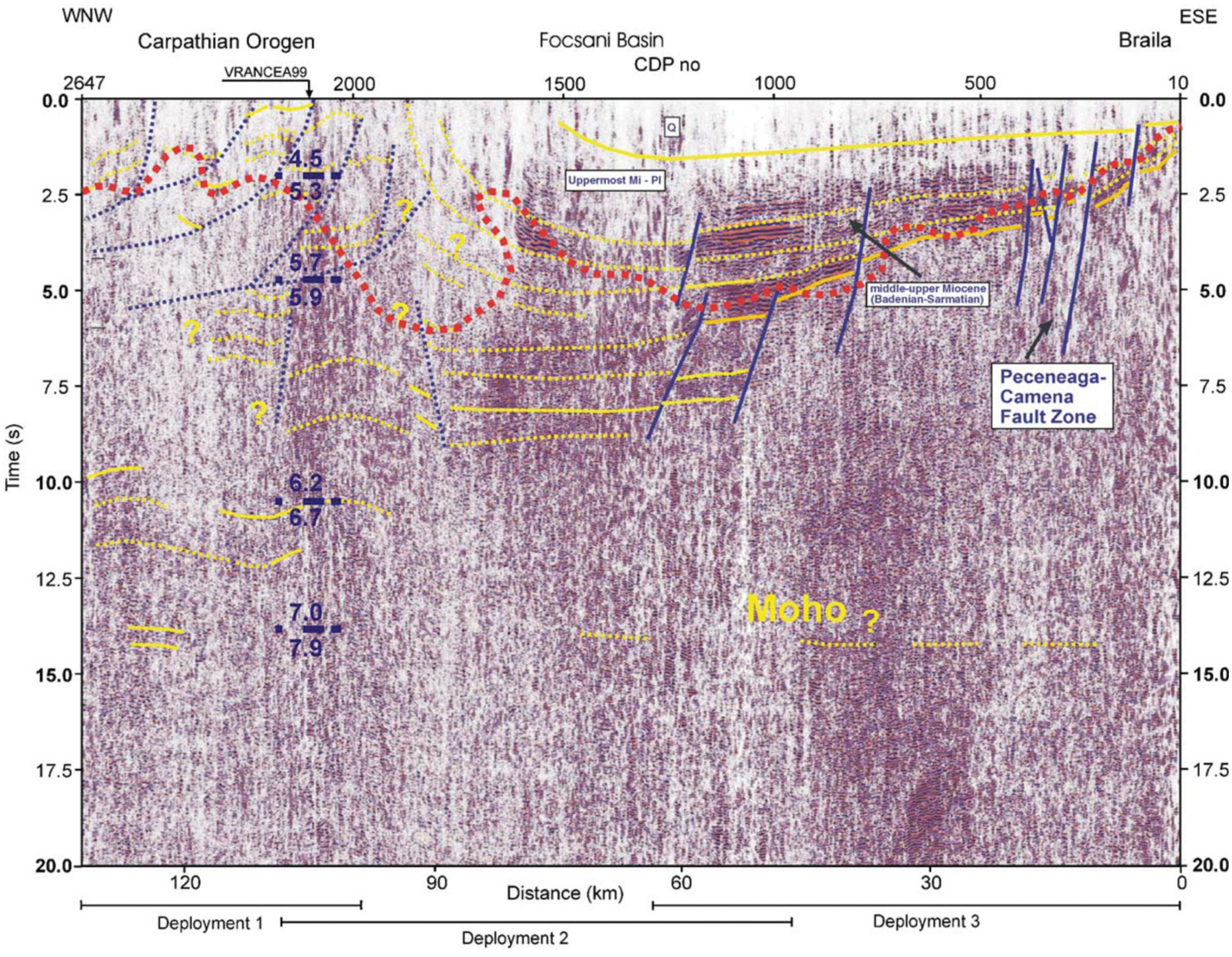

Figure 10.2.3-06. Interpreted time seismic section of the DACIA PLAN seismic survey (from Panea et al., 2005, fig. 10b). Dark blue velocity interfaces are from the VRANCEA99 model of Hauser et al. (2001), red dashed interface represents the 5.0 km/s velocity contour of the tomographic model of Bocin et al. (2005), blue and yellow lines—geological interpretation of the seismic-reflection data. [Tectonophysics, v. 410, p. 293–310. Copyright Elsevier.]

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centers as deep as 160–200 km (Martin et al., 2005, 2006), the seismic-reflection project DACIA PLAN of 2001 was continued in 2004 with the project DRACULA (Deep Reflection Acquisition Constraining Unusual Lithospheric Activity). It consisted of three parts. DRACULA I was collected across the Transylvanian Basin and the SE Carpathian bend zone. DRACULA II was a 35-km-long E-W–directed seismic-reflection line and was located east of Onesti in the northern part of the Carpathian foreland. DRACULA III was also a 35-km-long seismic-reflection line which was recorded in the southern foreland south of Buzau, halfway between the Intramoesian and the Capadiva-Ovidiu Faults (Enciu et al., 2009).

In the SEISMARMARA French-Turkish program (Carton et al., 2007; Laigle et al., 2007), the N/O *Le Nadir* acquired multichannel seismic-reflection profiles in the North Marmara Trough in August 2001. This acquisition was restricted to the deep part of the Sea of Marmara, in water depths greater than 100 m. The profiles had an unprecedented depth-penetration due to the 4.5 km length of a 360-channel streamer and the strength of the low-frequency airgun arrays. Efficient penetration was obtained with the original "single-bubble" method (Avedik et al., 1996), which resulted from the modification of conventional airgun array shooting. The data allowed imaging the deep structure of the marine North Marmara Trough on the strike-slip North Anatolian Fault west of the destructive Izmit 1999 earthquake. A reflective lower crust and the Moho boundary were detected. The OBS array data allowed especially constraining velocities for the deeper structural units, which ranged between 5.7 and 6.3 km/s for the upper crust and on the order of 6.7 km/s for the lower crust. Crustal thinning was evidenced by the seismic imaging of the reflective lower crust and the Moho boundary on an E-W profile with a shallowing of the lower crust from the south of the Central Basin toward the east into more internal parts of the deformed region.

In the Ukraine, after the successful investigations of the Donbas Foldbelt by both refraction and reflection profiling in 1999, in 2005 and 2006 the DOBRE-2 project extended the DOBRE-99 line (see Fig. 9.3-13) to the south across the Skythian Platform (Fig. 10.2.3-07). In 2005 common-depth-point profiling on land was completed with 100 km near the Azov Massif and 47 km through Crimea, while for 2006 the survey through the Azov Sea (160 km) and a short section (43 km) into the Black Sea had been planned using sea-bottom seismic stations (Starostenko et al., 2006).

A detailed investigation of the eastern Black Sea basin was performed in 2005 by the British universities at Southampton

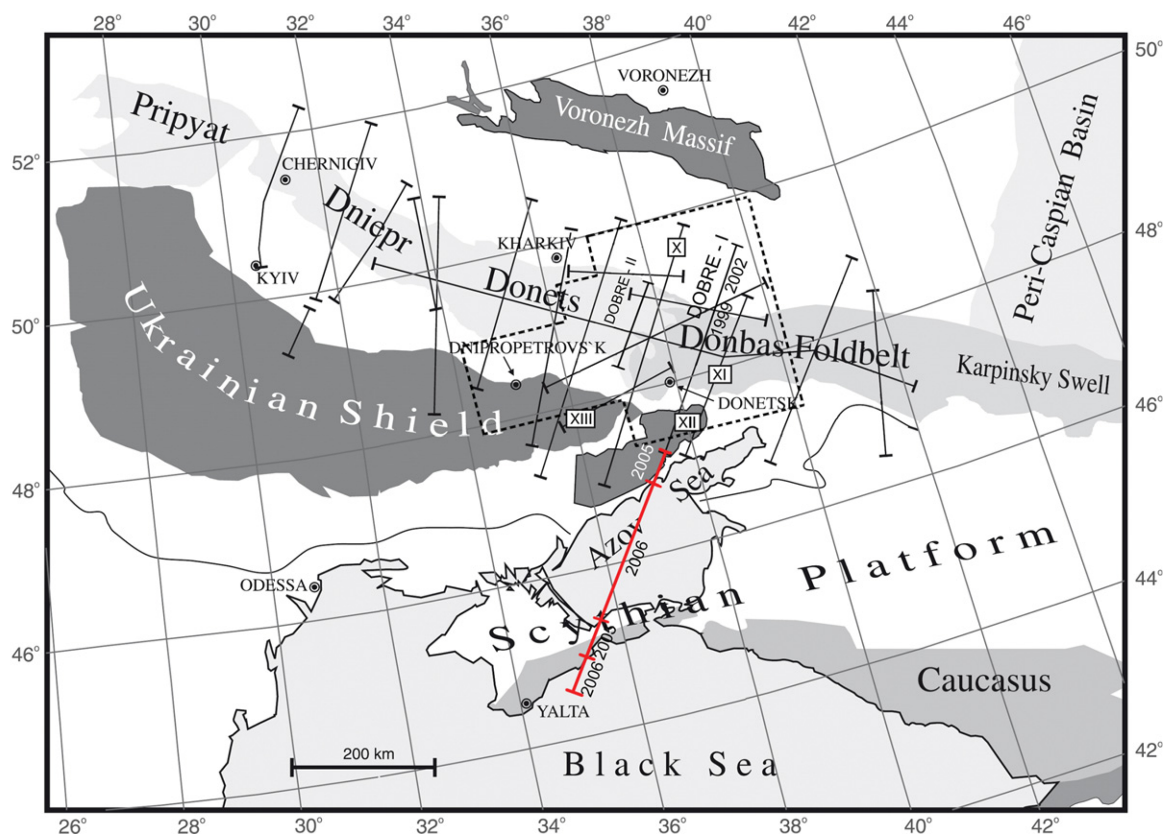

Figure 10.2.3-07. Location of the DOBRE-2 (2005–2006) seismic line (from Starostenko et al., 2006, fig. 1) in conjunction with DOBRE-1 (=DOBRE'99 in Figure 9.3-12). [*In* Grad, M., Booth, D., and Tiira, T., eds., European Seismological Commission (ESC), Subcommission D—Crust and Upper Mantle Structure, Activity Report 2004–2006.]

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and Cambridge. A 500-km-long ESE-WNW–trending profile was crossed by three shorter perpendicular lines of up to 90 km length (Scott et al., 2006). A preliminary interpretation revealed an 8–10-km-thick sedimentary package on top of the crystalline crust which thins slowly from ~28 km at the eastern margin to 7–8 km in the center of the basin. One of the profiles crossed the Archangelsk Ridge where a maximum crustal thickness of 32 km was detected followed by a rapid decrease to 8 km in the center of the basin over a distance of only 30 km.

Knapp et al. (2004) discussed the reprocessing and reinterpretation of the two perpendicular ABSHERON 20 s deep seismic-reflection profiles in the South Caspian region, which were recorded with 70 km length in the deep water (200–700 m) of the South Caspian Sea, offshore Azerbaijan, at the Absheron Ridge with industry-like marine acquisition parameters. According to Knapp et al. (2004) these data provided evidence that the South Caspian basin may contain the thickest accumulation of sediments (26–28 km) in the world. The data also provided seismic reflections at all crustal levels, down to ~16–17 s and identified the Moho at 38–40 km depth, resulting in a 10-km-thick crystalline crust.

The ESRU (Europrobe Seismic Reflection profiling in the Urals) project, a EUROPROBE project which had started in 1993 (see Chapter 9, Fig. 9.3-19), was continued in 2001–2003, when the line was extended to the west in three campaigns along the Serebrianka-Beriozovka profile (SB), resulting in a total length of ESRU-SB of 440 km (Kashubin et al., 2006). In 2001, ~50 km were acquired west of ESRU93 in the Uralian foreland (SB01). In 2002, an additional 42 km of data were recorded on profile 2 (SB02) between the western end of ESRU93 and SB01. Finally, 73 km of profile SB03 were acquired in 2003 as a western extension of SB01.

10.3. NORTH AMERICA

10.3.1 The Pacific States of the United States

In 2002, the Georgia Strait Geohazards Initiative (SHIPS 2002) added new wide-angle recordings to the 1998 SHIPS experiment data (Brocher et al., 2003; Pratt et al., 2003). Eight hundred km of wide-angle recordings were made together with shallow penetration multichannel seismic-reflection profiles acquired by the Canadian Coast Guard Ship *Tully*, using a 1967-l airgun. Onland, 48 3-component RefTek stations recorded the airgun signals at wide offsets reaching ranges as far as 120 km (Fig. 10.3.1-01).

The active seismic experiment was preceded by a passive experiment Seattle SHIPS 2002, when 87 three-component stations were deployed for a period of three months, recording local and teleseismic events (Pratt et al., 2003). One set of 26 seismographs was deployed along an east-west line across the center of the basin and on bedrock at both ends, approximately coincident with the 1999 SHIPS experiment (see Fig. 9.4.2–10), while another set of 24 seismographs was deployed along a north-south line through the basin center and the remaining 36 were distributed along two additional shorter north-south lines (Fig. 10.3.1-02). An example of the data quality is shown in Fig. 10.3.1-03, while more details of the projects and examples of data can be viewed in Appendix A10-2.

Starting in the 1990s, plans were developed to investigate the San Andreas fault zone by launching a deep-drilling project in central California named SAFOD (San Andreas Fault Observatory at Depth). Though only little populated, the Parkfield area, halfway between the densely populated areas of San Francisco and Los Angeles had attracted particular public interest. In 1966, a moderate earthquake had occurred with many aftershocks (Brown et al., 1967). At intervals of ~20 years, events of very similar characteristics (all with a magnitude of ~6) had repeatedly occurred in this area (1881, 1901, 1922, and 1934). This discovery led in the mid-1980s to the prediction of a similar event to occur in the near future, i.e., between 1985 and 1993. Therefore, in 1985, the U.S. Geological Survey initiated a large field experiment which should investigate the details of such an event (Bakun and Lindt, 1985). Even if the predicted event did not happen, the scientific interest in the Parkfield area has nevertheless remained extremely high. Thus, Parkfield became one of the target areas proposed as the location for a deep drillhole which should penetrate the San Andreas fault zone at various depth ranges by applying a particular drilling scheme proposed by Hickman et al. (1994), and which was finally named SAFOD. An initial shallow seismic experiment PSINE (Parkfield Seismic Imaging–Ninety Eight) was launched in 1998, comprising a 5-km-long high-resolution seismic-reflection/-refraction profile across the proposed drilling site (Catchings et al., 2002, 2003).

SAFOD is one of three major components of EarthScope, a National Science Foundation–funded initiative in collaboration with the U.S. Geological Survey, which is designed to investigate the powerful geological forces that shape the North American continent. The completion of SAFOD was foreseen for 2007. One of the prime goals of SAFOD is to be an earthquake observatory with instruments installed directly within the active fault where earthquakes occur. In July 2002, the first phase of this drilling project was realized when a test hole was drilled into the seismically active section of the San Andreas fault to a depth of 3 km.

The crustal structure in the surroundings of the proposed drilling site was only roughly known from large-scale investigations of the U.S. Geological Survey (for references see corresponding sections of Chapter 6 and Chapter 7 and Fuis and Mooney, 1990). The closest investigations had been the seismic-refraction survey in the surroundings of the Coalinga event of 1983 (for references see corresponding sections of Chapter 8) and the seismic-reflection and refraction line SJ-6, the data of which had been interpreted by a larger number of scientists within the frame of a CCSS (Commission on Controlled Source Seismology) Workshop (Walter and Mooney, 1987; for references, see corresponding sections of Chapter 8).

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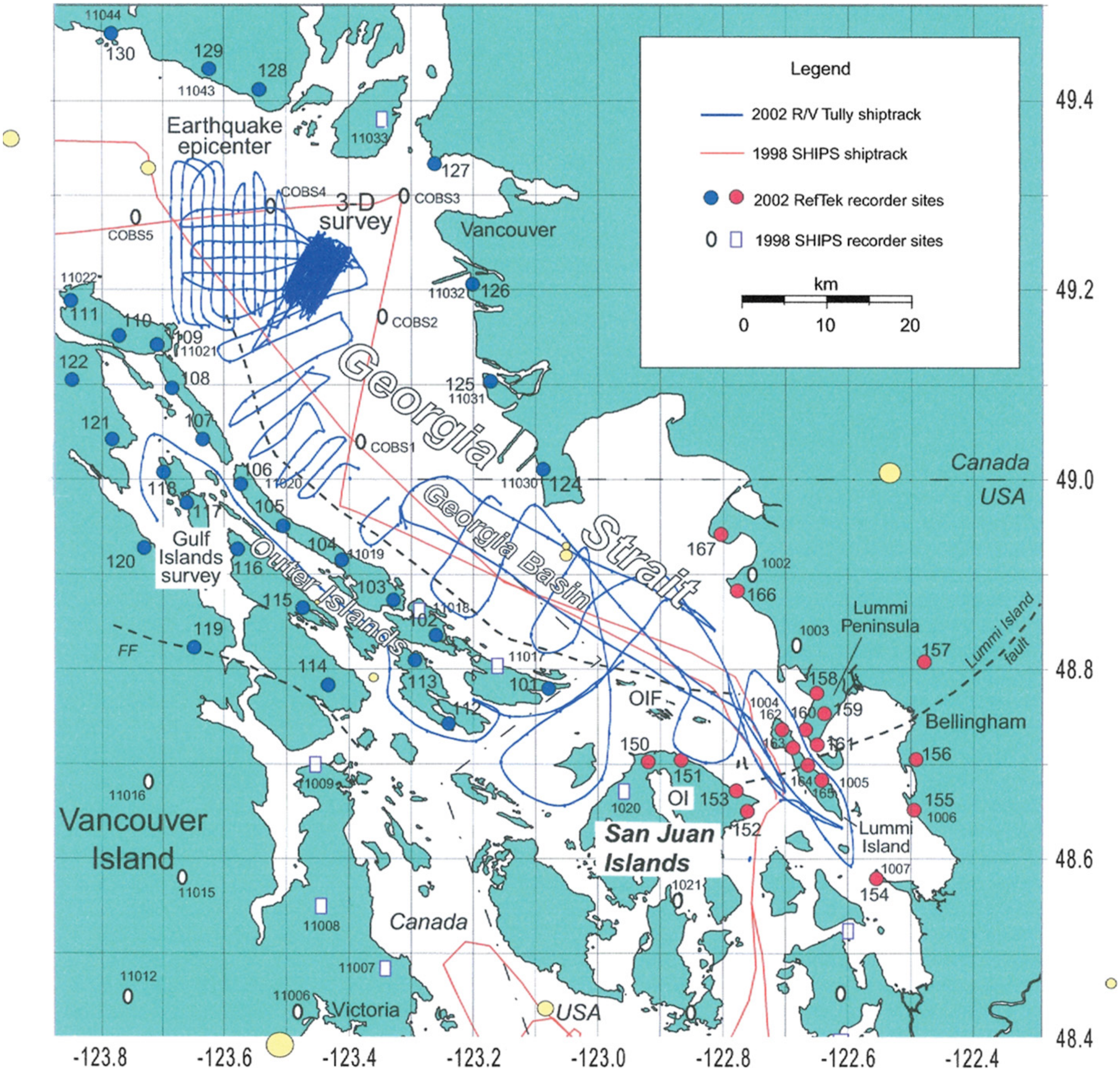

Figure 10.3.1-01. Locations of RefTek receivers (blue and red dots) and Tully tracklines (blue lines) of the active SHIPS 2002 project (from Brocher et al., 2003, fig. 1). Also shown are the 1998 SHIPS (see also Figure 9.4.2-09) recorder sites (open squares) and tracklines (red lines). Dashed lines—fault lines. [U.S. Geological Survey Open-File Report 03-160, Menlo Park, California, 34 p.]

Due to limited resolution of the seismic-refraction data, a detailed seismic-reflection line which crossed the SAFOD site had been planned (Hole et al., 2001) and was finally realized in 2004. The data were recorded along a 46 km profile centered on the SAFOD drill site and perpendicular to the San Andreas fault, with 62 shots (spacing 0.5–1.0 km) and 912 recorders (receiver spacing 25–50 m). The maximum depth penetration was 20 km. The interpretation of the data showed gently east- and west-dipping reflective bands within or below the granitic Salinian terrane at depths of 6–14 km, beginning at the San Andreas fault. Within the Franciscan terrane to the east of the fault, diffuse gently west-dipping reflectivity at 4–10 km depth was found (Ryberg et al., 2005; Hole et al., 2006; Bleibinhaus et al., 2007).

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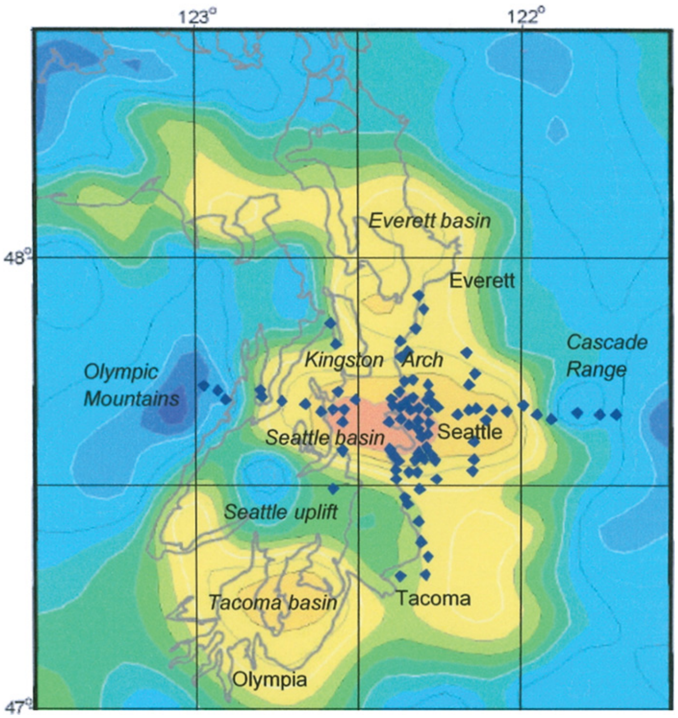

Figure 10.3.1-02. Location of RefTek receivers (blue dots) during the passive Seattle SHIPS 2002 project (from Pratt et al., 2003, fig. 1), superimposed on a tomography map showing isolines of speed at 2.5 km depth (VanWagoner et al., 2002). [Journal of Geophysical Research, v. 107, no. 12, p. 22-1–22-23. Reproduced by permission of American Geophysical Union.]

10.3.2. Basin and Range Province and Rio Grande Rift

In 2002, in the Walker Lane experiment, a new 450-km-long crustal refraction profile was collected between Battle Mountain, Nevada, and Auburn, California, traversing western Nevada, the Reno area, Lake Tahoe, and the northern Sierra Nevada (Fig. 10.3.2-01).

One hundred ninety-nine one-component instruments recorded mine blasts and earthquakes (Louie et al., 2004). Several ripple-fired mine blasts at the eastern end of the line, which were fired daily, produced arrivals visible up to distances of 300 km. From quarry blasts at the western end, energy was seen up to 600 km distance. A local earthquake, with an epicenter ~100 km SSE of Lake Tahoe, produced fan-shot data across the array. An unexpectedly deep crustal root of 50 km under the northern Sierra Nevada, centered west of the crest, and an anomalously thin crust with Moho depths of 19–23 km over a limited region near Battle Mountain in the Basin and Range province are the main results of this survey (Louie et al., 2004).

The northwestern margin of the Basin and Range province near the northern border of eastern California and western Nevada was the goal of an active-source seismic-refraction survey in 2004. It was part of the EarthScope Program investigating an area which is characterized by a transition from low-magnitude extension in northwestern Nevada to relatively unextended volcanic plateaus in northeastern California (Lerch et al., 2007). The experiment involved a 300-km-long east-west line with 1100 vertical seismometers which recorded five in-line shots and one off-line fan shot. Furthermore, ripple-fired mine blasts produced

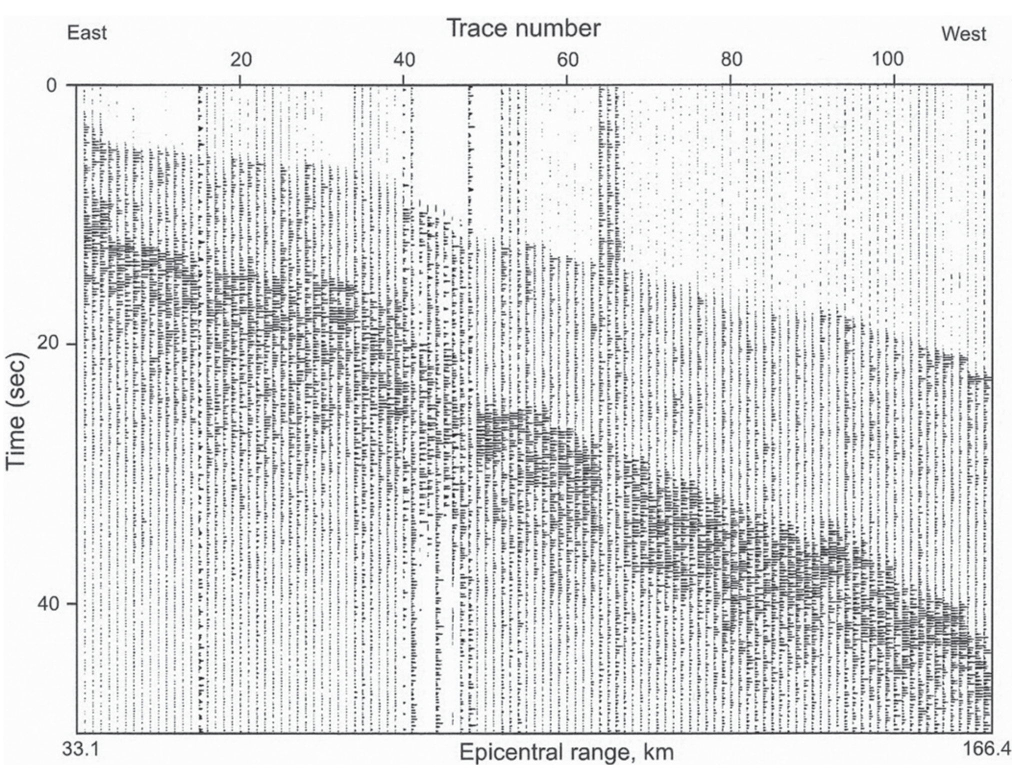

Figure 10.3.1-03. Three component recordings of a local M-2.7 earthquake with epicenter near Mount Vernon, recorded during the passive Seattle SHIPS 2002 project at distance ranges from 33 to 166 km (from Brocher et al., 2003, fig. 9). All three components of each station are plotted side by side. [U.S. Geological Survey Open-File Report 03-160, Menlo Park, California, 34 p.]

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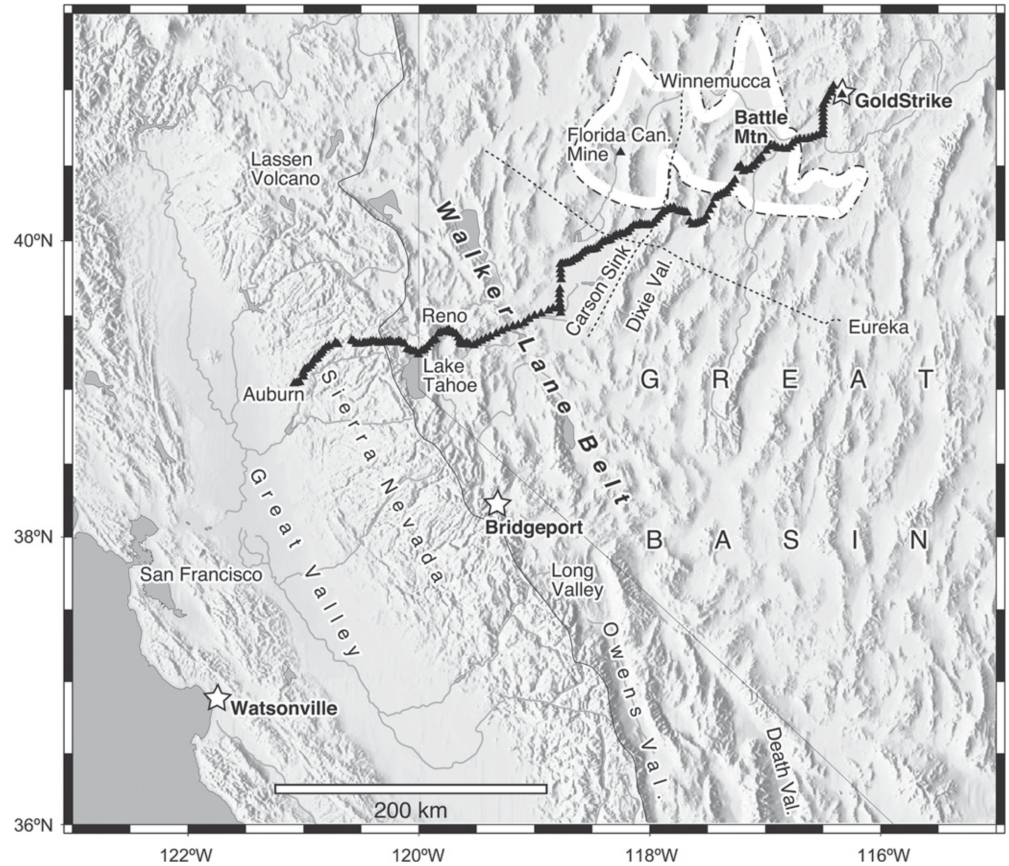

Figure 10.3.2-01. Location of receivers (triangles) and sources (stars) of the Walker Lane experiment 2002 (from Louie et al., 2004, fig. 1). Dotted lines: 1986 PASSCAL arrays (see Fig. 8.5.3-11). [Tectonophysics, v. 388, p. 253–269. Copyright Elsevier.]

useful first-arrival data. Altogether, average 300 m station spacing resulted. The interpretation of the data was able to document a 20% crustal thinning associated with Basin and Range extension from ~37 km crustal thickness under northeastern California to ~31 km under northwestern Nevada.

In 2003, the Potrillo Volcanic Field experiment was carried out in southern New Mexico and far west Texas. Its goal was to address the questions of how far to the south the Rio Grande rift extends and how far is it distinguishable from the Basin and Range province (Averill, 2007). The experiment consisted of a 205-km-long east-west–oriented line at ~32°N latitude with eight borehole shots with charges of 500–1000 kg. Almost 800 instruments (Texans) were deployed at variable spacing of 100 m, 200 m, and 600 m between Hachita, New Mexico, and Fort Bliss on the east side of El Paso, Texas. The western part of the line was located in the Basin and Range province. In the center of the line, an elevated platform of extensive volcanism occurs, making up the Potrillo Volcanic Field, while the eastern third of the line traversed the Rio Grande rift region. The most distinctive feature of the interpreted crustal model was an apparent thickening of the middle crust underlying the Potrillo Volcanic Field. In addition, an overall thinning of the crust from 35 km in the west to ~30 km in the east and a decrease in upper mantle velocities from 7.9 to 7.75 km/s provided evidence that the southern Rio Grande rift differs from the adjacent Basin and Range province.

10.4. THE AFRO-ARABIAN RIFT SYSTEM

10.4.1. The Jordan–Dead Sea Transform

In February 2002, the *Meteor* (1986) cruise M52 followed marine research projects in the Mediterranean, the Black Sea and the Red Sea. One of the projects was a seismic investigation offshore Israel. Twenty OBS/H were deployed along a 150-km-long profile, which was an extension of the DESERT 2000 line (Dead Sea Rift Transect). Signals of 4 vibrators ashore eastward of the Gaza Strip were recorded on land and by the OBH/S, followed by shooting with three airguns with a total volume of 100 l. The airguns were triggered every 60 s giving a shot distance of 120 m (Hübscher et al., 2003).

Four years after DESERT 2000, another seismic experiment was conducted across the Jordan–Dead Sea transform (ten Brink et al., 2006). The experiment consisted of two wide-angle seismic-reflection/-refraction profiles. The first line was a 250-km-long profile from the Gaza strip through the Dead Sea basin into eastern Jordan (Figs. 10.4.1-01A and 10.4.1-01B). The second line, 280 km long, ran along the international border between Jordan, Israel, and the West Bank at the center of the Dead Sea transform.

Only preliminary results of the first line were published hitherto (Figs. 10.4.1-01A and 10.4.1-01B). Along this profile,

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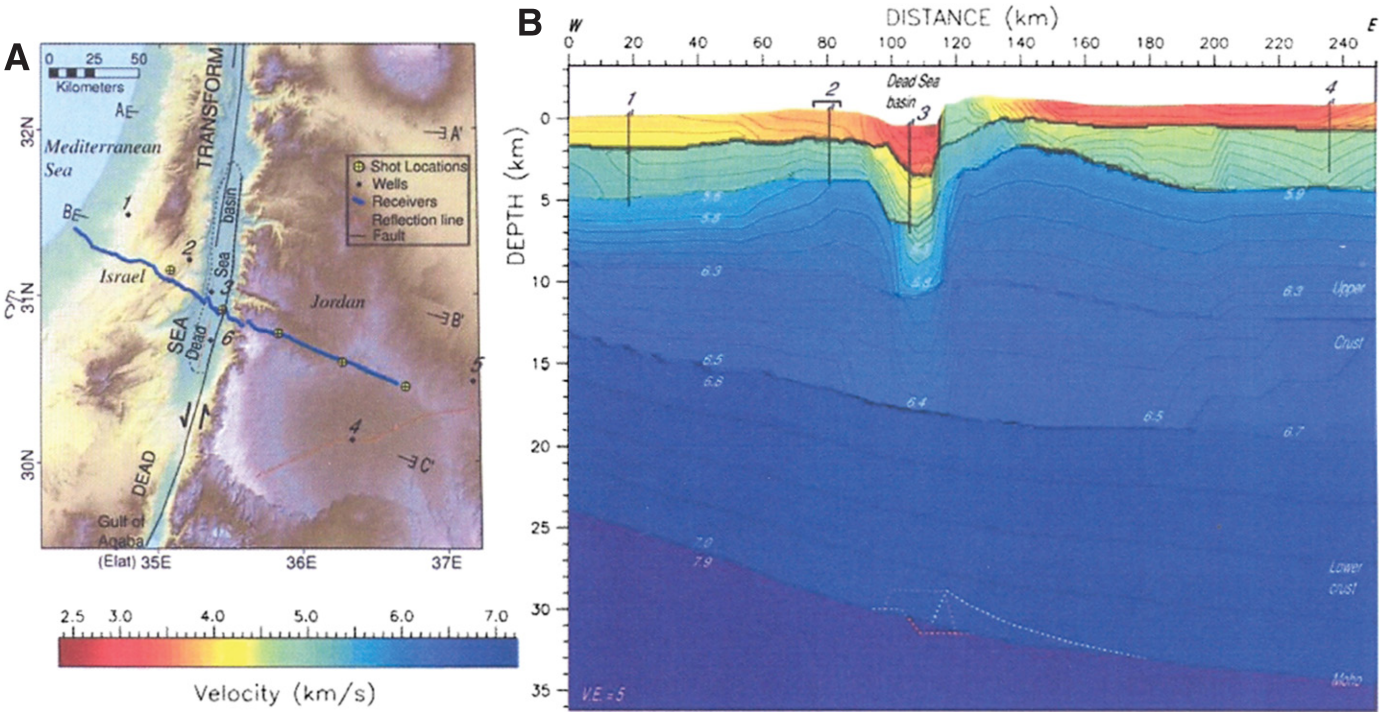

Figure 10.4.1-01. Location and model of the 2004 Dead Sea basin seismic refraction profile (from ten Brink et al., 2006, fig. 1). (A) Shaded relief map of the Jordan–Dead Sea rift showing the location of the Dead Sea basin profile of 2004. (B) P-wave velocity model along the seismic profile. [Geophysical Research Letters, v. 33, L24314. Reproduced by permission of American Geophysical Union.]

334 one-component stations (RefTek 125, Texans) were deployed at intervals of 0.65–0.75 km and recorded five one-ton explosions. Different from the DESERT 2000 line, crossing the Dead Sea transform ~70 km further south, was the observation of a narrow low-velocity zone within the basement underneath the Dead Sea basin proper, extending to 18 km depth (Figs. 10.4.1-01A and 10.4.1-01B). Moho depths varied from 35 km at the eastern end of the profile to 31 km under the rift valley and 24 km at the western end of the line.

Though only carried out after 2005, we want to mention a 235-km-long seismic wide-angle reflection/refraction profile across the Dead Sea Transform in the region of the southern Dead Sea basin (Mechie et al., 2009) which was completed in spring 2006 as part of the Dead Sea Integrated Research project (DESIRE). The DESIRE seismic profile crossed the Dead Sea Transform ~100 km north of where the DESERT 2000 seismic profile crossed the Dead Sea Transform. The wide-angle seismic-refraction measurements comprised 11 shots recorded by 200 three-component and 400 one-component instruments spaced 300 m to 1.2 km apart along the whole length of the E-W–trending profile. The depth to the seismic basement beneath the southern Dead Sea Basin was modeled at ~11 km below sea level beneath the profile, the interfaces below ~20 km depth, including the top of the lower crust and the Moho, appeared to show less than 3 km variation in depth beneath the profile as it crosses the basin.

10.4.2. The East African Rift System in Ethiopia

The investigation of the crust of the East African Rift System was revived in the beginning of the twenty-first century with a large international campaign in Ethiopia. With the funding of a new generation of mobile recording stations by NERC (National Environmental Research Council) to SEIS-UK (Maguire and SEIS-UK, 2002), funding for major crustal seismic research work in Ethiopia also became available.

Additional U.S. funding by the NSF (National Science Foundation Continental Dynamics Program) and other sources enabled to establish the Ethiopia Afar Geoscientific Lithospheric Experiment (EAGLE) under the heading of the Universities of Leicester, UK, and Texas at El Paso, United States, aiming to probe the crust and upper mantle structure between the continental main Ethiopian rift and Afar, an oceanic spreading rift. The region provided an ideal laboratory to examine the process of breakup as it is occurring (Maguire et al., 2003; Keranen et al., 2004).

EAGLE was a three-phase seismic experiment (Fig. 10.4.2-01), which started in October 2001 and was completed in February 2003. It was followed in March 2003 by a magnetotelluric project (Phase 4) and a variety of supporting efforts that collectively provided a diversity of data for integrated analysis.

The initial tomographic inversions of relative teleseismic residuals of Phase 1 showed low velocities underlying the

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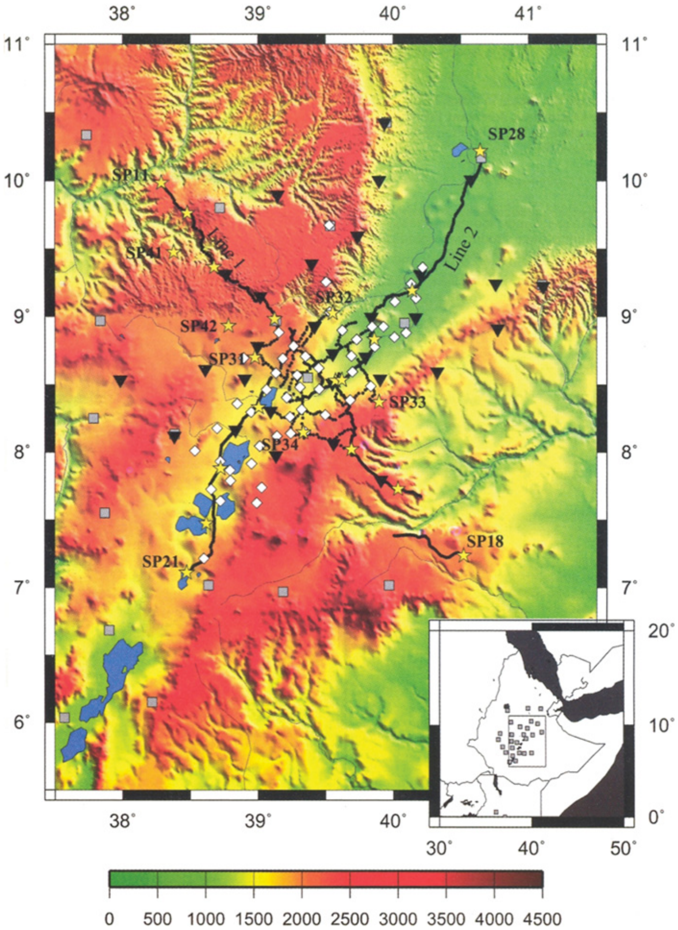

Figure 10.4.2-01. Topographic map of the central Ethiopian rift showing the locations of EAGLE (from Maguire et al., 2003, fig. 1): Phase 1 (inverted black triangles), Phase 2 (white diamonds), Phase 3 instruments (black dotted lines) and shots (yellow stars). Grey squares: locations of broadband seismic stations of Nyblade and Langston (2002, fig. 9.5.2-01). [Eos (Transactions, American Geophysical Union), v. 84, no. 35, p. 337, 342–343. Reproduced by permission of American Geophysical Union.]

Ethiopian rift down to depths of at least 200 km. The velocity anomaly appeared tabular in shape beneath the continental part of the rift in the southwestern region of the EAGLE-1 deployment, but was more diffuse and triangular in shape toward Afar in the northeast. An analysis of local events recorded during Phases 1 and 2 suggested a concentration of seismicity on the western margin of Afar.

The interpretation of the controlled-source seismic data (Fig. 10.4.2-02) involved forward and tomographic modeling techniques to obtain crustal and upper mantle models for the various lines (Maguire et al., 2006). The interpretation of the cross-rift profile of Phase 3 (line 1), e.g., resulted in a 2–5-km-thick layer of sedimentary and volcanic sequences across the entire region, underlain by a 40–45-km-thick crust under the central Ethiopian rift (Fig. 10.4.2-03) with a 15-km-thick high-velocity lowermost crustal layer beneath the western plateau (Mackenzie et al., 2005). This lowermost crustal layer was not found under the eastern side, where the crust was modeled to be 35 km thick under the sediments. Beneath the rift a slight crustal thinning was observed, where P_n velocities indicated the presence of hot mantle rocks containing partial melt.

10.5. CONTROLLED-SOURCE SEISMOLOGY IN SOUTHEAST ASIA

10.5.1. India

The first five years did not see any major seismic investigation of the entire crust in India, as far as can be inferred from the accessible international literature. Rather, the research effort concentrated on the support of the hydrocarbon exploration geophysics. One example will be briefly mentioned here, in spite of our general aim to concentrate on projects dealing with basement features.

The project dealt with a detailed seismic investigation of the shallow structure of the Naga thrust and fold belt, located in the Assam province in northeastern India (Jaiswal et al., 2008). The deepening of the Naga thrust fault in the northeast caused particular challenges when drilling for hydrocarbons, traditionally guided by surface manifestations of the thrust fault. Therefore multichannel 2-D seismic data were collected along a line perpendicular to the trend of the thrust belt. The recorded line was 21 km long with 50 m shot and receiver spacing, involving 313 small borehole shots with 2.5–5.0 kg charges and maximum offsets of ~6 km. The result of the data interpretation was a detailed picture of the basement surface, where the Naga thrust belt could be traced at depth.

10.5.2. China

Two of the projects, the 320-km-long line through the Altyn Tagh Range (Zhao et al., 2006) and the 1000-km-long profile investigating the northeastern margin of the Tibetan Plateau (Liu et al., 2006) from the Qaidam Basin to the Ordos Basin, were described in the previous Chapter 9.6.2, because the authors did not indicate any date. However, the experiments may actually have been performed after the year 2000.

To summarize the multitude of new crustal and upper mantle structure results, obtained since the late 1970s until recently, Li et al. (2006) have created new contour maps for crustal thickness (Fig. 10.5.2-01) and P_n velocities (Fig. 10.5.2-02) as well as representative crustal thickness columns for the various tectonic regions of China (Fig. 10.5.2-03) which have been reproduced here.

In general, the crust thins from west to east. Beneath the Tibetan Plateau, it reaches a thickness of at least 74 km, which is the maximum value measured in the world from DSS data (Li et al., 2006). Along the east coast of China, in contrast, the crust is only 28–30 km thick. A strong lateral gradient in crustal thickness extends in the north-south direction throughout central China, approximately along 103–105°E (Fig. 10.5.2-01).

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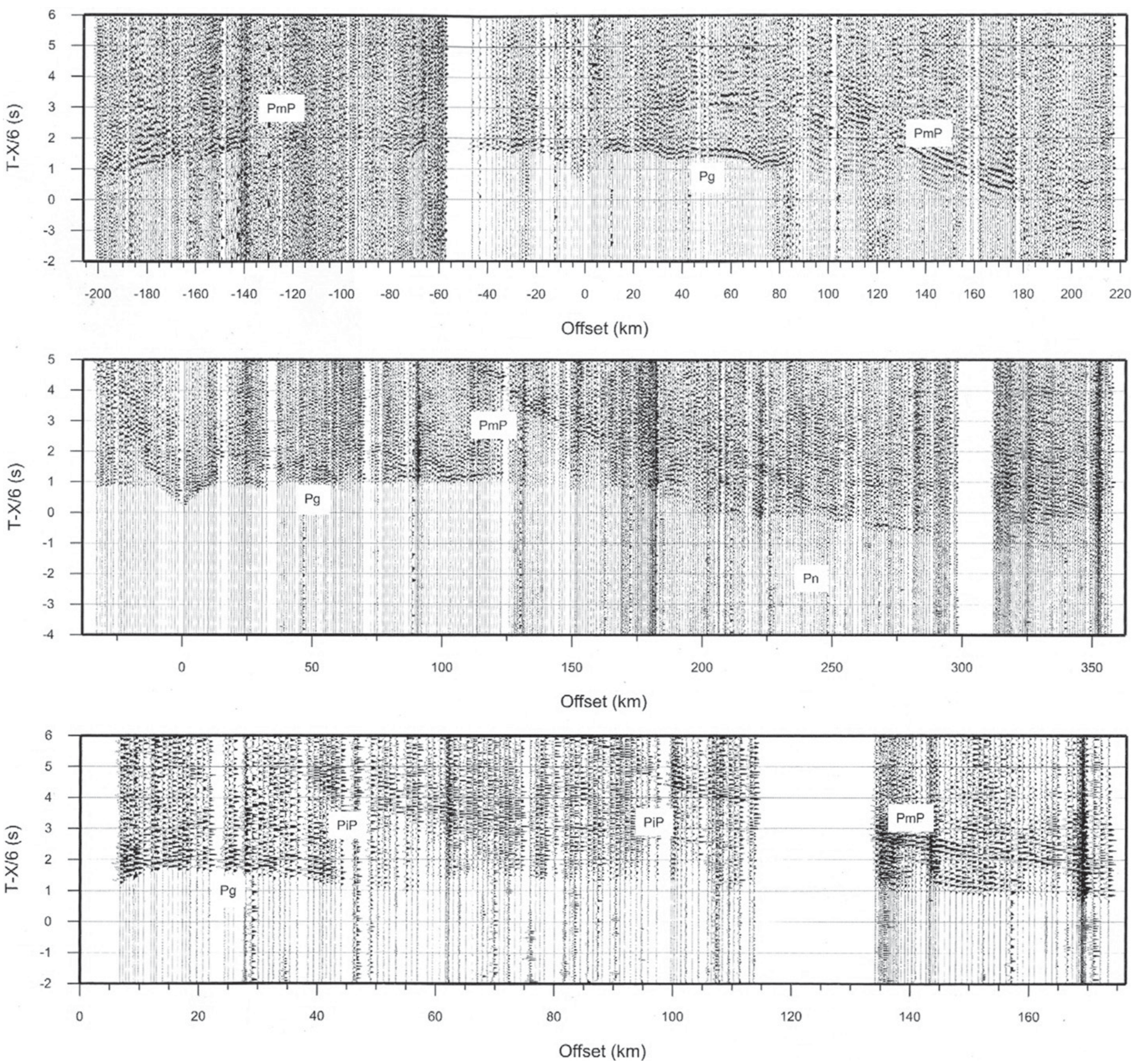

Figure 10.4.2-02. Data examples from the EAGLE 2002 project (from Maguire et al., 2003, fig. 3): Top: Line 1, central shotpoint 25. Center: Line 2, shotpoint 12 at NW flank of the rift. Bottom: Line 1 eastern half, central shotpoint 25. [Eos (Transactions, American Geophysical Union), v. 84, no. 35, p. 337, 342–343. Reproduced by permission of American Geophysical Union.]

The P_n velocity beneath China is relatively uniform, however, and was found to be between 7.9 and 8.0 km/s for the majority of observations, though the precision of P_n velocity determination is limited. The differences in crustal thickness are also evident in the crustal structure columns, shown in Figure 10.5.2-03 for selected tectonic regimes, shown in Figure 10.5.2-04, and which have been divided into a western China section with crustal thicknesses of 46 km and more and an eastern China section with crustal thicknesses usually less than 36 km.

10.5.3. Japan and South Korea

In Japan, a major crustal research project was launched in 2001 to complement a research project of 1985 (Iidaka et al., 2004).

A 260-km-long profile was recorded in southern Japan across south-central Honshu in N-S direction from coast to coast (Fig. 10.5.3-01). Three hundred ninety-one seismic stations with an average spacing of 670 m recorded five explosive sources with 500-kg charges and one 100-kg shot. sixty-three

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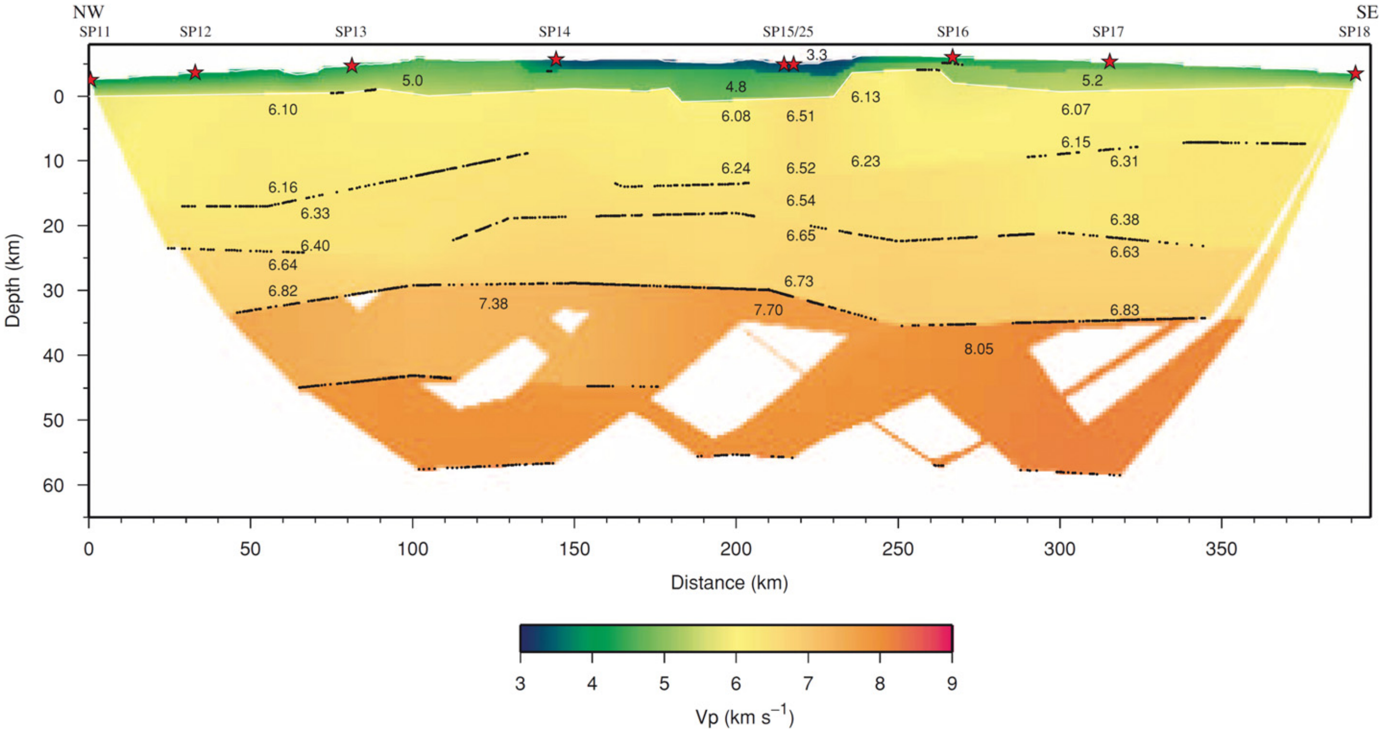

Figure 10.4.2-03. P-wave model across the central Ethiopian rift along EAGLE line 1 (from Mackenzie et al., 2005, fig. 6). For location, see Fig. 10.4.2-01. [Geophysical Journal International, v. 162, no. 3, p. 994–1006. Copyright John Wiley & Sons Ltd.]

of these stations were equipped with three-component geophones. The profile ran along line A–A′ in Figure 10.5.3-01 (identical with line B–B′ of Fig. 9.6.3-01) and had the same location as the Atsumi-Noto profile of Aoki et al. (1972). It crossed line B–B′ in Figure 10.5.3-01 which had been recorded in 1985 (Matsu'ura et al., 1991).

Figure 10.5.3-02 shows a record section of the 2001 survey (see also Appendix A10-3-1). The resulting crustal structure (Fig. 10.5.3-03) is similar to that in Figure 9.6.3-04, but shows less deepening of the Moho underneath the center of the line (Iidaka et al., 2004).

The most important experiments in 2001–2005 were intensive seismic-reflection/-refraction projects extending from the Philippine Sea across SW Japan to the Sea of Japan, which continued the investigations conducted during the 1990s (Kodaira et al., 2002; Ito et al., 2009b). Under the framework of disaster mitigation research program (the Special Project of Earthquake Disaster Mitigation in Urban Areas), a series of seismic investigations in and around Kanto plain (Sato et al., 2005), central Japan, and Kii peninsula and Kinki district, SW Japan (Ito et al., 2006; Sato et al., 2009) were performed.

In the Kanto region, four seismic profiles were recorded from 2002 to 2003 across the greater Tokyo region to image the Philippine Sea Plate which subducts northwestward underneath the Tokyo metropolitan region in central Japan (Sato et al., 2005, 2006). Seismic reflections from the upper surface of the Philippine Sea Plate were observed on all seismic sections and reached from 6 to 26 km depths. They were nearly concordant with the slab geometry estimated from seismicity.

In 2004, a deep seismic-reflection profile was recorded in the Kinki metropolitan area between Osaka and Suzuka, using Vibroseis and dynamite shots (Ito et al., 2006). Wide-angle recording using widely spaced shots of 300 kg charge size and some sets of 100 stationary Vibroseis sweeps was also used. The main targets were to unravel the deep geometry of an active fault and the velocity structure. Beneath the mountain range separating the two basins with the cities Osaka in the west and Suzuka in the east, horizontal, coherent mid-crustal reflectors at 16 km depth were identified with the base of the seismogenic zone. Also in the seismogenic zone dipping reflectors were detected which were interpreted as possibly deeper extensions of active faults. Another set of reflectors was seen at 26 km depth.

An active-source onshore-offshore 485-km-long seismic profile extended from the Nankai Trough to the northern shore of central Honshu into the Sea of Japan (Kodaira et al., 2004). The wide-angle seismic data from onland explosions (maximum 500 kg) were recorded by 70 ocean-bottom seismometers (OBS) and 328 land-based stations. Furthermore, signals from a 197 l airgun array were recorded by all OBSs and for ~100 km onshore by 63 land stations. On the offshore part, multichannel seismic-reflection data were also recorded. The seismic velocity and reflectivity images showed several regions of crustal thickening down to a depth of 45 km under the offshore part which was interpreted as subducted ridges. The subducted crust beneath

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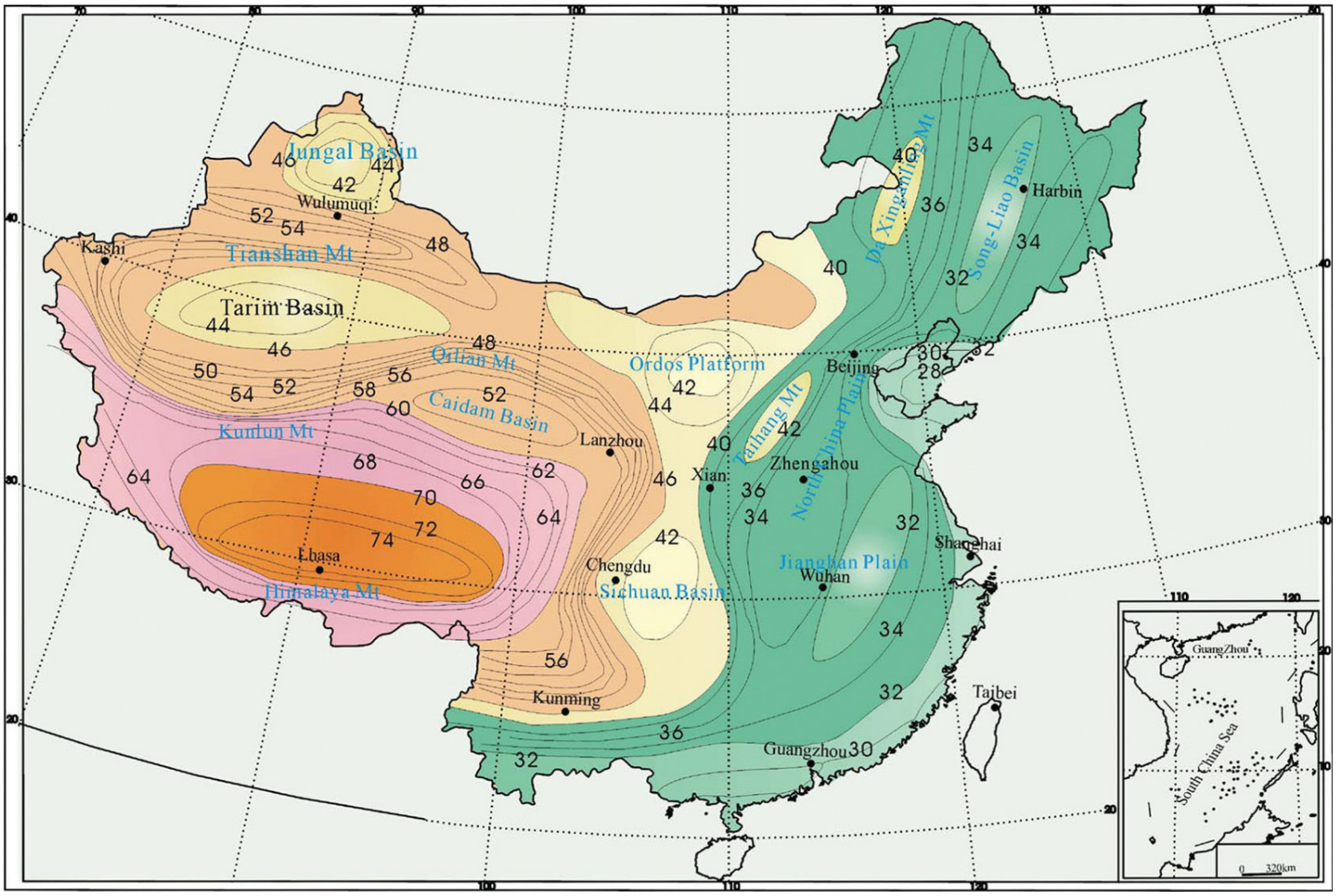

Figure 10.5.2-01. Contour map of crustal thickness in China from DSS data (from Li et al., 2006, fig. 4). For location of profiles, see Fig. 9.6.2-01 and Figure 10.5.2-02. [Tectonophysics, v. 420, p. 239–252. Copyright Elsevier.]

the onshore part appeared as a highly reflective interface from a depth of 25–45 km. Coincident in location with the highly reflective subducted crust was a landward-dipping zone recognized with a high Poisson's ratio of 0.34.

The most important results from these experiments were the detection of very strong reflections from the Philippine sea plate, which almost correspond to the aseismic part of the plate boundary. The seismogenic zone (asperity) along the plate boundary, on the other hand, appeared less reflective. Such structural difference was interpreted as probably being controlled by water dehydrated from the subducting oceanic lithosphere.

Furthermore, seismic-refraction/-reflection surveys were also conducted in inland active fault zones (e.g., the Itoigawa-Shizuoka tectonic line and Atototsugawa fault zone, central Honshu) (Iidaka et al., 2009; Ikeda et al., 2004, 2009; Sato et al., 2004).

In 2002, the Itoshizu seismic survey was recorded in the southwest of Honshu. It was a 68-km-long seismic line and was arranged perpendicular to the trend of major faults and folds across the Itoigawa-Shizuoka Tectonic Line (ISTL). For the western part of the line, a high-resolution image of the geometry of the active fault system was acquired by a standard common mid-point reflection experiment using Vibroseis trucks and a digital telemetry cable system. For the eastern half, 600 channels of offline recorders were deployed. To obtain a deeper image by refraction/wide-angle reflection, four explosive sources and six Vibroseis locations were recorded. The interpretation suggested that the Miocene basin was formed by an east-dipping normal fault with a shallow flat segment to 6 km depth and a deeper ramp penetrating to 15 km depth.

The first seismic investigation of the Earth's crust in South Korea was undertaken in 2002 and 2004 (Kim et al., 2007). In 2002, a 294-km-long profile was recorded in the southern part of the Korean peninsula, installed in a WNW-ESE direction with two shotpoints, one at the WNW end and one in the center of the line, reaching from the Yellow Sea in the west to the East Sea in the east. A second line, 335 km long, followed in 2004 in a NNW-SSE direction with four shotpoints, one at each end and two in the center, and ran from near the border to North Korea more or less parallel to the coasts through the center of the pensinsula to the southern coast bordering the East China Sea. Seismic waves were generated by 500–1000 kg borehole shots and recorded

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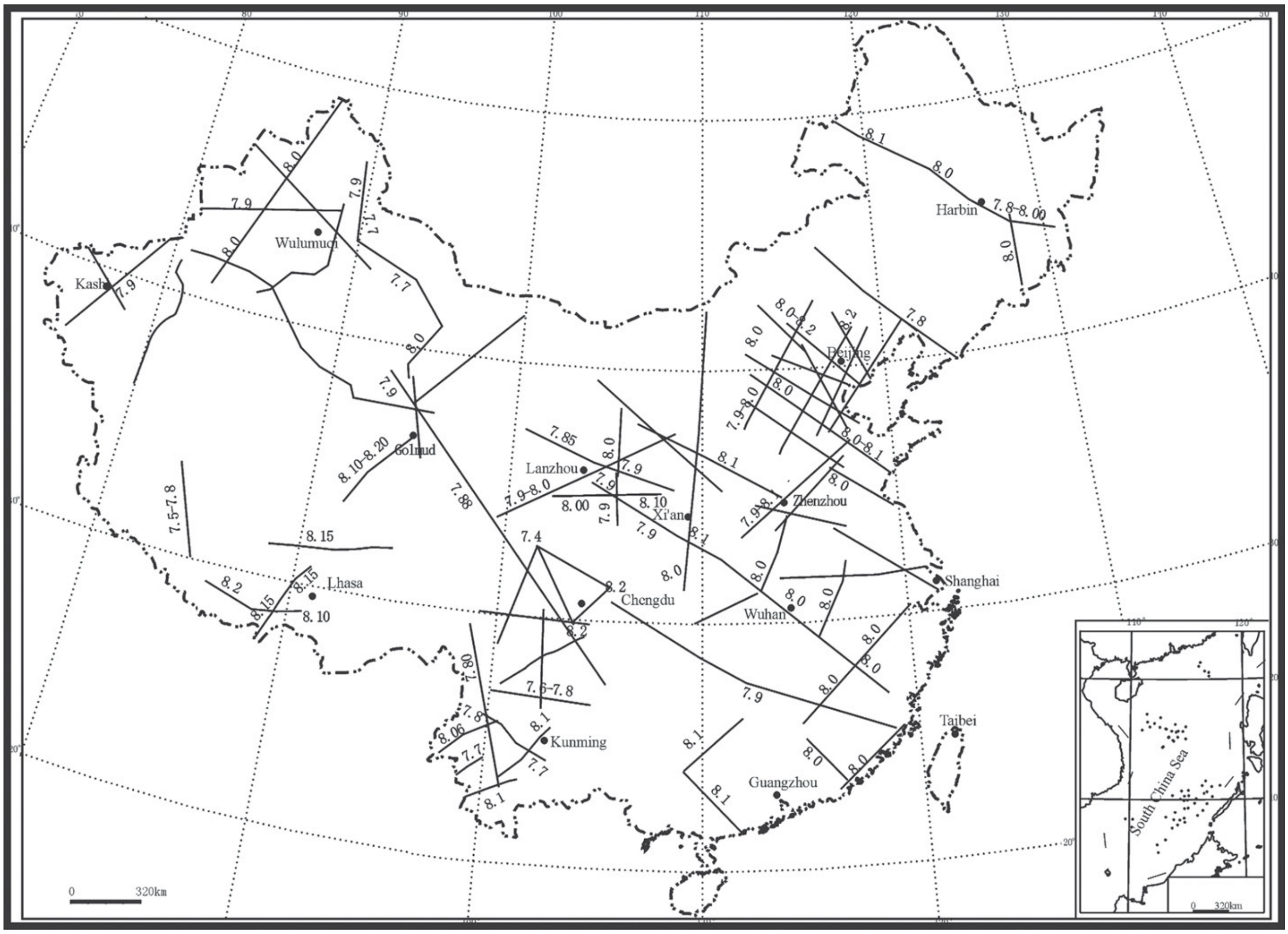

Figure 10.5.2-02. Seismic velocities of the uppermost mantle from P_n-waves (from Li et al., 2006, fig. 6). [Tectonophysics, v. 420, p. 239–252. Copyright Elsevier.]

along the lines by 170 PRS-1 portable seismographs at nominal intervals of 1.5–1.7 km. The interpretation indicated several crustal layers at depths of 2–3 km, 15–17 km, and 22 km. Moho was found at 37–39 km maximum depths with uppermost mantle velocities of 7.8–8.4 km/s. The Moho became shallower when approaching the Yellow Sea and the East Sea on the west and east coasts of the peninsula.

10.6. CONTROLLED-SOURCE SEISMOLOGY IN THE SOUTHERN HEMISPHERE

10.6.1. Australia and New Zealand

In western Australia in 2001, the deep seismic-reflection survey 01AGSNY was recorded (Goleby et al., 2004) as a continuation and supplement of the 1991 investigations of the Goldfields Province of Western Australia (Fig. 9.7.1-06). It comprised 430 km of deep seismic-reflection data across the northeastern Eastern Goldfields Province portion of the Yilgarn Craton and was already discussed in Chapter 9.7.1, together with the 1991 survey. Including a number of additional high resolution deep seismic-reflection data obtained during 2002 and 2004 (Finlayson, 2010; Appendix 2-2), Goleby et al. (2006) compiled a 3-D seismic model of crustal architecture. The review included wide-angle and reflection profiling as well as receiver function work.

In 2003, a 193-km-long, N-S–directed, deep seismic-reflection traverse was acquired across the Archean-Proterozoic Gawler Craton in South Australia, centered on the Olympic Dam Mine. The survey was carried out using Vibroseis and collected data up to 18 s TWT. The interpretation revealed a Paleoproterozoic succession reaching to a depth of 14 km which was underlain by a 5-km-thick mid-crustal reflective layer. The Moho was seen at ~13 s TWT (Drummond et al., 2006).

With the same techniques, another 197-km-long, E-W–directed, seismic-reflection traverse was recorded in 2003–2004 from the Broken Hill block in New South Wales across the Curna-

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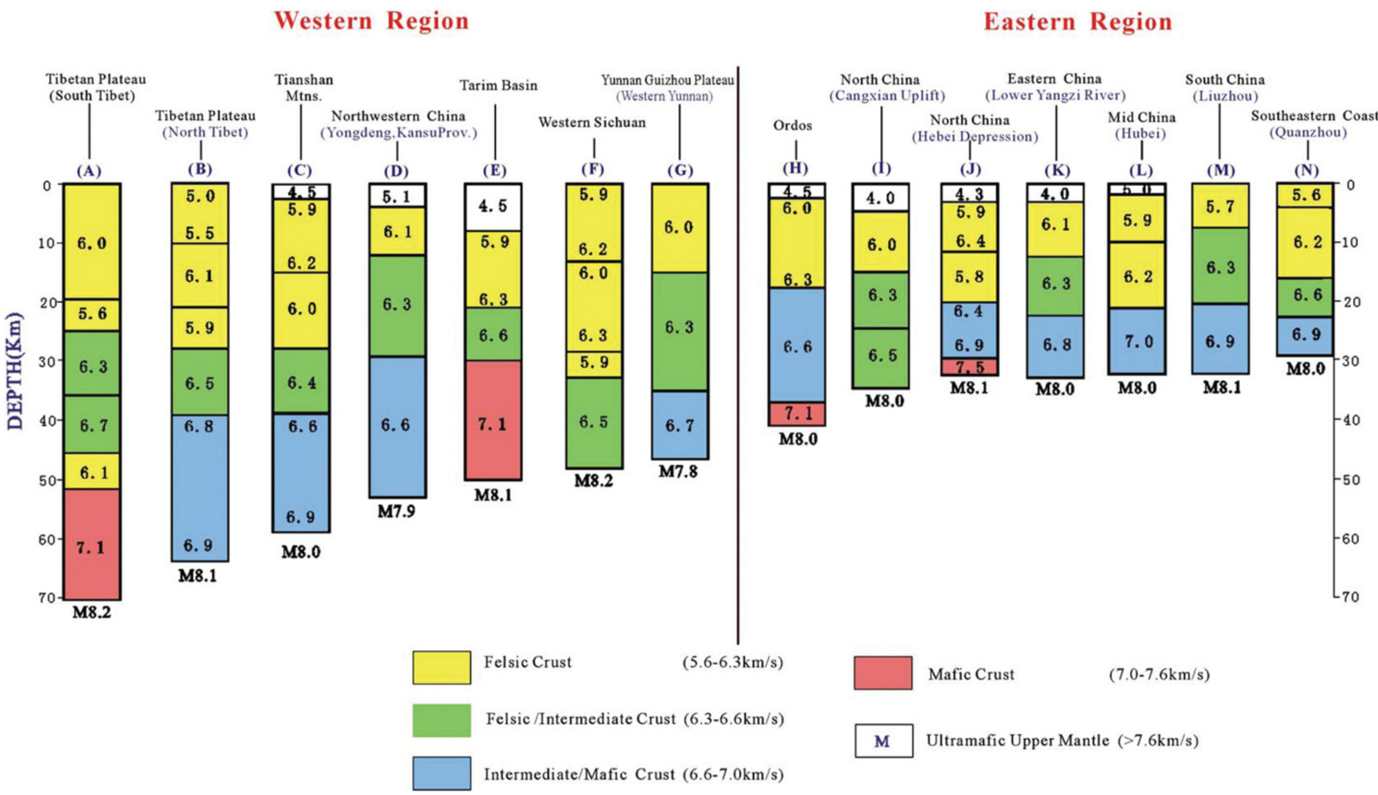

Figure 10.5.2-03. Representative seismic velocity-depth functions for 14 tectonic regimes of China (from Li et al., 2006, fig. 5). For location of the 14 regimes, see Fig. 10.5.2-04. [Tectonophysics, v. 420, p. 239–252. Copyright Elsevier.]

mona region of South Australia to the central Flinders Range to study the Meso- to Paleoproterozoic basement architecture. The line continued a line of a 1996–1997 survey across the Broken Hill block (Finlayson, 2010; Appendix 2-2).

An onshore-offshore operation in 2005 using the vessel *Pacific Sword* investigated the southwesternmost corner of Australia. The *Pacific Sword* was equipped with a 4900 cubic inch airgun array and a 6–8 km digital streamer. Marine seismic profiling off the southeastern and southwestern margins of the Yilgarn Craton intended to reveal the crustal architecture of the offshore frontier basins, acquiring a network of 2700 km of seismic data. During the marine work, seismic recorders were deployed onshore at 25–50 km intervals which recorded the airgun shots up to 400 km distance. A key feature of the modeling of the wide-angle data was a deep crustal root located ~100 km inland from the coast (Finlayson, 2010; Appendix 2-2).

In 2005, a 290-km-long north-south traverse was recorded across the boundary of the Thomson Orogen in western Queensland–northern New South Wales and the Lachlan Orogen in central and southern New South Wales. A 48-km-deep Moho underneath the Thomson Orogen and a 33-km-deep Moho under the Lachlan Orogen, separated by a major northward dipping fault that cuts the entire crust, was one of the major results. Also, the lower crust was more reflective under the Lachlan Orogen (Finlayson, 2010; Appendix 2-2).

A second project in 2005 collected 720 km of deep seismic-reflection data in a grid of four deep seismic traverses in the Tanami region of the Northern Territory. Associated with the reflection profiling was a large-scale passive listening refraction survey along a NW-SE transect to record wide-angle seismic data from the vibrator source and thus to provide the crustal velocity structure for the region and its relationship to lithology (Finlayson, 2010; Appendix 2-2). Moho was defined as the base of the reflective crust, dipping slightly from ~35 km depth in the NW to more than 50 km in the SE.

On the North Island of New Zealand, in 2001, a major seismic project was carried out. The Central Volcanic Region or Taupo Volcanic Zone occupying the northern half of the North Island of New Zealand is a region where onshore backarc extension within continental lithosphere resulting from the westward subduction of the Pacific oceanic plate could be studied. Therefore, in 2001 the NIGHT (North Island Geophysical Transect) project was initiated (Henrys et al., 2003a, 2003b; Harrison and White, 2006; Stratford and Stern, 2006). It involved both an active-source and a passive-source component and had also an offshore component (Fig. 10.6.1-01).

The active source part had two main deployments. First, in January-February 2001, 88 3-component stations (RefTeks), 200 1-component stations (Texans), and 15 OBSs were deployed with an average spacing of 1 km along a NW-SE profile and recorded

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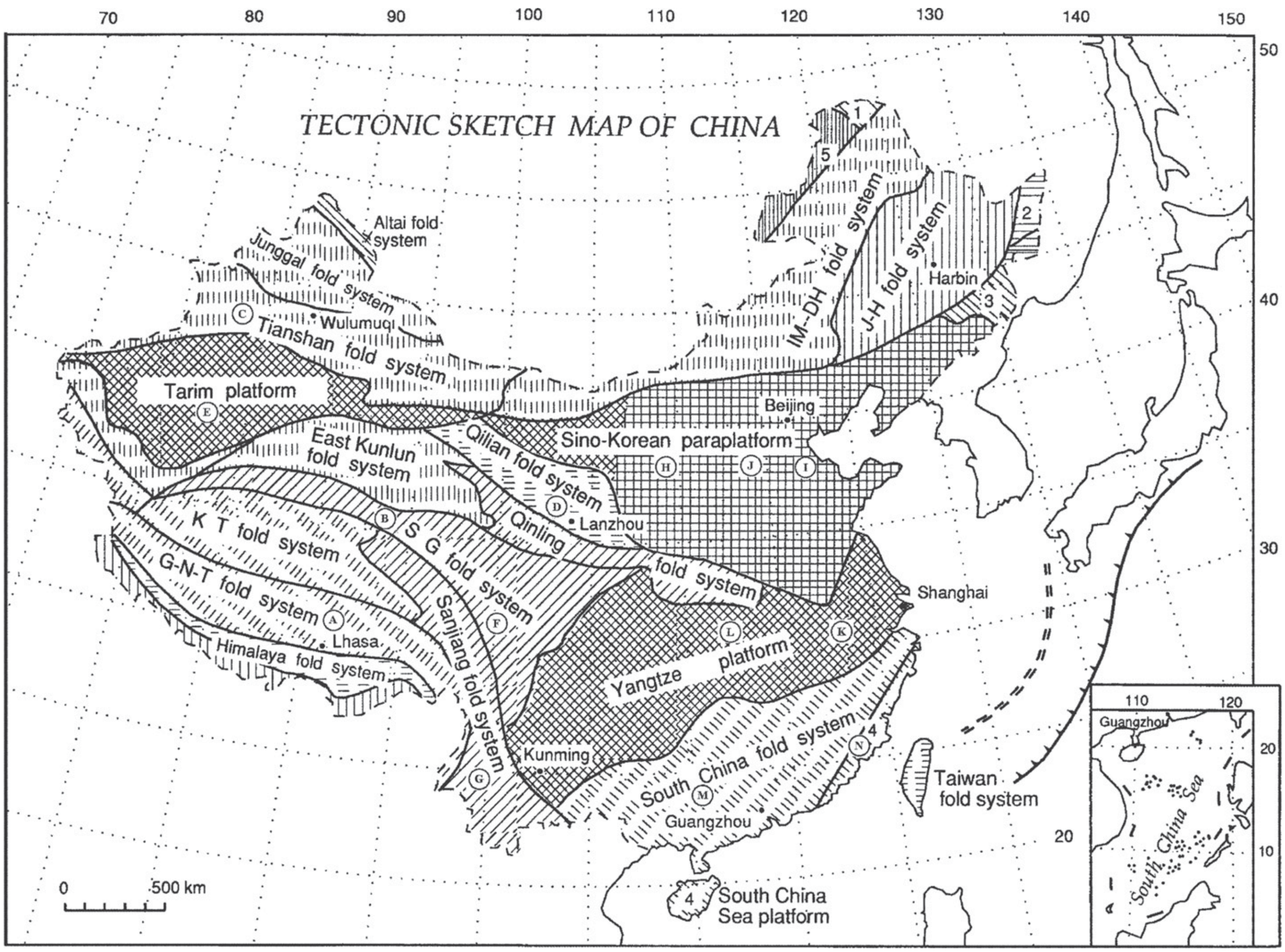

Figure 10.5.2-04. Tectonic map of China (from Li et al., 2006, fig. 2). The circled letters indicate the regimes for which representative crustal structure columns are shown in Fig. 10.5.2-03. [Tectonophysics, v. 420, p. 239–252. Copyright Elsevier.]

shots from M/V *Geco Resolution* (8200 cu in airgun array), that also recorded vertical incidence crustal multichannel seismic data (6000 m 480 channel array). The 288 land recorders were redeployed along the NW-SE profile and a N-S line through the back-arc Taupo Volcanic Zone, and nine 500 kg shots recorded (7 on the NW-SE profile and 2 offset onto the N-S line). The second main deployment, in December 2001, fired 3 shots into 200 1-component stations located on the N-S line and 100 1-component stations on the western half of the NW-SE line. Ninety-five stations were redeployed onto the eastern part of the NW-SE line, and two additional 500 kg shots were fired (Fig. 10.6.1-01). The NW-SE line was 250 km long and ran from coast to coast through the axis of the Taupo Volcanic Zone, while the N-S line was 120 km long and was located entirely within the Taupo Volcanic Zone.

To complement the active-source data, passive source (earthquake) data were recorded during additional deployments (Fig. 10.6.1-02). First, 63 short-period 3-component stations were deployed at 2-km spacing along the NW-SE line for two months following the active source phase 1, and second, following active-source phase 2, a broadband array of 20 stations (Guralp) was deployed along the same line with 5-km spacing (Harrison and White, 2006). The location and timing of the local shallow (<10 km depth) and deep (>40 km depth) earthquakes recorded by these linear passive arrays was constrained by the New Zealand National Seismograph Network as well as by the CNIPSE array (Henrys et al., 2003a). Data examples of the active-source experiment and the subsequent ray trace modeling are shown in Figure 10.6.1-03.

The long-range seismic-refraction data showed velocities of 6 km/s and less within the top 15 km of the crust of the Taupo Volcanic Zone. At 15 km depth, the P-velocity increased to 6.8 km/s and then to 7.4 km/s at ~20 km depth. Rocks between 15 and 20 km depth were interpreted as new crust formed by underplating. The strongest reflection, interpreted as the reflection Moho, was observed from the top of the proposed underplated

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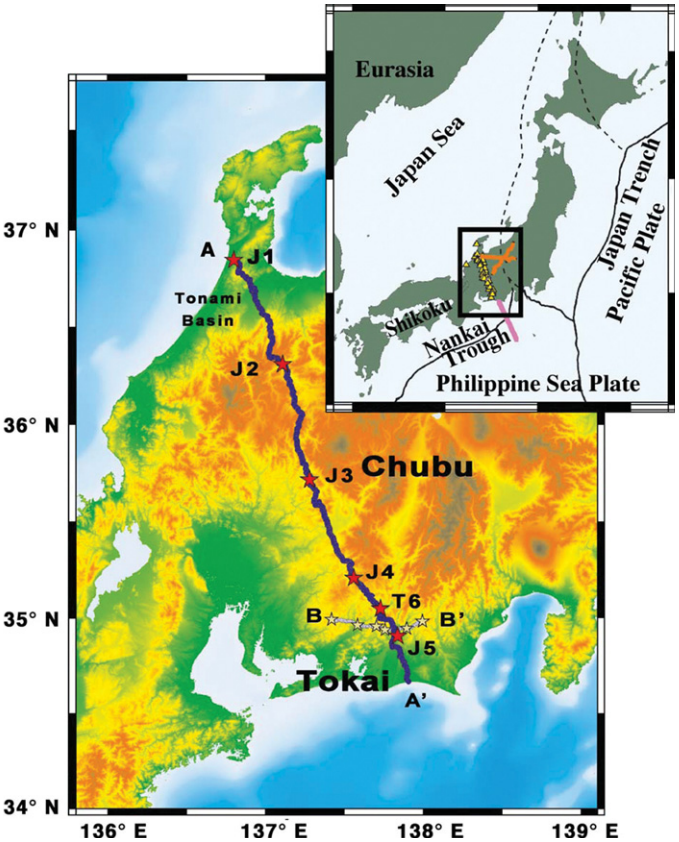

Figure 10.5.3-01. Location map of the seismic controlled-source experiment (line A–A′) of 2001 across south-central Honshu, Japan (from Iidaka et al., 2004, fig. 1). Line B–B′ was recorded in 1985 (Matsu'ura et al., 1991). Shotpoints are shown by stars. The orange lines in the inset (for location, see also Fig. 9.6.3-01) are profile lines analyzed by Takeda (1997). [Tectonophysics, v. 388, p. 7–20. Copyright Elsevier.]

layer at 15 km depth. No such distinct reflection was observed at 20 km depth. Rather, wide-angle reflection data showed a continuum of low-level reflectivity between 15 and at least 35 km depth. Thus, Stratford and Stern (2006) concluded that the transition from lower crust to upper mantle should be broad.

Harrison and White (2006) discussed two possible interpretations of the geophysical results. *Either* the crust beneath Taupo Volcanic Zone is 15 km thick with a huge layer of melt at the top of the mantle (Fig. 10.6.1-04), *or* the crust is 30 km thick with the lower half comprising extremely heavily intruded crust (Fig. 10.6.1-05). Harrison and White (2006) favored the latter interpretation.

The interpretation of the marine data which extended the line of observations toward southeast beyond the Hikurangi subduction zone showed the subducting crust as a shallow dipping (3°) strongly reflecting interface at 6 s TWT (two-way traveltime) which became less pronounced where the plate interface steepens landward at a depth of ~12 km, 120 km from the trench axis. From the velocity model, based on the wide-angle onshore-offshore refraction data and the inversion of arrival times from earthquakes recorded by the CNISPE array, the fore-arc had been seen as a region with low P-velocity (<5.5 km/s), high V_P/V_S (>1.85), high Poisson's ratio (>0.29) overlying subducting oceanic crust (V_P = 7.0 km/s) (Reyners et al., 2006). After a prestack depth migration a dominant reflector was observed which coincided with the top of the subducting plate and an increase of dip could be imaged as a pronounced step of the reflector by 5 km (Henrys et al., 2006).

Three more seismic-reflection surveys may be mentioned briefly. In 2001, 500 km of crustal reflection data were gathered across eastern Chatham Rise, recording a source of 8204 cu in along a 6000 m streamer up to 16 s TWT (Davy et al., 2008).

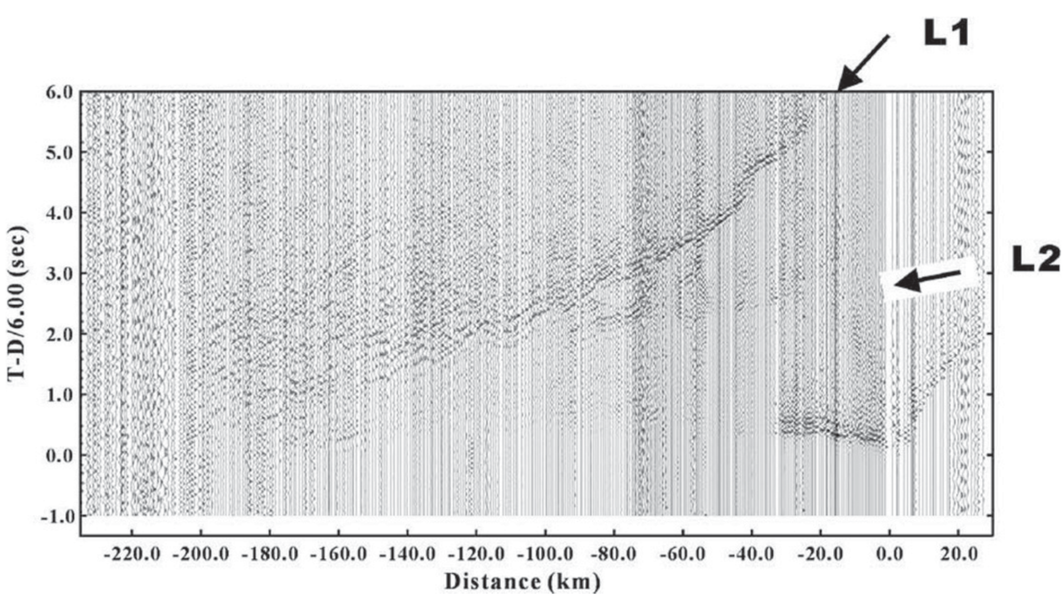

Figure 10.5.3-02. Onshore P-wave crustal data recorded across south-central Honshu, Japan from shot J5 (from Iidaka et al., 2004, fig. 2c). For location, see Fig. 10.5.3-01. [Tectonophysics, v. 388, p. 7–20. Copyright Elsevier.]

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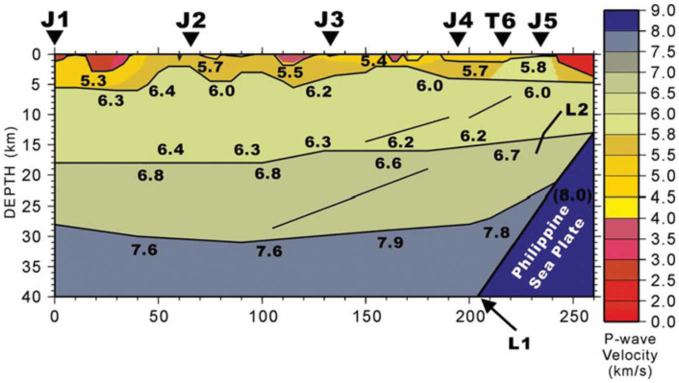

Figure 10.5.3-03. P-wave crustal model across south-central Honshu, Japan (from Iidaka et al., 2004, fig. 4). For location, see Fig. 10.5.3-01. [Tectonophysics, v. 388, p. 7–20. Copyright Elsevier.]

In 2003, two crustal transects were obtained east of South Island, recording a source of 3000 cu in by 25 OBSs and a 2250 m streamer. The first transect was observed across Bounty Trough and was 410 km long, the second transect extended for 500 km across Great South Basin and Campbell Plateau (Grobys et al., 2007, 2009). Finally, in 2005, 2950 km of marine reflection data were recorded off northeastern North Island to investigate the geometry of the Hikurangi subduction thrust and upper plate. Records of 12 s TWT were recorded by a 6–12-km-long streamer, using a source of 4140 cu in (Barker et al., 2009).

10.6.2. South Africa

In 2003, seismic investigations in Namibia supported an onshore-offshore experiment on the west coast of South Africa in order to reveal the structure of the oceanic-continent transition zone. The land part was jointly organized by the Council of Geoscience (RAS) and the GFZ Potsdam (Germany). The onshore part consisted of two profiles running almost perpendicular to the coastline with length of 100 km and three shots (100 kg, 50 kg, 100 kg) were fired on each line. The land stations also recorded airgun shots, fired along the offshore lines. One of the lines, the 500-km-long Springbok profile, was interpreted by Hirsch et al. (2009) and is described in more detail in subchapter 10.7.4.

A second seismic project of the GFZ Potsdam (Germany) was the 800-km-long Agulhas-Karroo transect, carried out in 2005 within the project INKABA ya Africa (Lindeque et al., 2007; Stankiewicz et al., 2007, 2008). It was a north-south offshore-onshore transect which ran over a distance of 400 km from the offshore Agulhas Plateau across the Agulhas Fracture zone and the continental margin onto to South African coast, and for other 600 km onland across the Cape Fold Belt, the Karoo Basin and into the Kapvaal Craton. The project also included the recording of 600 km of magnetotelluric data. For the offshore part the reader is referred to subchapter 10.7.4.

Within this frame, two wide-angle onshore seismic lines were collected. The lines ran parallel to each other, ~200 km

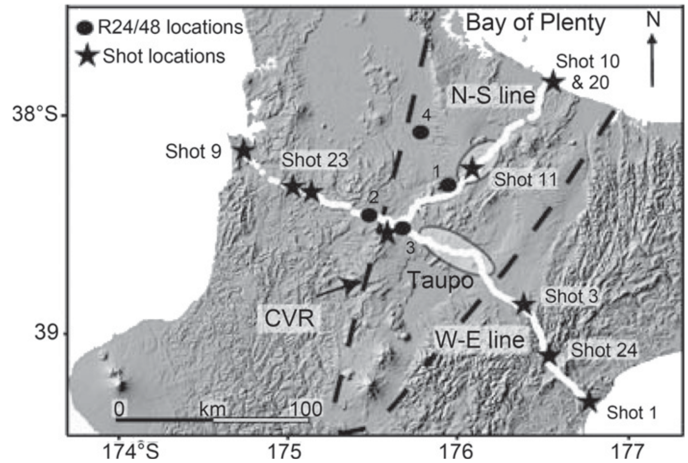

Figure 10.6.1-01. Location of the NIGHT active-source transects across the Taupo Volcanic Zone or Central Volcanic Region (CVR) on North Island of New Zealand (from Stratford and Stern, 2006, fig. 3). Black dots are the deployment locations of the R24/48-channel seismograph. [Geophysical Journal International, v. 166, p. 469–484. Copyright John Wiley & Sons Ltd.]

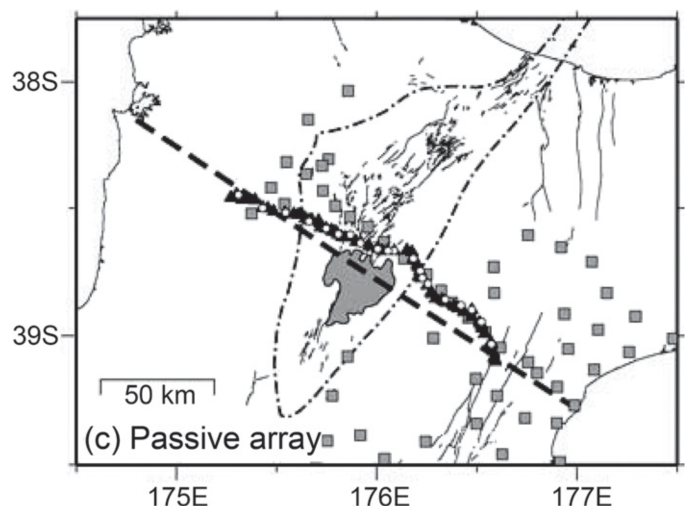

Figure 10.6.1-02. Location of the NIGHT passive-source transects across the Taupo Volcanic Zone on North Island of New Zealand (from Harrison and White, 2006, fig. 2c). Black triangles—linear short-period array of early 2001; white circles—linear broadband array of 2001–2002; grey squares—CNIPSE array. [Geophysical Journal International, v. 167, p. 968–990. Copyright John Wiley & Sons Ltd.]

apart, and were ~240 km long. At each line, 48 receivers recorded data from 13 shots fired in boreholes with charges between 75 and 125 kg. The average shot spacing was 20 km; that of the receivers was 5 km. The record sections from the land stations showed clear P_MP arrivals, both from the land shots and from part of the airgun shots, as well as a clear mid-crust reflection. In the joint model from airgun and land shots the Moho discontinuity was clearly visible as a high-velocity contrast. It was found at 40 km depth underneath the Karoo basin and slightly deeper

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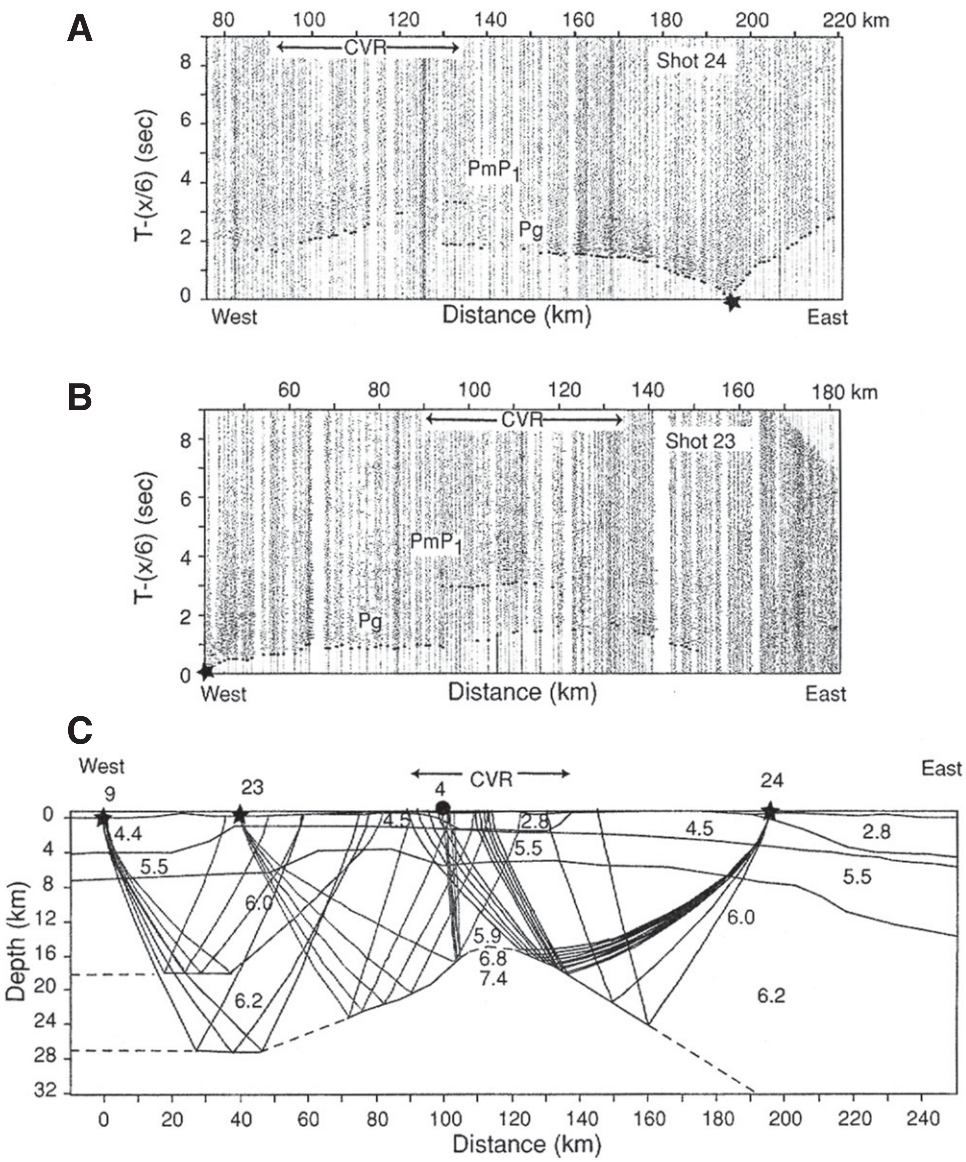

Figure 10.6.1-03. NIGHT active-source experiment across the Taupo Volcanic Zone on North Island of New Zealand (from Stratford and Stern, 2006, fig. 4). Data examples (A) shot 24, (B) shot 23, and (C) ray trace model. [Geophysical Journal International, v. 166, p. 469–484. Copyright John Wiley & Sons Ltd.]

(42 km) under the Cape Fold Belt. South of the Fold Belt, the Moho shallows abruptly to 30 km at the present coast.

Furthermore, a 100-km-long near-vertical seismic-reflection experiment yielded a high-quality seismic image of the crust and Moho across the southern Karoo basin in South Africa (Lindeque et al., 2007). The highly reflective crust comprised upper, middle, and lower layers. A well-defined middle crustal layer of 20 km thickness occurred below a seismically imaged unconformity. The underlying lower crustal layer is wedge shaped and 24 km thick in the north and decreases to 12 km thickness beneath the Cape Fold Belt. A clearly imaged undulating Moho occurs at a depth of ~43 km in the north with a nick point at 42–35 km depth and then deepens to 45 km in the south beneath the tectonic front of the Cape Fold Belt. A possible 1–2 km lowermost crustal layer of high seismic reflectivity overlies the Moho and was interpreted as underplated mafic material.

10.6.3. South America

In Venezuela, the ECCO (Estudio Cortical de la Cuenca Oriental) study of 2001 (Schmitz et al., 2005) targeted the Oriental Basin north of the Guayana Shield (see Fig. 9.7.3-06). It was a quasi-continuation of the 1998 ECOGUAY (Estudios de la Estructura Cortical del Escudo de Guayana) study targeting the Guayana Shield (Schmitz et al., 2002) and was therefore described already in Chapter 9.7.3.2.

The coastal area of Venezuela, representing the Caribbean–South America plate boundary, became the target of a large active-source land-sea seismic experiment in 2004 (Levander et al., 2006; Clark et al., 2008; Schmitz et al., 2008; Magnani et al., 2009). About 6000 km of marine multi-channel seismic-reflection data were collected offshore Venezuela. In addition five wide-angle seismic profiles were recorded both onshore and

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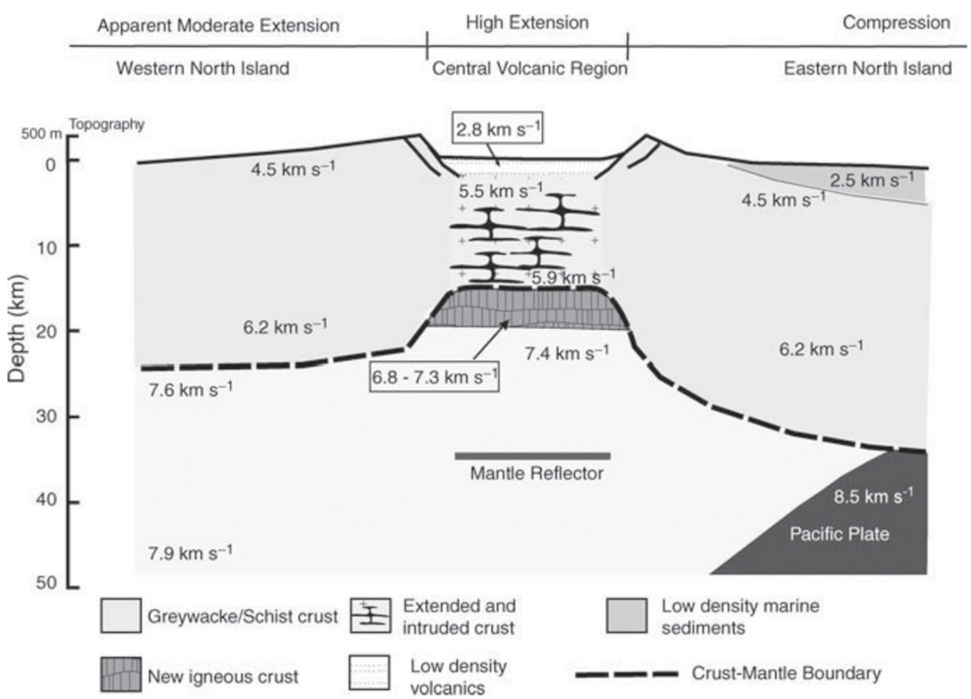

Figure 10.6.1-04. Model 1 across the Taupo Volcanic Zone on North Island of New Zealand (from Stratford and Stern (2006, fig. 10). [Geophysical Journal International, v. 166, p. 469–484. Copyright John Wiley & Sons Ltd.]

offshore Venezuela and the Antilles arc region (Fig. 10.6.3-01, spanning an area of almost 12 degrees of longitude and 5 degrees of latitude as part of the project BOLIVAR (Broadband Ocean Land Investigation of Venezuela and the Antilles Arc Region).

The 550-km-long N–S profile crossed the structures involved in the active 55-m.y.-long continent-arc oblique collision between the Caribbean and the South American plate. From the north to the south, these structures include the accretionary prism, the extinct volcanic arc (Leeward Antilles arc), the Tertiary Bonaire basin, the continental-size dextral strike-slip fault system (San Sebastián–El Pilar fault), the allochthonous exhumed terranes, and the autochthonous fold and thrust belt (Caribbean Mountain system) and foreland basin. The wide-angle data showed that these elements are characterized by different velocity structures and that they are separated by sharp lateral velocity variations. The Leeward Antilles island arc, being 27 km thick with a high velocity (7 km/s) crustal layer, exhibited a velocity structure similar to that of the Lesser Antilles active volcanic arc indicating that the extinct arc has not been modified by the collision with the South American plate.

The data showed an ~20 km change in crustal thickness across the San Sebastián fault, separating the 25-km-thick Bonaire crustal block with average crustal seismic velocities ranging between 5.5 and 6.7 km/s from the 45 km South American crustal block and suggesting that the dextral strike-slip fault is a crustal feature that likely continues in the mantle as a primary strand of the plate boundary between the South American and the Caribbean plates. South of the strike-slip fault and beneath the exhumed eclogitic terranes, the data imaged a north-dipping, high-velocity (>6.5 km/s) anomaly in the upper crust (3–11 km),

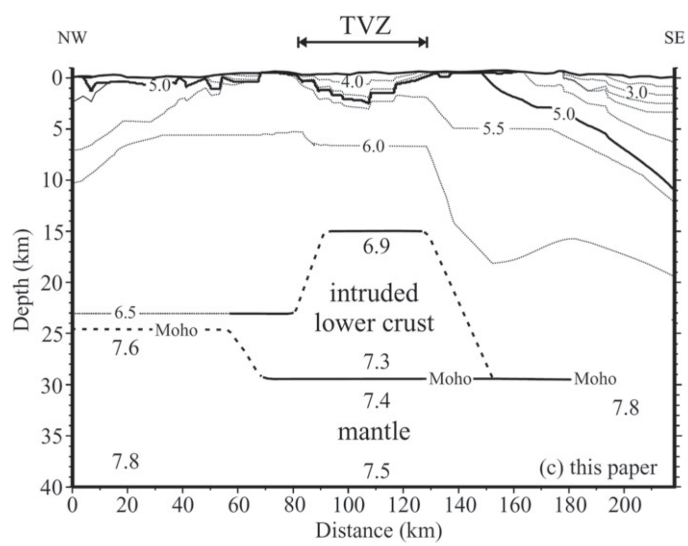

Figure 10.6.1-05. Model 2 across the Taupo Volcanic Zone (TVZ) on North Island of New Zealand (from Harrison and White, 2006, fig. 17). [Geophysical Journal International, v. 167, p. 968–990. Copyright John Wiley & Sons Ltd.]

indicating that high-pressure/low-temperature rocks are the likely lithologies responsible for the high seismic velocities and suggesting that exhumation of these assemblages is enabled by the strike-slip fault (Magnani et al., 2009).

Chile had become the target of a series of major research projects in the 1990s, such as PISCO94, CINCA95, CONDOR in 1995, ANCORP96, and ISSA2000. The research work con-

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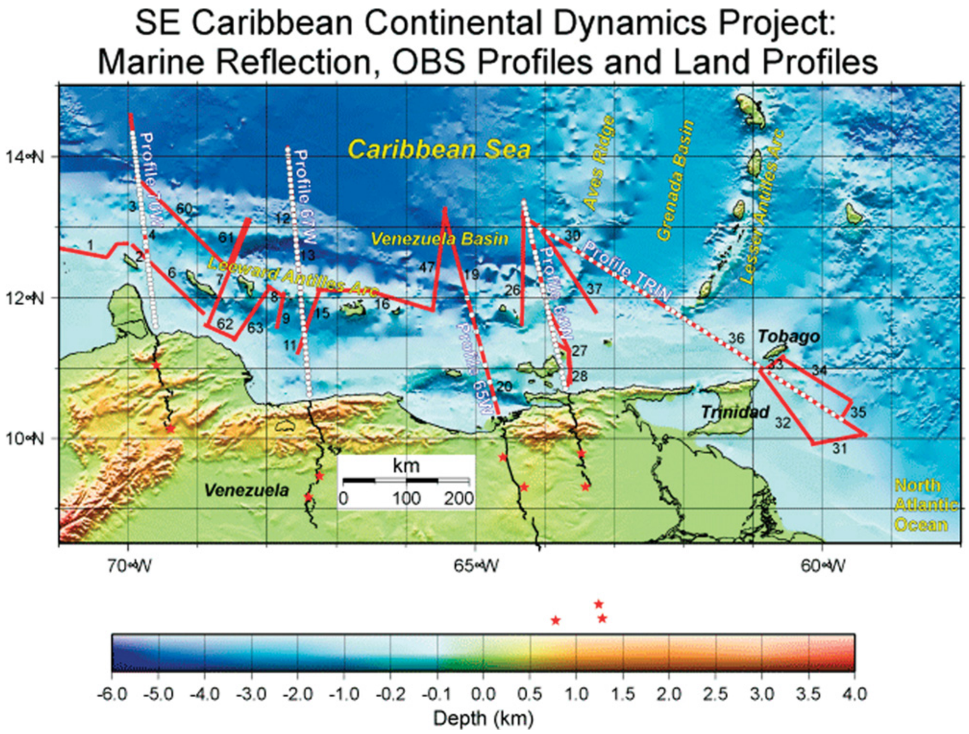

Figure 10.6.3-01. Location of the BOLIVAR controlled-source seismic project 2004 (from Magnani et al., 2009, fig. 1b). Red lines—seismic reflection lines; white circles—ocean-bottom seismometers; black lines—land-based seismometers; red stars—shotpoints. [Journal of Geophysical Research, v. 114, B02312, doi:10.1029/2008JB005817. Reproduced by permission of American Geophysical Union.]

tinued into the 2000s, of which the project SPOC (Subduction Processes off Chile) in 2001 (Krawczyk et al., 2003, 2006), due to its close relation to the foregoing project ISSA2000 (Bohm et al., 2002; Lueth et al., 2003), was already described in some detail in Chapter 9.7.3.3.

The latest experiment in southern Chile was the TIPTEQ (from The Incoming Plate to Mega-Thrust Earthquake Processes) array project of 2004 and 2005 (Fig. 10.6.3-02). The large-scale onshore-offshore array included 140 stations onshore with a dense station spacing (less than 7 km in the center) and 30 OBSs offshore. An active source, onshore seismic experiment was carried out in January 2005. The profile trended E-W at 38.2°S and ran from the Pacific coast for ~100 km inland, crossing the Coastal Cordillera and the western portion of the Longitudinal Valley. The profile thus crossed the area of the hypocenter of the great 1960 Chile earthquake (Mw = 9.5). The experiment was cored by a near-vertical incidence reflection survey with shots every 1.5 km and 3-component geophones every 100 m. With an active spread length of 18 km and a daily roll-along of 4.5 km, this resulted in an 8 fold common-depth-point coverage.

The near-vertical incidence reflection survey was supplemented by an expanding spread survey consisting of 15 extra shots with offsets up to almost 100 km. The expanding spread survey provided tenfold coverage of the middle portion of the profile. The project aimed to study the fine-scale structure around the 1960 Valdivia, Chile, earthquake, which was the largest earthquake ever recorded instrumentally, and to determine the key controlling parameters causing subduction zone earthquakes at convergent plate boundaries (Rietbrock et al., 2005; Groß et al., 2008).

Furthermore, a 90-day marine campaign, from the end of 2004 to the beginning of 2005, acquired a broad variety of geological and geophysical data offshore Chile between 35° and 48°S (Fig. 10.6.3-03) which included active and passive seismics. The experiment was set up to obtain data along corridors between fracture zones separating relatively small areas of distinct ages (Scherwath et al., 2006).

For the seismic wide-angle data acquisition, some 200 deployments of OBS and OBH were carried out along the TIPTEQ transects, each line with 30–50 stations at a nominal spacing of 5.5 km. A short seismic streamer towed by the research vessel complemented the data set. A first preliminary velocity model was published by Scherwath et al. (2006) for TIPTEQ corridor 3 (Fig. 10.6.3-04).

10.7. OCEANIC DEEP STRUCTURE RESEARCH

10.7.1. Introduction

The seismic structure of the oceanic crust and passive margins was reviewed by Minshull (2002) and published in Part A of the *International Handbook of Earthquake and Engineering Seismology*, edited by Lee et al. (2002). The structure of the oceanic crust, as known by 2000, is shown in chapters on P- and S-wave velocity structure, anisotropy and attenuation, and variations of crustal structure with spreading rate and with age. Other chapters deal with the seismic structure of the Moho and the uppermost

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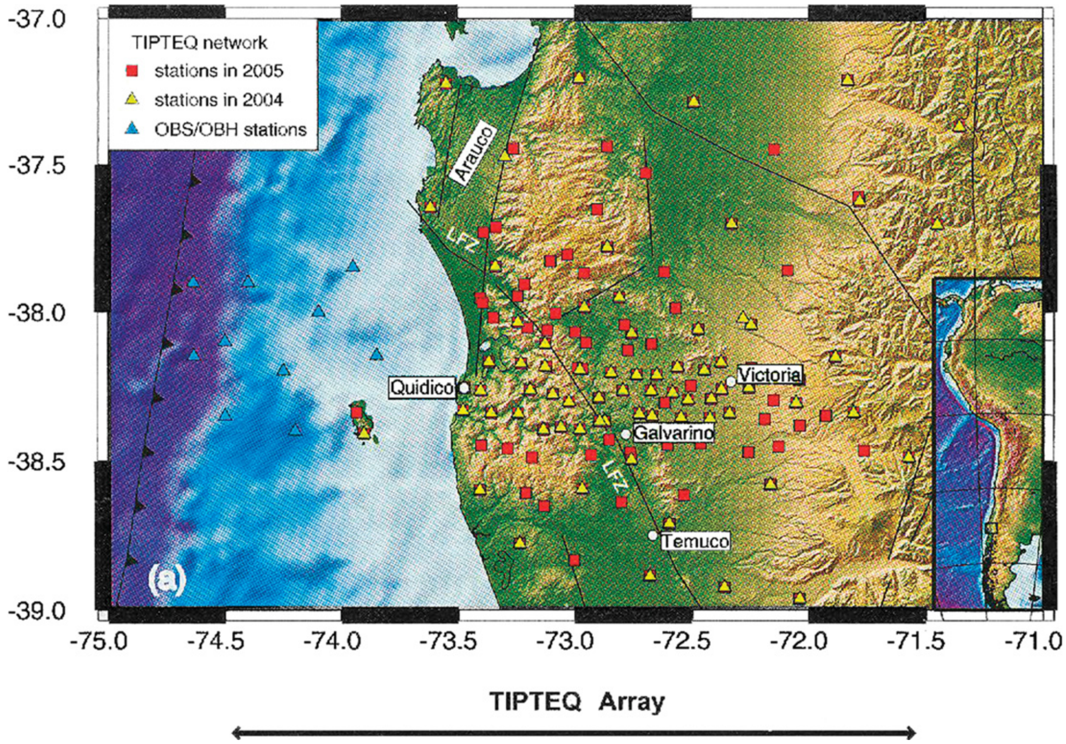

Figure 10.6.3-02. Location of the TIPTEQ seismic array project 2004–2005 (from Rietbrock et al., 2005, fig. 1). [Eos (Transactions, American Geophysical Union), v. 86, no. 32, p. 293, 298. Reproduced by permission of American Geophysical Union.]

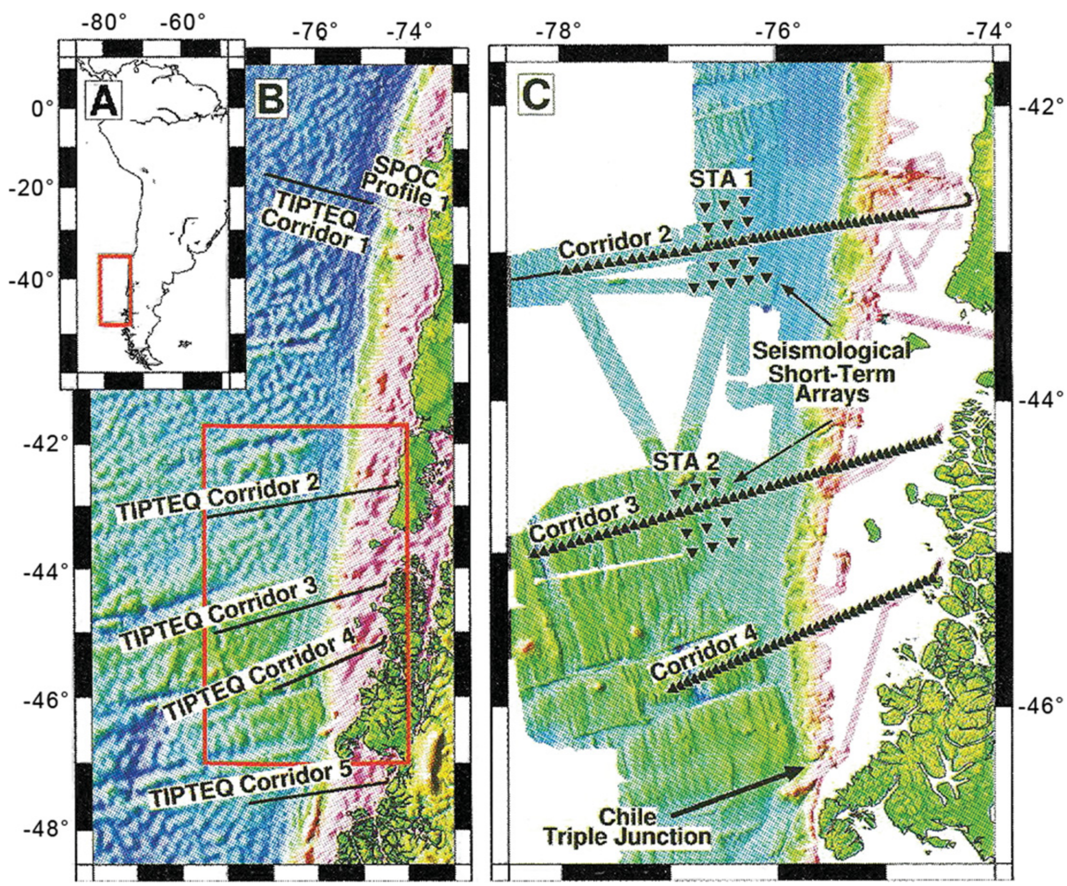

Figure 10.6.3-03. Location of the TIPTEQ project (from Scherwath et al., 2006, fig. 1). (A and B) Overview of all marine seismic corridors, 2004–2005, (C) Central transects with locations of ocean-bottom seismometers (triangles) along refraction profiles and the outer rise seismological networks STA1 and STA2. [Eos (Transactions, American Geophysical Union), v. 87, no. 27, p. 265, 269. Reproduced by permission of American Geophysical Union.]

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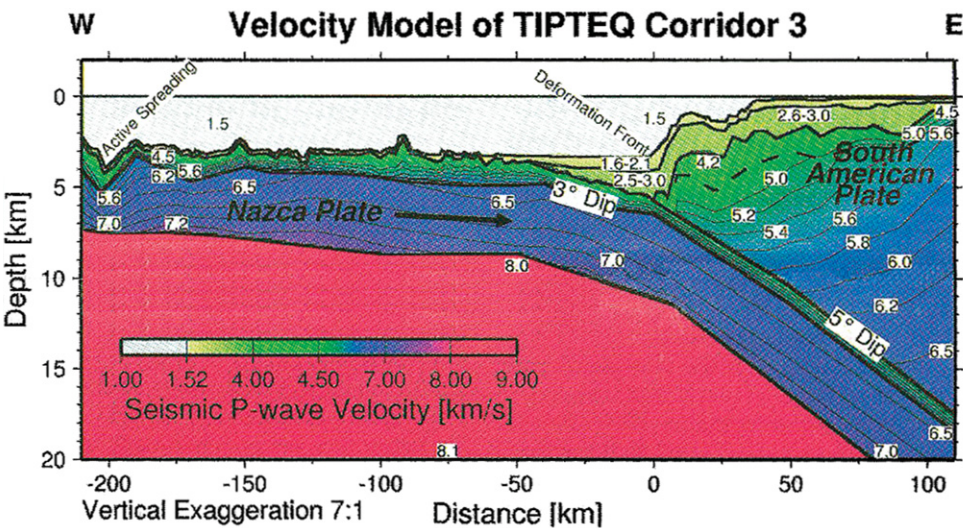

Figure 10.6.3-04. Preliminary structural velocity model of the TIPTEQ marine seismic corridor 3 (from Scherwath et al., 2006, fig. 3). Plate age is 6.5 Ma at the trench. [Eos (Transactions, American Geophysical Union), v. 87, no. 27, p. 265, 269. Reproduced by permission of American Geophysical Union.]

oceanic mantle, of mid-ocean ridges, of oceanic fracture zone and segment boundaries, and hotspots, ocean islands, aseismic ridges and oceanic plateaus. In the textbook *Marine Geophysics*, Jones (1999) has described in much detail the instrumentation and methodologies, as used in marine seismic exploration until the end of the 1990s.

Another summary on our knowledge on the structure of the lithosphere under the oceans, as obtained until 2000, was published in the *Encyclopedia of Sciences* (Steele et al., 2001), where individual papers inform on seismic structure (Harding, 2001), on mid-ocean ridges (Carbotte, 2001) and seismology sensors (Dorman, 2001) and other geophysical topics as, e.g., origin of the oceans (Turekian, 2001), geophysical heat flow (Stein and von Herzen, 2001), or magnetics (Vine, 2001).

It is interesting to compare the generalizing results of average oceanic crustal structure of Raitt (1963) and Ewing (1969) with those published by Harding (2001), who distinguishes between "traditional" and "modern." The "modern" summary of average oceanic crustal structure of Harding (2001) is based on models which were the result of synthetic seismogram analysis, where a range of typical velocities and velocity gradients characterizes layers 2 and 3 (Table 10.7.1-01).

For many projects carried out since 2000, full interpretations are still under way. Therefore, as for the continents, also for numerous oceanic research projects in many cases only abstracts of presentations presented at international meetings or internal reports have become available and only for a limited number full interpretations have been published. We will present a few examples.

10.7.2. Pacific Ocean

The continental margin off the coast of Nicaragua and Costa Rica was the target of a marine seismic survey carried out in 2005 by the research vessel *Meteor* (1986) cruise 66-4a. Two wide-angle seismic profiles were conducted seaward of the trench in the outer rise area offshore of central Nicaragua. Instruments were deployed at ~5 km intervals (Ivandic et al., 2010). An airgun array fired shots every 60 s, corresponding to a shot interval of ~130 m. Both profiles were 120 km long. The first one ran along the trench axis and intersected the trench at 11°N, the second one had the same orientation, but was located ~60 km seaward of the trench axis. Seismic structure was characterized by low velocities both in the crust and upper mantle. The crustal thickness on both lines was ~5.6–5.8 km. Velocities in the uppermost mantle were found in the range of 7.3–7.5 km/s, interpreted as caused by serpentinization.

The SALIERI (South American Lithosphere Transects across Volcanic Ridges) seismic experiment in 2001 followed the

TABLE 10.7.1-01. COMPARISON OF AVERAGE VELOCITIES IN OCEANIC CRUST AS OBSERVED IN THE 1960S AND 2000S (WITHOUT ERROR INDICATIONS)

	Layer 2, igneous crust		Layer 3, igneous crust		Layer 4, upper mantle	
Year	Velocity (km/s)	Thickness (km)	Velocity (km/s)	Thickness (km)	Velocity (km/s)	Thickness (km)
1963	5.15	1.21	6.82	4.57	8.15	
1969	4.5–5.5	1.5	6.5–7.1	5	7.7–8.3	
2001 ("Traditional")	5.07	1.71	6.69	4.86	8.13	6.57
2001 ("Modern")	2.5–6.6	2.11	6.6–7.6	4.97	>7.6	7.08

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PAGANINI and the G-PRIME experiments in 1999 and 2000 to investigate the seismic structure of the Galapagos volcanic province between 78°W and 95°W longitude and 3°S and 9°N latitude (see Fig. 9.8.2-04). It was already described in Chapter 9.8.2 (Sallares et al., 2003, 2005).

An experiment in the south-central Pacific, conducted in 2004, explored the region southwest of New Caledonia. It is centered on 164°E, 24°S and is already well documented. It was a deep seismic survey conducted within the western part of New Caledonia's Exclusive Economic Zone (EEZ) and revealed for the first time the thinned continental and oceanic natures of the crust beneath the eastern Tasman Sea. In a collaboration of French institutions with New Caledonia scientists, 2500 km of deep seismic-reflection and 60 km of wide-angle seismic data were collected within the western part of New Caledonia's EEZ (Fig. 10.7.2-01). Airgun shots were recorded by a 4.5 km, 360-channel digital streamer and 15 OBSs.

Since Cretaceous times, the southwest Pacific region has been dominated by an extensional episode which dismembered Gondwanaland and has led to a fragmentation of continental crust to form subparallel marginal basins such as the Tasman Sea basin and the New Caledonia basin. Today, e.g., the Tasman Sea basin is floored by oceanic crust. This and other basins isolated microcontinental fragments such as the Lord Howe Rise and the New Caledonia–Norfolk Ridge. The study area, located in the southwest Pacific east of both Australia and the oceanic Tasman Sea basin, comprises such continental fragments.

Onboard interpretation of seismic-reflection data and preliminary modeling of wide-angle data confirmed the continental nature of the Lord Howe Rise and the Norfolk Ridge and also revealed the continental-type seismic velocities and crustal thicknesses of the Fairway Ridge and basin systems (Fig. 10.7.2-02, top + bottom). To the east, wide-angle and near-vertical incidence reflection data showed the oceanic nature of the N-S central segment of the New Caledonia basin (Fig. 10.7.2-02, center + bottom), characterized by a shallow, 16 km deep Moho and velocities which are typical for 8-km-thick oceanic crust (Lafoy et al., 2005).

Twenty degrees farther east, around 178°–170°W, 18°–19°S, Crawford et al. (2003) have modeled the crustal structure across the Tonga–Lau arc–backarc system from the Lau-Ridge to the Pacific Plate, using data from an 840-km-long airgun

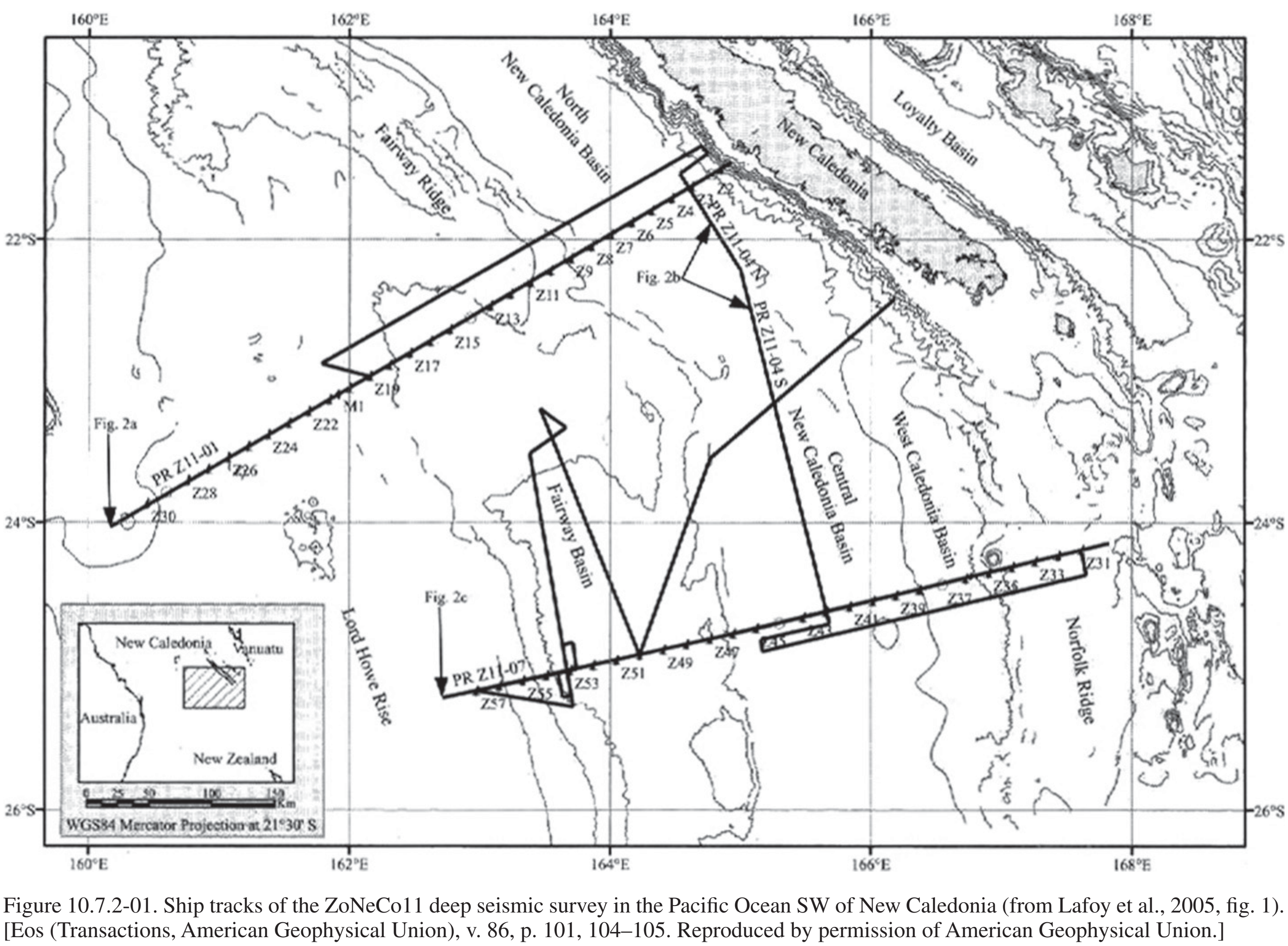

Figure 10.7.2-01. Ship tracks of the ZoNeCo11 deep seismic survey in the Pacific Ocean SW of New Caledonia (from Lafoy et al., 2005, fig. 1). [Eos (Transactions, American Geophysical Union), v. 86, p. 101, 104–105. Reproduced by permission of American Geophysical Union.]

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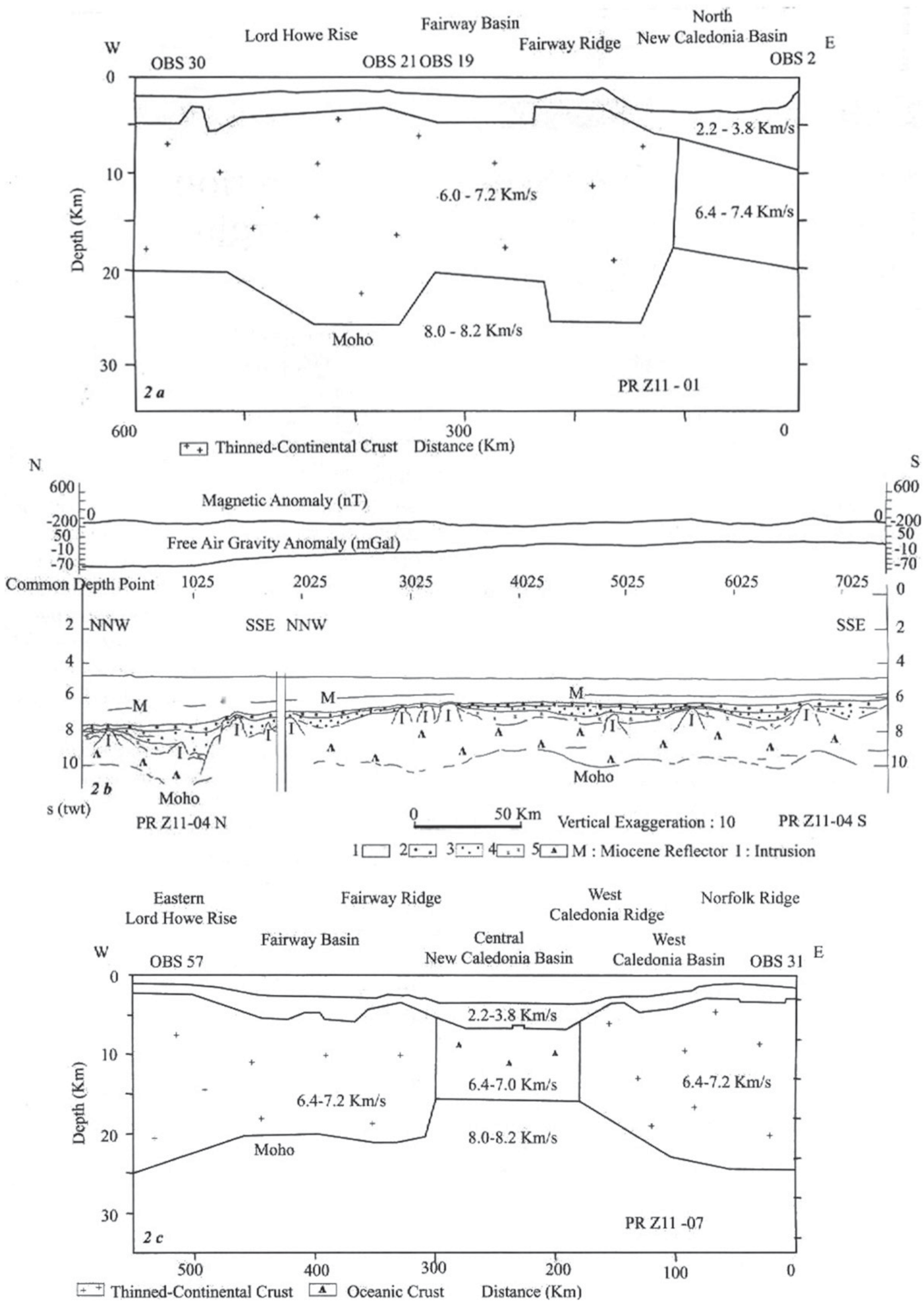

Figure 10.7.2-02. Preliminary models of the ZoNeCo11 deep seismic survey (from Lafoy et al., 2005, fig. 2). Top: preliminary velocity-depth model of the seismic refraction line Z11 01. Center: multichannel seismic reflection tie line Z11-04. Bottom: preliminary velocity-depth model of the seismic refraction line Z11 07. [Eos (Transactions, American Geophysical Union), v. 86, p. 101, 104–105. Reproduced by permission of American Geophysical Union.]

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seismic-refraction line over 19 OBSs and one land station (Fig. 10.7.2-03). The airgun line consisted of 5148 shots at 90s interval (160 m) and the average spacing of the seismometers was 42 km.

The overall crustal model (Fig. 10.7.2-04) showed a 5.5-km-thick Pacific crust in the east, thickening to 9 km beneath the flank of the Capricorn seamount at 172°W and showing an up to 7.5-km-thick intermediate-velocity layer (6–7 km/s) beneath the Tonga Ridge. Further west, the crust is exceptionally thin at the boundary between the Lau Basin and Tonga Ridge, before thickening again to 6 km in the east part and 9 km in the west part of the Lau Basin.

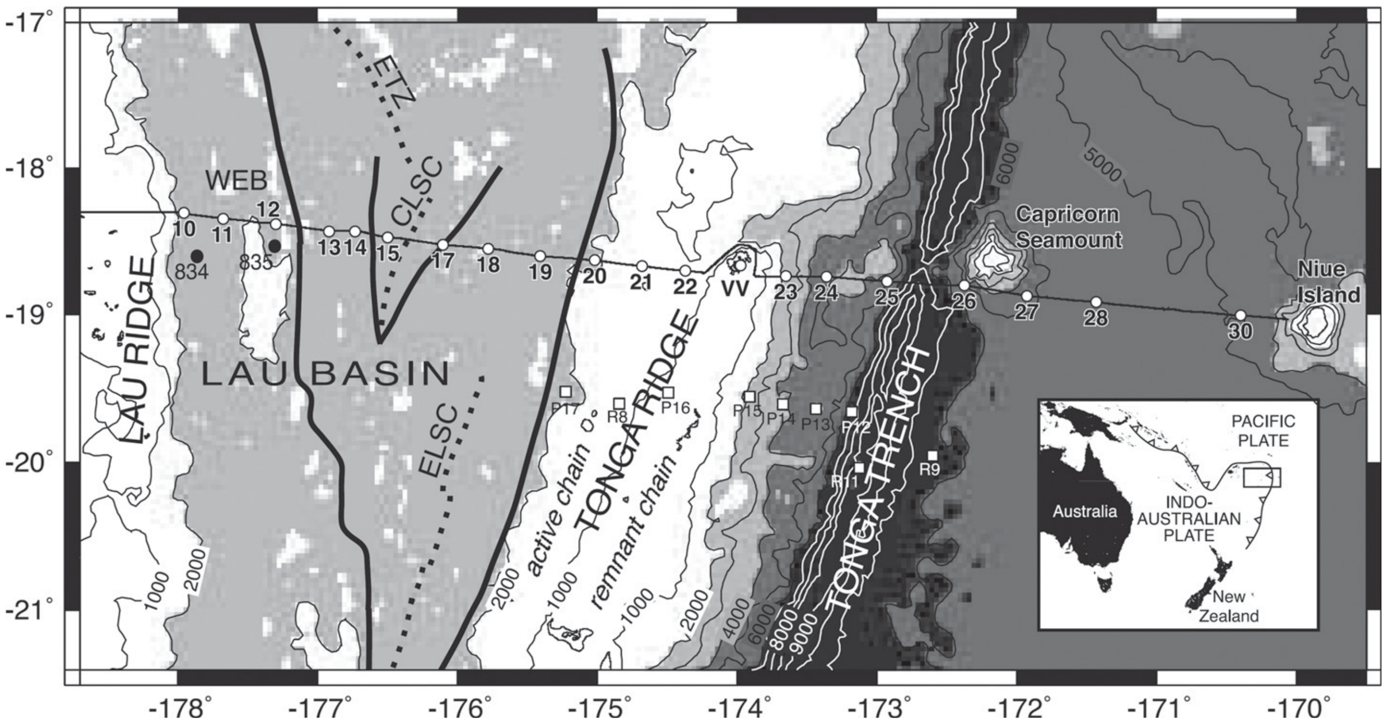

Figure 10.7.2-03. Location of an 840-km-long deep seismic airgun refraction line across the Tonga Ridge from the Pacific Ocean into the Lau Basin (from Crawford et al., 2003, fig. 1). WEB—Western Extensional Basin; CLSC—Central Lau Spreading Center; ELSC—Eastern Lau Spreading Center; ETZ—Extensional Transform Zone; 834 and 835 indicate ODP drill holes. Open squares: centerpoints of earlier 1-D surveys (R—sites from Raitt et al., 1955; P—sites from Pontoise and Latham, 1982). [Journal of Geophysical Research, v. 108, no. 4, doi:10.1029/2001JB001435. Reproduced by permission of American Geophysical Union.]

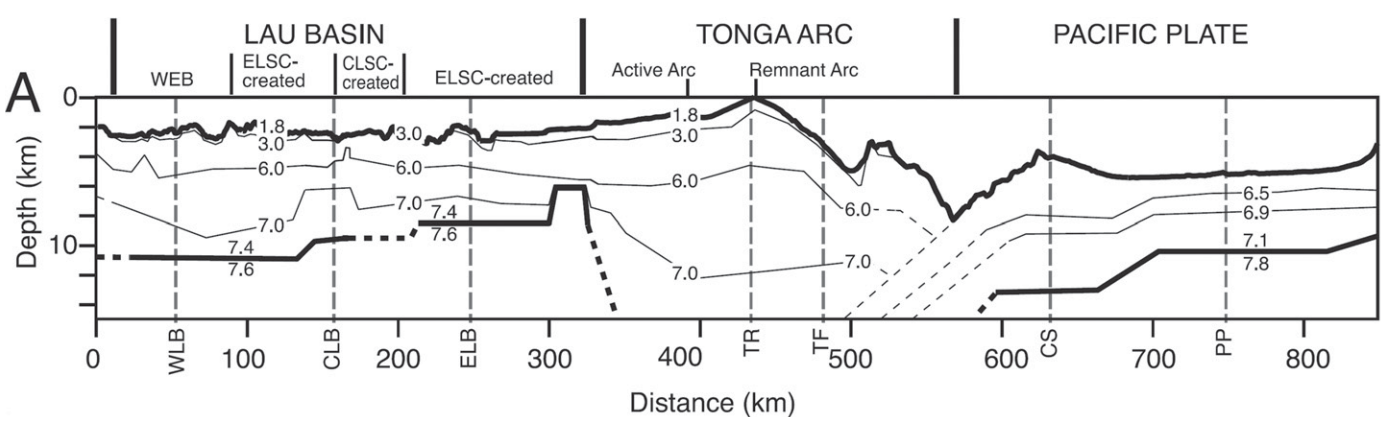

Figure 10.7.2-04. Crustal structure along an 840-km-long profile across the Tonga Ridge from the Pacific Ocean into the Lau Basin (from Crawford et al., 2003, fig. 8A). WEB—Western Extensional Basin; CLSC—Central Lau Spreading Center; ELSC—Eastern Lau Spreading Center; WLB, CLB, ELB—West, Central, East Lau Basin; TR, TF—Tonga Ridge, Forearc; CS—Capricorn Seamount; PP—Pacific Plate. [Journal of Geophysical Research, v. 108, no. 4, doi:10.1029/2001JB001435. Reproduced by permission of American Geophysical Union.]

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Major research activities were performed in the sea areas around Japan in the late 1990s and early 2000s. To investigate megathrust earthquake and tsunami generation in a subduction seismogenic zone, controlled-source seismology experiments continued to be conducted in the Nankai Trough and the Japan Trench, where the recurrence interval between the great earthquakes and coseismic slip distribution are well studied (e.g., Baba and Cummins, 2005; Yamanaka and Kikuchi, 2004). Recent availability of a large number of OBSs, a large airgun array, and a long streamer cable for academics provided the background to obtain data which revealed several new results of lithospheric-scale structures in subduction zones. Some of the most striking findings in the Nankai trough were several scales of subducted seamounts/ridges (Kodaira et al., 2002, 2005) and splay fault branching from the subducting plate boundary (Park et al., 2002). These structures strongly controlled the rupture propagations of the 1944 Tonankai and the 1946 Nankai megathrust earthquakes. Recently (after 2005) a high velocity and density domed body was detected in the overriding plate above the deeper part of the segmentation boundary, and strongly coupled patches at the segmentation boundary (Kodaira et al., 2006). Structural variations such as different velocities of the mantle wedge and different degrees of development (thickness) of a low-velocity layer at the plate boundary were detected along the Japan Trench (Tsuru et al., 2002; Miura et al., 2003, 2005; Takahashi et al., 2000, 2004). These variations correspond to the difference in the rate of large earthquake (M > 7) occurrence along the Japan Trench.

Crossing the rupture segmentation boundary between the 1944 8.1-Tonankai and the 1946 8.4-Nankai earthquakes, three wide-angle seismic-reflection profiles were recorded running parallel to the Nankai trough axis off the coast of Kii peninsula. Ocean-bottom seismographs were deployed at 5 and 7 km intervals and a large airgun array (197 l) fired every 200 m (Kodaira et al., 2006). Along the 145-km-long line farthest away from the coast also multichannel reflection seismic data were recorded. The other two lines were 175 km long. The wide-angle seismic data revealed a fractured oceanic crust with a strike-slip fault system in the segmentation boundary and a shallow high-velocity body near Cape Shionomisaki of Kii peninsula forming a strongly coupled patch at the segmentation boundary. The thickness of the subducted oceanic crust at the far-off profile varied from 5–7 km in the southwest to 7–10 km in the northeast. The oceanic Moho depth below sea level increases only slightly toward the coast from ~15 to 18 km.

The Izu-Ogasawara (Bonin)-Mariana (IBM) arc is one of the typical intra-oceanic arc that has been geologically and petrologically studied from long ago to investigate formation of the continental crust. It is necessary to obtain the seismic velocity structure to verify several petrological models explaining the crustal growth of the intra-oceanic arc. Suyehiro et al. (1996) have for the first time revealed the existence of the andesitic rock like as continental crust and high-velocity lower crust (>7 km/s) from the whole crustal structure across the arc (see project description in Chapter 9.8.2).

Two active-source experiments were conducted to image the structure immediately beneath the fronts of the Izu arc in 2004 (Kodaira et al., 2007a, 2007b) and the Bonin arc (Kodaira et al., 2007b). In both experiments, a linear array of densely deployed OBSs with 5 km spacing and a large airgun array were used. The seismic data revealed marked structural differences between the Izu arc in the north (at 35°–30°N and 139°–140°E) and the Bonin arc to the south (at 30°–25°N and 140°–141°E). The thickest crust (32 km) was found under the Izu arc and the thinnest crust (10 km) under the Bonin arc. The 1000-km-long profile along the volcanic front in the Izu-Bonin arc provided new seismological constraints on growth of continental crust in an intra-oceanic arc, e.g., crustal growth corresponding to basaltic arc volcanoes, structural variation of arc crusts and rifted margins.

In 2003, an active-source seismic experiment was conducted farther south around 16.5°–17.5°N latitude along a 700-km-long line across the middle Mariana arc region in an approximately WNW-ESE direction. The line started in the Parece Vela basin in the west, crossed the West Mariana ridge, the Mariana trough, and the Mariana arc, and ended in the Mariana Trench (Takahashi et al., 2008). The seismic line was almost perpendicular to the strike of the Mariana Arc and the West Mariana Ridge. One hundred and six OBSs at intervals of 5.4 km or 10 km recorded shots from a large airgun array (197 l). Reflection records were also obtained using a towed 12-channel hydrophone streamer during the airgun shooting. The characteristic data showed two clear refractions from ocean layers 2 and 3, clear Moho reflections, and small-amplitude upper-mantle refractions. The resulting model of the Mariana arc-backarc system showed a 4–6-km-thick oceanic crust (sediments and oceanic layers 2 and 3) under the Parece Vela basin and the Mariana trough, corresponding to a Moho depth of ~10 km below sea level. Under the West Mariana ridge and under the Mariana arc the crust thickens abruptly to near 16 km total crustal thickness, corresponding to maximum Moho depths of 18–19 km below sea level. Toward the east under the Mariana Trench the crust appears to remain relatively thick. While oceanic layer 2 remains fairly constant in thickness and follows more or less the topography of the sea bottom, the thickening of the crust occurs in layer 3 which was subdivided into two layers with velocity gradients from 6.0 to 6.5 km/s and 6.7 to 7.3 km/s. The upper-mantle velocity varies from 7.6–7.7 km/s under the West Mariana ridge and Mariana arc to 7.9–8.0 km/s under the Parece Vela basin and the Mariana trough (Takahashi et al., 2008).

The efforts to investigate the nature and architecture of the continental margins around Australia continued in 2000–2004. In the program to map the limits of the continental shelves for the Australian submission to the corresponding United Nations Commission, Geoscience Australia (the former Australian Geological Survey Organization) prepared various seismic transects. On the Pacific side major surveys targeted the Three Kings Ridge east to the South Fiji basin and the Lord Howe Rise, both located east of Australia and north of New Zealand, as well as the South Tasman Rise to the south of Tasmania (Finlayson, 2010; Appendix 2-2).

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10.7.3. Indian Ocean

The seismic investigations of Geoscience Australia in 2000–2004 on the Australian margins of the Indian Ocean side targeted the Great Australian Bight in the south and the Naturaliste Plateau as well as the Wallaby and Exmouth Plateaus to the west. In the northwest of Australia, the Argo Abyssal Plain was another goal (Finlayson, 2010; Appendix 2-2).

In the Indian Ocean, the Seychelles-Laxmi Ridge, recognized as a microcontinent, was the target of a major seismic experiment in 2003 (Fig. 10.7.3-01), carried out by scientists of the Universities of Southampton and Leeds, UK, and GFZ Potsdam, Germany. The project involved both a controlled-source and a passive seismic element (Collier et al., 2004).

The controlled-source part comprised a deep seismic-reflection/-refraction transect across the Seychelles/Laxmi Ridge

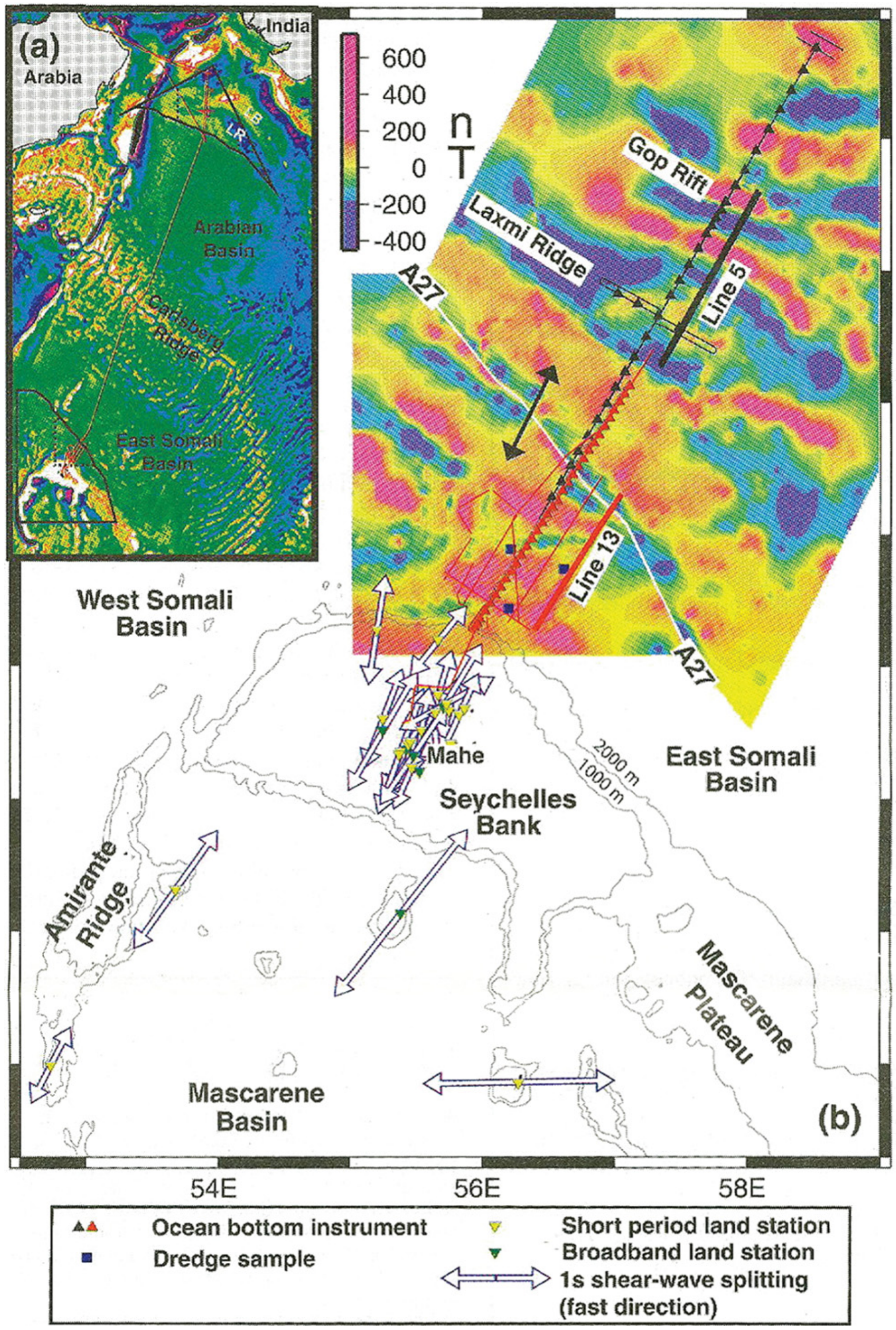

Figure 10.7.3-01. Location of the Seychelles-Laxmi Ridge seismic observations (from Collier et al., 2004, fig. 1). (a) Satellite gravity map of the NW Indian Ocean outlining the Seychelles and Laxmi Ridge margins. (b) Magnetic anomaly map with location of multichannel seismic reflection profiles 5 and 13 and locations of ocean-bottom instruments (black and red triangles). [Eos (Transactions, American Geophysical Union), v. 85, no. 6, p. 481, 487. Reproduced by permission of American Geophysical Union.]

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margins (reconstructed to A27 in Fig. 10.7.3-01) using an airgun array, ocean-bottom seismographs, and land stations installed on the central Seychelles islands. At some of the land stations, P_n arrivals could be recorded out to shot-receiver offsets of 380 km.

After the controlled-source seismic survey was completed, the land seismometers were redeployed widely across the Seychelles islands and recorded earthquakes for another 10 months.

Preliminary P-wave models (Fig. 10.7.3-02) showed evidence that the rifted margins are highly asymmetric. The Laxmi Ridge was seen as wide and complex, whereas the Seychelles side appeared narrow and simple. At both, the Seychelles margin and the India/Pakistan margin, the crust thins drastically from ~26 km to 10–12 km depth below sea level (Collier et al., 2004).

10.7.4. Atlantic Ocean

For the South Atlantic, we have selected a few recent projects investigating the continental margin areas of South Africa and South America, while for the North Atlantic, we will deal with investigations west of Ireland and east of Greenland.

In 2003, the project MAMBA (Geophysical Measurements across the Continental Margin of Namibia Experiment) of 1995 (Bauer et al., 2000) was continued with a similar onshore/offshore experiment on the west coast of South Africa in order to reveal the structure of the oceanic-continent transition zone. The involved institutions were the Council of Geoscience (RAS), the BGR Hannover and the GFZ Potsdam (both Germany). The onshore/offshore part consisted of two profiles running almost perpendicular to the coastline with length of 100 km on land and ~300 km on sea. Each minute a 52 l airgun produced seismic signals, while on land three shots (100 kg, 50 kg, 100 kg) were fired on each line. Furthermore, two coast-parallel lines on land recorded the seismic signals from two shotlines in the sea which ran also parallel to the coast. The aim of this investigation was to obtain a P_n tomographic image. One of the lines, the 500-km-long Springbok profile, was described in detail by (Hirsch et al., 2009). It crossed the western margin of the Republic of South Africa at 31°S. In the offshore part, the profile started at 3600 m water depth and ran through the central part of the Orange basin in the shelf region. The 100-km-long land part crossed the coast-paralleled Gariep belt, where the topography reaches maximum elevations of 1000 m. The offshore part was a combined transect of reflection and refraction seismic data. The velocity modeling revealed a segmentation of the margin into three distinct parts of continental, transitional and oceanic crust. The oceanic crust beneath the outer 50 km is subdivided into layers 2A and 2B, beneath of which the velocity increased to 7 km/s, interpreted as gabbroic layer 3. Along the following 200 km of the line transitional crust was identified where the middle and lower crust were characterized by high P-velocities of 6.9–7.4 km/s, as seen on many rifted volcanic margins. The remaining 250 km including the 100 km land section showed continental crust with 5.9–6.1 km/s near the surface. Here, the crust was characterized by a continuous velocity increase, but no significant velocity contrasts indicated a subdivision into an upper and a lower continental crust (Hirsch et al., 2009).

A second seismic project of the GFZ Potsdam (Germany) was the 800-km-long Agulhas-Karroo transect, carried out in 2005 within the project INKABA ya Africa (Parsiegla et al., 2007; Stankiewicz et al., 2007, 2008). It was a north-south offshore-onshore transect which ran over a distance of 400 km from the offshore Agulhas Plateau across the Agulhas Fracture zone and the continental margin onto to South African coast, and for other 600 km onland across the Cape Fold Belt, the Karoo Basin and into the Kapvaal Craton. The project also included the recording of 600 km of magnetotelluric data. The onshore part was already described in subchapter 10.6.2.

The offshore part (Parsiegla et al., 2007) consisted of 20 four-component (three-component seismometer and a hydrophone component) OBSs deployed over 400 km length. Eight G-airguns and one Bolt-airgun (volume of 96 l) were fired every 60 seconds during cruise SO-182 of the R/V *Sonne*, resulting in a shot spacing of about 150 m. As the onshore wide-angle and offshore parts were carried out simultaneously, all airgun

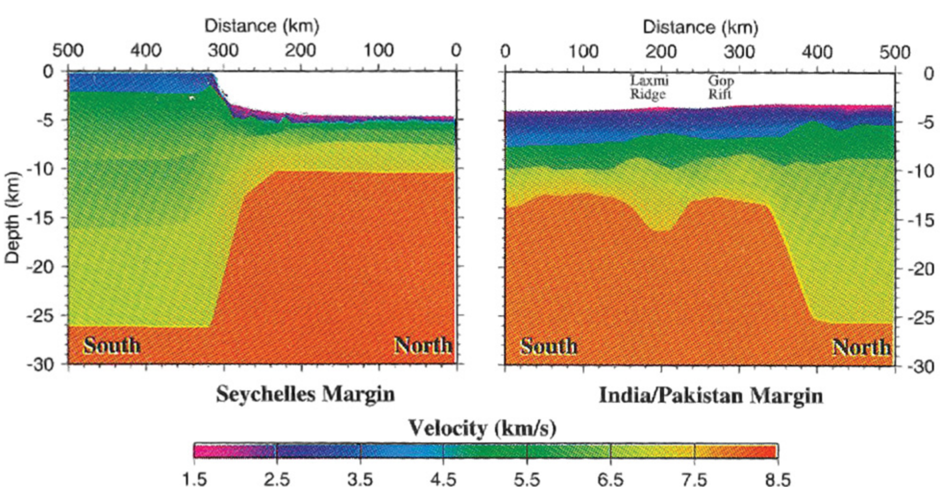

Figure 10.7.3-02. Preliminary P-wave models of the two halves of the transect indicated in Fig. 10.7.3-01 derived from wide-angle data by forward modeling and inversion (from Collier et al., 2004, fig. 3). [Eos (Transactions, American Geophysical Union), v. 85, no. 46, p. 481, 487. Reproduced by permission of American Geophysical Union.]

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shots were also recorded by the land receivers. The Moho, found at 30 km depth at the present coast, starts to shallow gradually seaward for a distance of 250 km across the continental margin to 20 km depth at the Agulhas-Falkland Fracture Zone which marks the transition zone between continental and oceanic crust. Here the Moho depth of 20 km is reduced to 12 km over a horizontal distance of 50 km and remains at 11–12 km depth, i.e., 6–7 km crust under 5 km of ocean water (Parsiegla et al., 2007; Stankiewicz et al., 2008).

A detailed investigation with numerous reflection and refraction profiles of the margin off Uruguay was carried out in 2004 (Temmler et al., 2006) by a joint venture of the BGR (Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany) and SOHMA (Servicio de Oceanografie, Hidrografia y Meteorologia da la Armada, Uruguay) with 70 OBSs along profile lengths exceeding 250 km. The interpretation of Temmler et al. (2006) resulted in a gradual decrease of Moho depth from 27 to 20 km from 50 to 140 km distance from the coast and a further decrease to 15 km, and finally a crustal thickness of 10 km beyond 170 km.

Another marine survey along the Atlantic side of South America was performed offshore French Guiana in 2003 (Greenroyd et al., 2006). The survey collected coincident multichannel seismic reflection and wide-angle seismic-refraction data along two transects across the margin. The wide-angle refraction data were derived from 39 OBS and nine land-based instruments and could be modeled along a 535 km profile across the Demerara Plateau and along a 427 km profile across the margin, 175 km to the south. Crustal velocities were generally lower than 7 km/s and both profiles showed abnormally thin oceanic crust of 3.5–5 km thickness. Furthermore two contrasting margin structures, separated by 175 km distance, were derived from the data: along the northern profile the continental crust thinned gradually over 300 km distance, while the southern profile showed a more rapid thinning over only 60 km distance (Greenroyd et al., 2006).

Also the coastal area of Venezuela, representing the Caribbean–South America plate boundary, became the target of a large active-source seismic experiment in 2004 (e.g., Levander et al., 2006; Schmitz et al., 2008). About 6000 km of marine multichannel seismic-reflection data were collected offshore Venezuela. In addition, five wide-angle seismic profiles were recorded both onshore and offshore Venezuela and the Antilles arc region, spanning an area of almost 12 degrees of longitude and 5 degrees of latitude as part of the project BOLIVAR (Broadband Ocean Land Investigation of Venezuela and the Antilles Arc Region; for more details, see subchapter 10.6.3).

The Mid-Atlantic Ridge area was visited by the *Meteor* (1986) cruise M62-4 in October 2004. The target of a seismic project was the region of the Ascension Transform system at ~7°S and the spreading segment immediately south of this transform. The Ascension Transform is actually a “double transform fault” consisting of two parallel transform fault/fracture zone systems sandwiching a very short segment. OBS/H were deployed along a WSW-ENE–trending profile (~120 km long between 11.8°W and 13.5°W) within the Ascension Fracture zone system and along several shorter profiles and clusters to the south of it at ~13.5°W (Reston et al., 2009).

Farther north, the Mid-Atlantic Ridge was studied in 2005 at the Lucky Strike Volcano at ~32°16′W, 37°17′N with a network of 39 cross lines of 19 km length and one along-strike profile (Singh et al., 2006b). The seismic-reflection data were acquired using a 4.5-km-long digital streamer with 12.5 m receiver intervals towed at 15 m depth. The cross lines were 100 m apart; the airgun shot interval was 37.5 m. The along-axis line was shot at an interval of 75 m. With a width of 6 km and a length of 15 km, the Lucky Strike Volcano is one of the largest volcanoes at the Mid-Atlantic Ridge. The existence of an axial magma chamber was inferred, the reflection from the top of the crustal magma chamber being ~3 km beneath the seafloor and 3–4 km wide and extending 7 km along-axis.

At the eastern side of the southern Atlantic, in the second half of 2004, the *Meteor* (1986) cruise M62-3 investigated the causes for a prominent bathymetric swell around the Islands of Cape Verde, a feature caused by hotspot volcanism. To study the mechanical properties of the lithosphere over the hotspot, a roughly 500-km-long, N-S–directed, deep seismic line was shot across the swell between the islands of Fogo and Santiago to image tomographically the crustal structure of the swell. Forty OBS/H stations were deployed at 1 km intervals to sample the seismic wave field from a 64-l array of airguns fired at 90 s intervals. Detailed seismic investigations in the area of the volcanically active islands of Fogo and Brava were aimed to reveal magma reservoirs and the magma plumbing system of the islands. Three profiles were obtained, one running from the island of Santiago toward Fogo, around the island and continuing roughly 100 km to the west, providing a 170-km-long profile across Fogo. Two shorter lines—between 60 and 80 km long—provided additional deep seismic data from the Fogo and Brava area. The recorded data were of high quality. On line 2, seismic energy was recorded to offsets of 120 km; shots from profile 3 were recorded on the other side of the island of Fogo. A land station on Fogo recorded many shots, and P_g, P_MP, and P_n phases could be identified in the data. While the ocean bottom instruments were on the seafloor, some stations did record signals associated with volcanic activity, including earthquakes and volcanic tremors (Grevemeyer et al., 2009).

Seismic projects of the twenty-first century in the waters surrounding the Iberian Peninsula and corresponding references were compiled by Díaz and Gallart (2009). Most of them, however, deal with sedimentary and uppermost crust only. The TASYO project aimed to investigate the tectonic structure of the Gulf of Cadiz and comprised two E-W–oriented multichannel profiles. In 2002, the VOLTAIRE project followed in the same area with more than 1000 km multichannel seismic profiles. In 2004, the TECALB project sampled the Eastern Alboran Sea. In 2006, the West-Med experiment acquired wide-angle data in the Alboran Sea and the transition to the South Balearic Basin, using a network of OBS and land stations, and the MARSIBAL cruise of 2006 added multichannel seismic data.

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In 2002, RAPIDS (Rockall and Porcupine Irish Deeps Seismic wide-angle seismic experiment) was extended by a new profile RAPIDS-4 (O'Reilly et al., 2006), following the RAPIDS 1 and 2 projects of 1988 and 1990 (see Fig. 8.9.4-05; Shannon et al., 1994, 1999; Hauser et al., 1995; O'Reilly et al., 1995, 1996; Vogt et al., 1998), and RAPIDS 3 of 1999 (see Fig. 9.8.4-16; Mackenzie et al., 2002; Morewood et al., 2003). The new profile RAPIDS-4 (Fig. 10.7.4-01) was a 230 km east-west–oriented profile across the Porcupine Arch, a deep structural feature in the Porcupine Basin. Sixty-five OBSs with 4 components (one hydrophone and 3 orthogonally directed geophones) were deployed at 3–4 km interval and seismic sources were fired every 120 m across the deployment line. The experiment gave the first well-resolved results of P-wave velocity variations in the deeper part of the Porcupine Basin (Fig. 10.7.4-02). The crystalline crust thins rapidly from almost 30 km under the Porcupine High in the west and Celtic Platform in the east to less than 2 km under the Porcupine Basin, overlain by a sedimentary basin of up to 10 km thickness and underlain by an upwarping mantle. Also the uppermost mantle velocity decreases from normal (8 km/s) to anomalously low values as low as 7.2 km/s.

Farther northwest of Ireland in the North Atlantic, in 2002 the Hatton Deep Seismic (HADES) project was designed to investigate the crust of the Hatton Basin and the Hatton continental

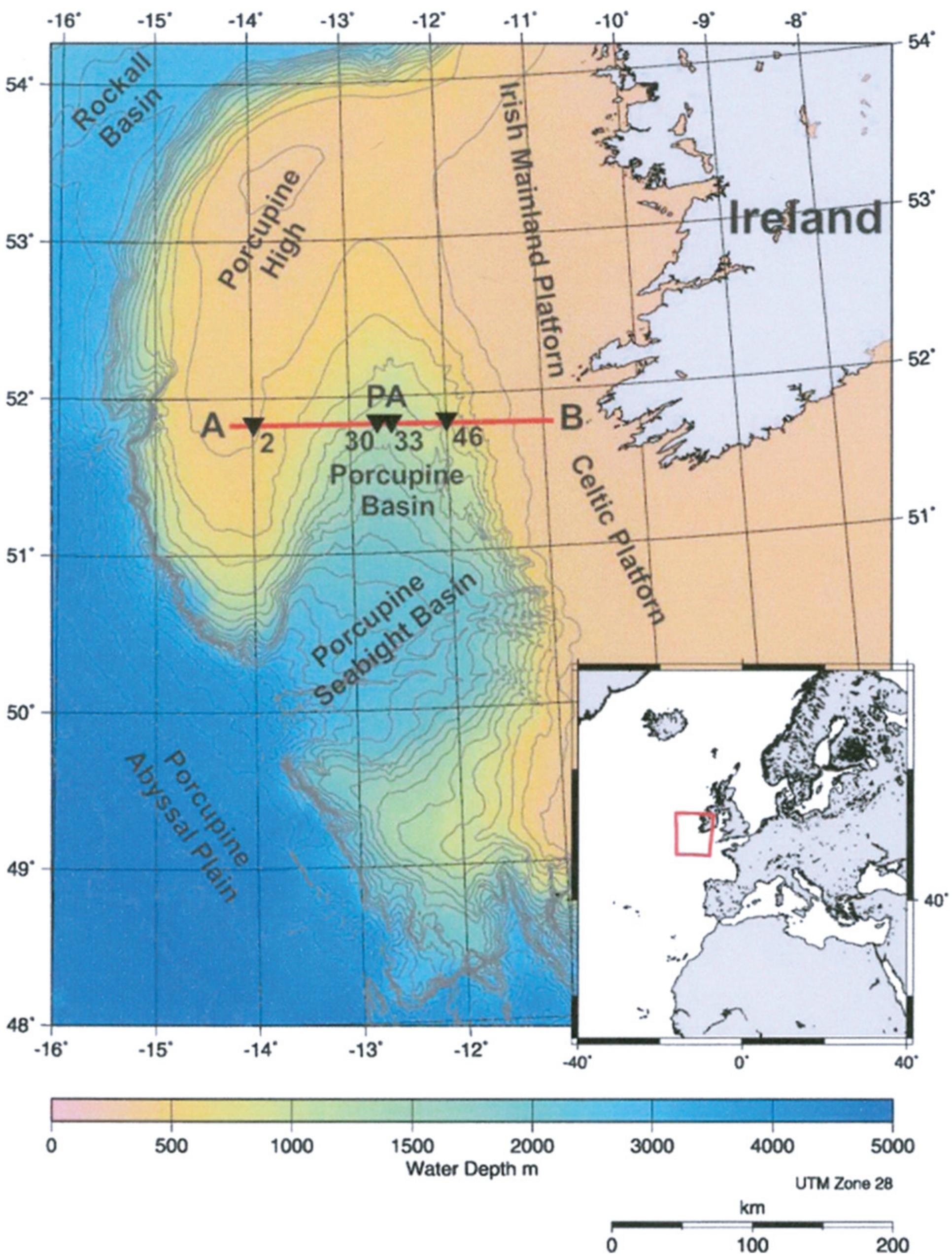

Figure 10.7.4-01. Location of the RAPIDS-4 profile in the northern part of the Porcupine Basin southwest of Ireland (from O'Reilly et al., 2006, fig. 1). [Journal of the Geological Society, v. 163, p. 775–787. Reproduced by permission of Geological Society Publishing House, London, U.K.]

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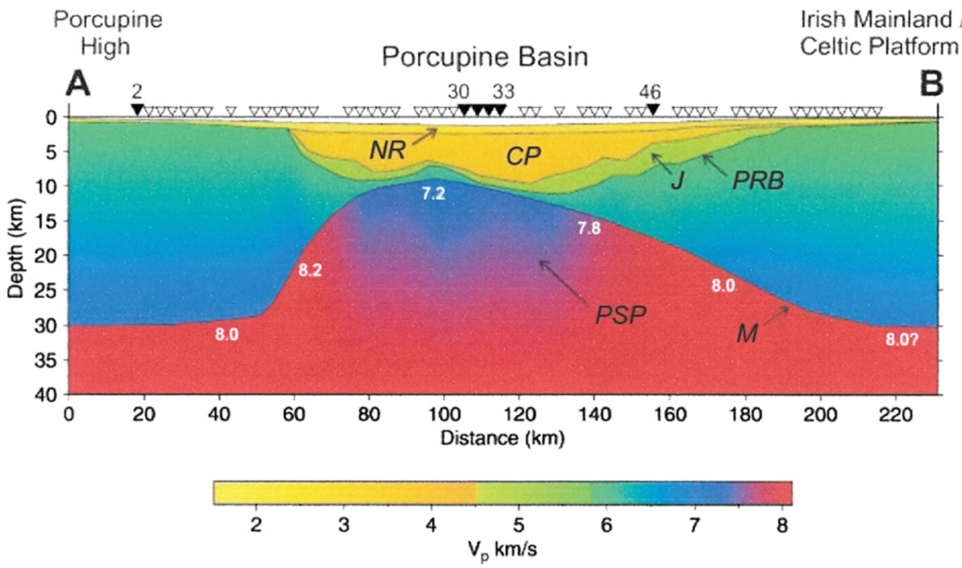

Figure 10.7.4-02. Crustal structure along the RAPIDS-4 profile in the northern part of the Porcupine Basin southwest of Ireland (from O'Reilly et al., 2006, fig. 10). NR, CP—Neogene to Recent, Cretaceous to Paleogene post-rift sequences; J—predominantly Jurassic syn-rift sediment sequence; PRB—pre-rift basement; M—Moho; PSP—partially serpentinized mantle peridotite. [Journal of the Geological Society, v. 163, p. 775–787. Reproduced by permission of Geological Society Publishing House, London, U.K.]

margin (Chabert et al., 2006, Smith et al., 2005). This is located to the northwest of the Rockall Bank at ~16–20°W, 56–58°N in the North Atlantic. The project provided an exceptionally large amount of wide-angle seismic data along the axis of the basin. Along a 363-km-long NE-SW profile, 100 OBS were deployed and airgun shots were fired at 130 m intervals.

In 2004, a joint project of GEOMAR (Kiel, Germany) and DIAS (Dublin, Ireland) re-investigated the southern Porcupine Basin to the southwest of Ireland along marine profiles along which in 1997 data had been obtained using a 6-km-long, 240 channel digital streamer and a tuned sleeve-gun array with record length up to 9 s TWT (Reston et al., 2004). This time, during the *Meteor* (1986) cruise M61-2 in 2004, 25 OBS/H stations were deployed along each line and additionally seven land stations recorded all shots (Fig. 10.7.4-03). The energy was generated by two to three 32-l airguns which fired over 2000 shots per profile. The water depth ranged from 200 m near the coast of Ireland to 1600 m in the center of the basin. It shallowed to ~400 m under the Porcupine Ridge. The seven land stations recorded all shots during the month-long duration of the marine experiment. On the better-quality record sections from the onshore stations clear primary and secondary phases could be seen out to 180 km offsets. The data quality apparently depended primarily on the number of airguns used for shooting (Hauser et al., 2007b; Reston et al., 2006).

Two major goals were set. First, both sides of a rift basin occurring in close proximity to each other could be studied here, allowing questions about the symmetry of extension to be addressed by several east-west profiles parallel to the direction of extension. Second, the amount of extension increases from north to south, so a series of east-west cross sections on different latitudes provided information on crustal structure during variable extension. The spatial changes between these sections also represent the temporal development of the rift through continued extension. The data quality was excellent in general; clear arrivals were apparent to offsets of over 70 km on most instruments, giving a complete coverage of the crust beneath the basin. In places, clear refraction-reflection-refraction triplications were observed for several interfaces (Reston et al., 2006).

Within the framework of the EUROMARGINS project, the investigations in the North Atlantic around Greenland of 1990 and 1994 (Schmidt-Aursch and Jokat, 2005; Fig. 9.8.4-30) were extended in 2003 east of Greenland toward the Greenland Basin (Voss et al., 2006), exploring the continent-ocean transition between the Jan Mayen and Greenland Senja fracture zones off East Greenland (Fig. 10.7.4-04). The investigations were carried out by the Alfred Wegener Institute for Polar and Marine Research during an expedition with the research vessel R/V *Polarstern*. The main aim of the project was to investigate the crustal architecture and the evolution of the conjugate volcanic margins off mid-Norway and East Greenland in the context of rifting.

Deep seismic-refraction data were acquired on four 300–450-km-long profiles (Fig. 10.7.4-04). On each profile, a total of 25 OBSs were deployed. On the northernmost profile, a typical oceanic crust, 6 km thick, was found further offshore. The other three profiles were extended onshore by six land stations each. The present interpretation revealed a division along these profiles into three parts: continental crust with a thickness of 29–32 km was found at the western ends of the profiles, followed by a diffuse continent-ocean transition zone, the width of which increased from 70 km in the north to 190 km in the south, and an oceanic crust whose thickness decreased from 16 km near the continent-ocean transition zone to 5–6 km at the eastern ends.

The complete data set provided new insights into the formation of the entire segment of the continental margin between the Jan Mayen and the Greenland fracture zones. The deeper structure of the East Greenland margin was of special interest, because it is conjugate to the Vøring Plateau off Norway (Voss et al., 2006).

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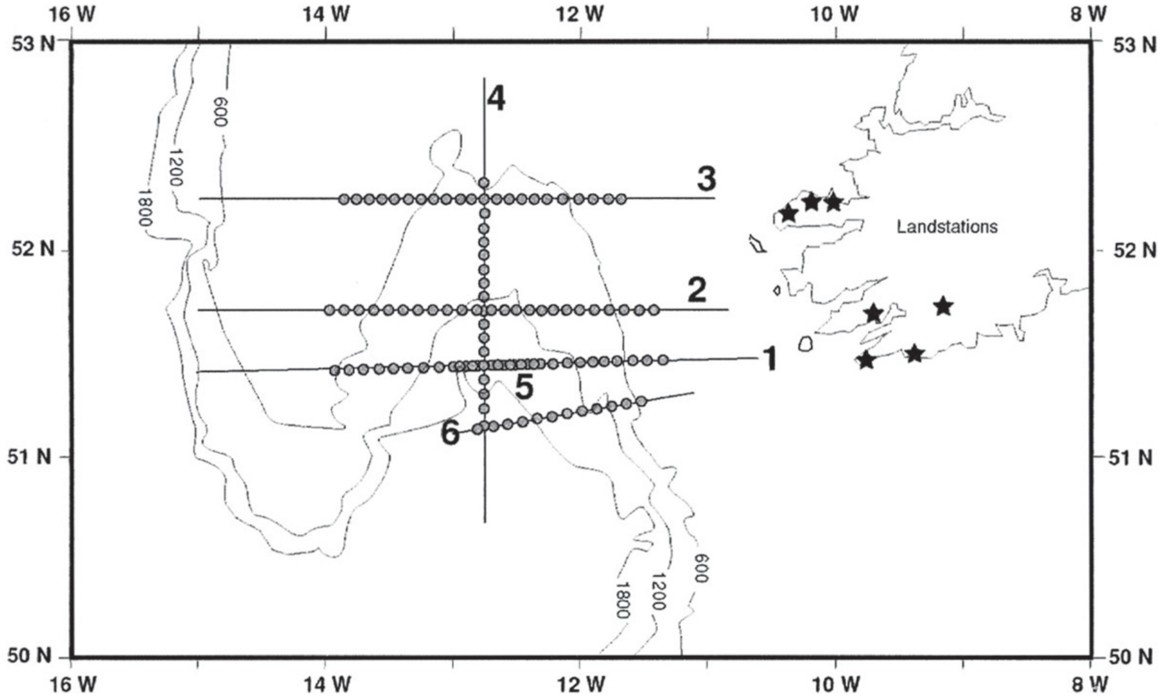

Figure 10.7.4-03. Map of a seismic survey in 2004 in the Porcupine Basin of the Atlantic Ocean southwest of Ireland. (from Hauser et al., 2007b). Straight lines and circles—shot profiles and ocean bottom seismometer/hydrophone stations of GEOMAR; stars—land stations operated by DIAS; thin lines—bathymetric contours (600 m interval). [50th Annual Irish Geological Research Meeting, School of Environmental Sciences, University of Ulster, Coleraine, Northern Ireland, 23–25 February (abstract). Reproduced by kind permission of the authors.]

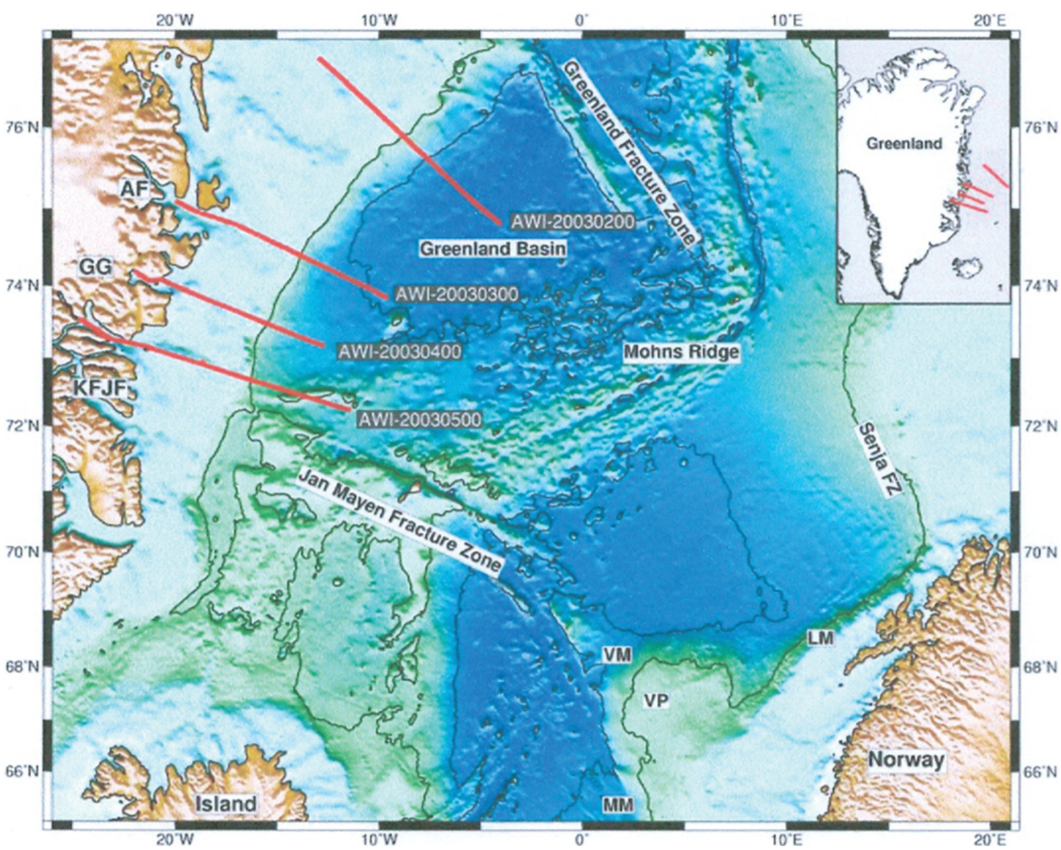

Figure 10.7.4-04. Overview of the East Greenland and Norwegian conjugate margins. Red lines represent the locations of the AWI seismic refraction profiles (from Voss et al., 2007, fig. 1). VM—Vøring margin; VP—Vøring Plateau; MM—Møre margin; LM—Lofoten Margin; GG—Godthåb Gulf; KFJF—Kejser Franz Joseph Fjord; AF—Ardencaple Fjord. Background is bathymetry grid with 1500 m and 3000 m contour lines. [European Seismological Commission (ESC), Subcommission D—Crust and Upper Mantle Structure, Activity Report 2004–2006. Reproduced by kind permission of the authors.]

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Geophysical surveys at the Norwegian Vøring and Lofoten margins (Mjelde et al., 1992, 1998, 2001; Raum et al., 2002) were described earlier in Chapter 9.8.4, revealing important vertical and lateral variations in crustal structure and composition.

The results of seismic experiments on velocities and associated crustal thickness along the entire East Greenland margin were compiled by Voss et al. (2009) in two new wide-angle seismic transects. In addition, maps were compiled for the East Greenland margin covering a distance range of ~500 km distance from the southeastern and central coast of East Greenland reaching as far as Iceland. The maps show the depth to the crystalline basement, the depth to Moho, the thickness of the crystalline crust and the thickness of a high-velocity layer with velocities above 7 km/s.

10.7.5. Summary of Seismic Observations in the Oceans from 1950 to 2005

In Figure 10.7.5-01, the approximate locations of marine experiments from 2000 until 2005 or even more recently were plotted as far as results were published until 2010. For a number of projects, however, publications may not yet be available. Other projects may have been published in conjunction with land seismic projects and do not appear as marine projects in the database. As was mentioned for previous decades, another reason for the fact that some of the projects which were discussed in the individual "Oceans" subchapters are not seen on this map may also be due to the database containing only projects which were published in easily accessible journals or books.

Evident on the map for the 2000s is a concentration of projects on the line Norway–Faeroe Islands–Iceland. Deep-ocean trenches and adjacent continental margins (Indonesia and South America) have also attracted increased activities.

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

Figure 10.7.5-02 contains a summary of projects carried out since 1950. The map shows all locations for which data, recognized as marine projects, are available in the database at the U.S. Geological Survey in Menlo Park, California. Some of the projects which were discussed in the individual "Oceans" subchapters for the Oceans do not show up in Figure 10.7.5-02 or on the maps shown for each decade at the end of the corresponding chapter. The reasons for these discrepancies are the same as those discussed above for Figure 10.7.5-01.

10.8. THE STATE OF THE ART AROUND 2006 AND OUTLOOK

We have terminated our historical review of controlled-source seismic experiments with projects planned and carried out until the end of 2005. The large number of recording devices available nowadays as well as the ability to record continuously over long time periods has allowed researchers to extend seismic surveys into three dimensions. This also has enabled researchers to avoid problems which may arise if using man-made sources such as quarry blasts, borehole or underwater explosions, but rather, at least for projects on land, to plan for seismic tomography surveys with teleseismic and/or local events as energy sources. Nevertheless, the interest in studying details of crustal and upper-mantle structure has remained until present, and many new projects were performed just recently or are in the planning stage, because many details of crustal structure can only be achieved by controlled-source seismic near-vertical incidence

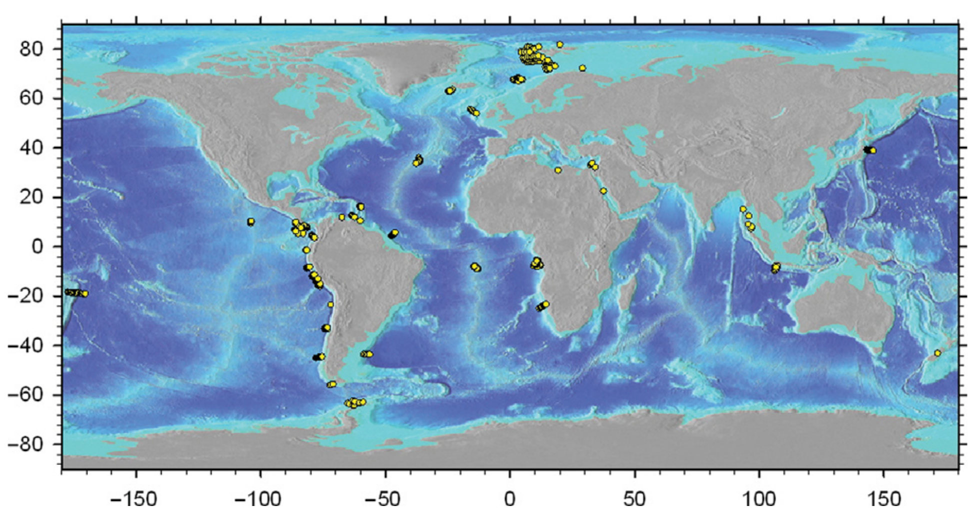

Figure 10.7.5-01. Seismic refraction measurements in the Atlantic, Pacific, and Indian Oceans performed between 2000 and 2008 (data points from papers published until 2010 in easily accessible journals and books).

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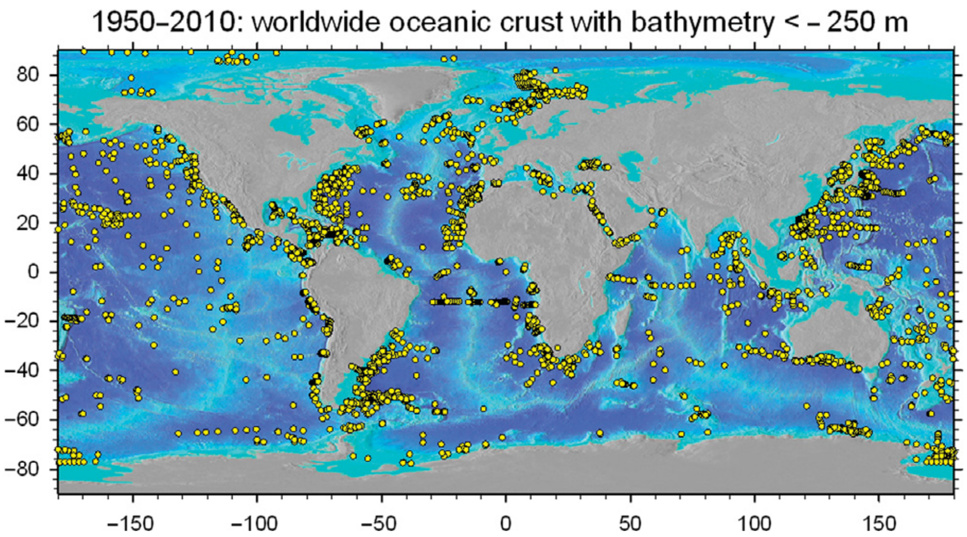

Figure 10.7.5-02. Seismic refraction measurements in the Atlantic, Pacific and Indian Oceans performed between 1950 and 2008 (data points from papers published until 2010 in easily accessible journals and books).

reflections seismics and/or seismic-refraction/wide-angle reflection experiments with densely spaced controlled sources and a multitude of seismic recorders.

In 2009, controlled-source seismology could have celebrated its 160th birthday, since Robert Mallet in 1849 for the first time used dynamite explosions to measure the speed of elastic waves in surface rocks (Mintrop, 1947; Dewey and Byerly, 1969). In 1947 Mintrop wrote the first history on the first 100 years of explosion seismology (Mintrop, 1947; Appendix 3-1 and 3-2). Since then an enormous amount of explosion-seismic data around the world has been compiled, and data and results were published in thousands of papers distributed in numerous journals and books, making a complete collection of explosion-seismic projects and their data and interpretations almost impossible.

Though not the scope of this publication, dealing mainly with academic non-profit research activities, it is of interest to note, that two companies, GSI in the United States and SEISMOS in Germany, which were founded in 1925 and mentioned in some detail in Chapter 3.3, both celebrated their 80th anniversary in 2005. As of 2005, after several mergers and acquisitions, the heritages of GSI and Western Geophysical still existed, along with several pioneering European companies such as GECO, SEISMOS, and PRAKLA, as part of the seismic contracting company WesternGeco. Many other companies using reflection seismology in hydrocarbon exploration, hydrology, engineering studies, and other applications have been formed since the method was first invented. Major service companies today include Compagnie Générale de Géophysique, Veritas DGC, and Petroleum GeoServices. Most major oil companies also have actively conducted research into seismic methods as well as collected and processed seismic data using their own personnel and technology. For more details of the worldwide history of exploration geophysics, the reader is referred to Lawyer et al. (2001), who have compiled a personalized history on the commercial application of controlled-source seismology starting at the time of World War I.

Reflection seismology has also found widespread applications in non-commercial research by academic and government scientists around the world. Many of those projects were described in the foregoing individual chapters, according to the decade when they were accomplished.

Textbooks on seismic theory, published in large numbers over the decades, have accompanied and guided the development of interpretation methods to deal with the proper interpretation of active source seismic data obtained on land and at sea (e.g., Nettleton, 1940; Bullen, 1947; Worzel and Ewing, 1948; Grant and West, 1965; Musgrave, 1967; Maxwell, 1970; Kosminskaya, 1971; Officer, 1974; Červený et al., 1977; Kennett, 1983; Bullen and Bolt, 1985; Yılmaz, 1987; Lay and Wallace, 1995; Aki and Richards, 1980, 2002; Jones, 1999; Kennett, 2001; Chapman, 2004; Borcherdt, 2009). There are in addition numerous articles that address various aspects concerning the theory for interpretations of controlled-source seismology data (e.g., Willmore and Bancroft, 1960; Steinhart et al., 1961c; Ewing, 1963a; Ludwig et al., 1970; Fuchs and Müller, 1971; Bessonova et al., 1974; Braile and Smith, 1975; Giese, 1976b; McMechan and Mooney, 1980; Červený and Horn, 1980; Spence et al., 1984; Červený, 1979, 1985; Zelt and Smith, 1992; Hole, 1992; Hole and Zelt, 1995; Zelt, 1999). Similarly, compilations of interpretation methods commonly used were also summarized from time to time (e.g., James and Steinhart, 1966; Mooney, 1989; Braile et al., 1995; Mechie, 2000). Levander et al. (2007) provided a convenient review of theory and application of controlled-source seismic data.

The idea to compile all data available worldwide was already born, shortly after Mintrop's first review, in the early 1950s when, e.g., Macelwane (1951) and Reinhardt (1954) compiled all hitherto published explosion seismic data in tables, and when Closs and Behnke (1961, 1963) constructed worldwide crustal cross sections, based on the knowledge obtained until the end of the 1950s. A tabular collection of then known facts of physics in general was published by the Springer Publishing Company

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(Heidelberg–New York–Tokyo) in the early 1950s in the series of handbooks ("Landolt-Börnstein"): Numbers and Functions from Natural Sciences and Techniques, of which Volume III (Bartels and ten Bruggencate, 1953) was dedicated to astronomy (P. ten Bruggencate, editor) and geophysics (J. Bartels, editor) and appeared in 1952.

Reviews on seismic data and results were repeatedly published, mainly on regional scales, as summarized in Tables 2.1 and 2.2 of Chapter 2 including Moho and other contour maps (e.g., Steinhart and Meyer, 1961; Morelli et al., 1967; Kosminskaya, 1969; Healy and Warren, 1969; Belyaevsky et al., 1973; Warren and Healy, 1973; Woollard, 1975; Giese et al., 1976a; Meissner et al., 1987b; Braile et al., 1989; Freeman and Mueller, 1992; Pavlenkova, 1996; Li and Mooney, 1998; Collins et al., 2003; Grad et al., 2009). Finlayson (2010) compiled the complete history of deep seismic profiling from 1946 to 2006 across the Australian continent and its margins.

In the early 1980s, the Springer Publishing Company (Heidelberg–New York–Tokyo) edited a new series of the handbooks ("Landolt-Börnstein") presenting a worldwide overview on Natural Sciences and Techniques, available around the end of the seventies in numerical form and functions. Group V was dedicated to Geophysics and Space Research, with subvolume V/2 in particular to Geophysics of the Solid Earth, the Moon and the Planets. In this volume V/2, a worldwide compilation of explosion seismic data on crust and uppermost mantle structure was published in tabular form as representative velocity-depth functions for the crust together with the corresponding location maps for Europe, North America, and the rest of the world (Prodehl, 1984).

At about the same time the earliest 3-D seismic velocity model of the Earth's crust was published by Soller et al. (1981), who assembled one of the first compilations of global Moho depths and upper mantle velocity. An up-to-date summary of our knowledge on seismic structure of the continental lithosphere, based on controlled-source seismic data, and a summary of the seismic structure of the oceanic crust and passive continental margins were compiled by Mooney et al. (2002) and Minshull (2002), respectively, in the framework of an *International Handbook of Earthquake and Engineering Seismology*, edited by Lee et al. (2002).

More than a decade after Prodehl's and Soller's global compilations, a $2° \times 2°$ cell model called 3SMAC was constructed (Nataf and Ricard, 1996). It was derived using both seismological data and non-seismological constraints such as chemical composition, heat flow, and hotspot distribution, from which estimates of seismic velocities and the density in each layer were made. Two years later, CRUST 5.1 was introduced (Mooney et al., 1998) incorporating twice the amount of active source seismic data than 3SMAC. At this time, regional compilations of depth-to-Moho values for the Middle East and North Africa were also published (Seber et al., 2001). The $5° \times 5°$ resolution of CRUST 5.1, however, was still too coarse for regional studies. In 2000, CRUST 2.0 updated the ice and sediment thickness information of CRUST 5.1 at $1° \times 1°$ resolution, while basically redistributing the crustal thickness data onto a $2° \times 2°$ grid.

Without the addition of a significant amount of new data, however, this redistribution did little to clarify the crustal structure at higher resolution. Therefore, under the leadership of Walter D. Mooney and Shane Detweiler, since the 1990s a database, the Global Seismic profiles Catalog (GSC), is being assembled at the Office for Earthquake Studies, U.S. Geological Survey, in Menlo Park, California.

As was discussed at the end of Chapter 9, this continuously growing database, having assembled more than 50 years of data on seismic crustal and uppermost-mantle structure studies, had already throughout the 1990s enabled the construction of various worldwide syntheses of crustal parameters or the compilation of syntheses on selected continental and oceanic areas (e.g., Christensen and Mooney, 1995; Mooney et al., 1998; Mooney, 2002, 2007; Chulick and Mooney, 2002).

The GSC is a computer database and master catalog of 1-D global crustal and mantle structures profiles constructed from the vast amount of velocity and layer thickness data derived from various types of seismic surveys. This includes data from refraction and reflection seismology, receiver functions, tomographic inversion, and earthquake modeling. Thus, it contains material derived from all types of seismic survey techniques used to determine seismic wave velocities and the depth and thickness of layers within the Earth's crust.

An extensive literature search has been undertaken to track down as many of the seismic survey publications as possible. A large number of these publications have been carefully scrutinized, and the appropriate data for the GSC have been extracted and put into a standardized format for inclusion in the database. At present, the database contains over 10,000 one-dimensional P- and S-wave profiles, making it the largest such catalog in existence. The database is continually being updated and enlarged—there currently exist enough data to create several thousand additional profiles, with enough publications each year to create hundreds more.

The database is in ASCII text format, and is designed for easy manipulation using spreadsheet applications (e.g., Microsoft Excel), or by application of advanced programming languages, especially on either personal computers or workstations. It is easily expandable, correctable and modifiable using standard word processors or by specially designed FORTRAN or other language code. New types of data can be and have been added to the GSC (e.g., tectonic age, velocity gradient, seismic coda, gravimetric and electrical resistivity data), which increases the sophistication of the database. In addition, portions of the GSC have been available via the Internet (http://earthquake.usgs.gov/research/structure/crust/NAm_data.txt)

A database like the GSC has a wide variety of potential use in a wide range of geophysical and seismological applications. It has been used to construct several 3-D global and regional seismic structure models of the Earth's crust, including the above mentioned $5° \times 5°$ average global block model (CRUST 5.1,

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Mooney et al., 1998), and structural models for North America (Chulick and Mooney, 2002) and South America (G. Chulick, 2010, written commun.).

Second, these models, in turn, can serve as input for mathematically modeling other properties of the crust and the Earth as a whole, including crustal density variations, regional gravity anomalies, and seismic wave traveltime (Chulick, 1997). For example, by applying an appropriate seismic velocity-density relationship (Christensen and Mooney, 1995), one can create a regional 3-D density model for the crust.

The full data set available up until the end of 2008 and collected in the Global Seismic profiles Catalog (GSC) has served as a basis for the construction of the following contour maps.

Figures 10.8-01 to 10.8-03 present the data points which served as basis to draw the Moho contour maps shown in the following figures (Figs. 10.8-04 to 10.8-13). For a better view, the map is shown in different scales, for the whole world (Fig. 10.8-01), as well as enlarged for both the western and the eastern hemisphere (Figs. 10.8-02A and 10.8-03B).

Furthermore, the map was converted into polar views to show the available data points around the South Pole (Antarctica) (Fig. 10.8-02B) and around the North Pole (Fig. 10.8-03A). The location maps of available data points clearly show where gaps in data still exist in spite of 60 years of concerted efforts of scientists around the world to unravel the structure of the Earth's crust. The majority of data gaps are naturally located in the hostile Arctic and Antarctic regions. But also around the equator, particularly in Africa and South America large areas exist where no seismic measurements have taken place. In part it may be due to hostile environments prohibiting extensive seismic research, but also political circumstances in many cases are contra productive for pure scientific work.

Figures 10.8-04 and 10.8-05 present crustal thickness maps of the world, Figure 10.8-04 showing the topography with data points and Moho depth contour lines overlain, Figure 10.8-05 showing the basement age (sediments removed) with contour lines of Moho depths overlain.

The average crustal thickness under continents is around 40 km. Exceptions are western, central, and southern Europe as well as the Basin and Range province of western North America, where the average crustal thickness is around 30 km. Areas with particular thick crust (up to 70 km) coincide with the topographic highest mountain ranges—the Himalayas in central Asia and the Andes in South America. The central parts of the Atlantic, Pacific, and Indian Oceans are enclosed by the 10-km depth contour, indicating average crustal thickness being less than 10 km.

More details of the crustal structure underneath the continents can be viewed in the individual maps for the different continents. We have ordered them in the same sequence, as the individual continents were discussed for each decade in the previous chapters.

The map for Europe (Fig. 10.8-06) shows crustal thicknesses of 40–45 km under the East European platform including the

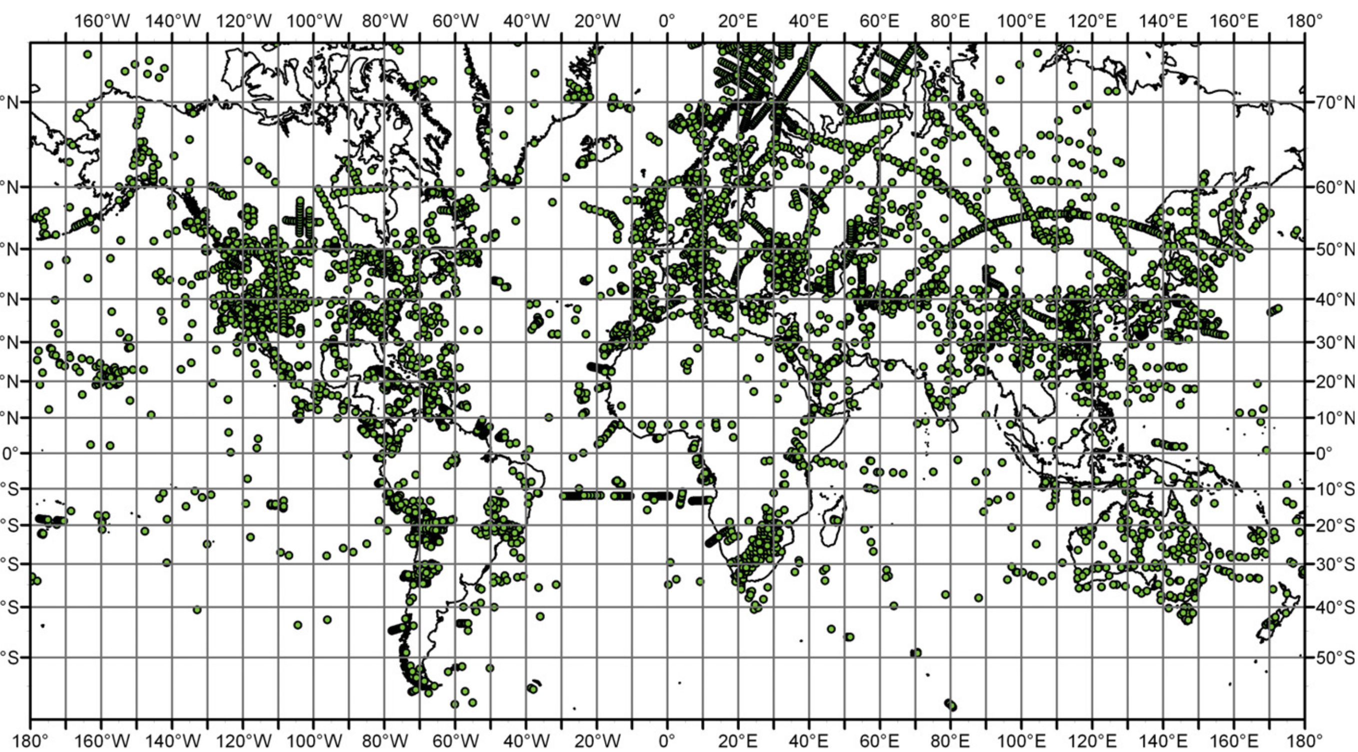

Figure 10.8-01. World map showing locations from which data for the global seismic studies were obtained.

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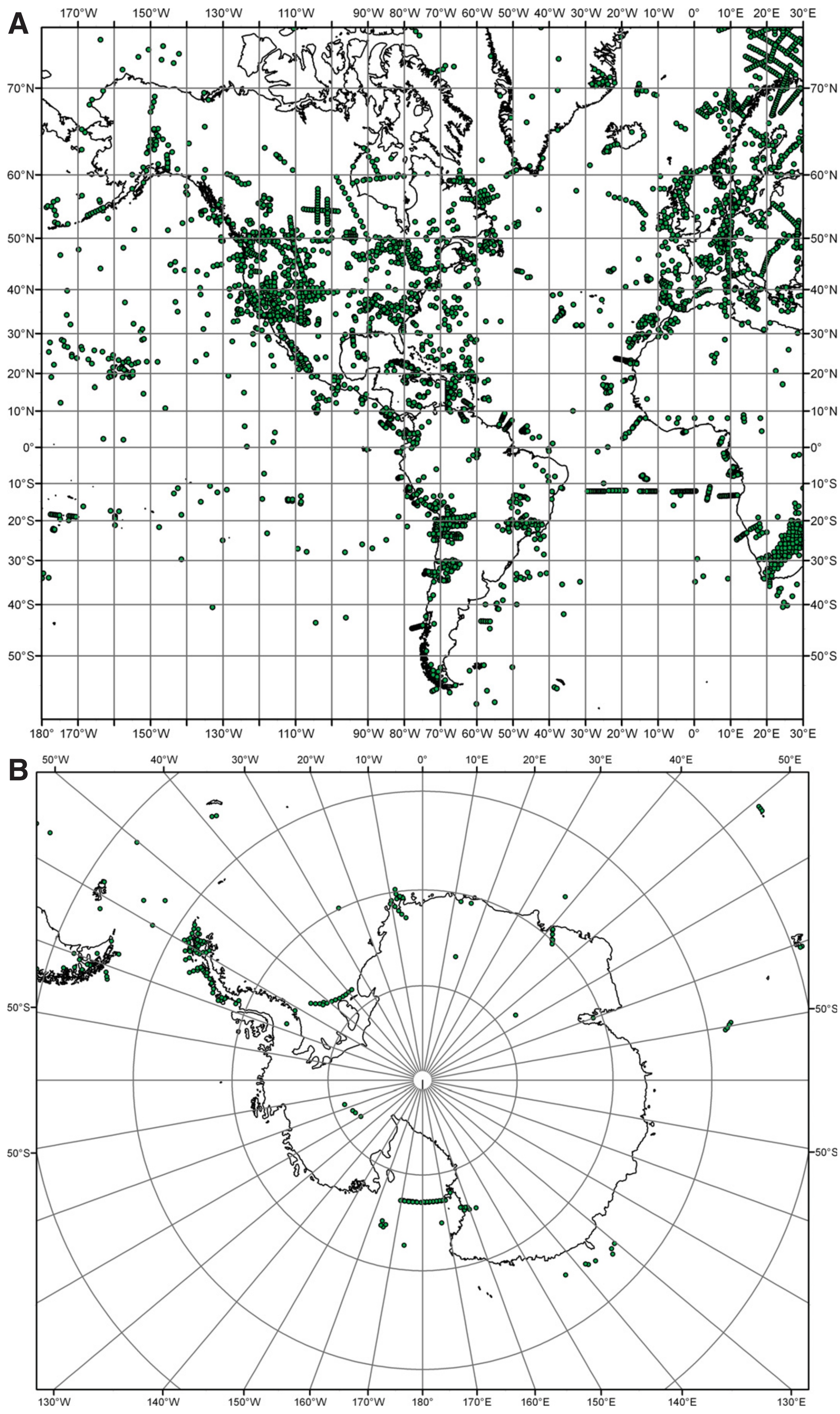

Figure 10.8-02. (A) Western hemisphere showing locations from which data for the global seismic studies were obtained. (B) Map of the South Pole region showing locations from which data for the global seismic studies were obtained.

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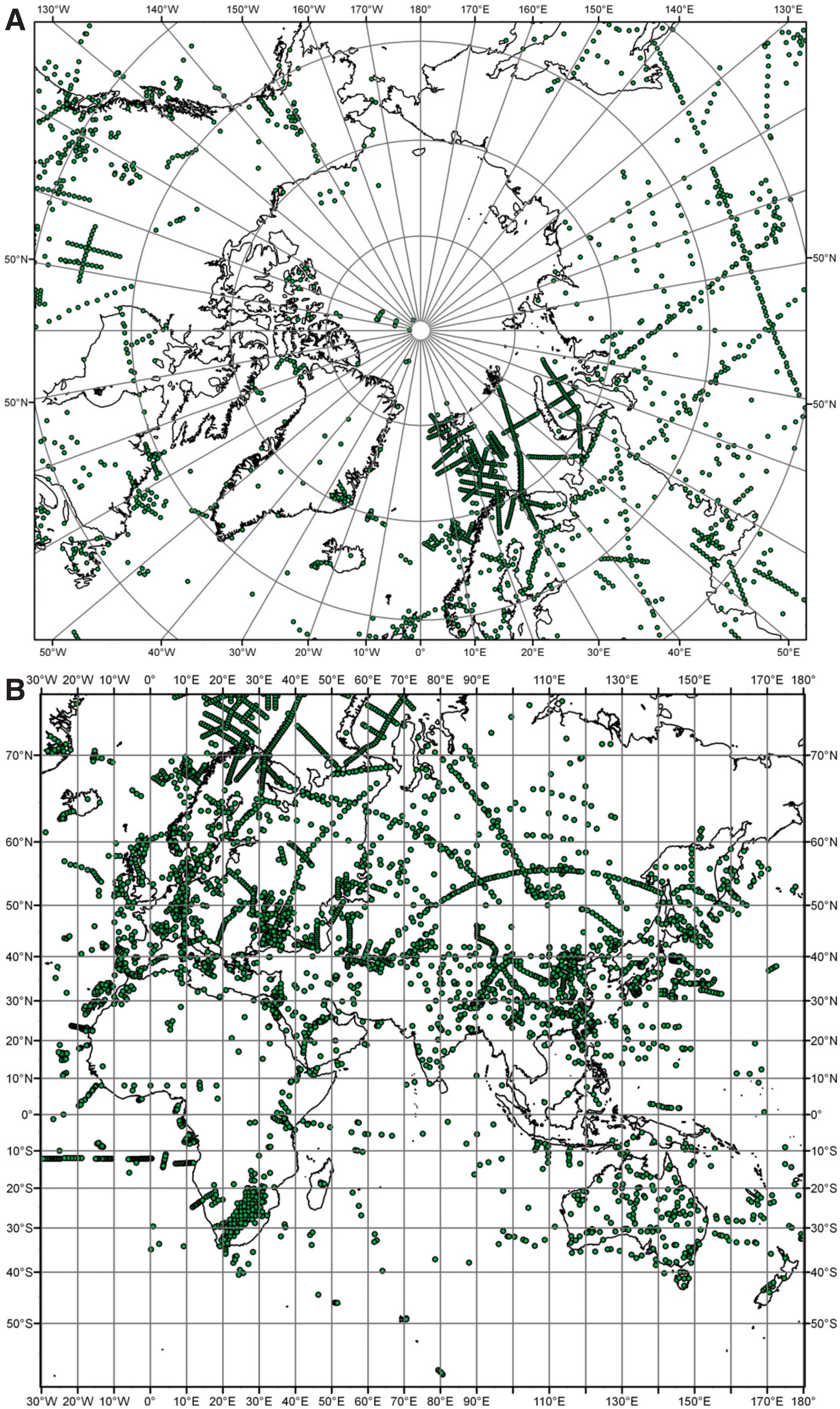

Figure 10.8-03. (A) Map of the North Pole region showing locations from which data for the global seismic studies were obtained. (B) Map of the eastern hemisphere showing locations from which data for the global seismic studies were obtained.

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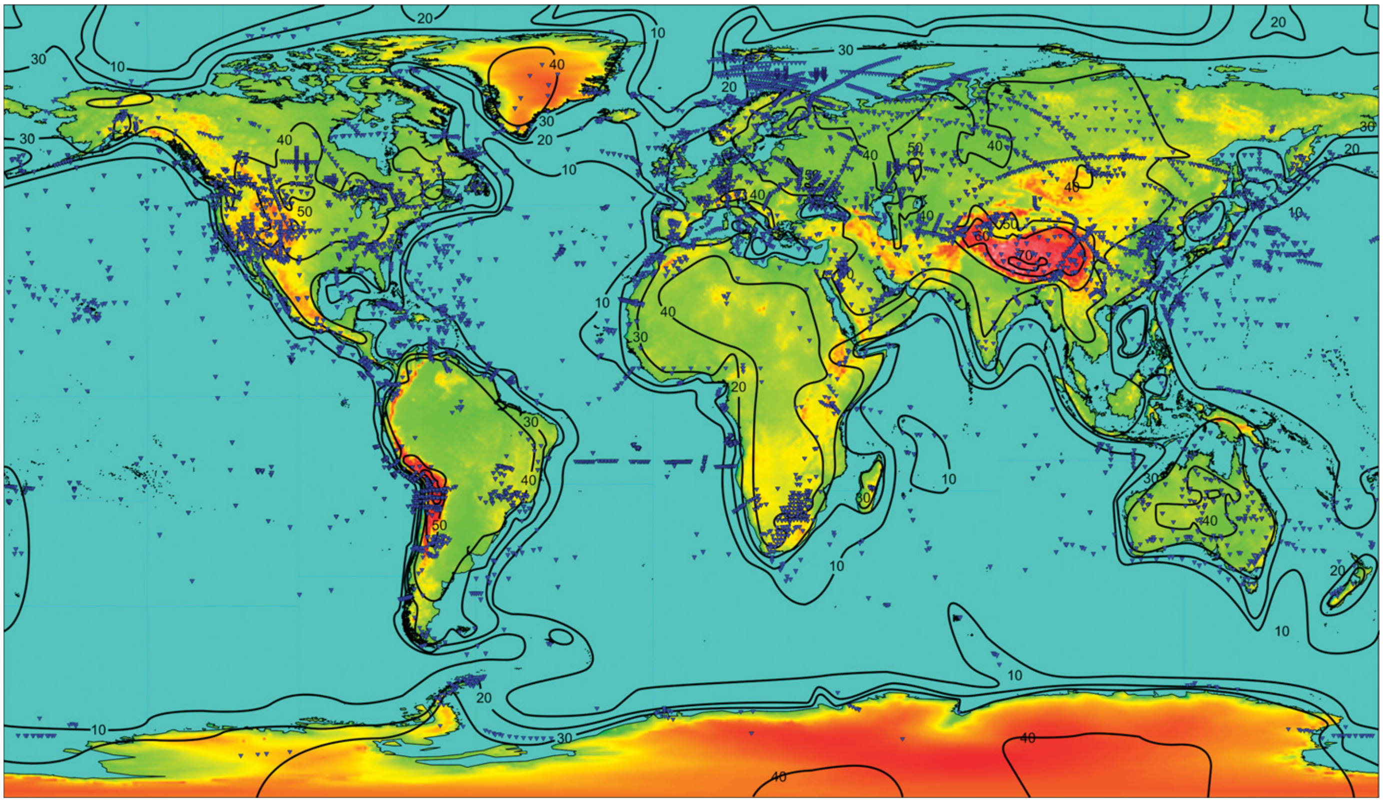

Figure 10.8-04. Topographic map showing data points and crustal thickness around the world as derived from global seismic studies, based on the Global Seismic Profiles Catalog.

Urals, under the Fennoscandian Shield, and—barely visible—under the Alps. For western, central, and southern Europe, 30 km thickness is the average. The increase in crustal thickness in the southeastern corner of the map indicates already the crustal thickening toward the Himalayas, shown in Figure 10.8-07, where up to 70 km Moho depth have been measured. The whole of northern Asia is characterized by 40–45 km average thickness. Under Japan and adjacent island arcs to the north and the south, crustal thickness is around 30 km

Crustal thickness under most of North America (Fig. 10.8-08) is 40–45 km, except for the relatively narrow Atlantic coastal plain and a wider area along the west coast including the Basin and Range province—not clearly seen on this map—and Alaska.

The Australian continent (Fig. 10.8-09) has a thick crust of 40–45 km in its center, but most of the continent has a slightly thinner crust with Moho depths between 30 and 40 km. The offshore areas to the northwest and north as well as to the southeast toward New Zealand apparently are underlain by a shallow continental crust near 20 km thickness in average. Also the southern shelf area is rather wide.

Both for Africa (Fig. 10.8-10) and for South America (Fig. 10.8-11), there is little known on crustal structure of the interior of both continents In Africa, the Afro-Arabian rift region, South Africa with Namibia, and Morocco were partly covered by seismic-refraction campaigns; in South America, most seismic surveys dealt with the Andean region. The continental shelves of both continents are evidently quite narrow. It is evident that the scale chosen for the Moho maps is too rough to recognize details such as narrow graben features with elevated crust-mantle boundary. Narrow mountain ranges with root structures or oceanic features like mid-ocean ridges do not appear as outstanding anomalies on these maps.

Finally, crustal thickness maps were compiled for the South Pole region (Fig. 10.8-12) and for the North Pole region (Fig. 10.8-13). While it is not surprising that the crust under Antarctica is around 40 km thick, the Arctic Ocean is in wide areas underlain by an oceanic crust of less than 10 km thickness.

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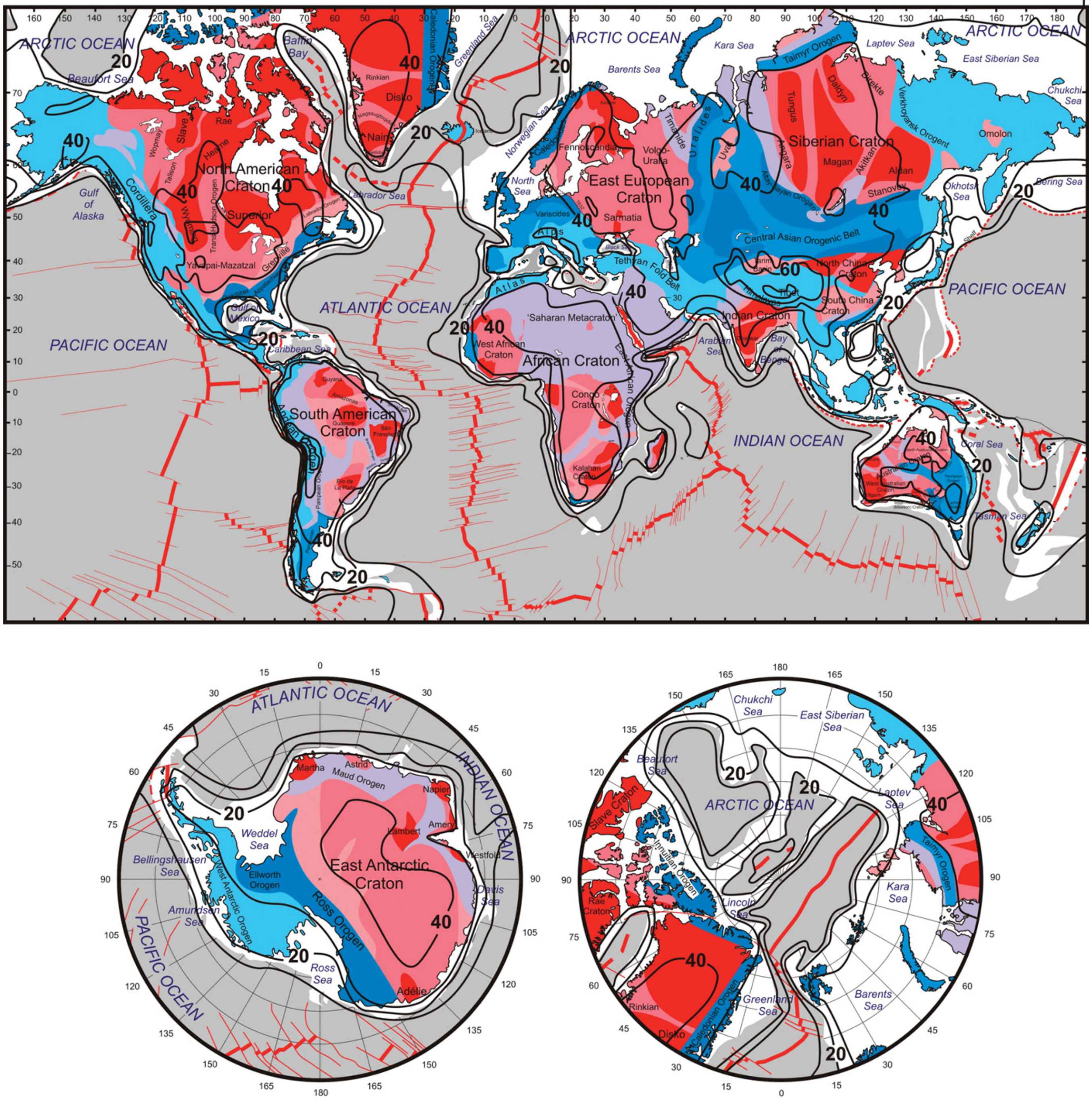

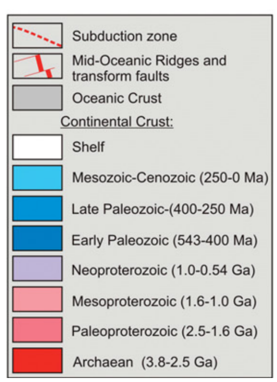

Figure 10.8-05. Basement age map showing crustal thickness around the world as derived from global seismic studies, based on the Global Seismic Profiles Catalog.

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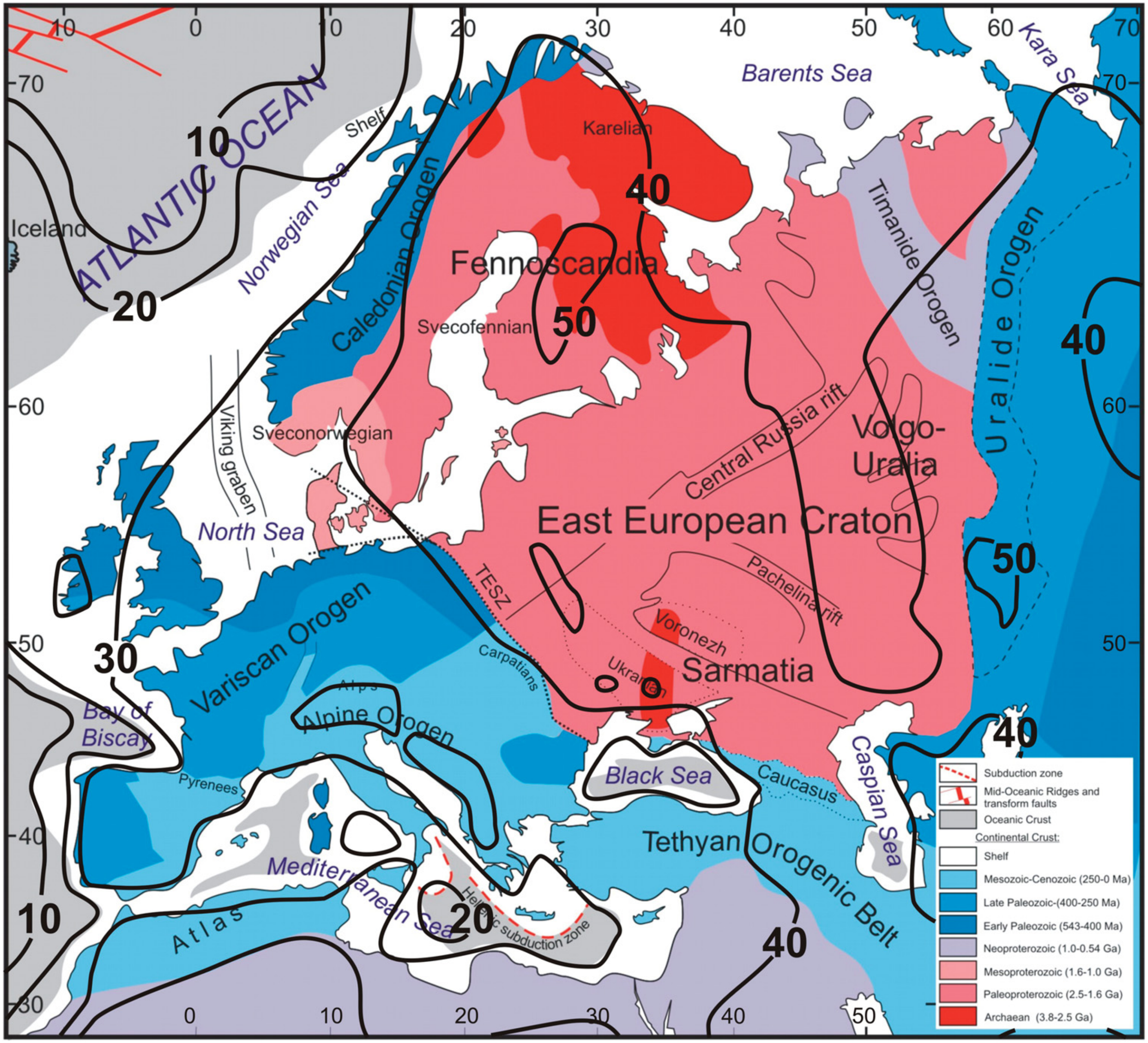

Figure 10.8-06. Basement age map of Europe showing Moho depth contour lines as derived from global seismic studies, based on the Global Seismic Profiles Catalog.

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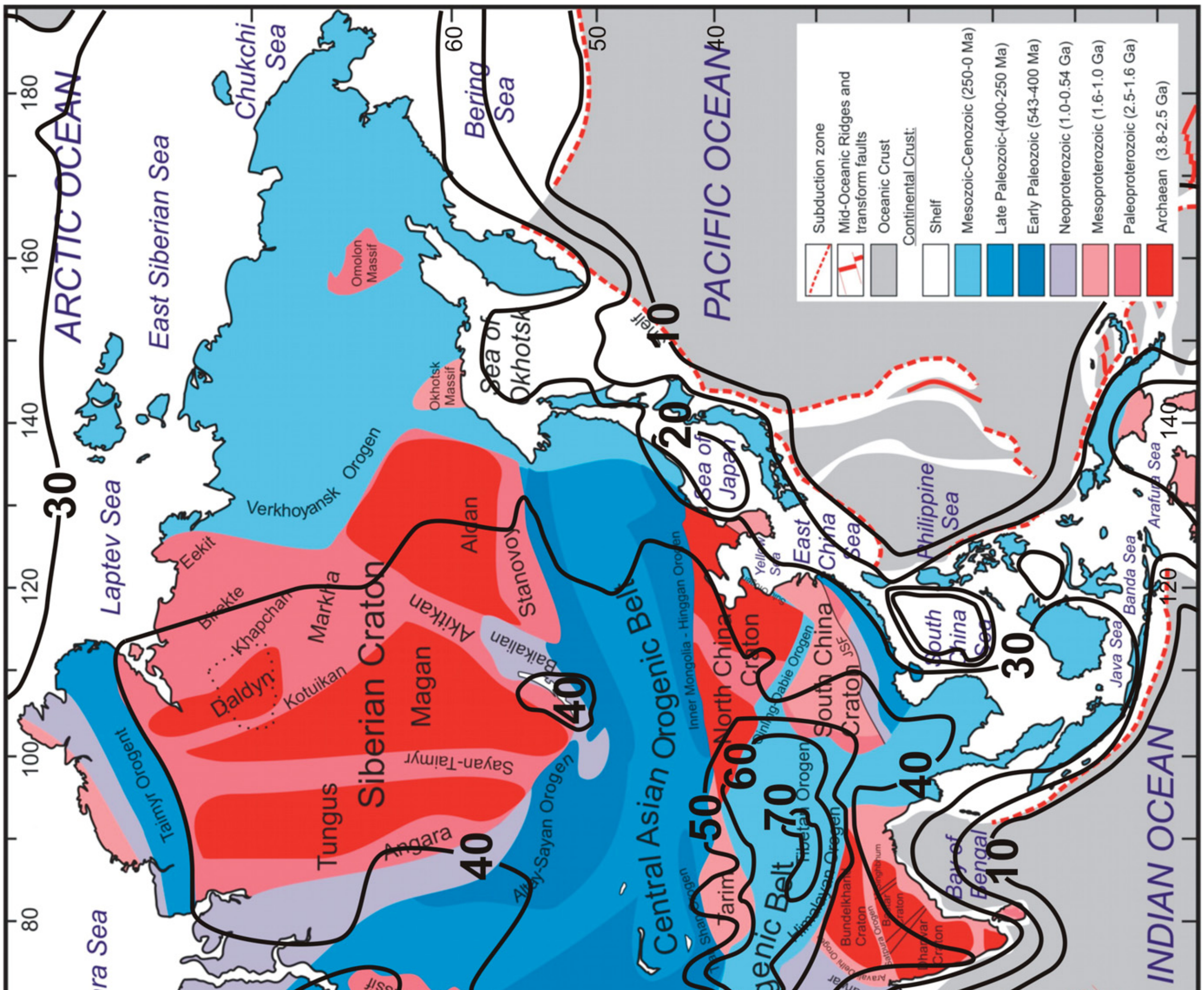

Figure 10.8-07. Basement age map of Asia showing Moho depth contour lines as derived from global seismic studies, based on the Global Seismic Profiles Catalog.

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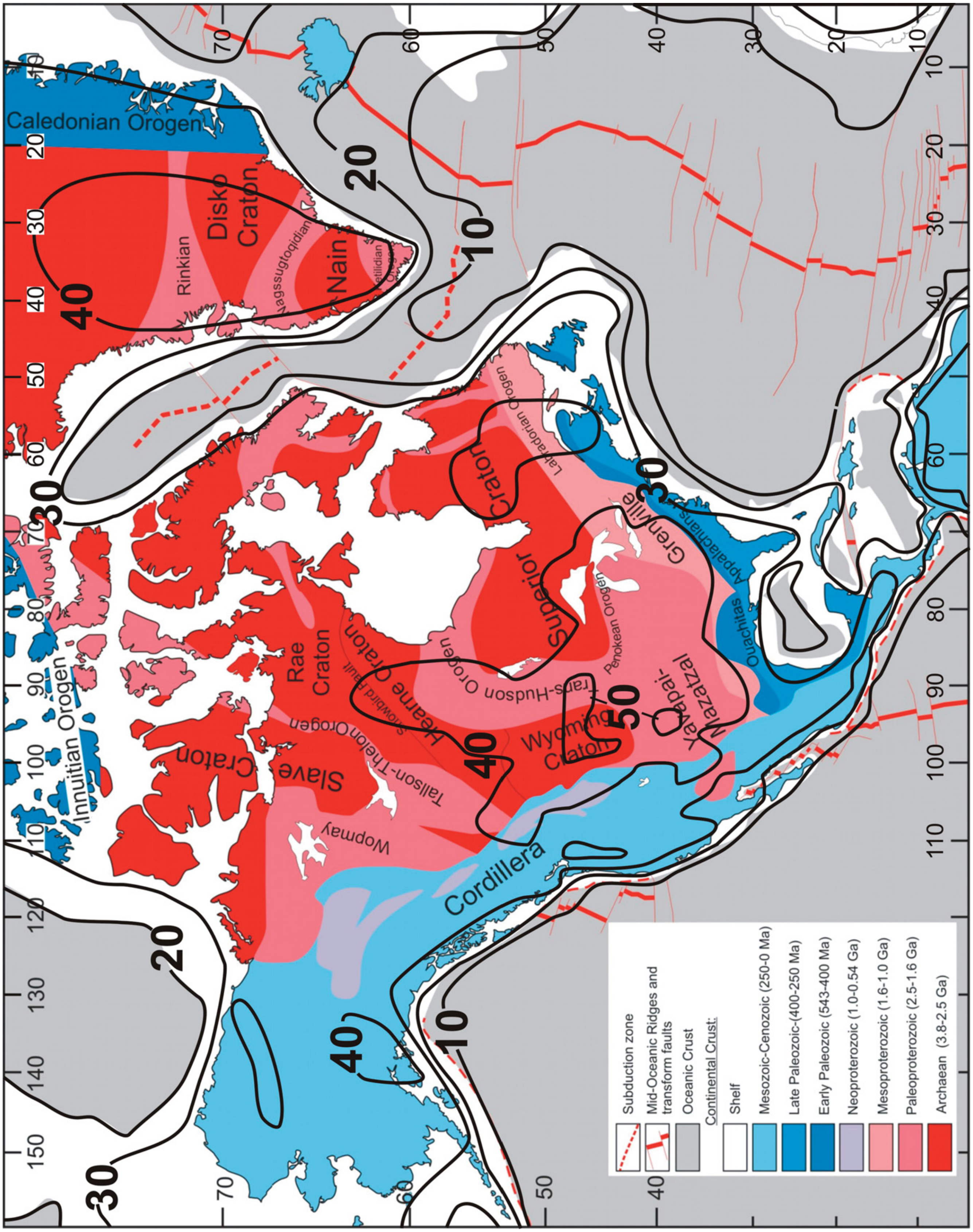

Figure 10.8-08. Basement age map of North America showing Moho depth contour lines as derived from global seismic studies, based on the Global Seismic Profiles Catalog.

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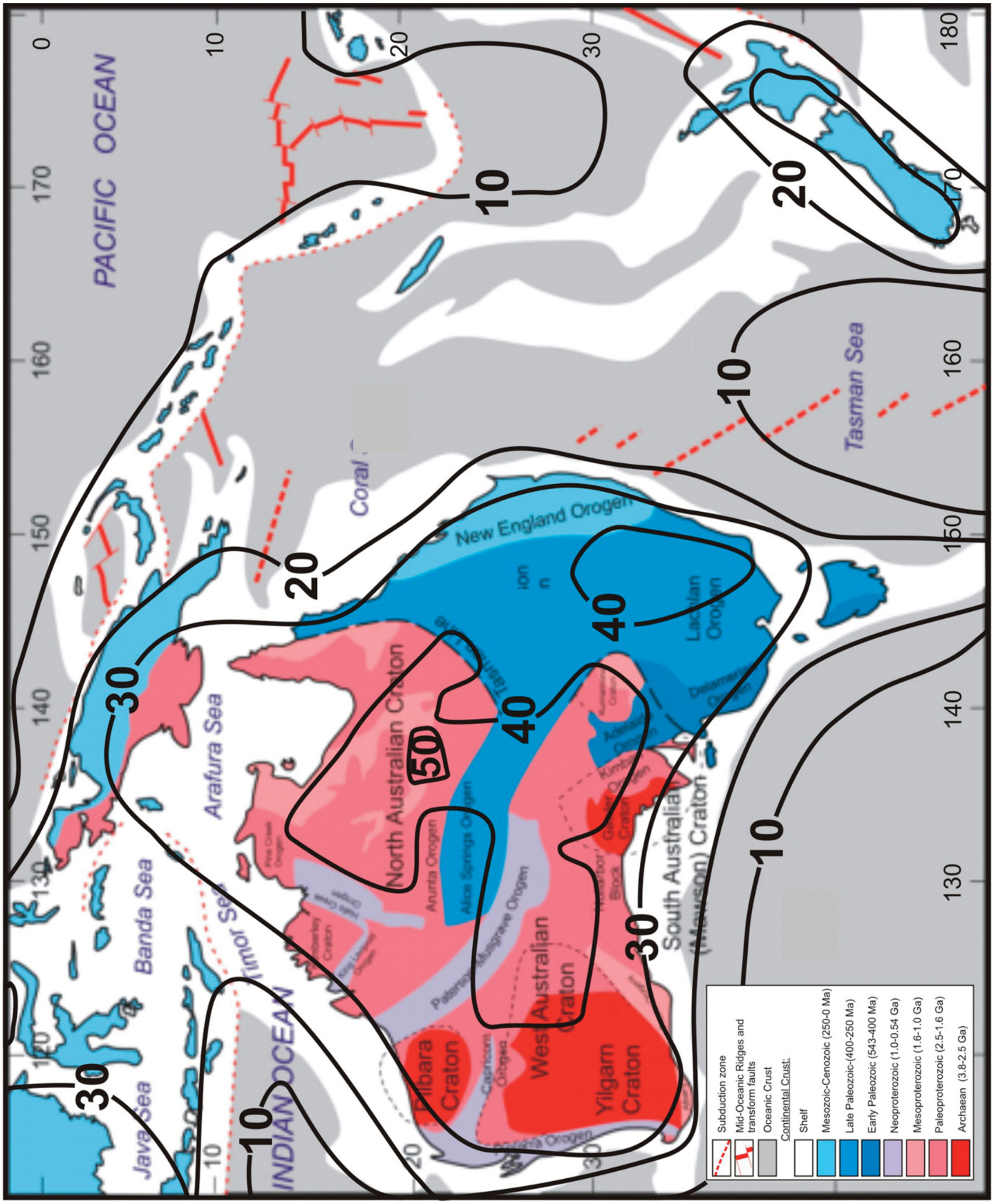

Figure 10.8-09. Basement age map of Australia and New Zealand showing Moho depth contour lines as derived from global seismic studies, based on the Global Seismic Profiles Catalog.

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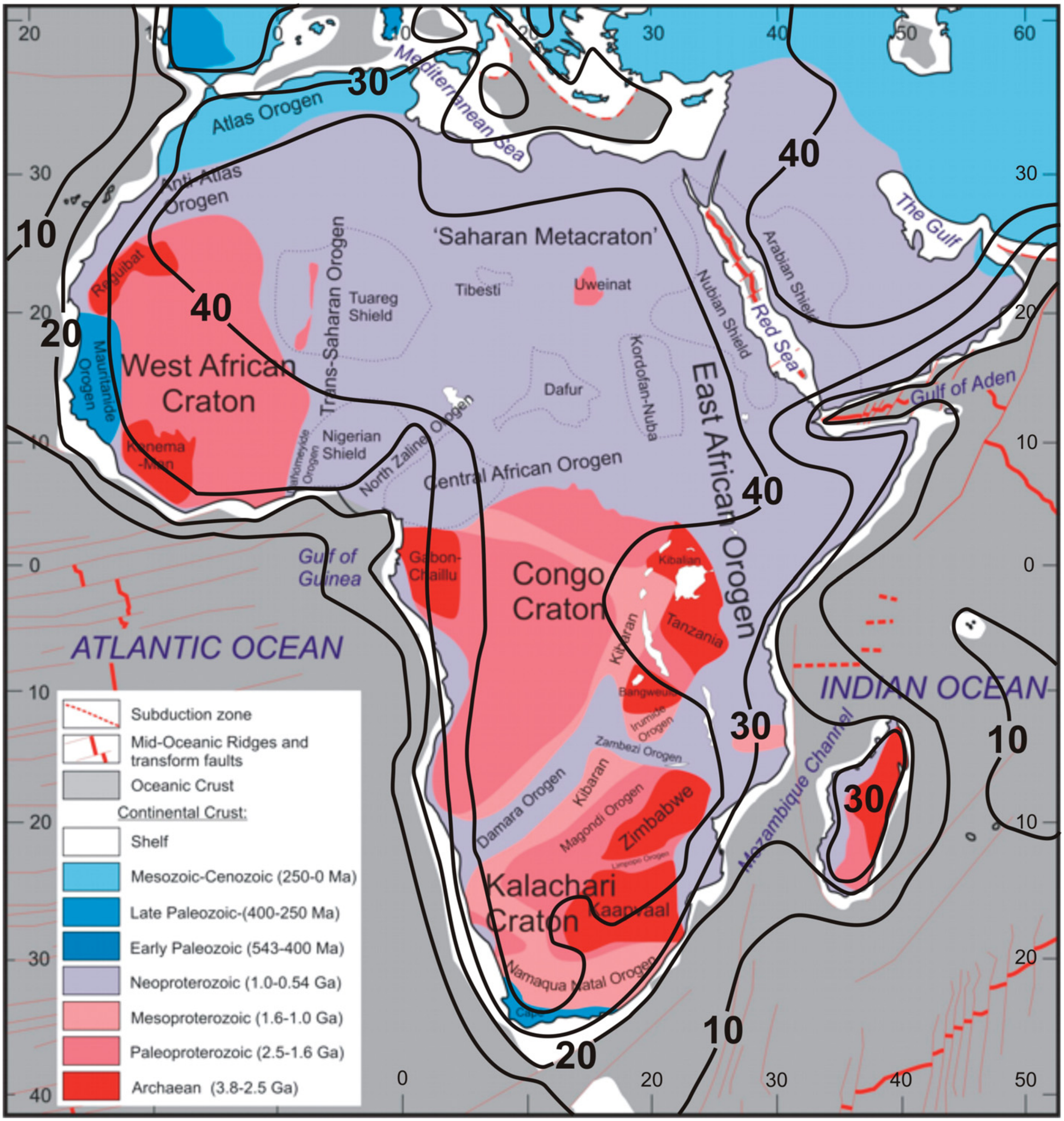

Figure 10.8-10. Basement age map of Africa showing Moho depth contour lines as derived from global seismic studies, based on the Global Seismic Profiles Catalog.

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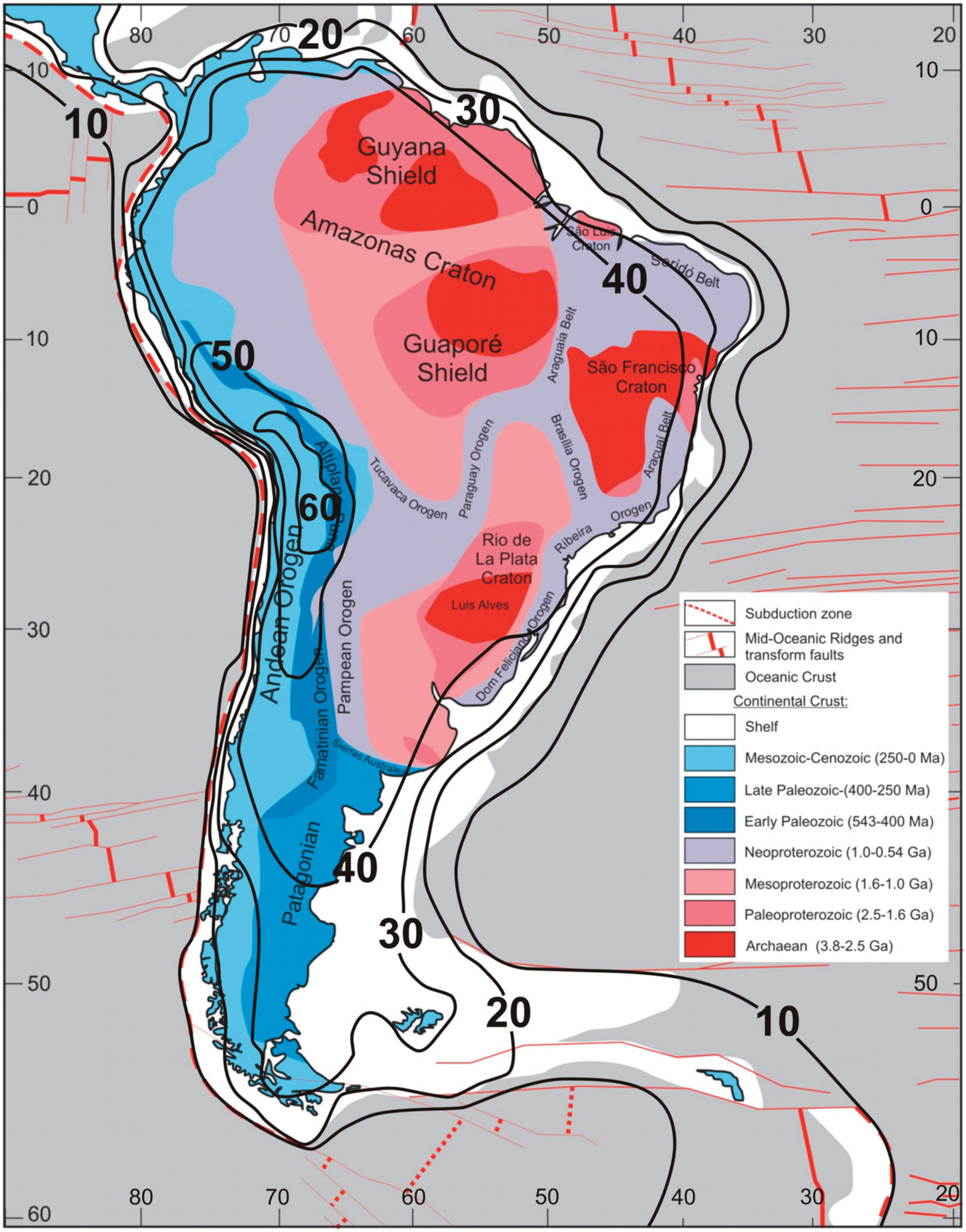

Figure 10.8-11. Basement age map of South America showing Moho depth contour lines as derived from global seismic studies, based on the Global Seismic Profiles Catalog.

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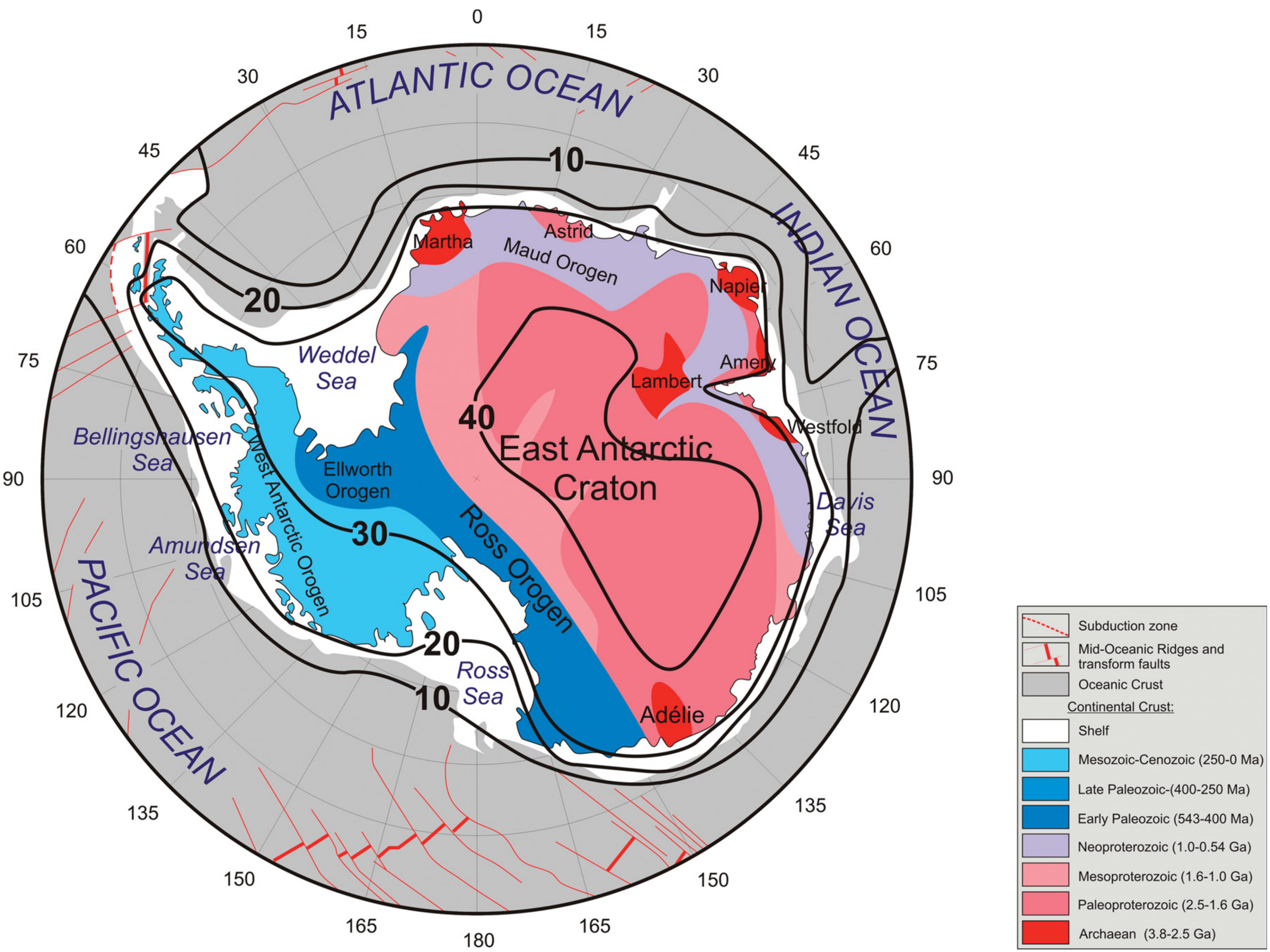

Figure 10.8-12. Basement age map of Antarctica and surrounding oceans showing Moho depth contour lines as derived from global seismic studies, based on the Global Seismic Profiles Catalog.

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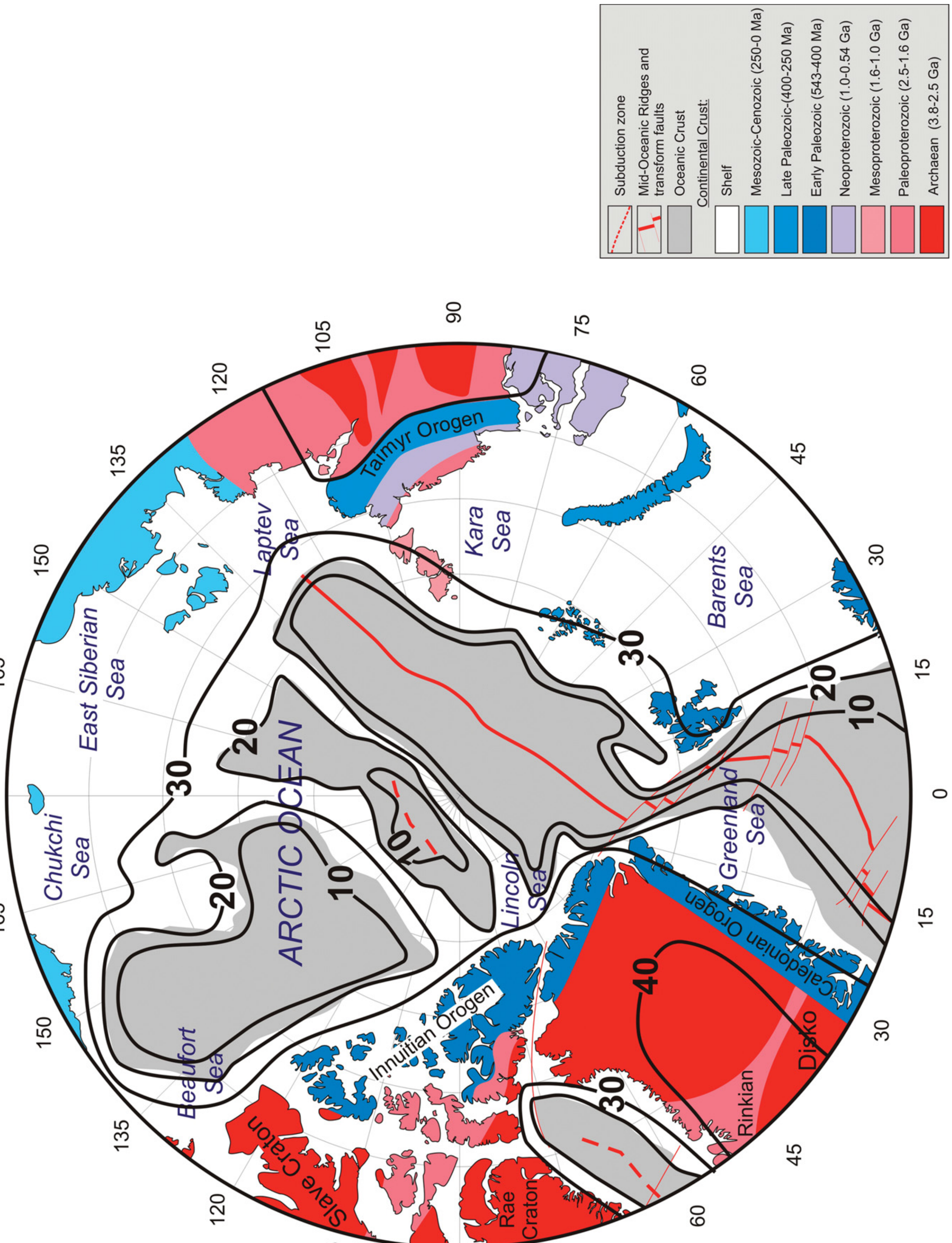

Figure 10.8-13. Basement age map of the North Pole Region (Arctic Ocean and surroundings) showing Moho depth contour lines as derived from global seismic studies, based on the Global Seismic Profiles Catalog.

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