Deep structure of the Eurasia–Pacific transition zone

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Abstract. The deep structure of the Eurasia–Pacific transition zone was investigated under the Geotraverse International Project along the deep sections of the tectonosphere, including the lithosphere and the asthenosphere, based on the complex interpretation of geological and geophysical data. The first geotraverse, investigated in cooperation with Japanese geoscientists, crossed the region of the Japan Sea. The second geotraverse, investigated in cooperation with Japanese and Chinese geoscientists, crossed the region of the Philippine Sea and the North China Plain. The third geotraverse crossed the region of the Okhotsk Sea. The total length of the geotraverses amounted to a few thousand kilometers with a depth of 100 km. The structure of the study region is distinguished by the fact that its upper mantle includes an asthenosperic layer with its diapirs of hot anomalous mantle, responsible for the formation of a transitional zone. The asthenosphere has a depth of 50–80 km under the old Paleogene basins, such as the West Philippine Basin, a roughly 30-km depth under the Neogene basins, such as the Parece Vela Basin of the Philippine Sea or the Kuril Basin of the Okhotsk Sea, and a merely 20–10-km depth under the Pliocene–Quaternary inter-arc basins, where it caused the break-up of the lithosphere, the formation of rifts, basalt magma flow, and hydrothermal activity. The sedimentary basins of the marginal seas are distinguished by an abnormal deep structure characterized by the localization of asthenospheric diapirs under these basins, the development of rifts and spreading centers at their bases, volcanic activity during the early phase of their formation, associated with hydrothermal processes and sulfide formation, and the high heat flow caused by the rise of the asthenosphere toward the surface. It appears that the asthenospheric diapirs with the partial melting of rocks represent channels by which hot mantle fluids from the asthenosphere penetrate to the sedimentary basins. Based on these geotraverses, researchers from the Geophysical Center of the Russian Academy of Sciences created a database including the deep geological and geophysical sections of the lithosphere under the transition zone from Eurasia to the Pacific and the related primary geological and geophysical data, the results of the bathymetric, magnetic, and gravity surveys, heat flow measurements, deep seismic sounding, tomography, seismology, the results of studying the fine structure of the Benioff zone, some data on the chemistry and age of the rocks, and the results of deep-sea drilling and dredging.

Introduction

The present-day period of the Earth science evolution is marked by a particular interest in investigating the deep structure of the Earth associated with a necessity to solve theoretical geodynamic problems, to predict deep-seated mineral deposits, to predict and mitigate the hazards of natural disasters, especially of earthquakes and volcanic erup-
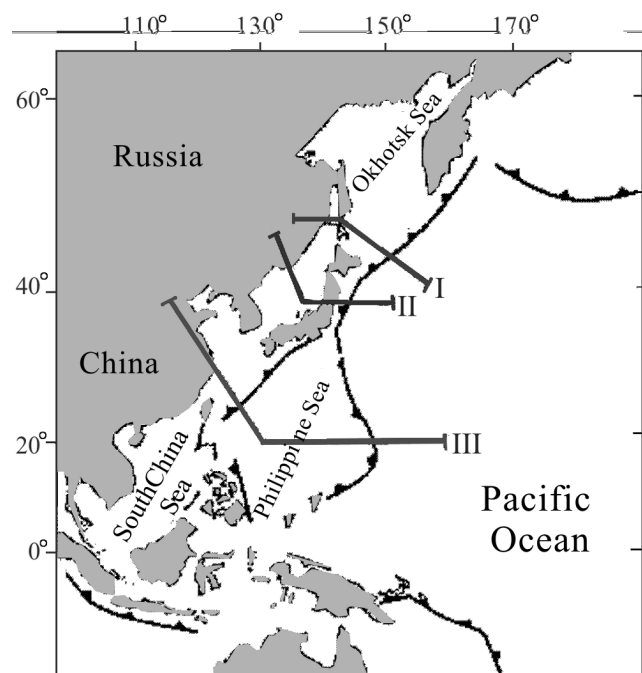
Figure 1. Location of the study region and of the geotraverses: I. Okhotsk Sea Geotraverse, II. Japan Sea Geotraverse, III. Philippine Sea Geotraverse.

tions, and to study the problems associated with the protection of the environment.

This study of the deep structure of the active zone of transition from the Eurasian continent to the Pacific ocean was carried out within the framework of the Geotraverse International Project [*Rodnikov,* 1986; *Rodnikov et al.,* 2000] along three deep sections of the tectonosphere, including the lithosphere and asthenosphere, based on the integrated interpretation of the available geological and geophysical data (Figure 1). The first geotraverse crossing the region of the Japan Sea was plotted in cooperation with Japanese geoscientists [*Rodnikov et al.,* 1985]. The second geotraverse, crossing the region of the Philippine Sea and the North China Plain, was plotted in cooperation with Japanese and Chinese geoscientists [*Geotraverse...,* 1991; *Rodnikov et al.,* 1996]. The third geotraverse crossed the region of the Okhotsk Sea [*Rodnikov,* 2000]. The total length of the geotraverses amounts to a few thousands of kilometers with a depth of 100 km.

Based on these geotraverses, in 2000 the workers of the Geophysical Center, Russian Academy of Sciences, created a database which includes the deep geological and geophysical sections of the lithosphere in the transition zone from the Asian Continent to the Pacific ocean and the primary geological and geophysical data such as the results of bathymetric measurements, gravity and magnetic surveys, heat flow measurements, deep seismic sounding, tomographic studies, evidence of earthquakes and the results of studying the fine structure of the Benioff zone, some data on the chemistry of the rocks and their age, and the results of deep-sea drilling and dredging [*Rodnikov et al.,* 2000]. The results of this work are included into the

Project "Global Geoscience Transects" of the International Program "Lithosphere" and are available in the Internet: http://www.wdcb.ru/GCRAS/traverse.html.

Okhotsk Sea Region

The profile of the geotraverse, along which the deep structure of the transition zone is described, crosses the Mesozoic structures of the Sikhote-Alin Range, the rift of the Tatar Strait, the Cenozoic formations of Sakhalin I., the Kuril Basin of the Okhotsk Sea, the volcanic structures of the Kuril Island Arc, the Kuril Trench, and the Mesozoic plate of the Northwest Pacific Basin. The length of this profile is 2000 km with a depth of 100 km (Figure 2).

The crustal thickness in the Okhotsk Sea varies from 35–40 km under Sakhalin and the Kuril Islands to 8–10 km under the Kuril Basin [*Avdeiko et al.,* 2000; *Crustal Structure...,* 1964; *Structure and Dynamics...,* 1996; *Zlobin,* 1987]. Sediments fill individual deep-sea basins with their thickness as great as 12 km (Deryugin Basin). This layer is composed mainly of sedimentary and partially of volcanogenic rocks of Late Cretaceous–Cenozoic age. During the late Cretaceous epoch sediments accumulated in rifts, this process being accompanied by a significant volcanic activity. Deep-sea basins were formed and filled with volcanogenic–siliceous deposits grading upward to more shallow-sea sediments [*Structure and Dynamics...,* 1996]. Most of the sedimentary basins originated during the Cenozoic time. The deposits of that time, covering the underlying formations as a continuous mantle, contain almost all of the oil- and gas-bearing rocks of the Okhotsk Sea.

The Tatar Strait is a large graben-shaped trough (Figure 3) filled with thick (8–10 km) Mesozoic and Cenozoic sediments [*Tronov et al.,* 1987; *Varnavskii,* 1994]. The sediments filling the trough are divided into four structural complexes separated from one another by regional stratigraphic unconformities and differing in structure, lithology, and physical properties. These are the Late Cretaceous, Paleogene, Oligocene–Early Miocene, and Middle Miocene–Quaternary units. In terms of its deep structure, the Tatar Strait trough is a rift roughly 50 km wide and 4 km deep [*Piip,* 1996]. The M discontinuity has a depth of ca. 30 km there. The origin of the rift structure of the Tatar Strait is believed to have been related to asthenospheric upwelling [*Rodnikov,* 1997]. The rift is the northern continuation of the spreading center located in the deep-sea basin of the Japan Sea.

The Kuril Basin of the Okhotsk Sea is a back-arc basin. The crustal thickness there is 8–10 km including 4 km of sediments (Figure 4). The sediments rest on the acoustic basement which is believed to be a Late Cretaceous volcanogenic–sedimentary layer [*Tuezov,* 1975], under which the third layer of the oceanic crust, as thick as 5 km, has been traced in the middle of the basin. Based on seismic data [*Snegovskoi,* 1974], the sedimentary cover was divided into two units. The upper unit, possibly of Pliocene–Quaternary age, 800–1000 m thick, is characterized by thin layering. In the central part of the basin, the deposits of the lower unit,
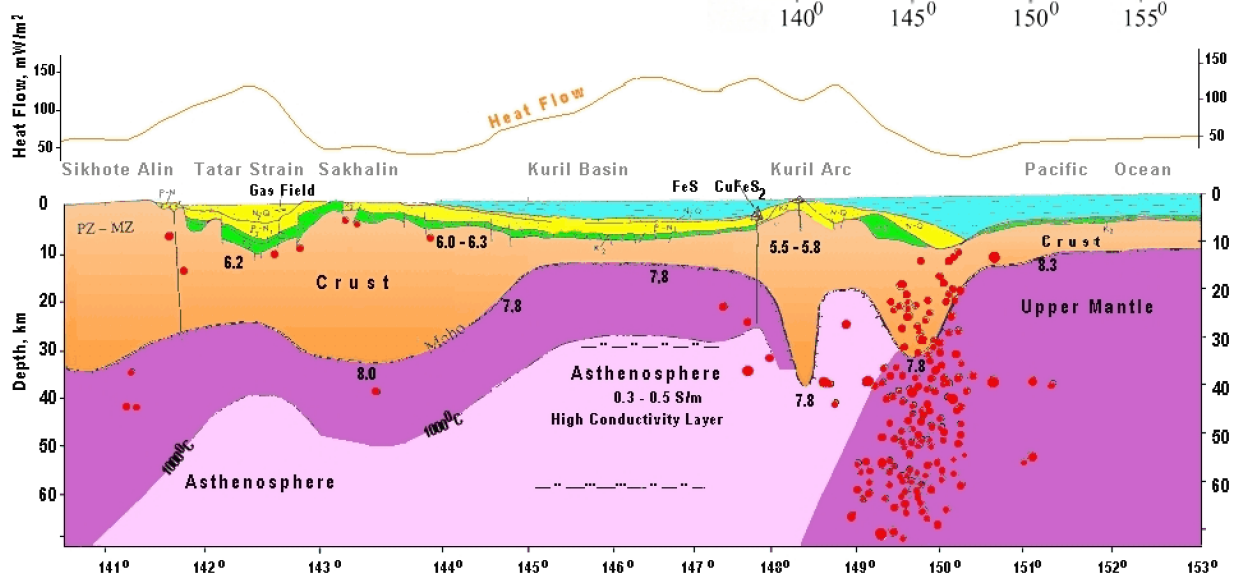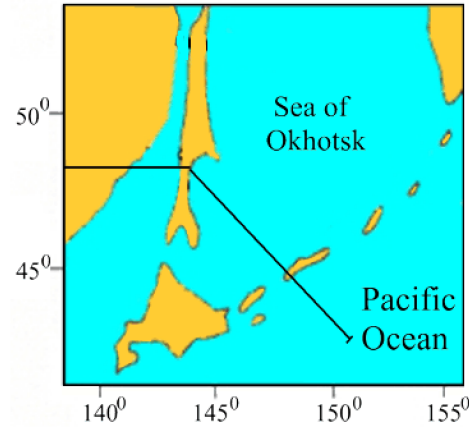
The Okhotsk Sea Geotraverse

Figure 2. Okhotsk Sea Geotraverse.

more than 3000 m thick, are mostly Oligocene–Miocene primarily argillaceous rocks [*Structure and Dynamics...*, 1996].

The origin of this basin, like of all other back-arc basins, was associated with the formation of rifts, the traces of which are usually expressed in the highly dissected topography of the acoustic basement, clearly depicted in seismic profiles [*Baranov et al.*, 1999; *Piip*, 1996; *Structure and Dynamics...*, 1996]. The high heat flow values restricted to the axial zone
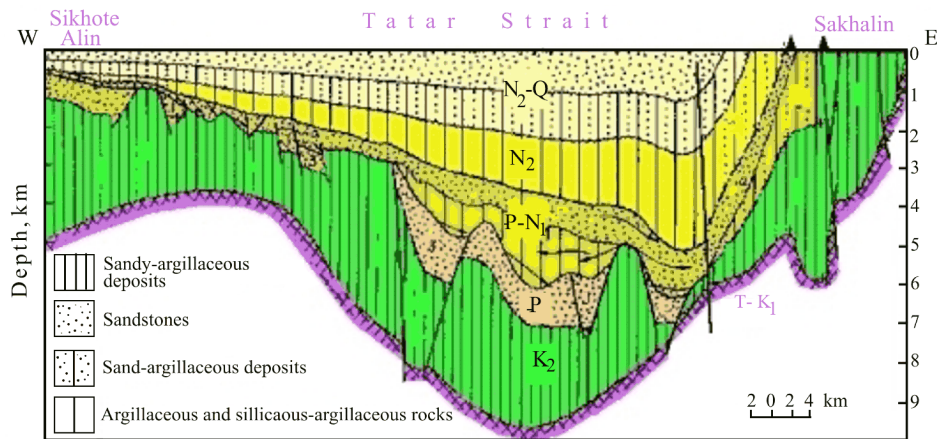

Figure 3. The deep structure of the Tatar Strait [*Structure and Dynamics...*, 1996].
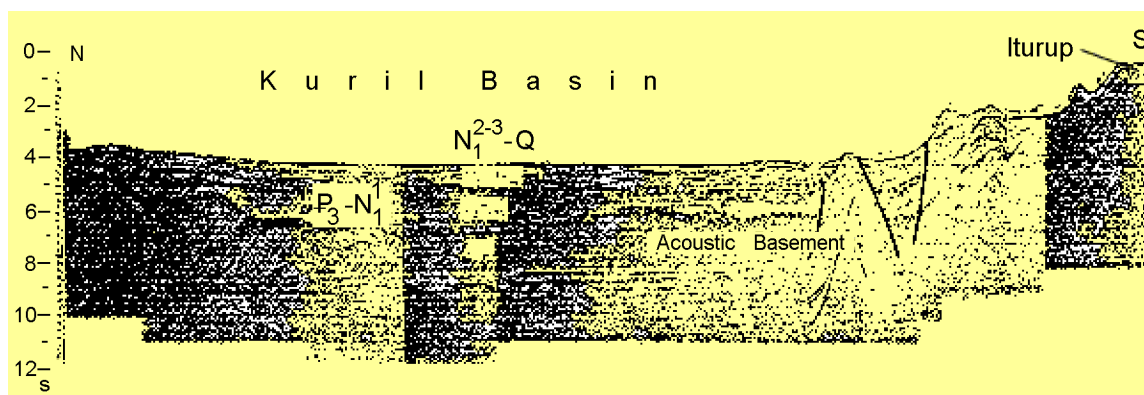
Figure 4. Seismic profile across the Kuril Basin [*Structure and Dynamics...*, 1996].

of the basin [*Smirnov,* 1986] served as another basis for recognizing an axial spreading zone in the central part of the basin.

The outer and inner island arcs are separated by a trough having the fault contacts with the former. The trough is 45–60 km wide and is filled with Neogene and Quaternary tuffaceous and sedimentary formations. The thickness of sediments in the axial zone is more than 3 km, though their bottom was not recorded by a seismic survey. The origin of volcanogenic rocks in the trough's sediments is believed to have been related to the formation of a rift which is now

covered by the sediments. The crustal thickness under the trough is as small as 20 km.

The Northwest Pacific Basin, having the oldest crust (ca. 150 million years), is covered wholly by a continuous sedimentary cover averaging 300–400 m in thickness (Figure 5). Judging by Holes 303 and 580 [*Larson et al.,* 1975], the sediments are diatomaceous and radiolarian ooze and stratified clay, enriched in Late Miocene–Quaternary ash, resting on zeolitic pellagic muds, clayey nannosilts, and siliceous rocks. At a depth of 211 m these deposits are underlain by Lower Cretaceous pelagic zeolite clay, the lower parts
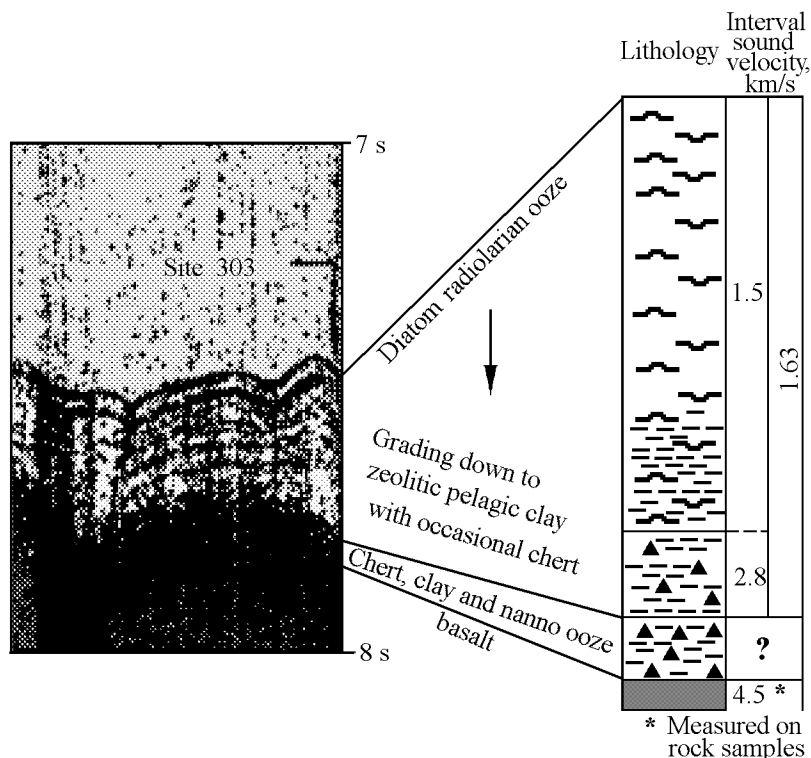

Figure 5. The structure of the sediments from the results of deep-sea drilling and seismic profiling [*Larson et al.,* 1975].

of the sequence including interbeds of siliceous shale and nannoplankton limestone. At a depth of 284.75 m the sedimentary deposits are underlain by basalt pillow lavas. The crustal thickness is roughly 6–8 km there.

The crustal structure of the Okhotsk Sea region differs from the adjacent continental and oceanic regions, the crust of which is characterized by a comparatively flat topography of the M surface, along which boundary velocities vary from 7.8 to 8.1 km/s [*Deep Seismic Sounding...,* 1987]. Under the deep-sea basins the M surface rises and the crustal thickness decreases accordingly, the rises correlating with large depressions in the M surface topography.

The upper mantle under the Okhotsk Sea has both horizontal and significant vertical heterogeneities. It has a lower density compared with the upper mantle under the Pacific Ocean [*Boldyrev et al.,* 1993; *Burmin et al.,* 1992] (Figure 6). According to the results of seismic tomography [*Anderson and Dziewonsky,* 1984; *Bijwaard et al.,* 1998], the upper mantle has lower seismic velocities under the Okhotsk Sea, like under the Japan Sea and the Philippine Sea. According to electromagnetic measurements, the upper mantle under the Kuril Basin includes a layer with conductivity of 0.3–0.5 S/m and integral conductivity of ca. 15000 S [*Lyapishev et al.,* 1987] (Figure 7). This layer is believed to be associated with partial melting and occurs within the limits of the basin. These results agree with the upper mantle temperatures, as well as with the seismic and other geophysical data. A low-velocity region dipping toward the continent to a depth of 150–250 km was discovered under the modern volcanic zones of the Kuril Island Arc [*Fedotov and Kuzin,* 1963]. This region produces local magma chambers feeding numerous volcanoes on the Kuril Island Arc. The temperature of the M surface varies from 100°C in the Pacific to
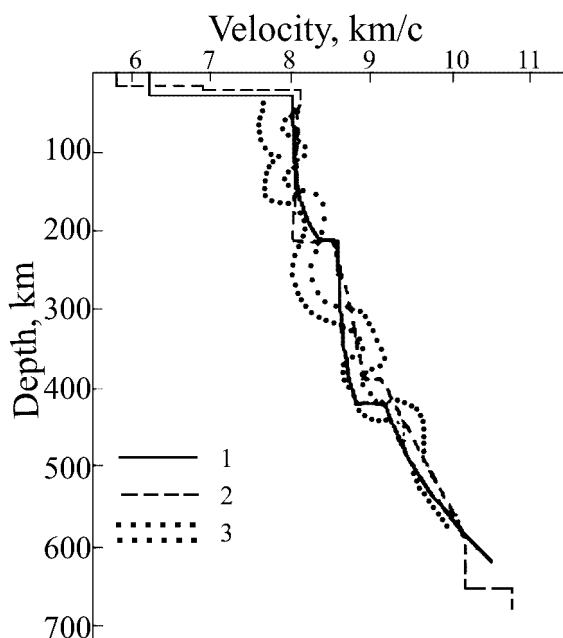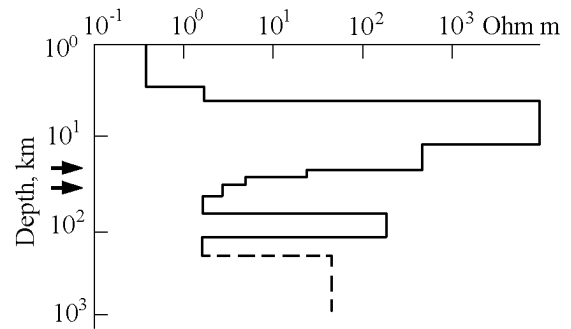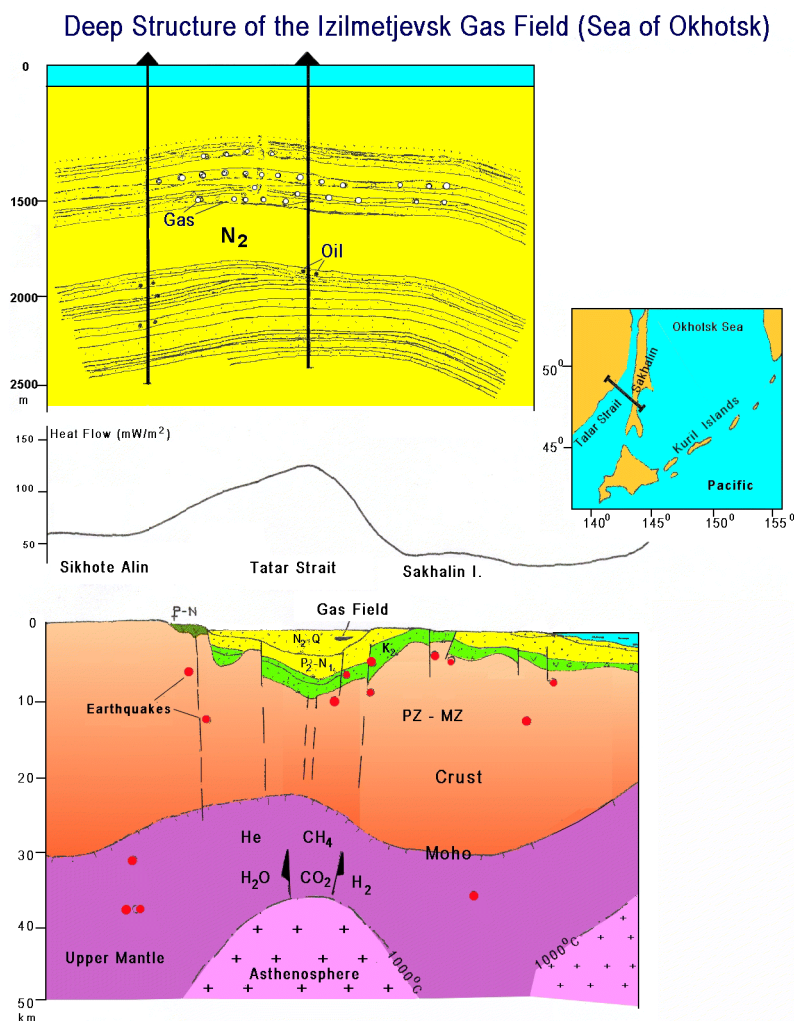

Figure 7. Electromagnetic model for the upper mantle under the Kuril Basin [*Lyapishev et al.,* 1987].

1000°C under the Tatar Strait, being 800°C under the Kuril Basin with a thin crust. The depth to the top of the partial melting region, identified as an asthenosphere, ranges from 15–25 km under the deep-sea basins to 100 km under the Pacific Ocean. The region of partial melting produced several asthenospheric diapirs under the Tatar Strait, the Deryugin Basin, and the Kuril Basin, which control the active tectonic conditions manifesting themselves as volcanic, seismic, and hydrothermal activities. Hydrocarbon deposits were discovered in the sediments of the Tatar Strait and Deryugin Basin [*Cruise Reports...,* 2000; *Obzhirov et al.,* 1999]. Sulfide mineralization was reported from the tops of submarine volcanoes in the Kuril Basin [*Kononov,* 1989].

The study of the deep structure of the Okhotsk Sea region shows that the crustal thickness varies from 35–40 km under Sakhalin and Kuril Islands to 10 km under the Kuril Basin. The asthenosphere has diapiric protrusions under the Kuril Basin and the trough of the Tatar Strait, with rifts (spreading centers) located at the bases of these structures. The rising of the asthenospheric diapirs toward the crust produced a high heat flow. The formation of the Tatar Strait trough was associated with a N-trending spreading center recorded in the deep-sea basin of the Japan Sea. The formation of the Kuril Basin was also associated with spreading processes which developed during the Late Cretaceous [*Baranov et al.,* 1999]. Figure 8 shows the deep structure of the lithosphere under the sedimentary trough of the Tatar Strait, where the Izylmetievskoe gas field was discovered. The sedimentary trough correlates with a hot asthenospheric diapir which produced breaks in the crust, the development of rifts at the base of the trough, magmatic activity, and the heating of the sedimentary sequence. This diapir might have served as an additional source of hydrocarbons and fluid flows responsible for a high hydrothermal activity.

Japan Sea Region

The geotraverse discussed crossed the Sikhote-Alin Range, the deep-sea basin of the Japan Sea, the Japanese Island Arc (in the north of Honshu Island), and the Northwest Pacific

Figure 6. Seismic velocity distribution in the upper mantle to a depth of 700 km [*Burmin et al.,* 1992].

Figure 8. Structure of the crust and upper mantle under the Izylmetievskoe gas field (the Tatar Strait).

Basin (Figure 9). The crustal thickness varies along the geo-traverse from 35–40 km in the southeastern margin of the continent to 12–15 km in the deep-sea basin of the Japan Sea. The crust has a thickness of ca. 35 km under Honshu I. and is less than 8 km thick under the oceanic structures adjacent to the island arc.

Under the Japan Sea the crust consists of three major layers. The upper layer has a thickness of 1.0–2.0 km and seismic velocities of 1.5 to 3.5 km/s with a relatively constant growth of velocity with depth. Below follows an intermediate layer with a thickness of 2.0–2.5 km and velocities of 4.8–5.6 km/s. It is underlain by the main crustal layer having a thickness of 8–10 km and velocities of 6.4–6.7 km/s. The upper mantle velocities vary along the M surface from 7.8 to 8.2 km/s. As follows from geophysical data [*Hirata et al.,* 1991], the deep-sea basins of the Japan Sea have an oceanic structure (Figure 10).

The structure of the sedimentary layer under the Japan Sea is known from the results of the "Glomar Challenger" and "JOIDES Resolution" deep-sea drilling [*Karig et al.,*

1975; *Tamaki et al.,* 1992]. The holes drilled in the Japan Sea revealed that to depths of 500–600 m this layer is composed of muddy, diatomaceous ooze, sand, sand and silt sediments, and mud with ash interlayers. The base of the sedimentary layer is made up of dense dark-green siltstone, sandstone, and green tuff consisting mainly of devitrified glass and feldspar. In the south of the sea Hole 798 crossed Middle Pliocene–Holocene rocks consisting of interbedded diatomaceous and terrigenous muds, argillite, and ooze, containing organic matter. A significant amount of methane was recorded. Holes 794, 795, and 797 reached basalts with an age of 25 Ma. The Miocene to Quaternary sediments are muds and sandstones with volcanic ash interlayers. A narrow trough filled with 2–3 km of Pliocene–Quaternary sediments was traced along the eastern margin of the Japan Sea [*Honza,* 1979]. The origin of this trough is believed to have been associated with the development there of a new zone of the subduction of the Japan Sea lithosphere under the Japan Island arc, recognized from seismic data [*Kuge et al.,* 1996; *Uyeda,* 1991]. Figure 11 shows the structure of this
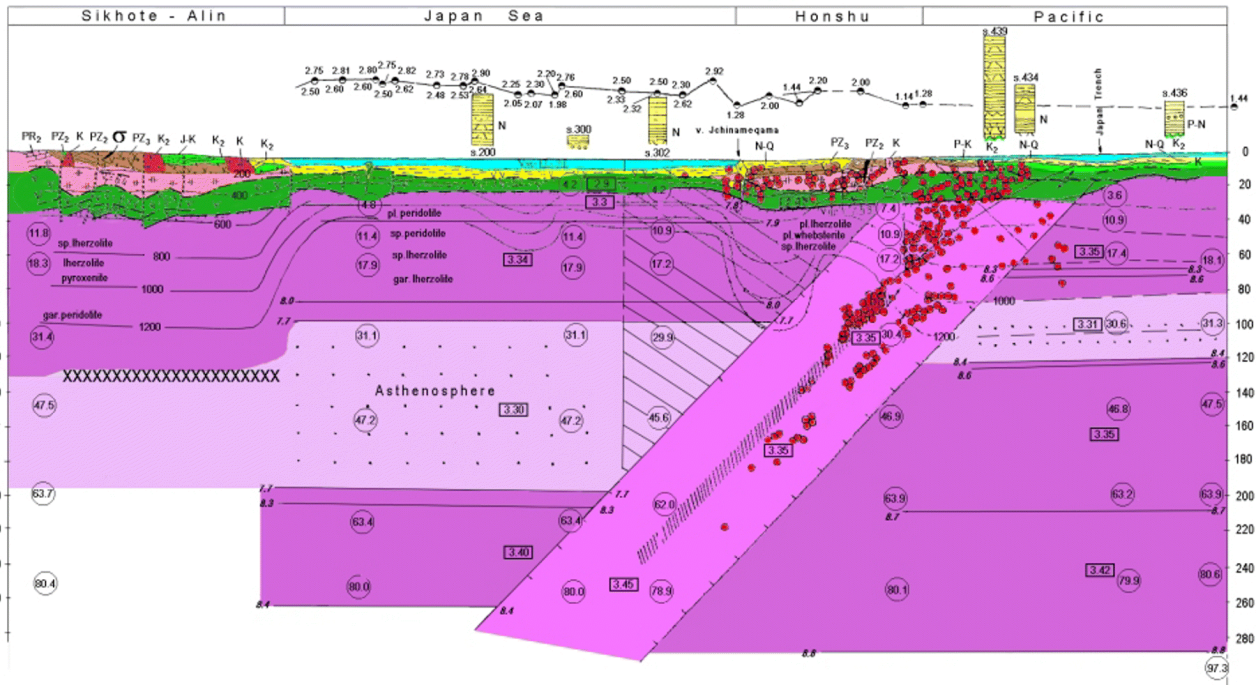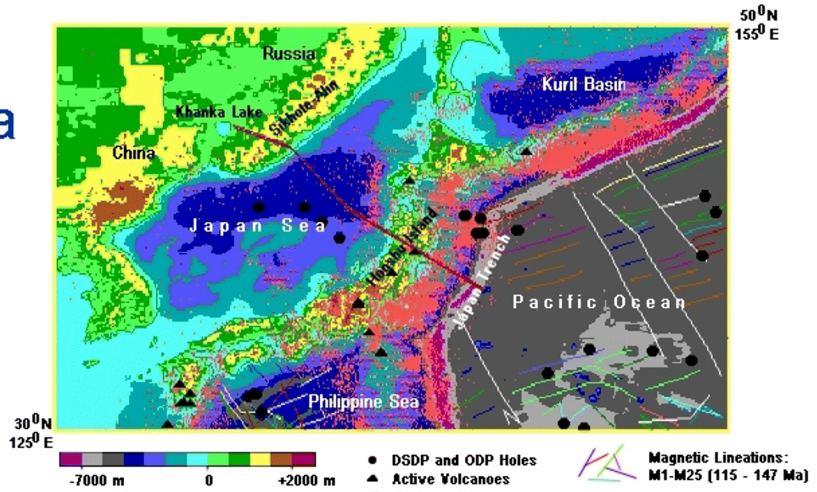
Figure 9. Geotraverse across the Japan Sea region. 1 – top of the crust; 2 – bottom of the crust; 3 – faults; 4 – Moho surface; 5 – earthquake foci; 6 – top of the focal zone; 7 – seismic velocities; 8 – isotherms across $200°$; 9 – density values (g/cm^3); 10 – high conductivity zone; 11 – low-velocity layer in the upper mantle; 12 – pressure, kbar; 13 – the contour of the Benioff zone assumed in gravity model calculations; 14 – low-density region.

new subduction zone in the Japan Sea. Earthquake foci are concentrated in a Benioff zone, as deep as 70 km, dipping under Honshu I. Earlier, the study of the submarine topography in the eastern part of the Japan Sea near the coast of the Japanese Islands [*Honza,* 1979] revealed the fragmentation of the sea floor, the strike of the Okusiri Trough parallel to the Japanese Islands, bounded in the west by the Okusiri Trough, the formation of which began about 2 million years

ago, which is believed [*Kuge et al.,* 1996] to have been caused by the plunging of the Japan Sea lithospheric plate under the island arc. Earthquake epicenters are known to be restricted to these structures. The Japan Sea is believed to have been formed as a result of the separation of the Japanese island arc from the continent roughly 25–15 million years ago [*Jolivet et al.,* 1995; *Maruyama et al.,* 1997].

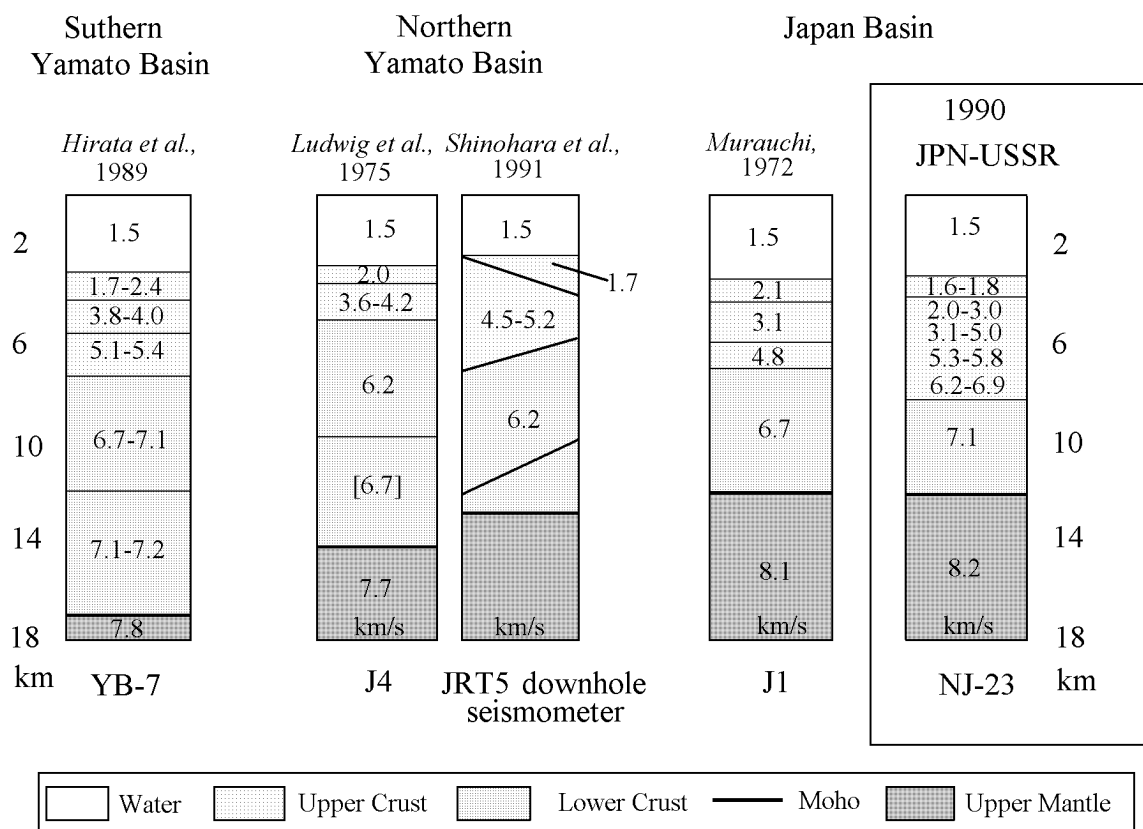The Japan Trench separates the island arc from the deep

Figure 10. Crustal structure from seismic data [*Hirata et al.*, 1991].

basin of the Northwest Pacific Basin (Figure 12). Under the eastern oceanward slope of the trench, the thickness of the crust was found to be 10–12 km, under the ocean basin it decreased to 6–8 km. Under the western insular slope of the trench the crust is as thick as 23–25 km. The thickness of the Cenozoic deposits increased to 8–10 km. In 1985 the Japan trench was surveyed using a Nautile submersible within the framework of the French–Japanese KAIKO Project. Large landslides were discovered on the continental slope of the trench, which produced an active erosional morphology of the trench floor with vertical and even overhanging slopes. Highly active fluid flows were recorded [*Cadet et al.*, 1987].

In the Pacific Ocean adjacent to the Japan Island Arc the crustal thickness is about 8 km, the M surface is topographically rough, its seismic velocity being 8.2 km/s. A 400-meter section of oceanic sediments exposed on the marginal rise of the ocean floor ranges from Cretaceous to Recent. The upper 300 m consist of argillaceousdiatomaceous and tuffaceous–diatomaceous oozes with interlayers of Late Miocene–Quaternary age. The amounts of siliceous radiolaria remains and clay material increase with depth. At a depth of 360 m the siliceous–argillaceous sediments are replaced abruptly by pelagic mud. The fact that merely 18 m of pelagic mud had accumulated from the Middle Miocene to the Early Paleogene indicates that the sedimentation rate

there was very low at that time. The pellagic mud is underlain by siliceous rocks which were dated tentatively as Cretaceous. The siliceous rocks were often found to be underlain by tholeitic basalts [*Larson et al.*, 1975].

The structural features found in the region of the Japan Sea have a distinct expression in the deep structure of the lithosphere. The deep-sea basins correlate with the M surface rises and with the low values of seismic velocities, the rises correlating with the growths of the crustal thickness (30–35 km) and normal velocities on the M surface.

The most important feature in the structure of the Japan Sea region is the development of an asthenospheric lens in the upper mantle. An asthenospheric layer, more than 100 km thick, occurs at a depth of ca. 50 km in the transitional zone distinguished by a heat flow higher than in the adjacent regions. It was located at a depth of ca. 100 km under the Maritime territory (Primorskii Krai) and the Pacific. The presence of a thick high-conductivity asthenosphere in the transition zone was confirmed by magnetotelluric soundings. The low density of the upper mantle under the marginal seas was proved by negative residual gravity anomalies. The seismic tomography data, presented in Figure 13, prove the existence of an asthenospheric diapir in the upper mantle at a depth of about 40 km under the Japan Sea and the western part of Honshu I., which controlled
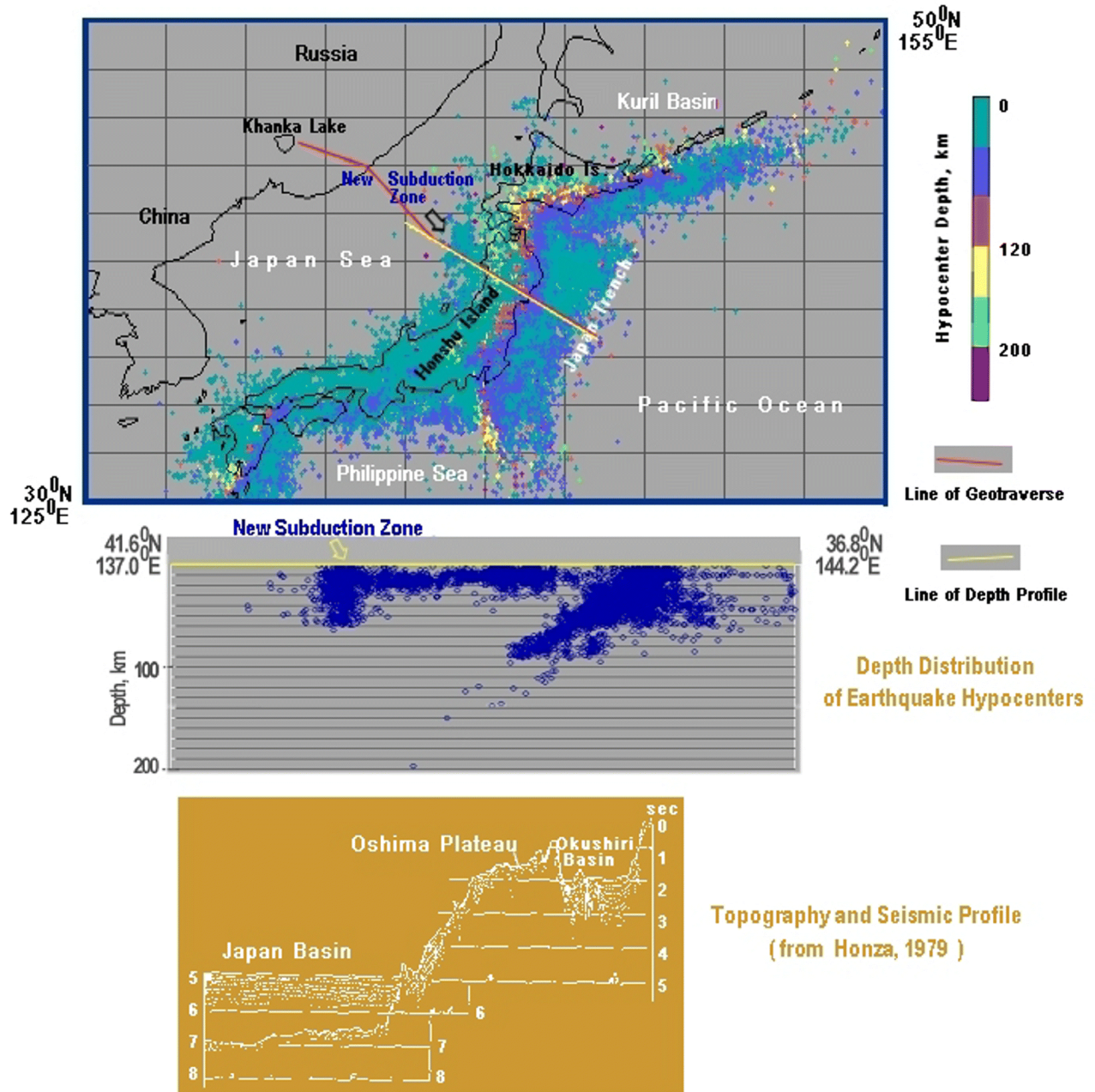
Figure 11. A new subduction zone in the Japan Sea along the western coasts of Honshu and Hokkaido Islands. The earthquake sources along the eastern coast of the Japan Sea produce a Benioff zone dipping under the island arc to a depth of ca. 50 km. Its origin is dated 1.8 Ma.

magmatic activity in the Cenozoic time [*Hasegawa et al.,* 1991]. The calculations of the upper mantle temperatures confirm the existence of the zone of partial melting in the upper mantle under the Japan Sea. The deepest isotherms are characteristic of the Sikhote-Alin Range, the Paleozoic structures of eastern Honshu I., and the adjacent continental slope and deep-sea trench. Zones of partial melting (1200°C) were recorded there at depths of ca. 100 km. The region of an abrupt isotherm rise coincides with the deep-sea basin of the Japan Sea and with a "green tuff" zone in western
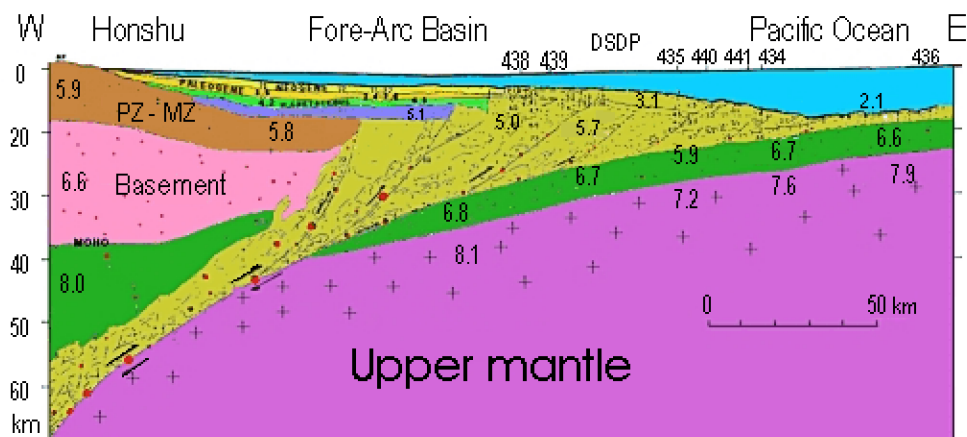
Figure 12. Structure of the Japan Trench [*Shiki and Misawa,* 1982].

Japan. The isotherms of 1200, 600, and 300° were recorded there at depths of 30–35, 10, and 5 km below the sea floor, respectively.

During the Neogene magmatic activity took place only in the region of the maximum rise of the 1200°C isotherm, that is, in the Japan Sea and in the western part of Honshu I. In the Pacific Ocean (Northwest Pacific Basin) magmatic activity (tholeiitic basalt flow) was found to have occurred mainly more than 100 million years ago. The position of this isotherm is not controlled by the type of the crust and is roughly similar in the Primorskii Krai and in the Pacific. It is remarkable that the most tectonically active region – the Japan Sea and the Japan Island Arc – is located presently between the continental and the oceanic block of

the tectonosphere. The low-velocity region (asthenospheric lens), recorded in the transitional zone, can be interpreted as a hot diapir rising toward the crust, which seems to control the endogenic situation in this zone.

Philippine Sea Region

The deep structure of this region was investigated along a geotraverse 100 km deep and 5000 km long (Figure 14). The geotraverse crossed the North China Plain, the sedimentary basins of the Yellow and East China seas, the deep-sea
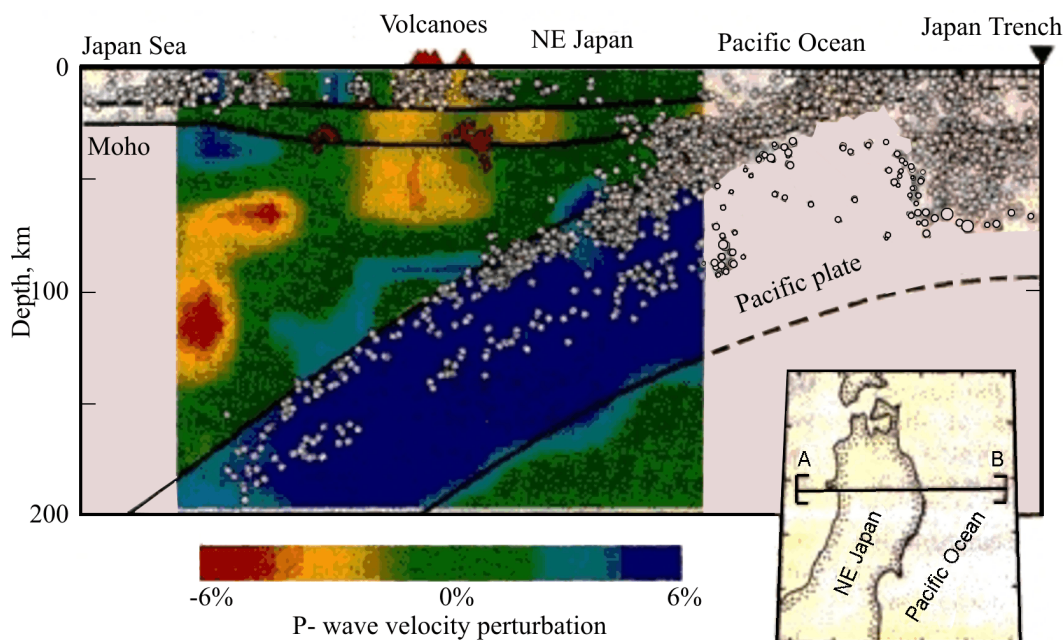

Figure 13. Structure of the upper mantle from seismic tomography data [*Hasegawa et al.,* 1991].
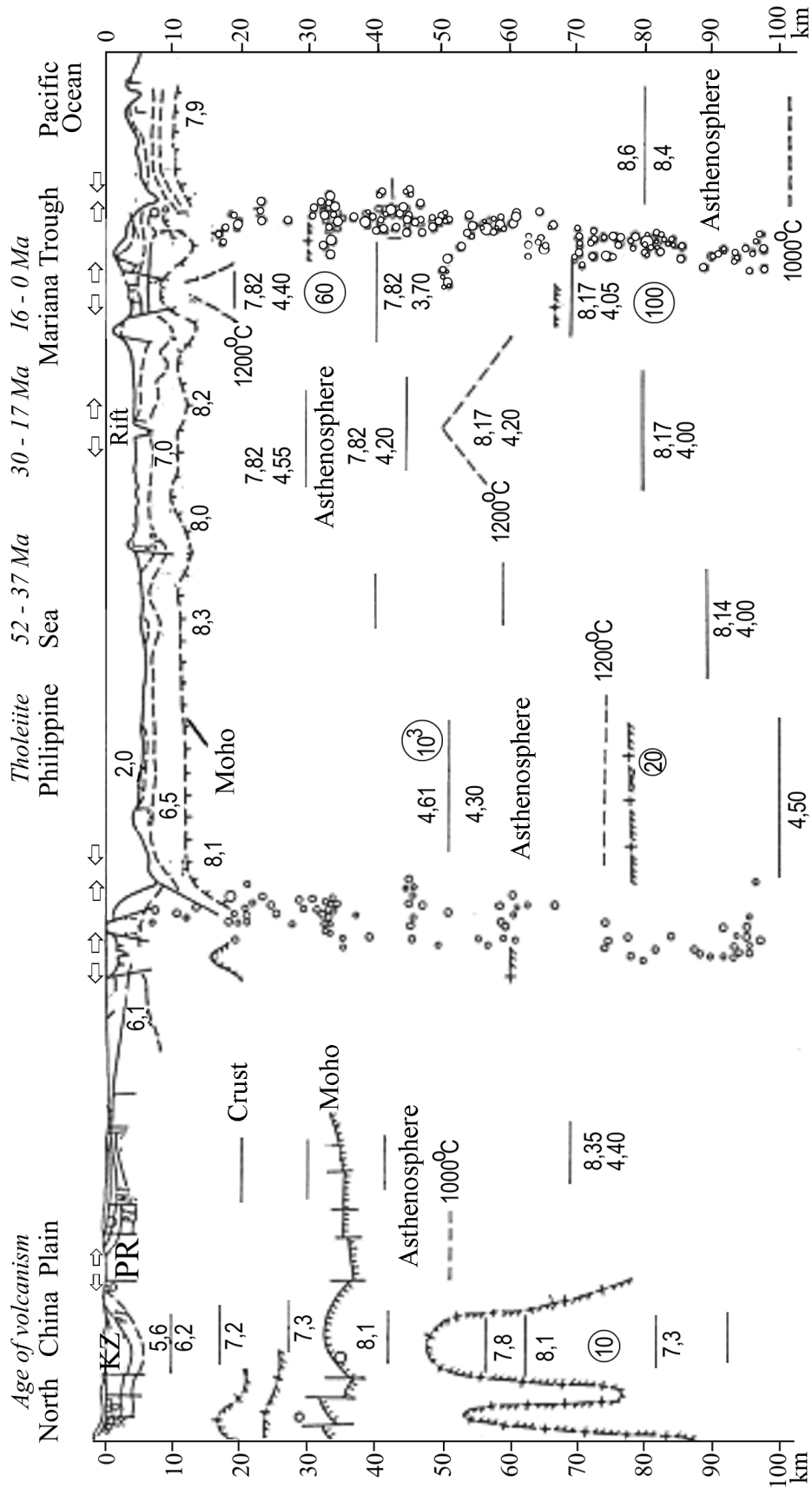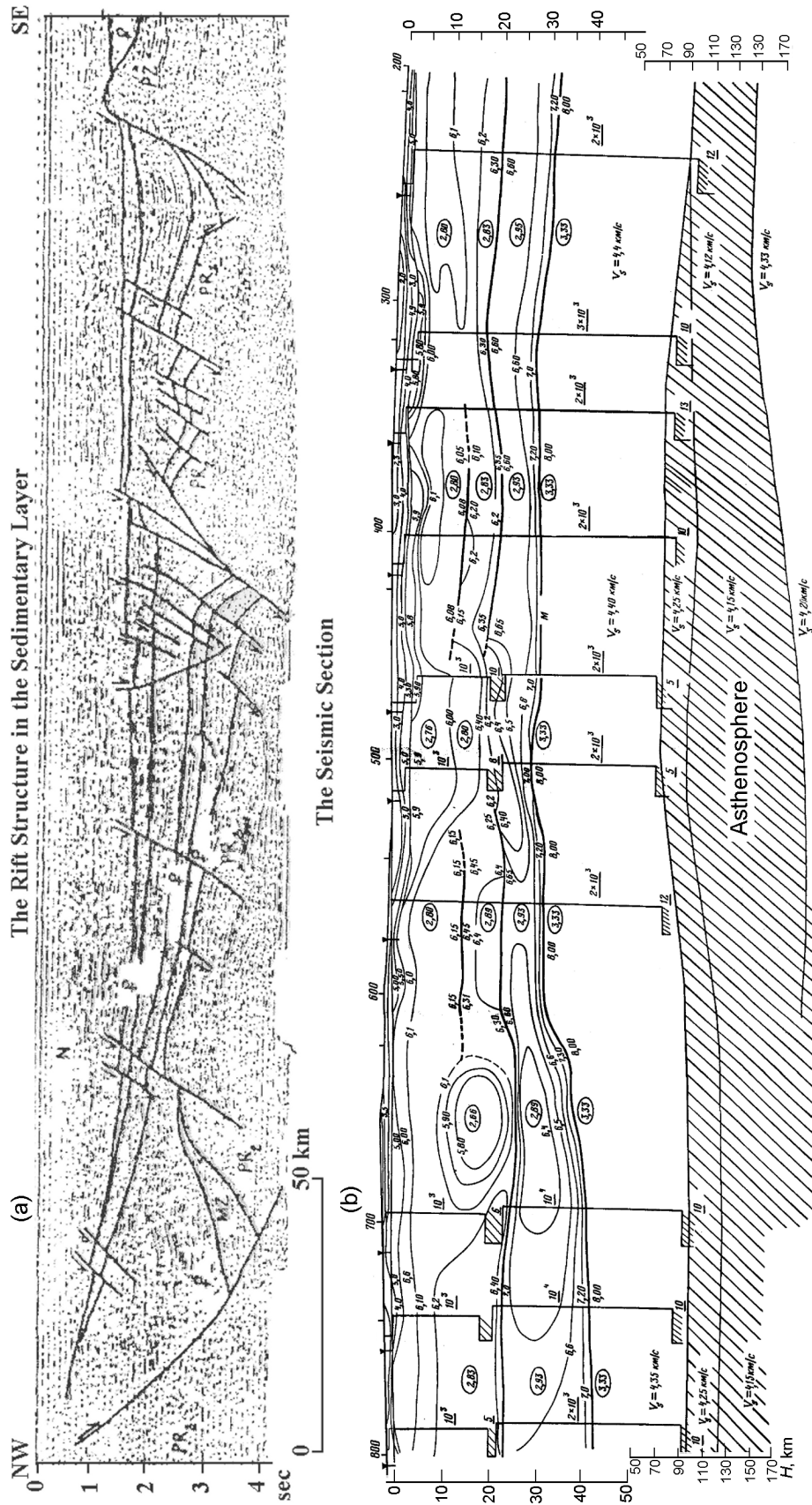
**Figure 14.** Philippine Sea Geotraverse.

Figure 15. Deep structure of the North China Plain. a - Structure of grabens; b - Structure of the crust and upper mantle from seismic data.

basins of the Philippine Sea, the Mariana Island Arc with its interarc trough, the Mariana Trench, and the Northwest Pacific Basin [*Geotraverse..., 1991; Rodnikov et al., 1996*].

The North China Plain is a constituent of the old Sino-Korean platform which was transformed to a craton 1900–1700 million years ago [*Huang, 1984*]. Its Middle and Late Proterozoic rocks form a transition-type cover, its Cambrian and Ordovician rocks being represented by shallow-sea carbonate deposits. A break of sedimentation has been recorded from the Late Ordovician to the Early Carboniferous (ca. 80 million years), which was marked by the renewal of endogenic activity expressed in the emplacement of kimberlite bodies. During the Middle and Late Carboniferous there was a sea transgression with the accumulation of paralic coal formations. Fluvial–lacustrine deposits accumulated during the Early Permian, and the continental conditions with the accumulation of red beds existed during the Late Permian–Triassic. The Indosinian movements (T_2–J_1) were accompanied by the emplacement of basic, alkaline, and mainly acid igneous rocks. The Yanshang movements (J_1–K_2) were distinguished by the intrusion of granite bodies and kimberlites and by the extrusion of calc-alkalic rocks.

During the Cenozoic the ancient Precambrian Platform was subject to tectonic reactivation. A few epochs of extension resulted in the formation of intracratonic grabens filled with oil-bearing sediments. There were three stages of magmatic activity. The Paleogene, mainly Eocene, basalts are represented by tholeiites. The Neogene alkalic olivine basalts are similar, in terms of their composition, to continental tholeiites. The Quaternary extrusive rocks are oversaturated alkali basalts [*Cong and Zhang, 1983*]. The system of grabens which controlled the basalt emplacement is underlain by a thinner crust and lithosphere, shows a high heat flow, and is marked by areally localized seismicity (Figure 15). Figures 15 and 16 show a correlation between the composition and age of the basalts and the upper mantle structure and changes in the state of the asthenosphere with time in the North China Plain. The seismic section plotted
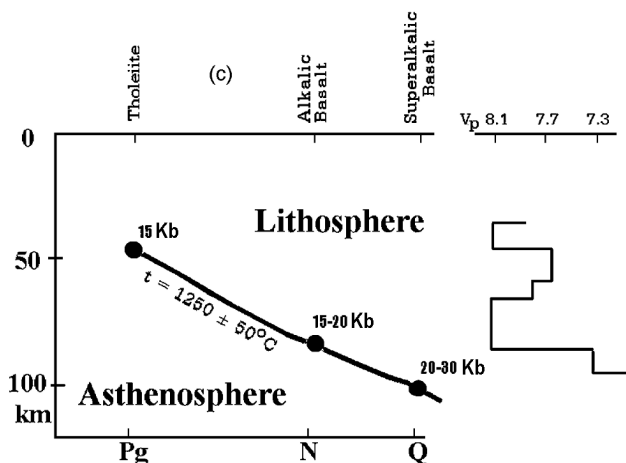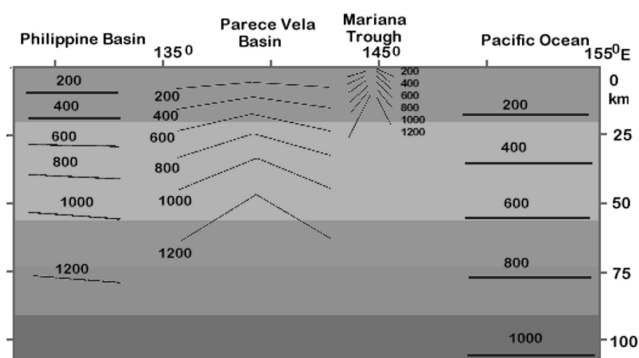
Figure 17. Temperature distribution in the upper mantle under the structures of the Philippine Sea [*Geotraverse..., 1991*].

in the figure is given after [*Teng et al., 1982*], and the magmatism and the PT conditions of the basalt emplacement, after [*Cong and Zhang, 1983; Liu and Liu, 1983; Wu et al., 1987*]. The tholeiitic magma that flowed during the Paleogene 60 million years ago (from a depth of ca. 50 km) was replaced in the Neogene by a more alkalic magma rising from a greater depth, and alkaline basalt was extruded in the recent time to produce individual volcanic cones. The depth of this magma generation was greater than 100 km, as indicated by a curve in the figure. The seismic velocity section presented in the right emphasizes the position of the magma sources in the upper mantle, as indicated by the lower seismic velocities. The lowest velocities were found at a depth of about 100 km, that is at the depth of alkaline basalt melting. The plot depicts the cooling of the lithosphere (subsidence of the asthenosphere) with time. According to the results of deep seismic sounding the average thickness of the crust under the North China Plain is about 35 km. The M surface is uneven showing relative rises above the grabens.

The best studied area of the North China Plain is the Bohai Gulf, the most important oil and gas province in East China. The graben-shaped structures, developed in the Paleogene deposits, originated [*Li, 1982*] as a result of crustal extension produced by the rise of the mantle material. The depth to the M surface is ca. 30 km there, and is as deep as 35 in the surrounding regions. The extension of the crust during the Paleogene resulted in the eruptions of basalt magma, the lava flows of which are found in most of the rift zones, where they occur, together with sedimentary rocks, as Eocene and Oligocene formations.

The East China Sea basin was formed on the highly denudated surface of Mesozoic and Paleozoic rocks [*Li, 1982*]. The lower part of the sequence accumulated in a Paleogene rift. The middle sequence accumulated in the Miocene and is as thick as 5000 m. The upper part of the section is composed of flat-lying Pliocene and Pleistocene deposits. The basement of the basin is broken by faults that originated during the Caledonian orogeny. Some of the Early Paleozoic faults were reactivated during the Paleogene phase of rifting. Intensive movements along the faults took place in the Miocene. The magnitudes of displacement along the faults

Figure 16. Correlation among the composition, magma eruption time, and depth of the asthenosphere containing magma sources on the North China Plain.

bounding the troughs were as great as several kilometers.

Okinawa Trough is a modern, still developing rift system [*Letouzey and Kimura,* 1985], bounded by Cenozoic faults which are still active. The central part of the trough is a recent rift system bounded by pull-apart faults and filled with recent basic lavas. Recent faults are widely developed in the central part of the trough. The trough includes a central graben, 20–50 km wide, enclosed into a wider graben measuring up to 200 km across. The development of the grabens was accompanied by magmatic activity. The rhyolite, andesite, and basalt samples dredged from the floor of the trough are not older than 1 Ma [*Letouzey and Kimura,* 1985]. The crust is very thin, merely ca. 17 km.

West Philippine Basin was generally produced during the Eocene time. As follows from the analysis of magnetic lineations [*Hilde and Uyeda,* 1983], the basin originated as a result of back-arc spreading along the NW-striking Central Fracture Zone of the Philippine Sea. The floor of the basin is made up of tholeiitic basalt covered by volcanogenic sedimentary rocks [*Geotraverse ...,* 1991].

Parece Vela Basin is believed [*Mrozowski and Hayes,* 1979] to have been produced in the course of back-arc spreading that occurred in the Philippine Sea in the Early Oligocene-Middle Miocene epoch. The axis of this spreading zone is the Parece Vela Rift. The floor of the basin is composed of tholeiitic basalt covered by a thin layer of volcanogenic sedimentary rocks. Samples of dunite, harzburgite, lherzolite, wehrlite, anorthosite, troctolite, and olivine gabbro were dredged from the western side of the Parece Vela Rift from a depth of 6 km, and ferrous, high-Ti oceanic tholeiites with a slightly elevated alkalinity, from a depth of 4 km [*Shcheka et al.,* 1986].

Mariana Island Arc consists of the West Mariana Ridge, Mariana Trough, and Mariana Ridge. The Mariana Trough was formed roughly 6 million years ago. The axis of the trough is traced by an active rift with a width of 10–15 km and a relative depth of 1–2 km. The rift is filled with tholeiitic basalt covered by silt, siltstone, and volcanic sand. The basement of the trough consists of various gabbroids penetrated by drill holes [*Hussong et al.,* 1981]. The Earth's crust is 5–8 km thick there.

Mariana Trench has a depth of 8.6 km, where it was crossed by the geotraverse, and is almost devoid of sediments. Two holes drilled at depths of 6450 and 7030 m penetrated the rocks less than 150 m thick. The upper 20-meter sequence consists of the Late Pleistocene diatomaceoussiliceous ooze with volcanic sand, resting on an olistostrome containing Oligocene to Cretaceous organic remains. Apart from the sedimentary rocks, the dredges contained fragments of metabasics, metadiabase, and gabbroids. The samples dredged from the trench slopes also included Miocene limestones and siliceous–argillaceous deposits, phosphate breccias [*The Geology...,* 1980], harzburgites, serpentinites, lherzolites, gabbro, and volcanic rocks ranging from basalt to dacite [*Bloomer and Hawkins,* 1983].

Magellan Seamounts were investigated during the cruises of R/V Akademik Nesmeyanov, R/V Akademik Keldysh, and R/V Conrad [*Smith et al.,* 1989; *Vasiliev et al.,* 1985]. Olivine–plagioclase basalts, agglomerate lavas, breccias, and tuffs of basic composition were dredged from the southeast-

ern and southern slopes of the seamounts at depths of 1400 and 4800 m. The basalts dredged by the R/V Conrad were dated 120 Ma for the samples from Himu Seamount and 100 Ma for the samples from Hemler Guyot [*Smith et al.,* 1989]. The DSDP Hole 452 drilled from R/V Glomar Challenger where the geotraverse crossed the oceanic side of the Mariana Trench penetrated 25 m of Neogene–Quaternary pelagic mud which had been deposited, after a long break in sedimentation, on a Late Cretaceous sequence of argillite, chert, radiolarite, and porcellanite [*Hussong et al.,* 1981].

The lithospheric structure of the region was studied using a variety of geophysical and geological data which yielded the thickness of the lithosphere to be 50–100 km in the North China Plain, 50–80 km in the West Philippine Basin, 30 km in the Parece-Vela Basin, and 10 km in the Mariana Trough [*Geotraverse...,* 1991; *Rodnikov et al.,* 1996] (see Figure 14). The analysis of the endogeneous temperature variations along the geotraverse [*Geotraverse...,* 1991] revealed that the older the lithosphere, the deeper were the isotherms (Figure 17). The isotherms of 1000–1200°C (typical melting temperatures of upper-mantle rocks) occupy the highest positions under the recent rifts of the Mariana Trough, where they reach the level of the Earth's crust. These isotherms reside at a depth of 30 km in the Miocene Parece Vela Basin and at a depth of ca. 60 km under the older Eocene West Philippine Basin marking the position of a potential melting zone inferred from the high electric conductivity data.

The Pacific Plate is characterized by the values typical of old oceanic regions. At a depth of about 80 km the top of a low-velocity layer was recorded in the mantle with lower velocity values ($V_p = 8.4$ km/s) and a thickness of ca. 40 km [*Asada and Shimamura,* 1976]. The upper mantle under the Mariana Island Arc showed abnormally low velocity values [*Seekins and Teng,* 1977]. In the narrow region along the trough axis the low-velocity layer seems to rise abruptly to depths of about 10 km. The trough is an interarc basin which had been formed 6 million years ago as a result of a spreading process. The rift structures are marked by tholeiitic basalt flows and intensive hydrothermal activity. High heat flow values were reported [*Hobart et al.,* 1983]. American geoscientists, who carried out investigations using the ALVIN submersible in 1987, discovered hot springs with a water temperature as high as 285°C [*Craig et al.,* 1987]. Hydrothermal activity with the deposition of zinc, copper, and iron sulfides was recorded during the Glomar Challenger deep-sea drilling and Hakuho-Maru dredging [*Hussong et al.,* 1981]. The water samples were found to be high in helium, hydrogen, and methane. The same gases were discovered on mid-oceanic ridges. The Mariana Trough has a thin crust (ca. 10 km). The hot asthenosphere rises as high as the crustal base, being responsible for high tectonic and magmatic activities. Figure 18 displays the deep structure of the Mariana Island Arc. Six million years ago the hot asthenosphere rose to the crustal base and split the Mariana Island Arc into two arcs with the formation of an interarc trough, broken into several grabens by faults, which are marked by a high hydrothermal activity with the deposition of zinc, copper, and iron sulfides. The Mariana Trough seems to be an example of the early formation of a sedimentary basin.

The asthenosphere is located at a depth of about 30 km

Sulfides in Mariana Trough
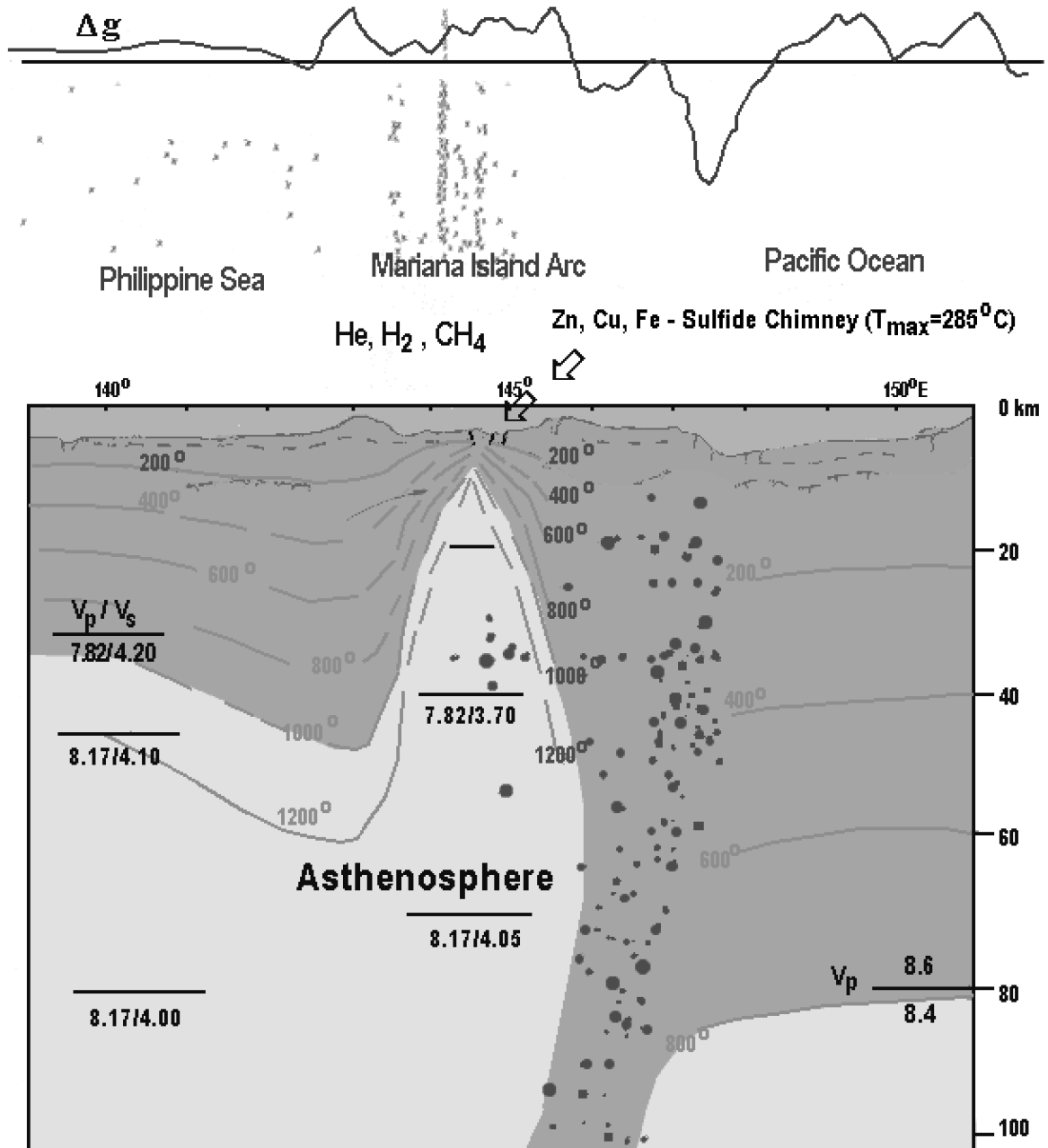
Figure 18. Deep structure of the Mariana Island Arc. Six million years ago the Mariana Island Arc was split, as a result of the rising of an asthenospheric diapir, into two arcs with the formation of an interarc trough, broken into several grabens containing black-smoker mounds composed of zinc, copper, and iron sulfides similar to those found on mid-oceanic ridges.

under the Miocene Basin of Parece Vela, and the top of a low-velocity layer was located at a depth of about 50 km under the Eocene Basin of West Philippine [*Abe and Kanamori,* 1970; *Seekins and Teng,* 1977; *Shiono et al.,* 1980].

Like in the case of the other marginal seas, the Philippine Sea region is marked by a certain correlation between the deep structure of the upper mantle and that of the surface geological formations. The more elevated is the astheno-

sphere, the higher is the heat flow and the younger are the deep-sea basins and sedimentary basins in the region of the Philippine Sea. The depth of the asthenosphere is 10 km under the Mariana Trough with its recent tectonomagmatic activity, 30 km under the Miocene Basin of Parece Vela, and 50–80 km under the Eocene Basin of West Philippine. The asthenosphere resides in a depth interval of 50–70 km under the North China Plain with its oil and gas sedimentary basins, which was reactivated during the Cenozoic.

These common features seem to reflect the common formation mechanism of the Philippine Sea basins in the course of the different-age processes of back-arc spreading, complicated by channelized rising fluid melt flows [*Rodkin and Rodnikov,* 1996].

The sedimentary basins of the marginal seas are distinguished by their anomalous structure compared to the other regions. Their typical features are the localization of diapirs under sedimentary basins, rifting or spreading centers at their bases, active volcanism during the early history of their formation, associated with hydrothermal activity and sulfide deposition, and the high heat flow caused by the rise of the asthenosphere toward the surface. It appears that asthenospheric diapirs involving the partial melting of the rocks operated as conduits channeling hot mantle fluids from the asthenosphere to the sedimentary basins [*Rodnikov et al.,* 2001].

Conclusion

A distinctive feature of the transitional zone between the Eurasian continent and the Pacific Ocean is the presence of an asthenospheric layer in the upper mantle and the rising of the diapirs of a hot anomalous mantle material, which controlled the formation of the sedimentary basins of the marginal seas. There is an obvious correlation among the geological features, tectonomagmatic activity, and the structure of the upper mantle. The tectonically active regions, such as the island arcs and the rifts of the marginal seas, correlate with a thick, clearly expressed magma-generating asthenosphere.

The asthenospheric rises are marked on the Earth's surface by rift formations and mainly tholeiitic magma flows. They reside in extension zones and develop in regions of a thinner lithosphere and high heat flow.

This study proved a correlation between the heat flow and tectonomagmatic activity [*Grachev,* 2000; *Smirnov,* 1986]. It is expressed in the growth of heat flow in the younger tectonic zones caused by the intrusion of asthenospheric diapirs into the lithosphere, involving tectonomagmatic reworking. The more elevated is the asthenosphere, the higher is the heat flow and the younger are the tholeiites covering the deep-sea basins of the marginal seas. The asthenosphere resides in a depth interval of 50–80 km under the old Paleogene deep-sea basins of the marginal seas, such as the West Philippine Basin, at about 30 km under the Neogene basins, such as the Parece Vela Basin in the Philippine Sea or the Kuril Basin in the Okhotsk Sea, and at a depth of merely 20–10 km under the Pliocene–Quaternary and recent inter-arc basins, causing the breaks of the lithosphere, the formation of rifts, basalt lava flows, and hydrothermal activity. Hydrothermal activity is restricted to the rifts of the inter-arc troughs, such as the Mariana and Okinawa Troughs and the Kuril Basin, where the asthenosphere is most highly elevated. The following sequence of events has been derived: the upwelling of the asthenosphere toward the base of the island arc crust – breaks of the lithosphere with the formation of inter-arc troughs – the formation of magma chambers in the crust and mantle – the development of rifts with a tholeiitic magma flow and hydrothermal sulfide deposition.

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