Chapter 3

Seismological Studies on the Deep Interiors of the Earth Viewed from the Polar Region

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Additional information is available at the end of the chapter

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Abstract

Seismological studies on the deep interiors of the Earth (depth range from the mantle to the inner core) viewed from the polar region have an advantage to promote global geosciences, such as for revealing the heterogeneous structural variations along the latitude from the poles to the equators. In this chapter, major seismological investigations, which had been held during the IPY, particularly newly identified founding of deep interiors of the Earth, will be introduced.

Keywords: deep interiors, polar region, IPY, seismic tomography, receiver functions, D″ layer

1. Introduction

Since the era of the International Geophysical Year (IGY 1957–1958), a lot of seismological studies concerning multiscaled and temporal-spatial heterogeneous structures in the deep interiors of the Earth have been investigated using the dataset obtained from the polar region (seismographs with various wavelengths, travel times of seismic phases, hypocentral information, source mechanism, etc.) by a significant number of seismologists in the world. Studies of the deep interiors from the polar region could contribute to global earth sciences such as for revealing the heterogeneous structures along the latitudinal variations in terms of their advantage in high latitude. The most important advanced studies of the Earth from the polar region before the IPY era were conducted to explore the boundary layers between the outer core and the lowermost mantle (i.e., the D″ layer with a few hundred km of thickness above the core-mantle boundary), as well as the structure and dynamics of the inner core (center core region).

Before the IPY, for instance, the major results obtained for the deep interiors of the Earth by using the data from Syowa Station are as follows: the heterogeneous structure of the D″ layer beneath the Antarctic Plate was determined by using the data from the Federation of Digital Seismographic Network (FDSN) including the Japanese Syowa Station of East Antarctica. Shear wave–splitting analysis of SKS phases demonstrated a shear wave isotropy of 2.0% for the maximum within the D″ layer beneath the Antarctic continent and the surrounding ocean [1, 2]. The depths of the velocity discontinuity above the D″ layer were determined as 50–100 km shallower than those of the Alaska region and the Caribbean Sea. Moreover, the heterogeneous structure and "super-rotation" of the inner core were observed by using the data from the Amundsen-Scott South Pole Station (ASSPS) and the Syowa Station including long-term analog records for more than 30 years [3, 4]. Thus, these long-term records obtained from the polar region have been efficiently utilized for the purpose of studying the Earth's interiors.

In this chapter, the major seismological investigations held during the International Polar Year (IPY 2007–2008), particularly the newly achieved founding involving deep interiors of the Earth, are summarized.

2. Antarctic region

Before the IPY, a three-dimensional seismic velocity structure of the Antarctic Plate had been investigated by surface wave tomography using the shallow earthquakes that occurred at the plate boundaries and the surrounding plates [5–8]. The utilized seismic data have been compiled in the Data Managing System (DMS) of the Incorporated Research Institutions for Seismology (IRIS) as the stations belong to FDSN. For instance, the seismic travel-time tomography beneath the Erebus Volcano of Ross Sea (near McM; see **Figure 1** of Chapter 1) indicated the existence of a remarkably low-velocity anomaly associated with hot spots, which originate from the volcano [8]. The average thickness of the continental crust of East Antarctica was 10–20 km larger than that of West Antarctica; the corresponding lithosphere of East Antarctica posed high-velocity layers down to a depth of 150 km. Moreover, an investigation by body wave propagation within the upper mantle of East Antarctica revealed the presence of a strikingly low-velocity anomaly in the 200-km depths underneath the lithosphere [9]. In order to explain the velocity models derived from both the observed and theoretical waveforms, the presence of the unique chemical composition and thermal gradient for the "depleted mantle" was required, which characterizes the Archean age in the Earth's history. Moreover, a three-dimensional seismic velocity model of the upper mantle beneath the Erebus Volcano of Ross Island was derived by travel-time tomography [10] using the data from the Transantarctic Mountains Seismic Experiment (TAMSEIS; 2000–2002) [11]. The low-velocity region corresponds to a hot plume of the volcano that continued from the surface of the Earth to the 410-km seismic discontinuity.

During the IPY, the total number of seismic stations was remarkably increased within the Antarctic continent by conducting several geophysical projects. As introduced in Chapter 2, obtaining data from the Antarctica's Gamburtsev Province (AGAP) of the Gamburtsev Mountain Seismic Experiment (GAMSEIS; **Figure 1a**) and the Polar Earth Observing Network (POLENET), the space resolution of the Earth's structure by seismological research had been significantly improved. The crust and upper mantle structures beneath the wide area of East Antarctica with the center at the Gamburtsev Subglacial Mountains (GSM) were precisely achieved by phase velocity analysis using the waveform data obtained from AGAP [12]. The shear wave velocity of the Precambrian cratons (continental blocks) at the inland plateau of East Antarctica represented an intermediate velocity model between the high-velocity structures that appeared at the Slave Province of Canada and the Yilgarn region of West Australia and the relatively low-velocity regions such as that of the north-east craton in the Mainland China. The lithospheric age down to a depth of 250 km under GSM was revealed to be early Proterozoic (or late-Archean) compared with that under the other globally distributing continents [12]. Moreover, the crustal thickness of GSM was found to be more than 55 km thick; this was comparable with those determined by body wave tomography and receiver function analyses.

Seismic travel-time tomography by using body waves obtained from AGAP demonstrated the existence of a high-velocity region in the upper mantle depths beneath the wide area including GSM [13] (**Figure 1b**). The evidence suggests the presence of the "thick lithospheric root" under the East Antarctic continent; however, there are also horizontal variations in high-velocity layers within the depths of 150–350 km. Therefore, conducting additional analysis in relation to the geological formation process of the mantle structure under the continent is required. The upper mantle isotropy of the wide area of East Antarctica was investigated by shear wave–splitting analysis adopting the teleseismic SKS waves recorded by AGAP [14]. A space distribution of the fast-splitting orientation for shear waves suggested the presence of several subtectonic terrains characterized by different orientations of the isotropic axis within the studied regions of AGAP. Particularly, beneath and around GSM, identically different results were achieved as the fast polarization orientation in shear wave isotropy; a local difference in the isotropy was assumed to be affected by several candidates of geoscientific information, such as the seismic velocity distribution within the continent and other geophysical and geological information, as well as the orientation of plate movement of the Antarctic Plate against hot spots that could reveal the tectonic history of the formation and breakup process of the supercontinent in the Southern Hemisphere.

In contrast, a clear difference of dispersion curves between West and East Antarctica in the phase velocity of Rayleigh waves was obtained from the POLENET data, together with a difference between the coastal area and the interior of the two continental terrains [15]. Moreover, P-wave receiver functions demonstrated a detailed structure of the seismic discontinuities and mantle transition zones of the upper mantle beneath the West Antarctic Rift System (WARS) using the IPY-retrieved data [16]. A complicated distribution of the thermally upwelling mantle plumes was clearly identified. In addition, a shear wave isotropy analysis by using the POLENET data in West Antarctica obtained the fastest splitting orientation for SKS waves (i.e., the strongest isotropic direction in the upper mantle), which did not correspond

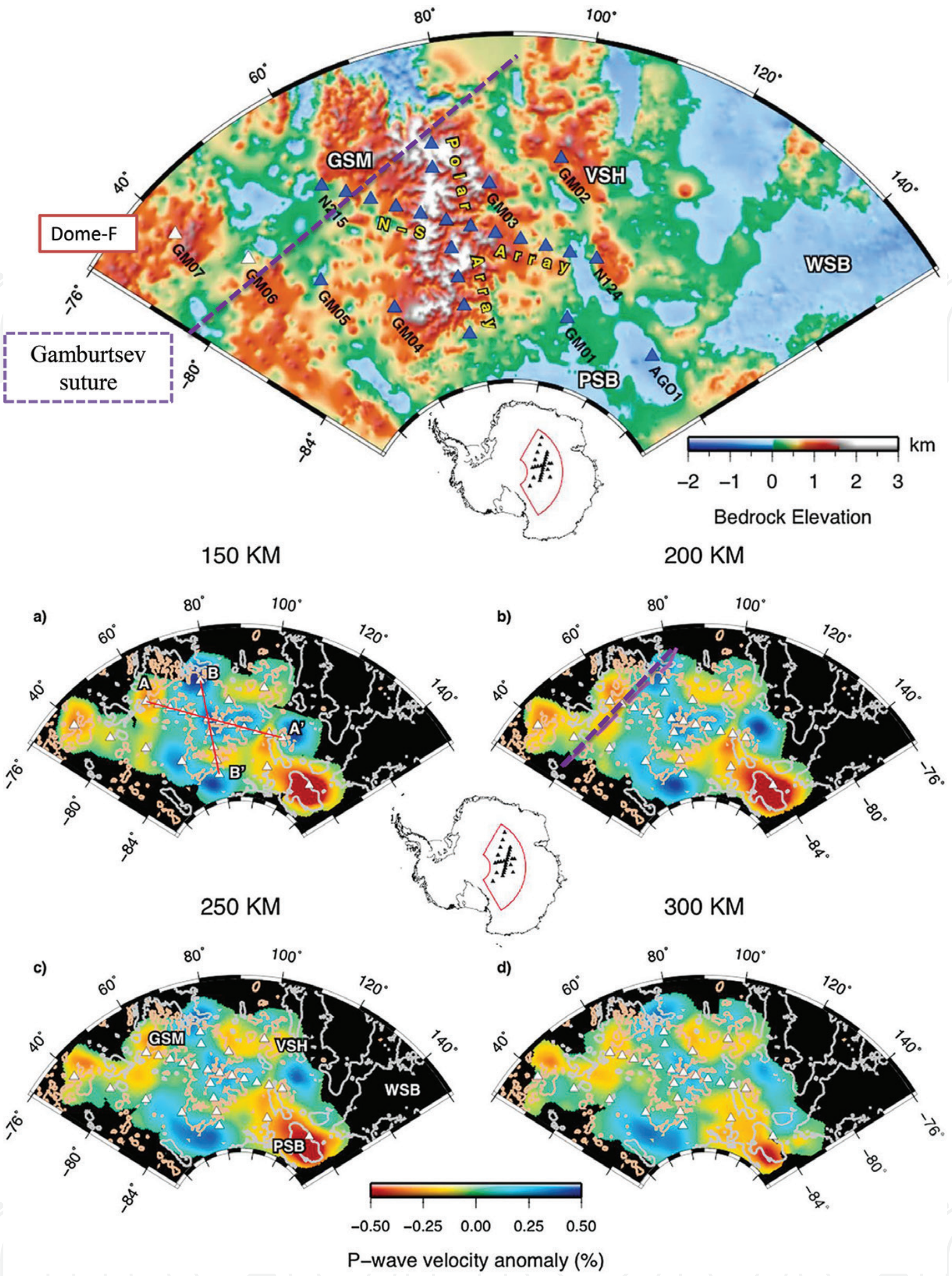

Figure 1. (a) Map of the AGAP-GAMSEIS seismic array, overlayed on the bedrock topography from BEDMAP2 [31] (modified after [13]). The blue and white triangles indicate the location of seismic stations provided by the United States and Japan, respectively. Abbreviations are as follows: GSM, Gamburtsev Subglacial Mountains; VSH, Vostok Subglacial Highlands; PSB, Polar Subglacial Basin; and WSB, Wilkes Subglacial Basin. Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4278571127723, license date: January 30, 2018. (b) Horizontal slices through the P-wave tomography model of the upper mantle structure beneath central East Antarctica by using the AGAP data, at the depths of 150, 200, 250, and 300 km, respectively (after [13]). Each slice shows the 0 m(gray) and 1000 m (tan) contours from BEDMAP2 ([31]). Abbreviations are the same as in (a). Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4278571127723, license date: January 30, 2018.

to the present plate movement rather the extensional tectonic regime within WARS [17]. However, a rather different oriented isotropy was achieved in the Marie Byrd Land (MBL), which reflected a past orogenic movement of the tectonic terrains.

Seismic tomography uses the P-wave travel times of all the POLENET data; moreover, the heterogeneous structure of the upper mantle with wavelengths more than 1000 km was clearly imaged with a high space resolution for the Antarctic continent, rather than those obtained from surface wave tomography [18]. In West Antarctica, particularly under MBL, hot plumes were recognized down to a depth of 800 km. The POLENET data were efficiently utilized in addition to the existing FDSN data. For instance, a very high-resolution three-dimensional shear velocity model was achieved for the upper mantle (both lithosphere and asthenosphere) of the Antarctic Plate, by applying a multifilter technique to the surface waves generated by earthquakes that occurred at the surrounding plate boundaries [19] (**Figure 2**). The tomography study imaged a lithospheric root in East Antarctica almost reaching down to a depth of 200 km as well as clear boundaries to separate each tectonic terrain (geological fragments) within the continent. Moreover, low-velocity regions were clearly found to spread out surrounding GSM, which might reflect an existence of a deep crustal root beneath the mountains.

As one of the tectonic regions in East Antarctica, the Lützow-Holm Bay area where the Japanese permanent station (Syowa) has been situated, the upper mantle isotropy and seismic discontinuity were studied during the IPY by using broadband seismic data distributed by the Japanese Antarctic Research Expedition (JARE) [20, 21]. A long-period P-wave receiver

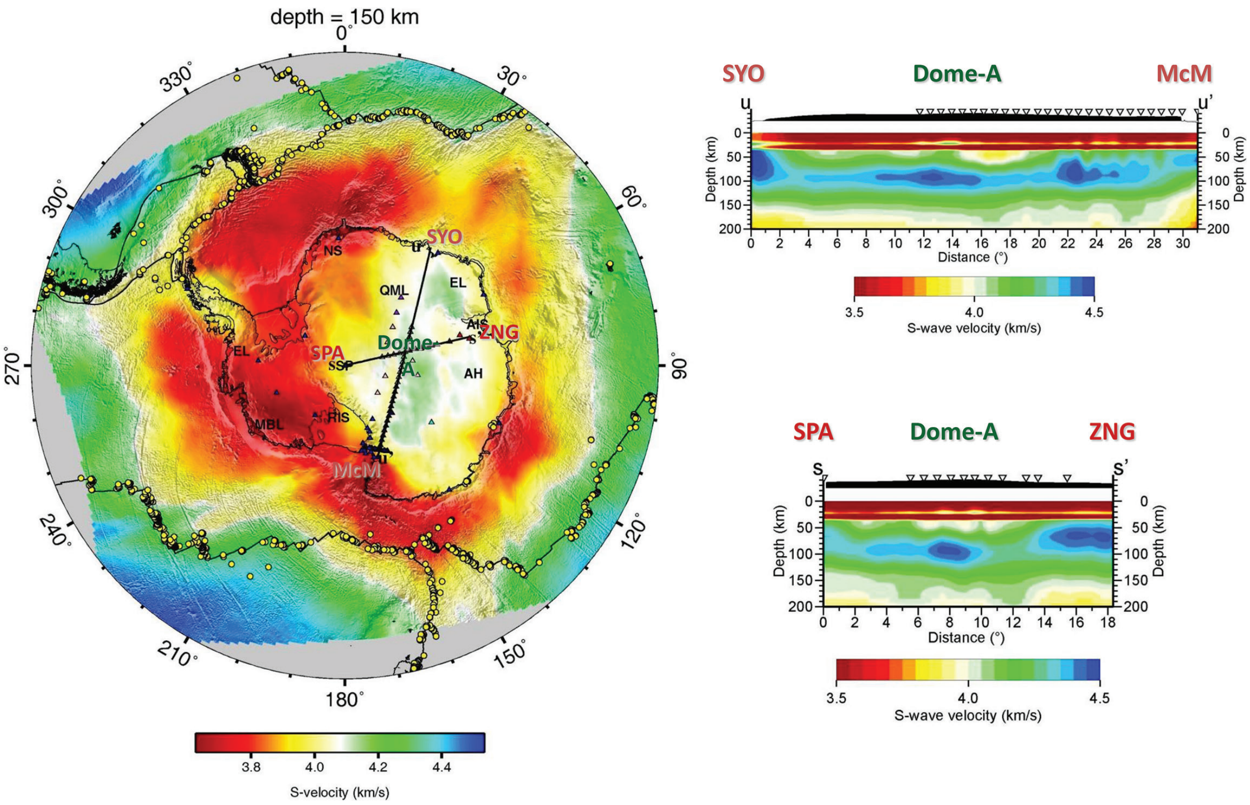

Figure 2. 3D image of the upper mantle shear velocity structure by surface wave tomography from the AGAP/POLENET data (modified after [19]). (Left) The 150-km depth slice for S-wave velocity distribution. (Upper right) Cross section down to a depth of 200 km depth for the profile SYO (u)-Dome-A-McM (u′). (Lower right) Cross section down to a depth of 200 km for the profile SPA (S)-Dome-A-ZHG (S′). Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4278580124881, license date: January 30, 2018.

function analysis demonstrated the heterogeneous velocity structures and distribution of upper mantle seismic discontinuities around the depths of 410 and 660 km [20]. Moreover, a shear wave–splitting analysis for SKS waves determined an isotropy of the upper mantle in LHB associated with the past mantle flows within the lithosphere-asthenosphere system and also a relationship with the tectonics of the region. Usui et al. pointed out a possibility that the breakup process of the Gondwana supercontinent had affected both the formation of seismic isotropy of the continental margins in LHB and the generation of orientation distribution of the depths of upper mantle discontinuities of the region.

3. Arctic region

There are several seismological research studies of the deep interiors of the Earth in the Arctic region during and after the IPY; a few examples are introduced, particularly the northern Eurasia continent (Siberia region), in this section.

By using active source dataset applied to the long-distance seismic profiles by the Peaceful Nuclear Explosions (PNEs), a wide area of Siberia has been investigated, and thickness of the lithosphere was derived [22]. However, variations in the thickness of the asthenosphere underneath the lithosphere could not be determined by the surveys. The derived velocity variations in the upper mantle were supposed to be caused by a vertical-layered structure or otherwise horizontal heterogeneity; however, it is difficult to distinguish the candidate exactly because of the sparse distribution of the PNE shot interval about 1000 km. Among the upper mantle models on the basis of seismic velocity at the Moho discontinuity derived from the high-resolution PNE data, the horizontal heterogeneity of the density structure was precisely examined [22]. The derived velocity model was characterized by three layers: the first layer is of 8.0–8.5 km/s, the second of 8.6–8.7 km/s, and the third of ~8.5 km/s. The thickness of the second layer varied strikingly, and a high-velocity portion was supposed to be composed of a high-density eclogite. The bottom of the second layer corresponded to the base of the lithosphere, followed by the existence of low-velocity asthenosphere underlying as the third layer. Horizontal variations in seismic velocities within the first layer, as well as the thickness variations in the second layer, correspond to the main tectonic terrains, that is, the West Siberian Basin, continental flood basalt associated with the P-T boundary, Yakutian kimberlite region, and others. In the West Siberian Basin, the thick sediment and the thin crust were clearly identified in terms of isostasy, together with the evidence of the "eclogite layer" within the upper mantle, where it is characterized by a large seismic attenuation as a result of a huge magmatic activity. However, as the physical/chemical condition of the mantle might have been deformed after 250 Ma, it is not enough to reveal the actual formation mechanism of the strong attenuation region with the available data.

The Baikal Rift Zone (BRZ) is located in the central part of the large Eurasia continent and far from the subduction zone of the Western Pacific to the east and the India-Himalaya collision zones to the south. BRZ is situated between the northern Siberian craton and the southern Paleozoic-Mesozoic mobile belts, together with the Mongolia-North China craton to the further south. BRZ has been characterized by the Cenozoic volcanism and local seismicity [23],

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the formation process of the great rift system, and the higher heat flow values compared with the surrounding areas [24]. BRZ has been recognized as the Moho depths on the basis of both the deep seismic surveys of active sources by the Russian Academy of Science [25] and the receiver function analysis using broadband teleseismic data around BRZ ([26], **Figure 3**). In addition, Nielsen and Thybo [27] revealed no Moho uplift below BRZ on the basis of a seismic refraction profile across southern Lake Baikal. Their velocity model showed a gentle deepening Moho from the Siberian Platform (41-km depth) to the Sayan-Baikal Fold Belt (46-km depth).

However, the crustal thinning feature was also identified, which is usually recognized at normal rift zones by a different receiver function study using temporary deploying broadband data in which the seismic station profile crossed the north-south direction in BRZ [28]. A difference in the crustal thickness in BRZ could be explained by an interpretation of the velocity anomaly structure at the lowest part of the crust in the deeper part of the rift. The formation process of BRZ has been explained by both the active force associated with the upwelling of mantle plumes and the passive far-field extensional force involving

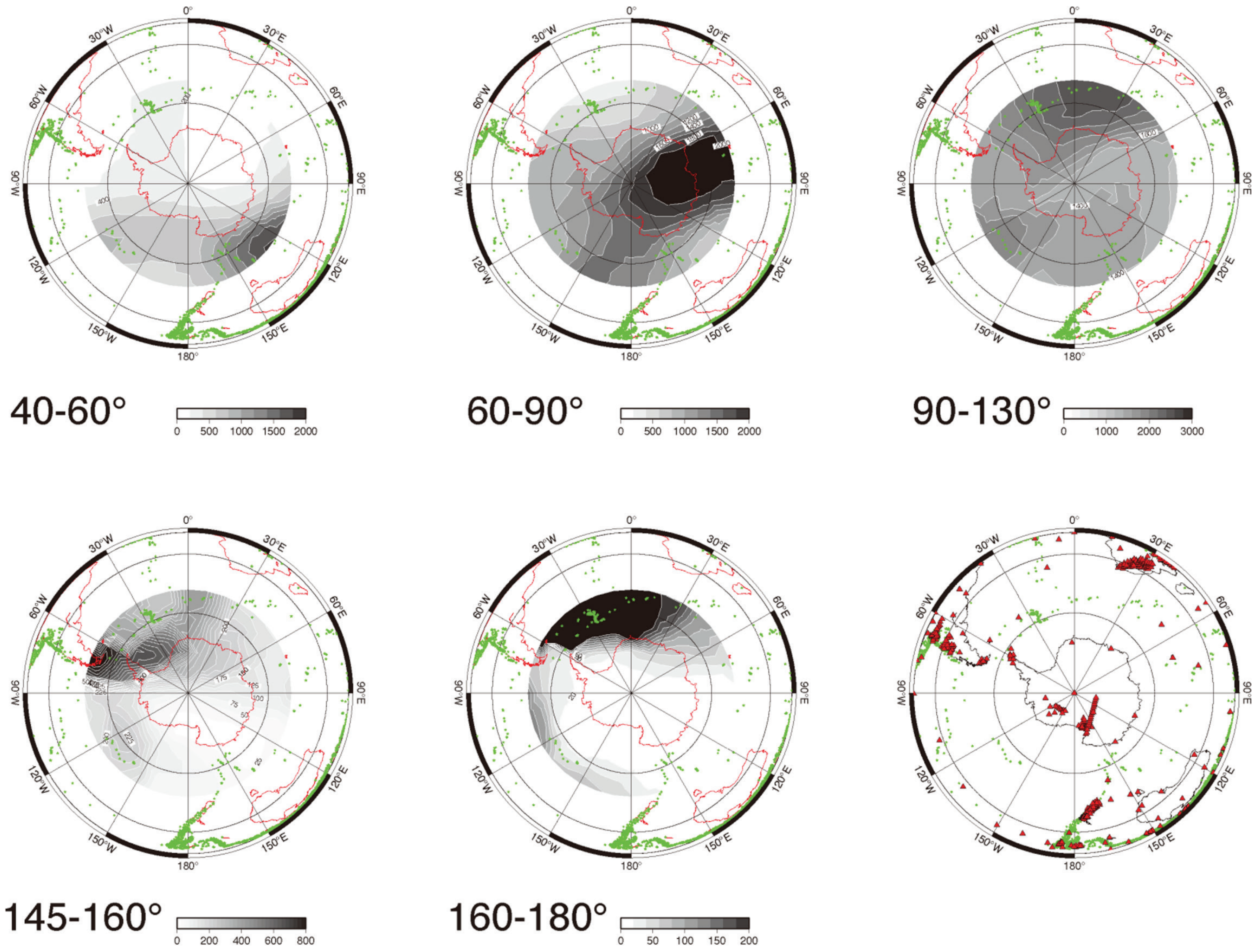

Figure 3. Geographical distribution of teleseismic event numbers (gray horizontal scales) observed at each location in the Antarctic for epicentral distances of 40–60, 60–90, and 90–130° (from the left to the right in the upper row) and 140–160 and 160–180° (in the lower row), respectively. A list including globally distributed earthquakes is used for counting magnitude mb greater than or equal to 5.5 for the period of 1990–2004. Epicenters are represented by green dots (lower right); red triangles are the permanent and temporary stations in Antarctica from IRIS/GSN and PASSCAL (after [30]) (first and corresponding author of this article) http://www.annalsofgeophysics.eu/index.php/annals/article/view/6379.

India-Asia continent-continent collision. In contrast, the top portion of mantle plumes was identified within the upper mantle depths beneath the rift on the basis of gravity anomalies and surface wave seismic tomography [29].

4. Monitoring the deep interiors

In addition to the analyses of the mantle structure underlying the Antarctic continent, teleseismic data detected by AGAP and POLENET have the advantages to study the heterogeneous structures and dynamics of the deeper part of the Earth's interior. Target depth areas are the lowermost layer of the mantle (D″) and the core-mantle boundary (CMB) [2], together with the inner core [3]. The heterogeneous and anisotropic structures of these depth ranges might be investigated by using teleseismic data retrieved from the polar regions, as a large aperture array located at a high latitude. **Figure 3** demonstrates the distribution of teleseismic event numbers at each location in the Antarctic region counted from a list including earthquakes with a magnitude greater than or equal to 5.5 in the period of 1990–2004, for different epicentral distance ranges. The epicentral distance range from 60° to 90° could be suitable for the observation of the D″-reflected phases, SdS, as well as the core-reflected phases of ScS and PcP. The epicentral distance range from 90° to 130° might be appropriate for the observation of the core-diffracted phases of Pdiff and Sdiff and the core phase of SKS.

As mentioned earlier, the Antarctic seismic stations play a key role in probing the Earth's deep structures, such as the D″ layer and the CMB. Kanao et al. [30] demonstrated efficiency to detect an interesting structure around the D″ layer, by using the stations as large aperture arrays across the Antarctic continent. By simulating teleseismic waveforms, continental scaled broadband seismic arrays of AGAP and POLENET have a high potential to precisely conduct and explore the D″ regions beneath many areas in the Southern Hemisphere. Seismic data obtained from the inland Antarctic continent could be expected to figure out clear images of the Earth's deep interiors with an enhanced resolution due to the high signal-to-noise ratio and the wide extent of this region, as well as the rarity of their sampling PKIKP paths along the rotation axis of the Earth [3, 4].

5. Summary

Geophysical bipolar networks deployed during the IPY (POLENET) in Antarctica, Canada, Greenland, Lapland, and northern Eurasia significantly contributed to the existing global networks (FDSN and CTBTO), as well as to the improvement of the space resolution in seismological structure of the Antarctic Plate and the pan-Arctic Ocean. Several seismic tomography studies using the data from AGAP/GAMSEIS and POLENET identified a precise heterogeneous structure of the Earth beneath the Antarctic continent with a high space resolution before the IPY. In order to investigate the deep interiors [the lowermost mantle (D″ layers) the outer and inner cores], bipolar regions have significant advantage to seek into the inner part of the Earth as a "window" at a high latitude. The POLENET stations, for instance, are utilized for the studies of global waveform propagation as "a large spanned (profiled) array," which crosses the Antarctic continent and/or the Greenland.

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