Chapter 4

Structural Studies on the Earth's Crust, Plates, and the Ice Sheet in the Polar Region

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Abstract

During the International Polar Year (IPY 2007–2008), a number of seismological studies regarding the structure and dynamics of the Earth's surface layers, the static inner structure of the crystalline crust and lithosphere involving Earth's history, earthquake occurrence mechanism, inner deformation of the plates, crustal movement relating to deglaciation, seismic isotropy, and the other topics of the ice sheet overlying the solid earth were conducted. In this chapter, recent seismological results as for the structural study of the crust, plates, and ice sheet in bipolar regions are overviewed.

Keywords: crust, upper mantle, lithosphere, plates, ice sheet, polar region

1. Introduction

After a half-century of the International Geophysical Year (IGY 1957–1958), a significant number of research activities relating to the Earth's environment were conducted in bipolar regions as a big global program during the International Polar Year (IPY 2007–2008). In geophysics branches such as seismology and geodesy, an international project of the Polar Earth Observing Network (POLENET) was carried out with strong cooperation and coordination between related scientists. (The details are introduced in Chapter 2.) In addition to the contribution of global seismology as viewed from high latitude, understanding of the inner structure of the Antarctic Plate and the Antarctic continent, the continental structure surrounding the Arctic Ocean, and the investigations of the overlying ice sheet could provide fundamental and useful information on variations of surface environment in the polar region. POLENET could be efficient in order to identify the source location of local earthquake and ice quake, occurrence mechanism using the information on structural parameter so as to derive surface layers of the Earth.

In this chapter, major seismological studies conducted during the IPY are summarized, in particular focusing on newly identified finds regarding surface layer of the Earth, crystalline crust and lithospheric plate, and overlying ice-sheet environment.

2. Antarctic region

Until the IPY era from the IGY, investigation on structure and dynamics of surface layers of the Earth in the Antarctic had been much improved by a combination of the globally distributed stations and earthquake locations, especially using the pairs of stations and events occurring in the bipolar region. Several categories of seismological research could be included: the inner structure of the crust and lithosphere relating to the Earth's history, earthquake occurrence mechanism and inner deformation of the plate, crustal uplift involving deglaciation, seismic isotropy associated with plate movement, and so on. For instance, seismic velocity models of the deeper part of continental crust in East Antarctica have been obtained by teleseismic waveform inversion using broadband data including from the Syowa Station (SYO) in the Lützow-Holm Bay (LHB). The velocity models were utilized to estimate physical characteristics of the rock composition of the crystallized crust based on a comparison with surface geology, microtectonics, and physical features measured by high-pressure laboratory experiments [1, 2]. In addition to the permanent seismic observations at the Syowa Station, deep seismic surveys (DSS) using active seismic sources were carried out in 2000–2002 on the ice sheet at the continental margin (Mizuho Plateau). (Details of the DSS logistics and operation were introduced in Chapter 1.) Fine velocity structure and seismic reflection section of the lithosphere in the LHB were achieved [3–6], and the past tectonics was estimated involving the formation process of the lithosphere by taking into account the information on ductile deformation of metamorphic rocks (**Figure 1**). Moreover, combining with other geological and geophysical information, formation and breakup history of the Gondwana supercontinent such as Pan-African orogenic events were estimated [7, 8]. In addition to these deep surveys of the crust and upper mantle, temporary shallow seismic reflection surveys were also conducted at the outcrops in East Ongul Island, where the Syowa Station is located. The layered structure of the metamorphic gneisses that compose a surface layer of the Lützow-Holm Complex (LHC), together with faulting system and fracture zones near the island, has been investigated [9].

During the IPY, in addition to the existing global network (Federation of Digital Seismographic Network, FDSN), a bipolar geophysical network (POLENET; refer Chapter 2 for details) was established and successfully conducted in collaboration with many involved countries. Using these data, space resolution within the Antarctic continent and surrounding oceanic plate has been remarkably improved, particularly inland plateau area of the continent. For example, using the teleseismic waveform data retrieved from Antarctica's Gamburtsev Province (AGAP)/ Gamburtsev Mountain Seismic Experiment (GAMSEIS) (Figure 2 of Chapter 2), crustal structure of a wide area of inland plateau in East Antarctica was obtained by simultaneous inversion of body waves (waveforms of S-receiver functions) and dispersion curves of surface waves [10].

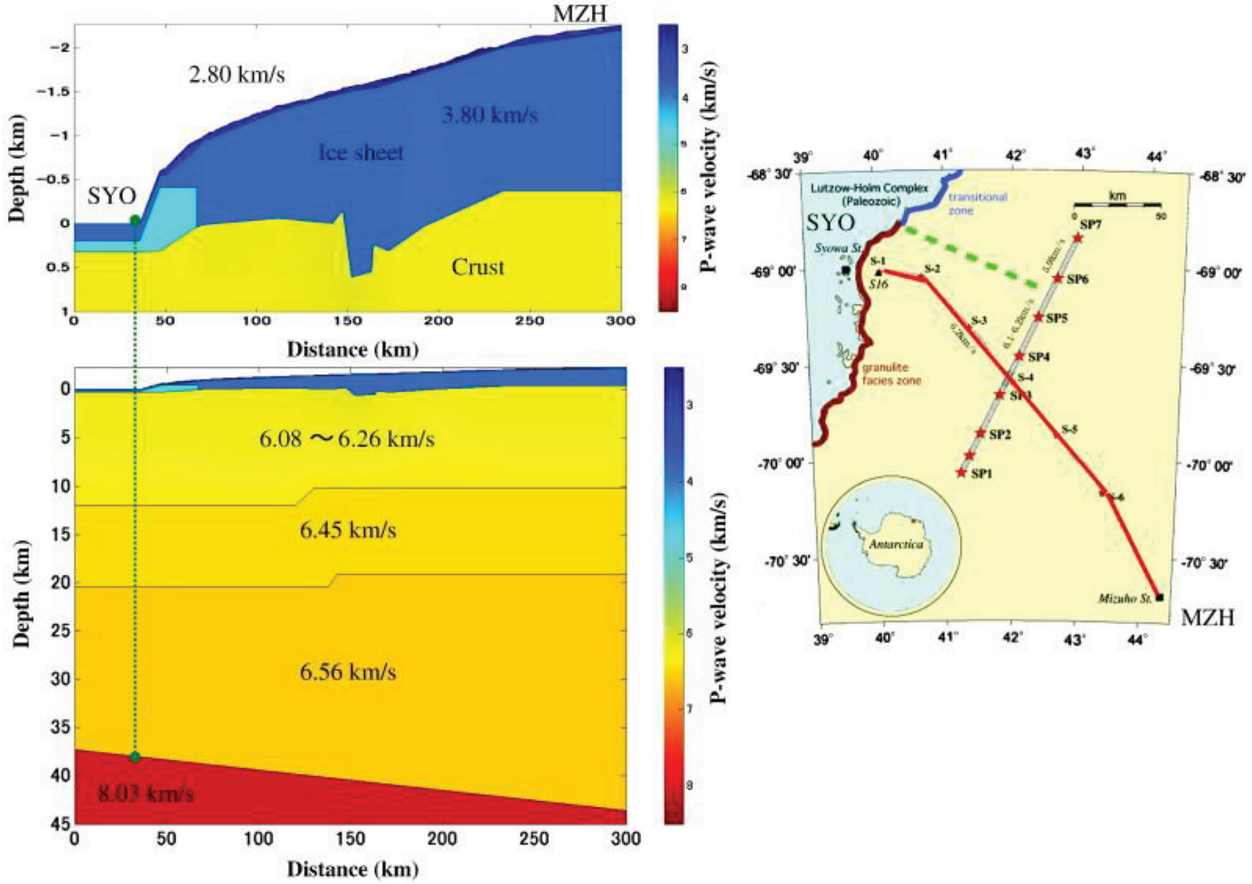

Figure 1. Left: P-wave velocity model of the crust, uppermost mantle, and the overlying ice sheet on the Mizuho Plateau, derived from refraction experiments by SEAL-2000 DSS (modified from Yoshii et al. [5]). The average depths of the discontinuities between the upper and the lower crust (Conrad) and between the lower crust and the upper mantle (Moho) are 20 and 40 km, respectively. Right: location of the DSS profiles on the Mizuho Plateau. SEAL-2000 profile is indicated by the red line, which was the same location as the pre-SEAL DSS in 1980. The NE-SW seismic profile (SP1–SP7) indicates DSS conducted by SEAL-2002. (All the figures are from Kanao et al. [13]). Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4279620091481, license date: January 31, 2018.

On the basis of the distribution in travel times for the S to P conversion points at the Moho discontinuity by S-receiver functions, crustal depths beneath each seismic stations were estimated by assuming the upper mantle seismic velocities determined by the surface waves [11]. In particular, beneath the Gamburtsev subglacial mountains (GSM; see Figure 2 in Chapter 2), quite large crustal depths over 55 km were identified; the evidence suggested the existence of a "crustal root" associated with the continent-continent collision at the orogenic events during the Pan-African age. Moreover, as the crustal uplift model supports the present high-elevation and formation process of GSM, extension effects by rift origins at 250 and 100 Ma were expected in addition to the crustal formation process before 1000 Ma, by compiling the data from AGAP (potential field data of gravity, geomagnetism, and bedrock topography) and information on geological structure surrounding GSM [12].

At the western end of the area deployed by AGAP/GAMSEIS in the high plateau of East Antarctica, Dome-F, a Japanese station, is located. The seismic crustal structure between Dome-F and a coastal area of the Eastern Dronning Maud Land (DML), which is LHB, had not yet been investigated before the IPY. Therefore, the total crustal structure from the coastal area of LHB to Dome-F was derived by extending the structure determined by deep seismic surveys on the Mizuho Plateau [5, 8] toward the inland high-elevation region until Dome-F, on the basis of gravity anomalies measured by several inland traverses [13]. The estimated crustal thickness of Dome-F was about 47 km, which had a smooth connection with that obtained by a receiver function analysis around GSM by the AGAP data [10]. These crustal structures beneath the high plateau of the DML-GSM area were connected to the eastward adjacent regions toward the Northern Victoria Land, using temporal broadband seismic data from the Transantarctic Mountain Seismic experiment (TAMSEIS), which was held in 2000–2002. By combining the crustal structure from receiver function inversion by TAMSEIS [14], a total profile that crosses the East Antarctic continent was achieved [13] (**Figure 2**).

In contrast, the crustal structure in West Antarctica was mainly obtained by the POLENET data. In addition to the conventional travel-time seismic tomography methods [15], a study using Ambient Noise Correlation method was carried out. The obtained seismic structure corresponding to the crustal depths can be achieved by taking the noise correlation between the two ambient stations using "green functions." The result [16] indicated a difference in the crustal structure between West and East Antarctica at a depth of 27 km, especially at the West Antarctic Rift System (WARS) where the region from the Antarctic Peninsula to the Ross Sea was identified to be a small crustal thickness and relatively hot temperature structure in the upper mantle underneath. Recently, moreover, new volcanoes were identified beneath the ice sheet of the Marie Byrd Land (MBL) by using the POLENET data of East Antarctica [17]. Low-frequency seismic tremors associated with the volcanic activities were determined to occur concentrating around the depths of 25–40 km beneath the ice sheet; the volcanic ash layers inside the ice sheet of the region were estimated about 8000 years ago on the basis of radar echo sounding measurements. With these concerns, tectonic activities have been found to continue around WARS until now. Moreover, P-wave travel-time tomography research obtained three-dimensional velocity structure of the Bransfield Strait (BFS) by using the data from both the temporary and permanent networks in the northern Antarctic Peninsula [18]. The tomography result imaged the presence of steeply subducting oceanic plate (slab, the Phoenix Plate) under BFS, as well as strong low-velocity anomalies in the 100–300 km depths involving the formation of volcanoes inside the strait.

Following the above results, temporal observation networks deployed during the IPY (AGAP/GAMSEIS and POLENET) have greatly contributed to the increase of space resolution in constraining the seismic structure of the Antarctic. Surface wave tomography using the whole dataset of POLENET achieved higher resolution images of the Antarctic Plate ever than before. Striking scientific achievements were conducted about the lithospheric structure and uplift mechanism of GSM and the formation process of the Gondwana supercontinent, together with bedrock topography and geological structure underneath the ice sheet. Crustal structure for all over the Antarctic continent was compiled by seismological studies including those during the IPY [19] (**Figure 3**). The data obtained during the IPY are also expected to provide basic information for seeking the deep interiors of the Earth, inner structure of the ice sheet, subglacial environment, fine and small-scale crustal structure, tectonic and cryodynamic seismic events, and the other new frontier topics on polar seismology.

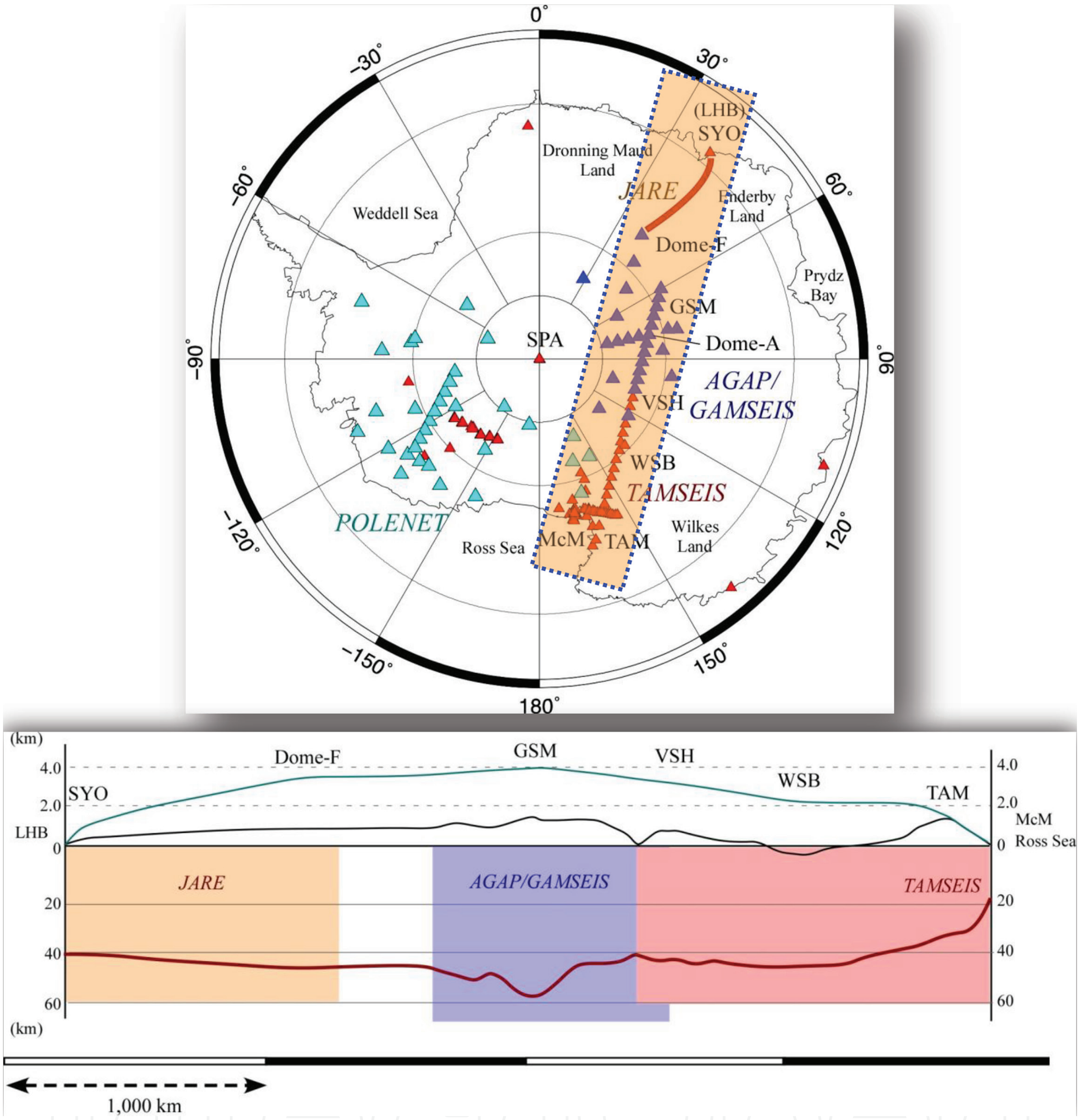

Figure 2. Upper: general location of inland traverse area for gravity surveys conducted by JARE (red thick line; from SYO to Dome-F), along with broadband seismic stations deployed by AGAP/GAMSEIS (dark blue triangles) and TAMSEIS (red triangles; extending from McM to near Dome-A) (after [13]). Some of the seismic stations deployed before the IPY 2007–2008 are also indicated by the other red triangles (mainly located in West Antarctica and near McM). POLENET stations in West Antarctica deployed during the IPY are also indicated by the light blue triangles. Major location names are provided. Abbreviations are as follows: McM, McMurdo Station; TAM, Transantarctic Mountains; WSB, Wilkes Subglacial Basin; VSH, Vostok Subglacial Highlands; SPA, South Pole Station; GSM, Gamburtsev Subglacial Mountains; SYO, Syowa Station; and LHB, Lützow-Holm Bay. Lower: an illustration of the combined crustal cross section across East Antarctica from LHB (SYO) to Dome-F, GSM, and TAM (McM) (after [13]). The Moho topography (thick solid red line), bedrock topography (black solid line), and the surface elevation of the ice sheet (light blue solid line) are shown. Abbreviations of the region names are the same as in the upper panel. The JARE structure is obtained from Kanao et al. [13], while the GAMSEIS and TAMSEIS structures are from Refs. [10] and [14], respectively. Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4279620091481, license date: January 31, 2018.

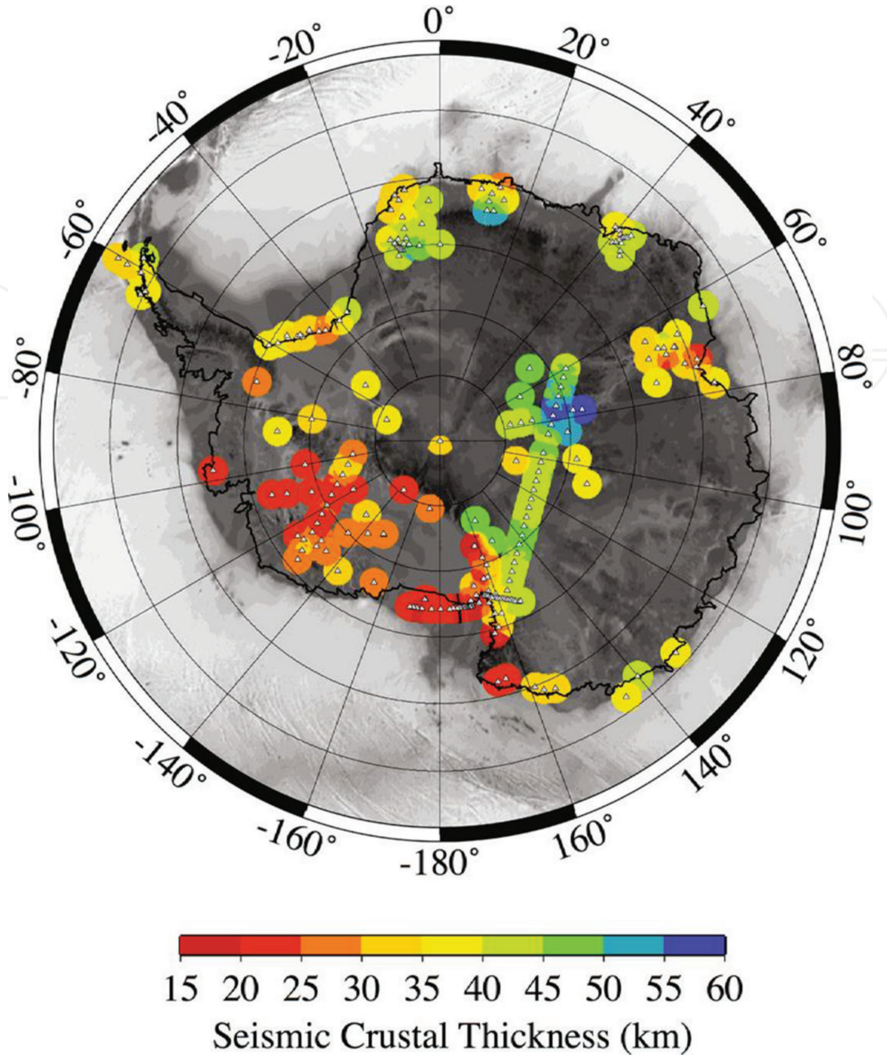

Figure 3. Distribution of Antarctic seismically inferred crustal thickness compiled from the results during the International Polar Year (IPY 2007–2008) (after [19]). Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4279621203188, license date: January 31, 2018.

3. Arctic region

As there are a lot of seismological investigations for the crustal and lithospheric structure in the Arctic region during the IPY, several examples are demonstrated in this section.

Seismic investigations were performed along three refraction and wide-angle reflection profiles in southern Svalbard (SV; see Figure 1 of Chapter 1), between the Mid-Atlantic Ridge and the Barents Sea [20]. By combining both the gravity and seismic datasets, structures of the oceanic crust, transition zone between continent and ocean (COT), and continental area down to lithosphere-asthenosphere boundary (LAB) were obtained. The seismic velocity structure indicates the presence of the lherzolite composition in the uppermost oceanic mantle, together with dunite composition under the continental area. It has been considered that the observation of regional scale Lg waves suggested the existence of continental crust with a thickness of 30–40 km along the propagation paths. The propagation characteristics of the Lg waves suggest the difference between continental and noncontinental features around the area of the Amerasia Basin [21]. By comparing the observed arrival times and synthetic ones, majority of the area of the Amerasia Basin could be explained by an intermediate crustal thickness between the thin continental feature and the oceanic one, which is similar to the structure of the North Sea.

An explosive refraction/wide-angle reflection seismic experiment was conducted on the ice cap in east-central Greenland [22]. To constrain a velocity model for the whole depths within the crust, significant surface waves that propagate over the surface of the ice sheet were clearly observed (the "ice wave"). Using a teleseismic dataset recorded at ice-sheet stations in Antarctica and Greenland, POLENET, the velocity models within a whole depth range of the ice sheets were derived [23]. Identical two-layered structure of the ice sheets was determined: the upper was characterized by a variable thickness (about 2/3 of the total) and velocities similar to the standard ice caps and the lower held about constant thickness with normal P-wave velocities in spite of smaller S-wave velocities. The low S-velocities could be explained by the presence of unfrozen liquids as a result of premelting at grain joints. As a third study, synthetic seismograms were constructed so as to figure out a realistic regional structure model beneath Greenland [24]. Elastic wave propagation up to 2 Hz against different ice-sheet models was calculated by assuming various focal depths and seismic source mechanisms. Ice-sheet–guided S waves (the "ice wave") were generated in the cases with near-surface seismic sources, characterized by surface wave group velocities with smaller than the S-wave speed within the ice layer.

4. Summary

Geophysical observation networks deployed during the IPY both in the Antarctic and in the Arctic, POLENET, significantly contributed to the existing global networks, FDSN, as well as to the improvement of space resolution in crustal structure of the Antarctic Plate. Remarkable achievements were conducted about the lithospheric structure and uplift mechanism of GSM and the formation process of Gondwana, together with bedrock topography and geological structure underneath the ice sheet. Moreover, by combining the crustal structure from Dome-F to Syowa Station in Eastern Dronning Maud Land with the western end of the GAMSEIS profile, the whole crustal section crossing the East Antarctic continent was imaged and contributed for understanding the structure and evolution of the upper mantle underneath the crust. The data obtained during the IPY are also expected to provide new information on surface layers of the Earth, inner structure of ice sheet, subglacial environment, fine and small-scale crustal structure, tectonic and cryoseismic events, and so on. Regarding the Arctic domain, several investigations to study the interiors of the upper crust and ice sheet were carried out in many areas of the Arctic Ocean, Siberia, Greenland, and Canada by using both passive and active seismic sources. A lot of new findings have been compiled such as the trapped waves inside ice sheet, isotropy and propagation features within the ice sheet, microseismicity at the bottom of ocean, and so on. These fruitfully achieved datasets could surely provide efficient

information on revealing the activities and mechanism of glacial earthquakes, cryoseismic events in terms of climate change in the Arctic after the IPY era.

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