LAKSHMAN SIDODIA

A Comprehensive Approach to
POLAR SEISMOLOGY

A Comprehensive Approach to Polar Seismology

A Comprehensive Approach to Polar Seismology

Lakshman Sidodia

VIDYA BOOKS

Published by Vidya Books,
305, Ajit Bhawan,
21 Ansari Road,
Daryaganj, Delhi 110002

Lakshman Sidodia
ISBN: 978-93-5431-309-7

Contents

Chapter 1

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

Masaki Kanao

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

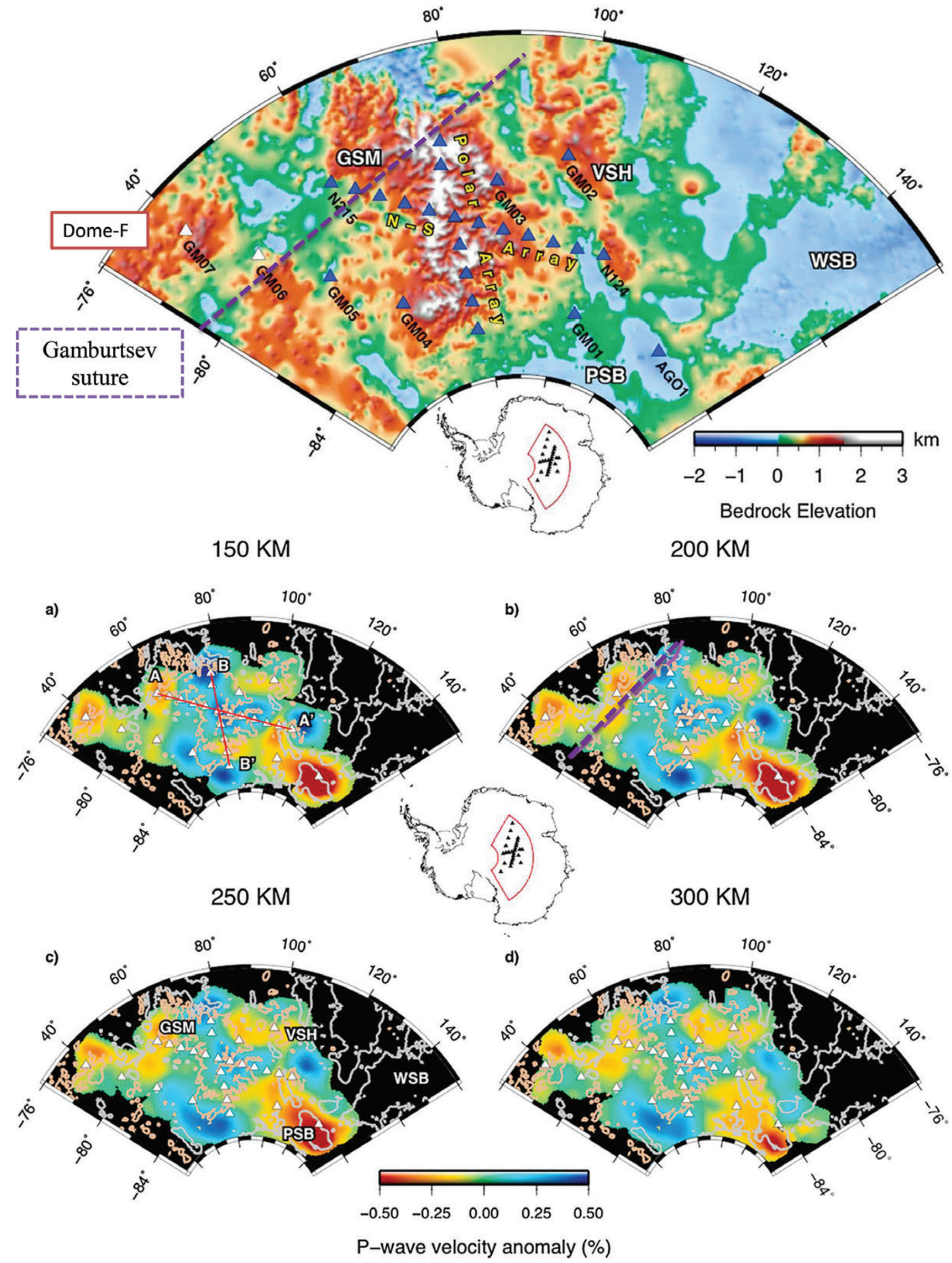


Figure 1. (a) Map of the AGAP-GAMSEIS seismic array, overlayed on the bedrock topography from BEDMAP2 [31] (modified after [13]). The blue and white triangles indicate the location of seismic stations provided by the United States and Japan, respectively. Abbreviations are as follows: GSM, Gamburtsev 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

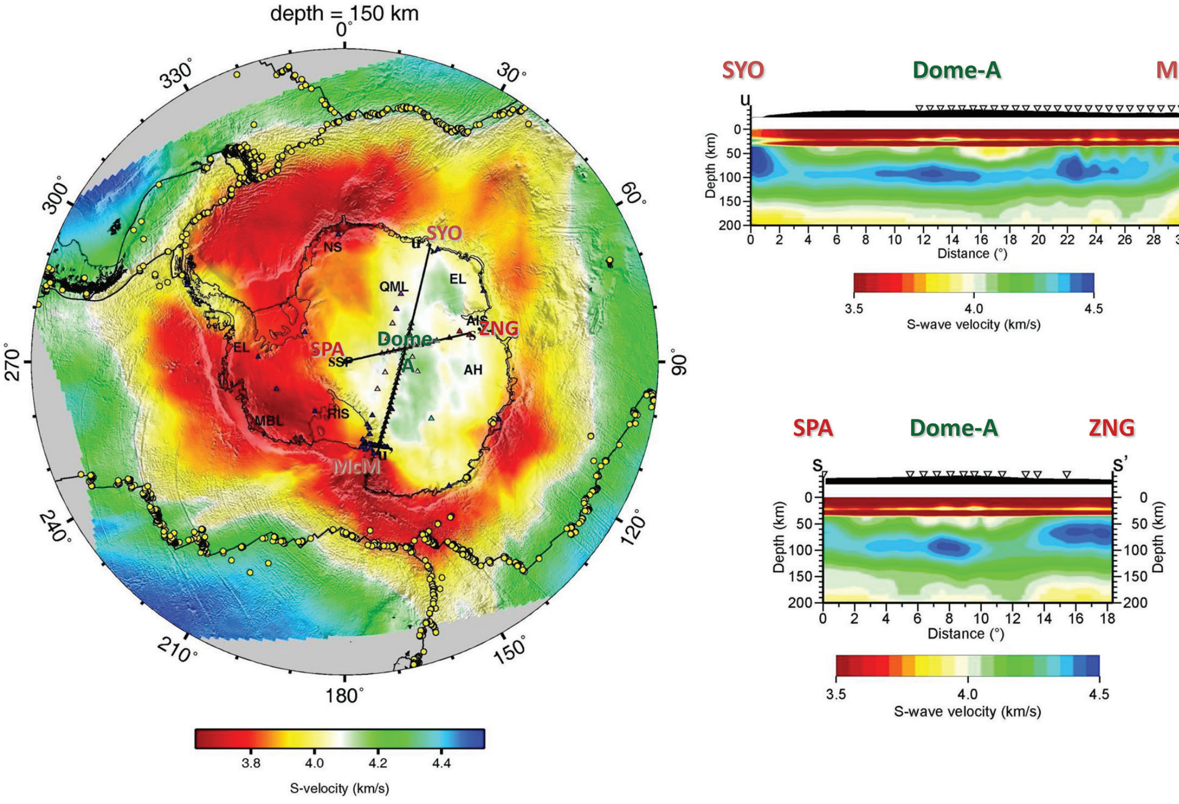


Figure 2. 3D image of the upper mantle shear velocity structure by surface wave tomography from the AGAP/POLENET data (modified after [19]). (Left) The 150-km depth slice for S-wave velocity distribution. (Upper right) Cross section down to a depth of 200 km depth for the profile SYO (u)-Dome-A-McM (u′). (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], 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

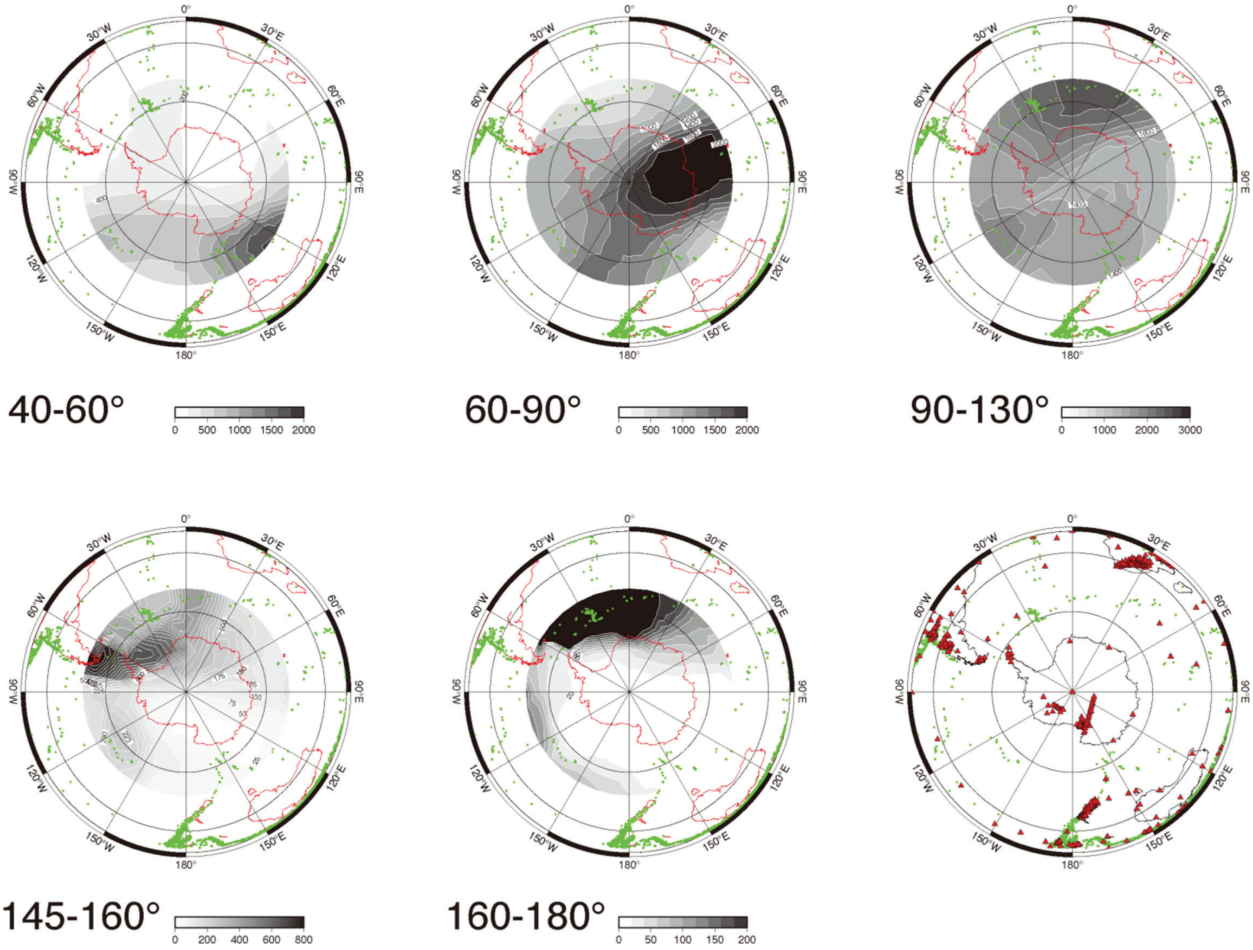


Figure 3. Geographical distribution of teleseismic event numbers (gray horizontal scales) observed at each location in the Antarctic for epicentral distances of 40–60, 60–90, and 90–130° (from the left to the right in the upper row) and 140–160 and 160–180° (in the lower row), respectively. A list including 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.

Author details

Masaki Kanao

Address all correspondence to: kanao@nipr.ac.jp

National Institute of Polar Research (NIPR), Organization of Information and Systems (ROIS), Tokyo, Japan

References

[1] Usui Y, Hiramatsu Y, Furumoto M, Kanao M. Thick and anisotropic D″ layer beneath Antarctic Ocean. Geophysical Research Letters. 2005;**32**:L13311. DOI: 10.1029/2005GL022622

[2] Usui Y, Hiramatsu Y, Furumoto M, Kanao M. Evidence of seismic anisotropy and a lower temperature condition in the D″ layer beneath Pacific Antarctic ridge in the Antarctic Ocean. Physics of the Earth and Planetary Interiors. 2008;**167**:205-216. DOI: 10.1016/j.pepi.2008.04.006

[3] Isse T, Nakanishi I. Inner-core anisotropy beneath Australia and differential rotation. Geophysical Journal International. 2001;**151**:255-263

[4] Song X, Richards PG. Seismological evidence for differential rotation of the Earth's inner core. Nature. 1996;**382**:221-224

[5] Roult G, Rouland D, Montagner JP. Antarctica II: Upper-mantle structure from velocities and anisotropy. Physics of the Earth and Planetary Interiors. 1994;**84**:33-57

[6] Ritzwoller MH, Shapiro NM, Levshin AL, Leahy GM. The structure of the crust and upper mantle beneath Antarctica and the surrounding oceans. Journal of Geophysical Research. 2001;**106**:30645-30670

[7] Danesi S, Morelli A. Structure of the upper mantle under the Antarctic plate from surface wave tomography. Geophysical Research Letters. 2001;**28**:4395-4398. DOI: 10.1029/2001gl013431

[8] Kobayashi R, Zhao D. Rayleigh-wave group velocity distribution in the Antarctic region. Physics of the Earth and Planetary Interiors. 2004;**141**:167-181

[9] Kuge K, Fukao Y. High-velocity lid of East Antarctica: Evidence of a depleted continental lithosphere. Journal of Geophysical Research. 2005;**110**:B06309. DOI: 10.1029/2004JB003382

[10] Gupta S, Zhao D, Rai S. Seismic imaging of the upper mantle under the Erebus hotspot in Antarctica. Gondwana Research. 2009;**16**:109-118

[11] Wiens DA, Anandakrishnan S, Winberry JP. Simultaneous teleseismic and geodetic observations of the stick-slip motion of an Antarctic ice stream. Nature. 2008;**453**:770-774

[12] Heeszel DS, Wiens DA, Nyblade AA, Hansen SE, Kanao M, An M, Zhao Y. Rayleigh wave constraints on the structure and tectonic history of the Gamburtsev Subglacial Mountains, East Antarctica. Journal of Geophysical Research. 2013;**118**:2138-2153

[13] Lloyd AJ, Nyblade AA, Wiens DA, Shore PJ, Kanao M, Hansen SE, Zhao D. Upper mantle seismic structure beneath the East Antarctic shield from body wave tomography: Implications for the origin of the Gamburtsev Subglacial Mountains. Geochemistry, Geophysics, Geosystems. 2013;**14**:902-920

[14] Wiens DA, Hernandez S, Accardo N, Nyblade AA, Anandakrishnan S, Aster RC, Huerta AD, Kanao M, Wilson TJ. Upper mantle seismic anisotropy of Antarctica from shear wave splitting analysis. In: Proceedings of the 11th International Symposium on Antarctic Earth Sciences, PS18.3; July 10-16; Edinburgh, UK. 2011

[15] Heeszel DS, Sun X, Wiens DA, Lloyd AJ, Nyblade AA, Anandakrishnan S, Aster RC, Huerta AD, Wilson TJ, Kanao M, An M, Zhao Y. Seismic velocity structure of Antarctica from data collected during IPY. In: Proceedings of the 11th International Symposium on Antarctic Earth Sciences; PO15.4; July 10-16; Edinburgh, UK. 2011

[16] Emry EL, Nyblade AA, Julià J, Anandakrishnan S, Aster RC, Wiens DA, Huerta AD, Wilson TJ. The mantle transition zone beneath West Antarctica: Seismic evidence for hydration and thermal upwellings. Geochemistry, Geophysics, Geosystems. 2014;**16**:40-58. DOI: 10.1002/2014GC005588

[17] Accardo NJ, Wiens DA, Hernandez S, Aster RC, Nyblade AA, Huerta AD, Anandakrishnan S, Wilson TJ, Heeszel DS, Dalziel WD. Upper mantle seismic anisotropy beneath the West Antarctic rift system and surrounding region from shear wave splitting analysis. Geophysical Journal International. 2014;**198**:414-429. DOI: 10.1093/gji/ggu117

[18] Hansen SE, Graw JH, Kenyon LM, Nyblade AA, Wiens DA, Aster RC, Huerta AD, Anandakrishnan S, Wilson TJ. Imaging the Antarctic mantle using adaptively parameterized P-wave tomography: Evidence for heterogeneous structure beneath West Antarctica. Earth and Planetary Science Letters. 2014;**408**:66-78

[19] An M, Wiens DA, Zhao Y, Feng M, Nyblade AA, Kanao M, Li Y, Maggi A, Lévêque J-J. S-velocity model and inferred Moho topography beneath the Antarctic plate from Rayleigh waves. Journal of Geophysical Research. 2015;**120**:359-383. DOI: 10.1002/2014JB011332

[20] Usui Y, Kanao M, Kubo A, Hiramatsu Y, Negishi H. Upper mantle anisotropy from teleseismic SKS splitting beneath Lützow-Holm Bay region, East Antarctica. U. S. Geological Survey and The National Academies, USGS OF-2007-1047. Short Res. Paper 013; 2007. DOI: 10.3133/of2007-1047.srp013

[21] Kanao M, Usui Y, Inoue T, Yamada A. Broadband seismic deployments for imaging the upper mantle structure in the Lützow-Holm Bay region, East Antarctica. International Journal of Geophysics. 2011;**2011**:1-15

[22] Melnik EA, Suvorov VD, Pavlov EV, Mishenkina ZR. Seismic and density heterogeneities of lithosphere beneath Siberia: Evidence from the Craton long-range seismic profile. Polar Science. 2015;**9**:119-129. DOI: 10.1016/j.polar.2014.09.002

[23] Sherman SI, Gladkov AS. Fractals in studies of faulting and seismicity in the Baikal rift zone. Tectonophysics. 1999;**308**:133-142

[24] Golubev VA. Conductive and convective heat flow in the bottom of Lake Baikal and in the surrounding mountains. Bulletin du Centre de recherches Elf Exploration Production. 1998;**22**:323-340

[25] Suvorov VD, Mishenkina ZM, Petrick GV, Sheludko IF, Seleznev VS, Solovyov VM. Structure of the crust in the Baikal rift zone and adjacent areas from deep seismic sounding data. Tectonophysics. 2002;**351**:61-74

[26] Ananyin LV, Mordvinova VV, Gots MF, Kanao M, Suvorov VD, Tatkov GI, Thubanov TA. Velocity structure of the crust and upper mantle in the Baikal rift zone on the long-term observations of broad-band seismic stations. Doklady Earth Sciences. 2009;**428**: 1067-1071

[27] Nielsen C, Thybo H. No Moho uplift below the Baikal rift zone: Evidence from a seismic refraction profile across southern Lake Baikal. Journal of Geophysical Research. 2009;**114**:B08306. DOI: 10.1029/2008JB005828

[28] Gao S, Liu KH, Chen C. Significant crustal thinning beneath the Baikal rift zone: New constraints from receiver function analysis. Geophysical Research Letters. 2004;**31**:L20610. DOI: 10.1029/2004GL020813

[29] Zorin YA, Turutanov EK, Mordvinova VV, Kozhevnikov VM, Yanovskaya TB, Treussov AV. The Baikal rift zone: The effect of mantle plumes on older structure. Tectonophysics. 2003;**371**:153-173

[30] Kanao M, Wiens D, Tanaka S, Nyblade A, Toyokuni G, Shore P, Tsuboi S, Heeszel D, Usui Y, Parker T. Broadband seismic deployments in East Antarctica: IPY contribution to monitoring the Earth's interiors. Annals of Geophysics. 2014;**57**. DOI: SS0322, 10.4401/ag-6379

[31] Fretwell P et al. BEDMAP2: Improved ice bed, surface, and thickness datasets for Antarctica. Cryosphere. 2012;**6**:4305-4361. DOI: 10.5194/tcd-6-4305-2012

Chapter 2

A Decade of Advances in Cryoseismology

Masaki Kanao

Abstract

Among the various kinds of seismological features observed in the polar region, the characteristics of the wavelets and involved seismicity related to cryosphere dynamics are introduced to mark a decade of advances in "cryoseismology." Classifying the seismic waves originating from the cryosphere dynamics and understanding the generating mechanism as well as the temporal-spatial distributions in seismicity should be important in order to realize surface environmental variations associated with global warming in the polar region.

Keywords: cryosphere, ice quakes, glacial earthquakes, cryoseismology, global warming

1. Introduction

The Antarctic continent and the Greenland Island are covered by thick ice sheet and surrounded by various kinds of evolving parts of the cryosphere, that is, sea ices, ice shelves, glaciers, ice caps, crevasses, tide cracks, pressure ridges, and so on. In the polar region, in terms of recent trends in global warming [1], characteristic earthquakes involving cryosphere dynamics and evolution have been reported and are increasing in number [2–5]. Among these cryoseismic events, polar seismologists named the relatively large events as "glacial earthquakes," which were identified to be located at the exit areas (including calving fronts) of large glaciers in Greenland for the first time [2, 4]. In contrast, events of relatively small magnitude have been called "ice quakes" or "ice shocks" by the polar research community, otherwise known as "cryoseisms" more generally. The "ice quakes" appeared to be the most generally known terminology of these cryoseismic events, which contain "glacial earthquakes" as a part of them. In this chapter, however, there is no strict difference in the usage of these different terminologies of cryoseismic signals. We use these terminologies depending on the context of individual sentences.

Occurrence origins of these cryoseismic events are known as multigenetics. For instance, the “ice quakes” observed in the Antarctic were generated by oceanic swells, oceanic tides, and related sea-ice movements; collision and break off of sea ices and icebergs; discharges of ice shelves and outlet glaciers; calving of ice falls and ice cliffs; collapses inside the firn layers over the ice sheet; basal sliding beneath the ice sheet; and friction between the bedrocks and the tectonic crustal uplift associated with deglaciation [5] (**Figure 1**). The study of these multiaspects in seismological research (including waveform propagation analysis, source mechanism, and seismicity analysis) in terms of cryosphere dynamics and evolution is called “cryoseismology,” a new interdisciplinary branch of geoscience combining glaciology, geodesy, and other geophysical approaches.

In this chapter, a decade of advances in “cryoseismology” is reviewed with a focus on a new terminology in geosciences, “glacial earthquakes,” in relation to global climate changes appearing in the polar region. Several topics are explained in terms of earthquake generation mechanism by global warming, seismic activities and characteristics, a relationship with dynamic movement of ice sheet and glaciers, the correlation between sea-ice dynamics and oceanic swells, seismic wavelet propagation studies within the cryosphere, inner structure and dynamics of the surface layer of the crust and ice sheet, and so on.

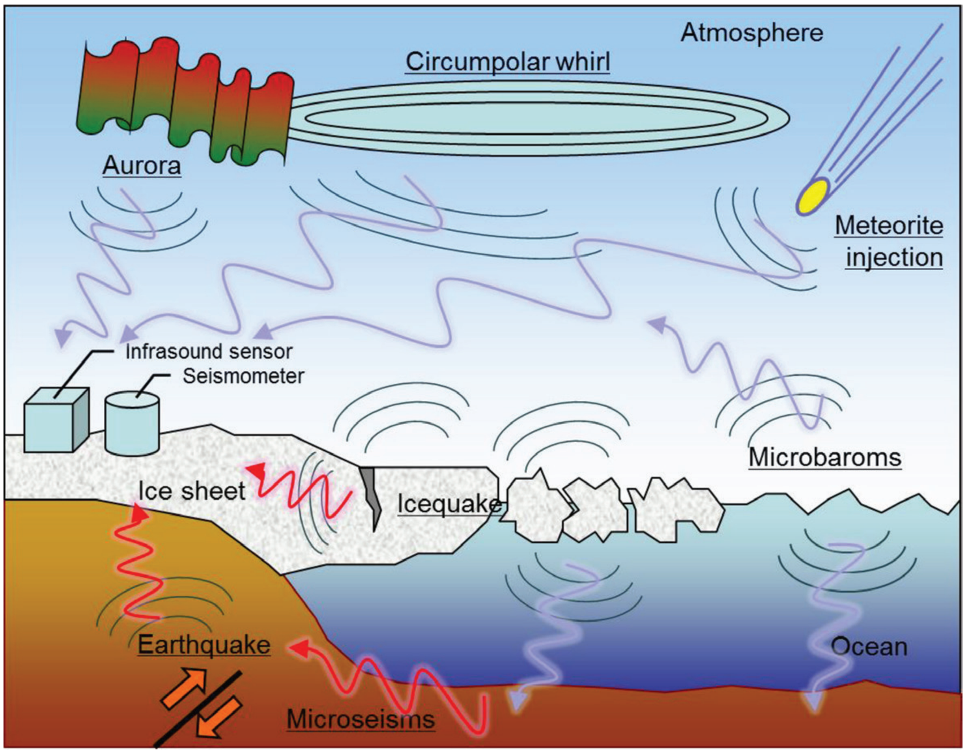


Figure 1. Schematic illustration of the excitation of atmospheric pressure changes and seismic waves in polar regions. Physical interaction among the solid Earth, atmosphere, ocean, and cryosphere systems can be detected by using infrasonic waves, which are generated by several sources around the coast and the Southern Ocean (after [32]). Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4280630150211, license date: February 02, 2018.

2. Antarctic region

There are many aspects of source origins for cryoseismic signals in the Antarctic. For example, around the Syowa Station, in the Lützow-Holm Bay (LHB) of East Antarctica, the observed "ice shocks" have been classified into several categories depending on their origins. The events generated in relation to sea ices and oceans are as follows: the solid Earth response to oceanic swells (microseismic noises and microseisms), sea-ice movement involving oceanic tides along the coastal lines and their associated openings of the tide cracks, covibrations by the movements of large mass of sea ices and icebergs, and discharges of the fast sea ice or ice shelves from LHB [5].

Frequently observed examples of cryoseismic events include local events associated with oceanic tide cracks along the coasts of the Ongul Islands in which Syowa Station is located. The overlying sea ices change their elevation according to the vertical movement of oceanic tides. When the oceanic tide level decreases, tide cracks open, and seismic energy is released from the cracks and recorded by the seismographs of the station. There is a strong relationship between the oceanic tides' daily variations and time-shift feature of the occurrence number (frequency) of the ice shocks [6]. When counting these tide cracks originating from cryoseismic signals, more than 10,000 events were recorded at the Syowa Station. A more detailed investigation shall be conducted in the near future.

Another remarkable example of the cryoseismic signals from ocean-related phenomena is the discharge events of fast sea ices in LHB, which occurred during the winter season in 1997. The discharge events of the sea ices emerged from characteristic seismic tremors of harmonic overtones with a few Hz of frequency and with more than few hours of duration [5]. The harmonic seismic tremors were considered to be generated by the collisions among sea ices, icebergs, and pack ices in the bay, otherwise a collision with the oceanic bottom. Understanding the accurate generation mechanism by using characteristic nonlinear wavelets of harmonic overtones could reveal the physical interaction between the solid Earth and the cryosphere in the polar region.

The other category of cryoseismic events was known to be triggered by the dynamics inside the continental environment in the Antarctic. Continental ice sheet and glaciers produce a huge mass of ice and snow from the inland plateau to the coastal area, followed by discharging outlet glaciers, ice cliffs, ice falls, and ice shelves into the Southern Ocean. The outlet glaciers extinguish the ice mass by calving events at their edge and by basal sliding events with frictions against the bedrocks underneath. These signals can be recorded as the relatively large "glacial earthquakes," which have been famous in Greenland. In contrast, there is another category of cryoseismic events, which occurred inside the firn layers (the top 100 m from the ice-sheet surface); the firn events were also named as "snow quakes" with "sounds" from the surrounding area. Around LHB near the Syowa Station, various kinds of cryosphere surroundings have continuously generated surface vibrations to be recorded by the seismographs in particular in austral summer seasons when the temperature increases.

Seismicity of the cryoseismic events (including “glacial earthquakes”) in the whole Antarctic continent and the surrounding sea-ice area is known to be concentrated in the continental margins in particular around the exits of large glaciers (calving fronts). Hypocenters of these events are located along the coast of the Whillans Ice Stream of the West Antarctic Rift System (WARS; see **Figure 1** of Chapter 1) [7], near the McMurdo Station (McM) of the Ross Sea [8], Neumayer Station of Dronning Maud Land of East Antarctica [9, 10], and other places. From 3 years of observations of the table-type icebergs of the Ross Sea, harmonic overtone signals with a frequency of a few Hz were recorded [11] similar to those of LHB, followed by a comparison between the observed and theoretical wavelets to clarify the propagation paths and source mechanism of the harmonic tremors [3]. The collision process between the two tabulate icebergs associated with tidal variations was found to be the generation mechanism of the cryoseismic tremors. In the Whillans Ice Stream of WARS, in contrast, cryoseismic activity in relation to basal sliding was identified by combining data from seismographs, GPS, and tide gages [12, 13].

The distribution of glacial earthquakes over the whole Antarctic continent with a magnitude more than 4 was determined by the long-period surface wave analysis using the global network data [the Federation of Digital Seismographic Networks (FDSN)] [4, 14]. Hypocenters of glacial earthquakes located around the coastal areas near the edge of ice shelves and large glaciers such as the Antarctic Peninsula, the Wilkes Land, and the Weddell Sea suggest a strong relationship between the calving and discharge events at the regions (**Figure 2**). Moreover, on the basis of the Polar Earth Observing Network (POLENET) data collected during the International Polar Year (IPY), high-frequency signals associated with the sea-ice movements were identified around the oceans near the coast of the Antarctic continent (particularly the Weddell Sea, the Ross Sea, and the Amundsen Sea) [15].

Inside the plateau of the Antarctic continent, in contrast, particularly within the Wilkes Land and the Victoria Land, a small number of seismic events have been reported since the 1960s [16–18]. In this area, a significant number of “subglacial lakes” have been found by using radar echo soundings and satellite data from around “Lake Vostok” between Dome-C and Dome-A [19, 20]. The complex features of the bedrocks with a lower elevation of these regions could be a plausible reason for the existence of many subglacial lakes (i.e., the Wilkes Basin, the Aurora Basin, etc.). The discharge events from subglacial lakes (“Outburst Flood” [7]) or the upper part of glaciers/ice streams, by increasing the number of seismic stations inside the Antarctic continent as done during the IPY (POLENET), are also expected to be detected. From the POLENET data, moreover, new hypocenters of cryoseismic events were determined at the upper stream of the Lambert Glacier in the Enderby Land and the inland area of the Aurora Basin [21].

The detection of a new class of “cryoseismic” events is an interesting way to evaluate the influence of global warming/climate change on the inland area of the Antarctic continent and to advance the science of “subglacial hydrology.” In addition, using the POLENET dataset, a lot of ice quakes were excited beneath the ice sheet in a wide area of WARS by teleseismic surface waves generated from huge deep earthquakes in South America [22, 23]. New findings in the branch of “cryoseismology” are expected to be established by the analyses of phenomena such as “dynamic triggering” of the ice quakes excited by teleseismic events outside the Antarctic Plate.

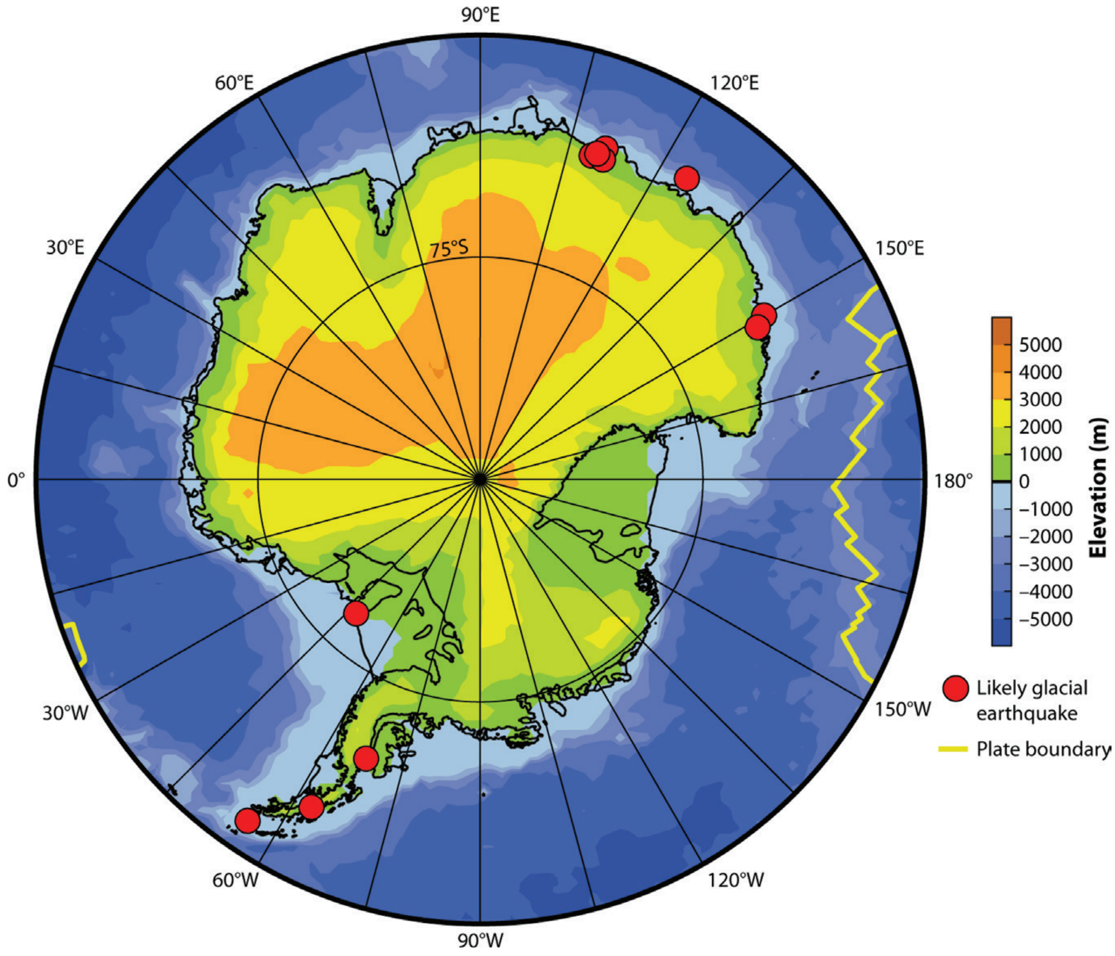


Figure 2. Hypocenters for the detected events that are likely to correspond to glacial earthquakes around Antarctica during 1993–2008 (red circles) (modified after [4]). Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4280640194100, license date: February 02, 2018.

3. Arctic region

The recent trends in cryosphere evolution in the Arctic, especially the total mass of the Greenland ice sheet and glaciers, have been rapidly decreasing based on the satellite data [24, 25]. According to the evidence, cryoseismic signals (including "glacial earthquakes") associated with the dynamic movement, calving, and collapse of the ice sheet have been strikingly observed at the edges of Greenland and surrounding islands [2, 4, 26] (**Figure 3**). Understanding the occurrence mechanism and temporal-spatial distribution of the Greenland glacial earthquakes has a significance to reveal the amplification mechanism of ice-sheet melting process in terms of global warming. Glacial earthquakes are known to be generated by cryosphere dynamics such as discharge of glaciers and ice shelves, calving of ice cliffs, basal sliding and friction between the bedrocks, surface melting of the ice sheet, discharge from subglacial lakes, and so on. However, details of the occurrence mechanism of the earthquakes have not yet been understood, including those of the Antarctic region. In addition, as there is a relationship between the glacial isostatic adjustment (GIA) associated with sea-level change and the deglaciation, the glacial earthquakes could be a new proxy for monitoring the surface environment in the polar region.

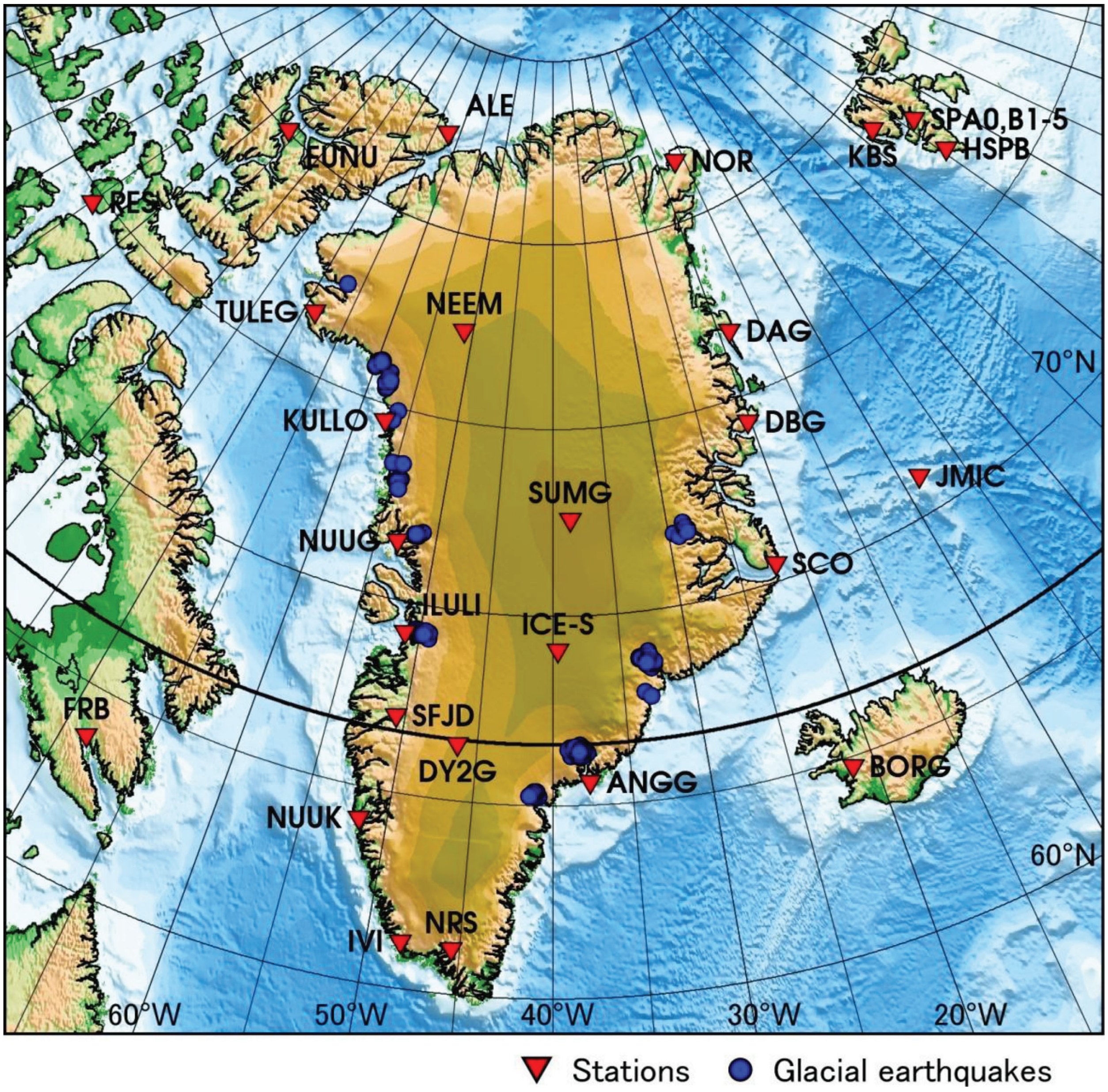


Figure 3. Distribution of glacial earthquakes around Greenland and the surrounding area during 1993–2008 (blue circles). Seismic stations including both permanent and temporal are shown by red triangles. Hypocenters are taken from [4] (figure is after [33]).

In order to monitor the dynamics of the Greenland ice sheet, more than one decade ago, an international program "the GreenLand Ice Sheet monitoring Network (GLISN)" was initiated after the IPY by 14 countries involved in the Arctic research, including the USA, Denmark, and Japan [27, 28]. By collaborating with existing global seismic networks (FDSN), a relationship between the occurrence mechanism of glacial earthquakes and the shrinking ice sheet caused by global warming can be revealed. Moreover, it is expected that the correlation between the cryosphere dynamics and the sea-level change, as well as an understanding of the amplification process of global warming in the Arctic, could be clarified. The significance of seismic activities of glacial earthquakes in Greenland and Antarctica, for example, could be determined by using the statistical methods for estimating the temporal-spatial distribution of the aftershocks such as the epidemic type aftershock sequence (ETAS) model. Statistical analysis of both the tectonic and glacial earthquakes regarding plate movement and volcanic activities around Greenland has been reported [29]. Seismically active regions of glacial earthquakes were found to be expanding from the southeast to the northwest part of Greenland since 2005. The evidence corresponded to the ice mass loss distribution obtained by the satellite data from the Gravity Recovery and Climate Experiment (GRACE) [25].

By utilizing the observed seismic waveforms recorded from GLISN, source mechanisms of glacial earthquakes could be obtained by assuming the source parameters of the calving events. Accurate hypocentral information and source mechanism can demonstrate the occurrence locations inside the ice sheet, as well as the seismic fault parameters and released seismic energy. Moreover, by comparing the observed and theoretical waveforms, the validity of the source mechanism could be achieved by adopting the inversion technique efficiently. As mentioned, in addition to the calving events and basal melting processes underneath the ice sheet in terms of the recent progression of global warming in the northern hemisphere, seismic activities associated with the crustal uplift (GIA-related events) involved deglaciation at the regions (i.e., at the Hudson Bay in Northern America, the Baltic Bay in Northern Europe, etc.), which had been covered by ice sheets over 10,000 years ago [30, 31]. A relationship between the deformation of the Laurentide ice sheet and the variations in tectonic stress field within the crust and the occurrence of characteristic earthquakes has been described in detail [31].

4. Summary

In this chapter, characteristic seismic waves and seismicity involving cryosphere variations in the polar region were introduced. Hypocenters of the local tectonic events, ice quakes, and glacial earthquakes were concentrated at the continental margins of the polar ice sheet and the outlet glaciers. It is not yet fully understood whether these events were caused by collapses of the “ice” itself, otherwise the friction between the bedrocks under the ice. The other reason for generating source of the cryoseismic events could be explained by the crustal movements involved in the ice-sheet deformation/shrinking after deglaciation. It is expected that the improvement of the hypocentral determination of local and glacial earthquakes will be clarified by the temporal-spatial distributions and estimation of generating sources. Cryoseismic events characterized by their various types of generating sources seldom occur compared with the natural tectonic earthquakes; statistical analysis with a quantitative approach shall be required so as to investigate their source magnitude and frequency distribution in more detail. In this regard, it is expected that “cryoseismology” which connects cryosphere dynamics and vibration of the solid Earth will be a new proxy for detecting the time-space variations in the surface layers of the Earth’s complex system.

Author details

Masaki Kanao

Address all correspondence to: kanao@nipr.ac.jp

National Institute of Polar Research (NIPR), Organization of Information and Systems (ROIS), Tokyo, Japan

References

[1] Intergovernmental Panel on Climate Change (IPCC) (2013): Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, and Midgley PM, editors. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2013. pp. 1535. DOI: 10.1017/CBO9781107415324

[2] Ekström G, Nettles M, Tsai VC. Seasonality and increasing frequency of Greenland glacial earthquakes. Science. 2006;**311**:1756-1758

[3] MacAyeal D, Okal EA, Aster RC, Bassis JN. Seismic observations of glaciogenic ocean waves on icebergs and ice shelves. Journal of Glaciology. 2009;**55**:193-206

[4] Nettles M, Ekström G. Glacial earthquakes in Greenland and Antarctica. The Annual Review of Earth and Planetary Sciences. 2010;**38**:467-491

[5] Kanao M, Maggi A, Ishihara Y, Yamamoto M-Y, Nawa K, Yamada A, Wilson T, Himeno T, Toyokuni G, Tsuboi S, Tono Y, Anderson K. Interaction on seismic waves between atmosphere–ocean–cryosphere and geosphere in polar region. In: Kanao M, Takenaka H, Murai Y, Matsushima J, Toyokuni G, editors. Seismic Waves—Research and Analysis. Rijeka, Croatia: InTech; 2012. pp. 1-20

[6] Kaminuma K. Seismic activity in and around the Antarctic continent. Terra Antarctica. 1994;**1**:423-426

[7] Winberry JP, Anandakrishnan S, Wiens DA, Alley RB. Nucleation and seismic tremor associated with the glacial earthquakes of Whillans Ice Stream, Antarctica. Geophysical Research Letters. 2013;**40**:312-315

[8] Bannister S, Kennett BLN. Seismic activity in the Transantarctic Mountains: Results from a Broadband Array Deployment. Terra Antarctica. 2002;**9**:41-46

[9] Eckstaller A, Müller C, Ceranna L, Hartmann G. The geophysics observatory at Neumayer stations (GvN and NM-II) Antarctica. Polarforschung. 2006;**76**:3-24

[10] Schlindwein V, Läderach C. Earthquakes and icequakes recorded on drifting ice floes as seismometer platforms. In: IAHS-IAPSO-IASPEI Joint Assembly G22-26 July; Gothenburg, Sweden; 2013. p. S105PS.02

[11] MacAyeal D, Okal EA, Aster RC, Bassis JN. Seismic and hydroacoustic tremor generated by colliding icebergs. Journal of Geophysical Research. 2008;**113**:F03011. DOI: 10.1029/2008JF001005

[12] Anandakrishnan S, Alley RB. Tidal forcing of basal seismicity of ice stream C, West Antarctica, observed far inland. Journal of Geophysical Research. 1997;**102**:15183-15196

[13] Anandakrishnan S, Catania GA, Alley RB, Horgan HJ. Discovery of till deposition at the grounding line of Whillans Ice Stream. Science. 2007;**315**:1835-1838

[14] Chen X, Shearer PM, Walter F, Fricker HA. Seventeen Antarctic seismic events detected by global surface waves and a possible link to calving events from satellite images. Journal of Geophysical Research. 2011;**116**. DOI: B06311, 10.1029/2011JB008262

[15] Lough AC, Barcheck CG, Wiens DA, Barklage ME, Nyblade AA, Aster RC, Anandakrishnan S, Huerta AD, Wilson TJ. Detection of seismic sources associated with ice movement in Antarctica Using POLENET seismic array, AGAP seismic array, and GSN seismic stations. In: AGU Fall 2011 Meeting, S43D-07; San Francisco, California, USA

[16] Kaminuma K. A revaluation of the seismicity in the Antarctic. Polar Geoscience. 2006;**13**:145-157

[17] Reading AM. On seismic strain-release within the antarctic plate. In: Futterer DK, Damaske D, Kleinschmidt G, Miller H, Tessensohn F, editors. Antarctica: Contributions to Global Earth Sciences. Berlin Heidelberg New York: Springer-Verlag; 2006. pp. 351-356

[18] Storchak DA, Kanao M, Delahaye E, Harris J. Long-term accumulation and improvements in seismic event data for the polar regions by the International Seismological Centre. Polar Science. 2015;**9**:5-16. DOI: 10.1016/j.polar.2014.08.002

[19] Bell RE, Studinger M, Tikku AA, Clarke GKC, Gutner MM, Meertens C. Origin and fate of Lake Vostok water frozen to the base of the East Antarctic ice sheet. Nature. 2002;**416**:307-310

[20] Dietrich R, Shibuya K, Pötzsch A, Ozawa T. Evidence for tides in the subglacial Lake Vostok, Antarctica. Geophysical Research Letters. 2001;**28**:2971-2974

[21] Lough AC, Wiens DA, Barcheck CG, Nyblade AA. Waveform studies of strong cryoseismic sources near the top of the Antarctic ice sheet. In: AGU Fall 2013 Meeting, C51B-0523; San Francisco, California, USA; 2013

[22] Peng Z, Walter JI, Aster RC, Nyblade AA, Wiens DA, Anandakrishnan S. Antarctic icequakes triggered by the 2010 Maule earthquake in Chile. Nature Geoscience. 2014;**7**: 677-681. DOI: 10.1038/ngeo2212

[23] Walter JI, Peng Z, Tulaczyk SM, O'Neel S, Amundson JM. Triggering of glacier seismicity (icequakes) by distant earthquakes. Seismological Research Letters. 2013;**84**:372

[24] Khan SA, Wahr J, Bevis M, Velicogna I, Kendrick E. Spread of ice mass loss into Northwest Greenland observed by GRACE and GPS. Geophysical Research Letters. 2010;**37**:L06501. DOI: 10.1029/2010GL042460

[25] Matsuo K, Chao BF, Otsubo T, Heki K. Accelerated ice mass depletion revealed by low-degree gravity field from satellite laser ranging: Greenland, 1991-2011. Geophysical Research Letters. 2013;**40**:1-6

[26] Ekström G, Nettles M, Abers GA. Glacial earthquakes. Science. 2003;**302**:622-624

[27] Clinton JF, Nettles M, Walter F, Anderson K, Dahl-Jensen T, Giardini D, Govoni A, Hanka W, Lasocki S, Lee WS, McCormack D, Mykkelveit S, Stutzmann E, Tsuboi S. Real-time geophysical data enhance earth system monitoring in Greenland, Eos Trans. AGU. 2014;**95**:13-24

[28] Toyokuni G, Kanao M, Tono Y, Himeno T, Tsuboi S, Childs D, Anderson K, Takenaka H. Japanese contribution to the Greenland Ice Sheet Monitoring Network (GLISN). Antarctic Record (New Zealand). 2014;**58**:1-18

[29] Kanao M, Tsuboi S, Butler R, Anderson K, Dahl-Jensen T, Larsen T, Nettles M, Voss P, Childs D, Clinton J, Stutzmann E, Himeno T, Toyokuni G, Tanaka S, Tono Y. Greenland ice sheet dynamics and glacial earthquake activities. In: Müller J, Koch L, editors. Ice Sheets: Dynamics, Formation and Environmental Concerns. Hauppauge, NY: Nova Science Publishers, Inc.; 2012. pp. 93-120. Chap. 4

[30] Wilson T, Bell R. Earth structure and geodynamics at the poles. In: Krupnik I et al. Understanding Earth's Polar Challenges: International Polar Year 2007-2008. Edmonton, Canada: CCI Press; 2011. pp. 273-292

[31] Kozlovskaya E. Monitoring of slow seismic events from Arctic using the data of the POLENET/LAPNET broadband temporary array. In: IAHS-IASPO-IASPEI.IUGG Joint Assembly, S105S2.03, Gothenburg, Sweden, July; 2013. pp. 22-26

[32] Murayama T, Kanao M, Yamamoto M-Y, Ishihara Y, Matshushima T, Kakinami Y. Infrasound array observations in the Lützow-Holm Bay region, East Antarctica. Polar Science. 2015;**9**:35-50. DOI: 10.1016/j.polar.2014.07.005

[33] Kanao M, Suvorov VD, Toda S, Tsuboi S. Seismicity, structure and tectonics in the Arctic regions. Geoscience Frontiers. 2015;**6**:665-677. DOI: 10.1016/j.gsf.2014.11.002

Chapter 3

Seismic Detection in the Inland Plateau of East Antarctica

Masaki Kanao

Abstract

Several international programs to deploy broadband seismic stations over the Antarctic continent were conducted during the International Polar Year (IPY 2007–2008). Antarctica's Gamburtsev Province (AGAP)/Gamburtsev Mountains Seismic Experiment (GAMSEIS), which was a part of AGAP and the Polar Earth Observing Network (POLENET), contributed greatly to establish a geophysical network in Antarctica. AGAP/GAMSEIS was an internationally coordinated deployment of more than 30 seismographs over the crest of the Gamburtsev Mountains and the areas of Dome-A, -C, and -F. The project provided a detailed information on the crust and mantle structures and, key constraints on the origin of the Gamburtsev Mountains and more broadly on the structure and evolution of the East Antarctic craton and subglacial environment. With the data from GAMSEIS and POLENET, the local and regional seismic signals associated with ice movements, oceanic loadings, and local meteorological variations were recorded in addition to a number of teleseismic events around the globe. The characteristic seismic signals of local origin in the inland plateau of the ice sheet were demonstrated with a capability to investigate subglacial environment, particularly at the marginal areas of the East Antarctic continent.

Keywords: Antarctic continent, inland plateau, seismic deployments, ice quakes, IPY

1. Introduction

Existing seismic stations belonging to the Federation of Digital Seismographic Networks (FDSN) allowed resolution of the structure beneath Antarctica at a horizontal scale of ~1000 km, which was sufficient to detect fundamental differences in the lithosphere beneath East and West Antarctica, however, not sufficient to clearly define the structure within each sector. The identification of seismicity around the Antarctic continent was limited by sparse station distribution, and the detection level of earthquakes remained inadequate for making a full evaluation of the tectonic activity [1, 2]. A strategy for achieving a sufficient density of seismic stations over the Antarctic continent allowed for an optimal ray path coverage across the continent and the improvement of seismic tomography resolution [3–5]. The International Polar Year (IPY 2007–2008) provided an excellent opportunity to progress seismic deployments so as to achieve these scientific targets.

After the seismic array project of the Transantarctic Mountains Seismic Experiment (TAMSEIS) [6, 7] during 2000–2002, several projects were conducted to reveal the interior structure of the Antarctic continent (**Figure 1**). The Antarctica's Gamburtsev Province (AGAP), the Gamburtsev Mountains Seismic Experiment (GAMSEIS) as a part of AGAP, and the Polar Earth Observing Network (POLENET) were the largest contributors in establishing a whole seismic network to reveal the Antarctic interiors during the IPY. Moreover, the broadband seismic deployment around the eastern Dronning Maud Land-the Enderby Land by the Japanese Antarctic Research Expedition (JARE) [8, 9] greatly contributed as a part of POLENET and AGAP. From the GAMSEIS and POLENET data, the local and regional seismic signals associated with cryosphere dynamics, oceanic loadings, and local meteorological variations were recorded with a significant number of teleseismic events.

In this chapter, field operations over the inland plateau of East Antarctica and seismic event data retrieved from AGAP/GAMSEIS/POLENET are demonstrated. In addition to reviewing

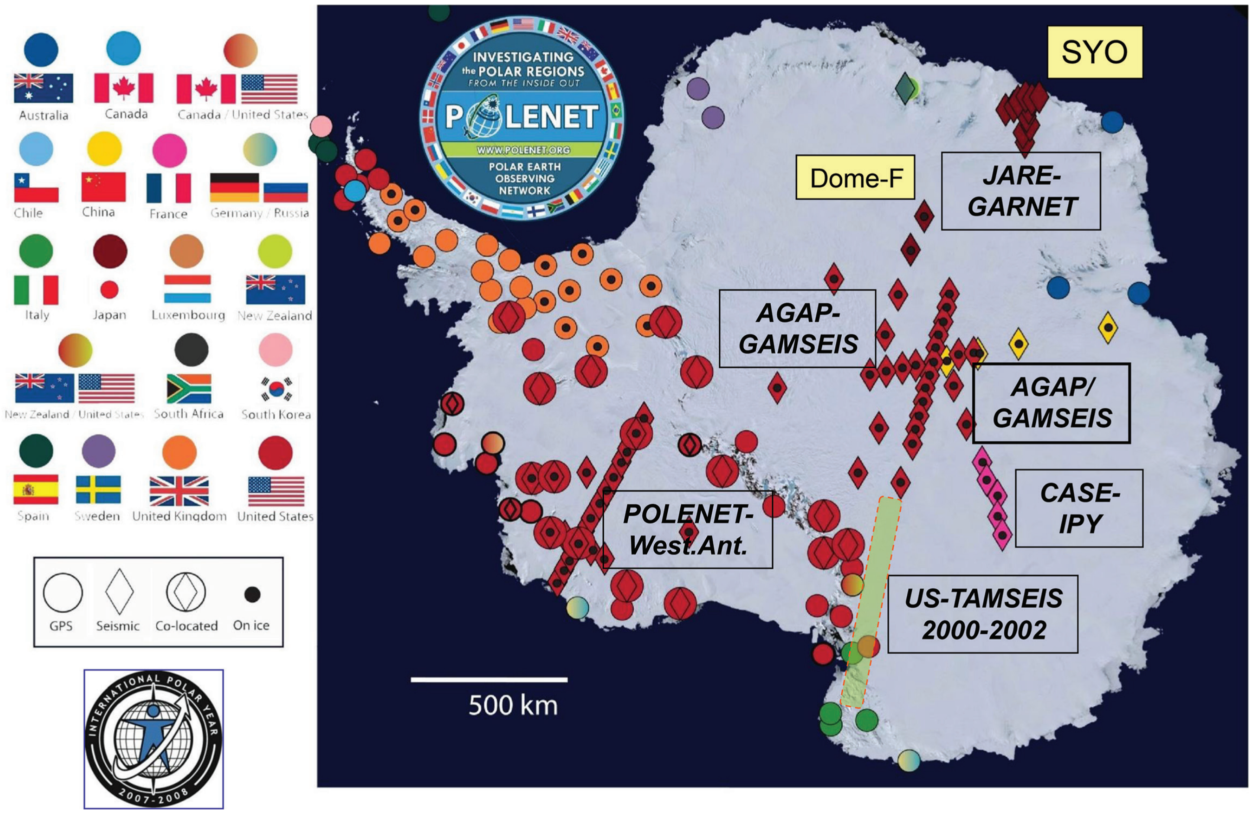


Figure 1. Map of seismic and other geophysical stations deployed by major projects during the IPY 2007–2008 (modified after [21]). The project names are labeled as JARE-GARNET, AGAP-GAMSEIS, CASE-IPY, POLENET-West. Ant. and US-TAMSEIS (2000–2002), respectively. All stations in the Antarctic continent have contributed to the POLENET program as a whole.

achievements of seismological studies of the crust and upper mantle, emphasis was on the description about local seismicity of the inland plateau over the ice sheet.

2. Field operations in the inland plateau

Revealing the inner structure of the underlying ice sheet, present dynamics, and tectonic evolution of a broader part of East Antarctica, AGAP was an internationally coordinated program composed of airborne geophysics, seismic, and ice-core drilling teams [10]. Multinational collaboration between scientific studies and field logistics was carried out by the USA, Japan, China, France, Italy, and Australia. Two field base camps were established at AGAP-N and AGAP-S, at opposite sides of the Chinese station in Dome-A (**Figure 2**). Moreover, the Chinese traverse team conducted seismic deployment along the routes from the Zhongs station to Dome-A. The GAMSEIS team deployed a few tens of broadband seismographs over a wide area of the continental ice sheet from the Gamburtsev Subglacial Mountains (GSM), Lake

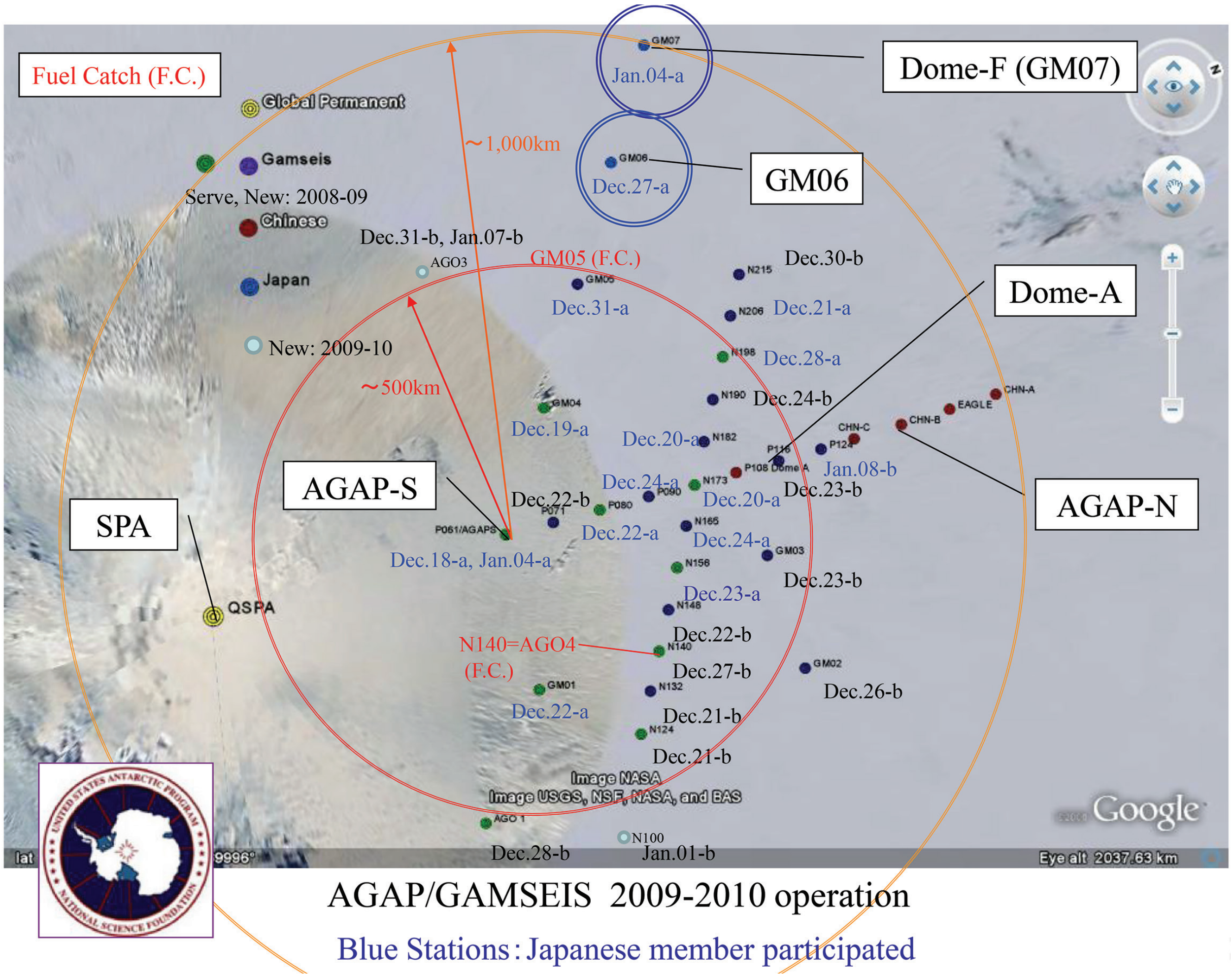


Figure 2. Map showing the broadband seismic location of stations by AGAP/GAMSEIS during 2009–2010 austral summer season. Two circles in different distances of 500 and 1000 km are indicated with their center at AGAP-S. The visiting (installed) dates for each station are labeled: (a) first flight and (b) second flight of the day. The fuel catches were prepared in some places approximately at 500 km from AGAP-S. The original local map is taken from Google Earth™.

Vostok, and the vicinity of the Dome-F station (**Figure 2**). A significant number of flights were conducted by Twin Otter aircrafts in order to install seismic stations over the ice sheet. The Japanese Dome-F (GM07) station was the most distant one, which was almost 1000 km away from AGAP-S.

Seismic instrumentations used for GAMSEIS/POLENET were majorly provided by the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) of the Incorporated Research Institutions for Seismology (IRIS). PASSCAL polar instruments were developed with inputs from the community of Antarctic seismologists, and the main specifications are summarized as follows [11, 12]: seismometer, Guralp CMG-3T with a special configuration to operate at −55°C; Datalogger, Quanterra Q-330 with a flash memory (operating at −55°C); enclosures; insulated vacuum to keep at ~15°C above the ambient temperature without additional heating; solar panels; and AGM batteries for summer power and lithium batteries for winter power. These instruments were optimized for ease of deployment from Twin Otter aircrafts. In addition to these PASSCAL observation systems, originally coordinated seismic station systems were developed by the Japanese team (Dome-F (GM07) and GM06 stations; **Figure 2**), as well as by other groups from China and France. The Japanese instrument system used the same sensor and datalogger as those of the PASSCAL's; however, electric power supply and enclosures were independently developed with the technical support of PASSCAL staff. The seismic data were recorded in MiniSEED format, which has been an international standard in global seismology. Logistic supports were provided by the US researchers and staff at the AGAP-S camp for the installation of Japanese stations in GM06 and GM07.

3. Seismic data and local events

During the IPY, a significant number of teleseismic events, as well as many local seismic signals, were recorded by AGAP/GAMSEIS/POLENET stations in East Antarctica. **Figure 3** shows waveforms of the earthquake in the Kermadec Islands region (February 18, 2009, Mb 6.8) detected by the GAMSEIS stations, including the Japanese Dome-F (GM07) station. These teleseismic data provided detailed information on crustal thickness and mantle temperatures beneath the East Antarctic continent. Data collected from AGAP/GAMSEIS were capable of providing key constraints on the origin of GSM as a crustal root associated with ancient orogenic events [13] and more broadly on the structure and evolution of the entire area of the East Antarctic craton [14–16]. Understanding the origin of GSM and seismological structure of the East Antarctic craton can be linked to the geologic history of the adjacent terrains, the role of its topography and heat flow in the Earth's climate and glacial history, and the geophysical and geologic controls of subglacial lakes [17]. A map of the crustal thickness beneath GSM showed large values, over 55 km, which imply that an ancient mountain range might have been supported by the thick, buoyant crust [13, 14]. These new findings of the crust and upper mantle aided in understanding the evolution of the Gondwana supercontinent in the Earth's history.

Several kinds of seismic signals associated with the atmosphere-ocean-cryosphere system were also detected. The dynamic movement of the cryosphere was capable of causing small-magnitude earthquakes, generally named "ice quakes" (or "ice shocks") for their relationship between glacial dynamics and evolution [18–21]. Such cryoseismic sources have been classified into the

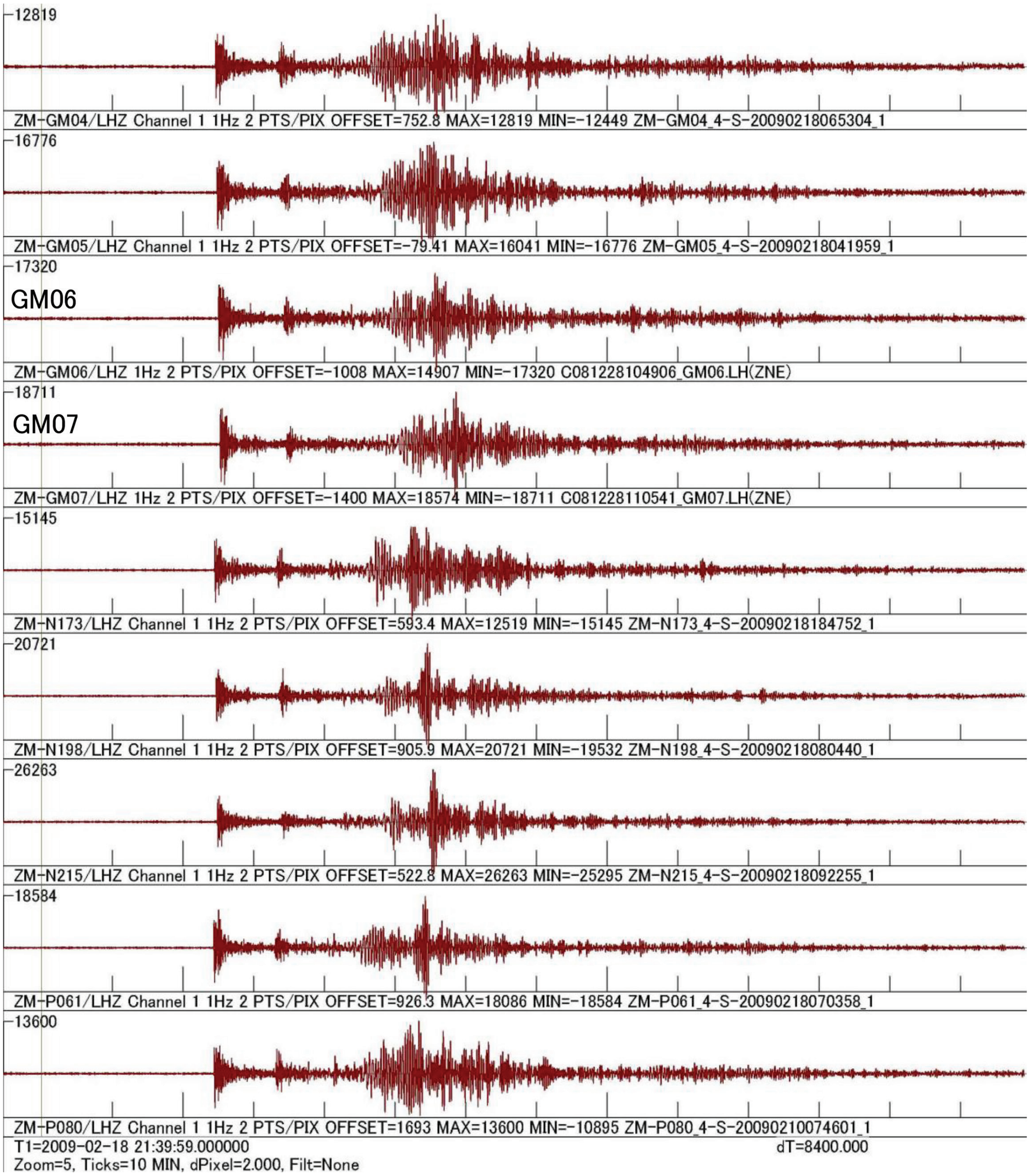


Figure 3. Teleseismic waveforms of the earthquake in Kermadec Is. region (February 18, 2009, Mb 6.8) recorded by several stations of AGAP/GAMSEIS, including Dome-F (GM07).

movement of ice sheets, sea ices, oceanic tide cracks, oceanic swells, and icebergs and the calving fronts of ice caps. These cryoseismic sources were likely to be influenced by environmental conditions of the surface layers of the Earth, and the detailed studies of their temporal variations may provide indirect evidence of climate change in the polar region. In addition to these cryoseismic signals, atmospheric vibrations were also recorded on seismographs deployed in the Antarctic inland area. **Figure 4** represents an example of seismic waveforms in the period of storms (i.e., the names of the “blizzard” in the polar region) overlapping with several seismic events during the austral summer in 2009 recorded by the GAMSEIS stations, including Dome-F (GM07). In spite of the limited time periods, temporal variations were investigated by detecting seismic events in GM06 (**Figure 5**). Variations in the number of detected teleseismic events, estimated local events, and noise or undefined events and in the periods of storms were compared. The shadowed areas in **Figure 5** appeared to correspond with the time periods of storms, which are also supposed to generate high amplitudes of the “microseismic” signals generated from the oceanic swells. More detailed studies can be carried out by comparing these observations with meteorological data, including the data from the autonomous weather stations (AWS) deployed over the Antarctic. The detection of these types of cryoseismic signals could be a new proxy to understand the effects among the atmosphere-ocean-cryosphere system in the central part of the continent.

Figure 6 presents hypocentral information of local seismic events detected by the AGAP network in 2009, in addition to those detected by the TAMSEIS network in 2002 [22]. These local events occurring inside the ice sheet were considered to have cryodynamic origins. These sources, termed “firn quakes,” were characterized by dispersed surface wave trains with frequencies of 1–10 Hz, propagating distances up to 1000 km [22]. They proposed that these events were linked to the formation of small crevasses in the firn layers at the surface of the

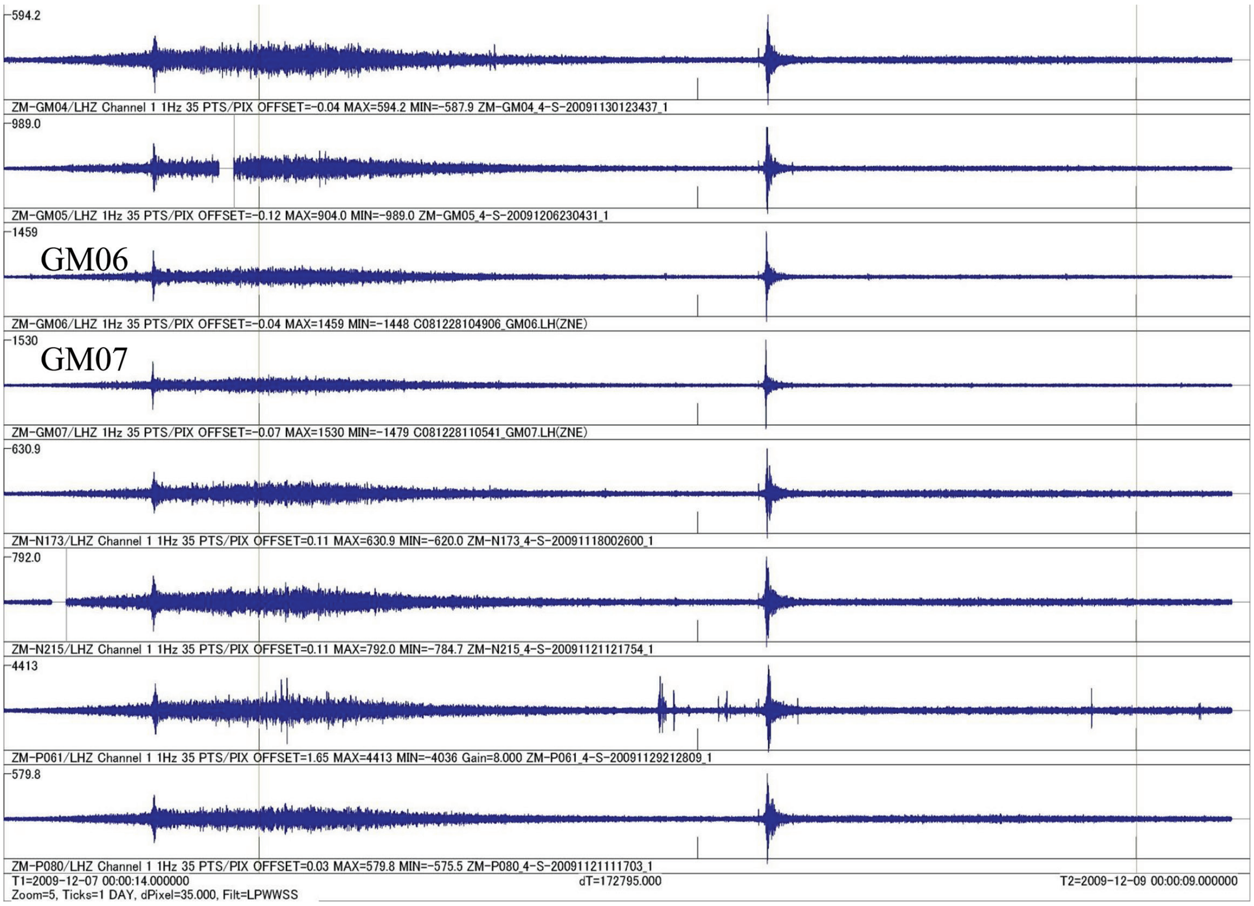
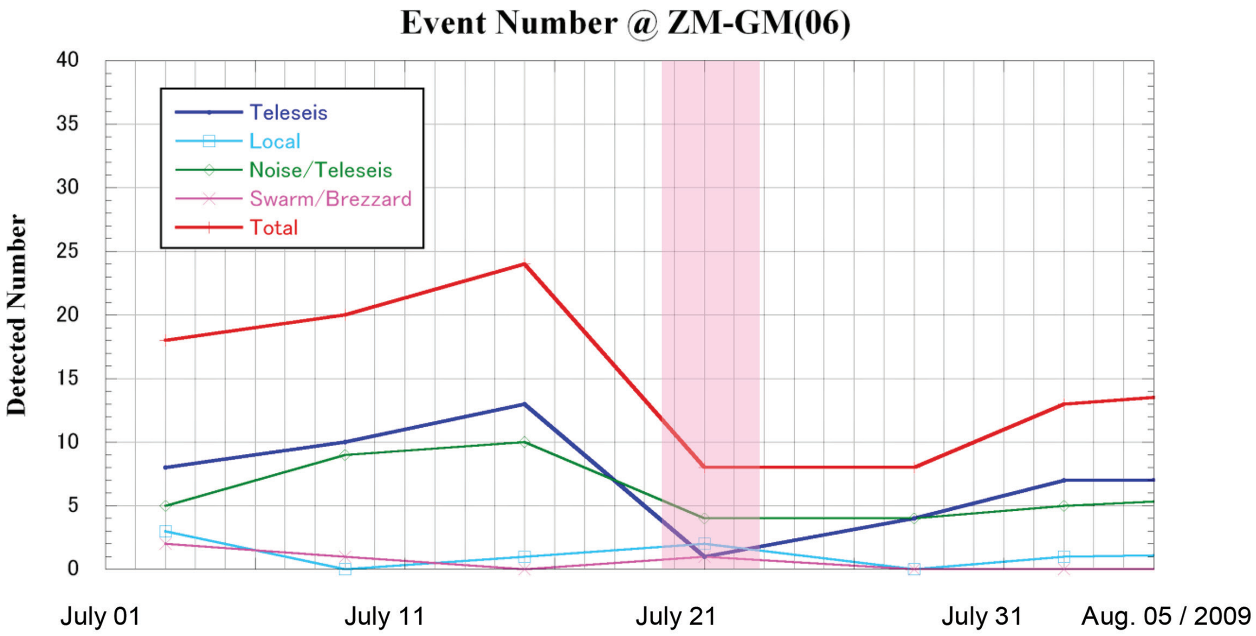


Figure 4. Waveforms of the blizzard and seismic events after the low-pass filters (February 6–9, 2009) recorded by several stations of AGAP/GAMSEIS, including Dome-F (GM07).



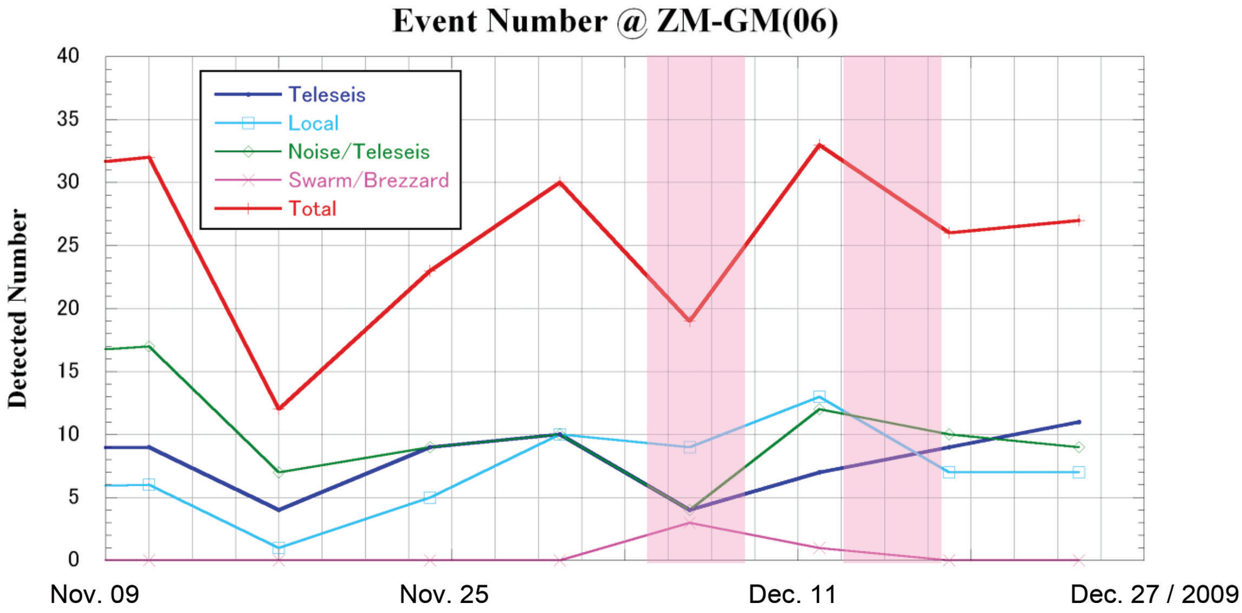


Figure 5. Temporal variations in detecting the seismic events in the GM06 station for July-August 2009 (upper) and November-December 2009 (lower), respectively. Several solid lines in different colors represent the variations in teleseismic events (blue), local events (light blue), noise (undefined) events (green), swarm/blizzard (pink), and total events (red). The shadowed areas appear to correspond with the time periods when passed by the swarm/blizzard phenomenon.

ice sheet, and several events could correlate with shallow crevasse fields mapped on satellite imagery. The hypocentral location of these events appeared to be close to the location of the existing crevasses, that is, near the upstream of the Lambert Glacier and inland area of the Transantarctic Mountains. The local events detected by the GM06 station could possibly include some of these events detected by Lough et al. [22].

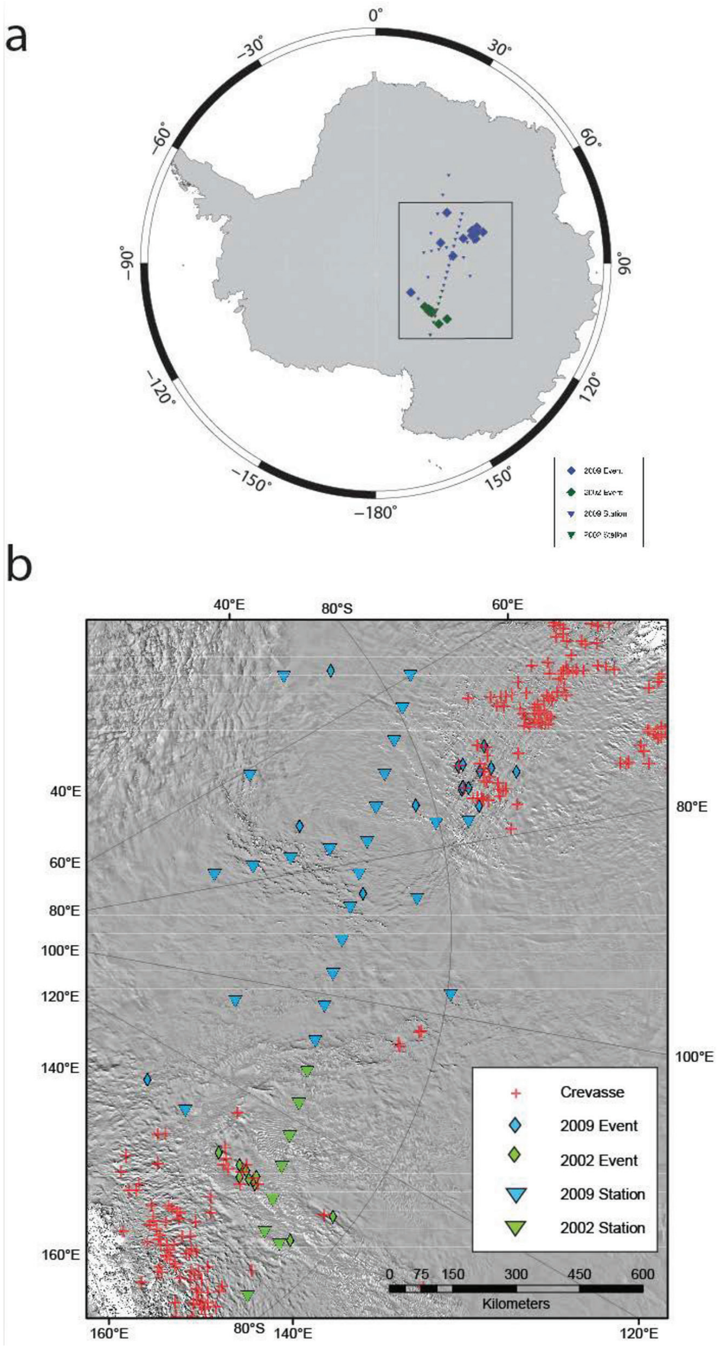


Figure 6. Local seismic events detected by the AGAP network (2009, blue diamond) and the GAMSEIS network (2002, green diamond; refer [22]). Red crosses indicate the location of crevasses. Copyright Clearance Center (CCC, http://www.copyright.com/). License Number: 4282210713648, License date: February 04, 2018.

4. Summary

By deploying broadband seismic instruments over the whole area of Antarctica, more detailed understanding of the tectonics and upper mantle structure can be obtained. After combining these data from numerous IPY projects in seismology and geophysics, it was possible to provide constraints on the origin of GSM and the broader structure of Precambrian cratons, as well as the subglacial environment near the region. The detection of seismic signals associated with basal sliding of the ice sheet and ice streams [7, 19, 23, 24] is expected in future, together with the detection of outburst floods from subglacial lakes. Temporary seismic stations along the inland traverse routes on the continental ice-sheet plateau can be installed using snow vehicles with sufficient support from air transport. These field observation stations over the ice sheet may also be utilized for other science studies, such as geophysics, meteorology, glaciology, and biology. Multidiscipline inland data collected around the Antarctic continent can be utilized by the nations involved in the Antarctic research in order to monitor long-term variations especially under cold temperature environments.

The IPY 2007–2008 provided an excellent opportunity to make significant advances in geophysical monitoring in the bipolar region. The advances served as an important contribution to the studies of the global network of FDSN, the projects of GARNET/POLENET, and other science bodies and communities. The high-quality data obtained from the Antarctic can be efficiently utilized to clarify the characteristics of local seismicity and heterogeneous structure of the Earth. From the AGAP/GAMSEIS data obtained during the IPY, the local and regional seismic signals associated with the ice-sheet movement and meteorological variations were recorded, together with a significant number of teleseismic events. The detection of seismic signals from the phenomenon at the base of the ice sheet, such as outburst floods from subglacial lakes, can be expected from detailed analyses in future.

Author details

Masaki Kanao

Address all correspondence to: kanao@nipr.ac.jp

National Institute of Polar Research (NIPR), Organization of Information and Systems (ROIS), Tokyo, Japan

References

[1] Reading AM. Antarctic seismicity and neotectonics. In: Gamble JA, Skinner DNB, Henrys S, editors. Antarctica at the close of a millennium, Vol. 35. Wellington, New Zealand: Royal Society of New Zealand Bulletin; 2002. pp. 479-484

[2] Reading AM. On seismic strain-release within the Antarctic plate. In: Futterer DK, Damaske D, Kleinschmidt G, Miller H, Tessensohn F, editors. Antarctica: Contributions to Global Earth Sciences. Germany: Springer - Verlag Berlin Heidelberg; 2006. pp. 351-356

[3] Roult G, Rouland D, Montagner JP. Antarctica II: Upper-mantle structure from velocities and anisotropy. Physics of the Earth and Planetary Interiors. 1994;**84**:33-57

[4] Ritzwoller MH, Shapino NM, Levshin AL, Leahy GM. Crustal and upper mantle structure beneath Antarctica and surrounding oceans. Journal of Geophysical Research. 2001;**106**:30645-30670

[5] Kobayashi R, Zhao Z. Rayleigh-wave group velocity distribution in the Antarctic region. Physics of the Earth and Planetary Interiors. 2004;**141**:167-181

[6] Lawrence JF, Wiens DA, Nyblade AA, Anandakrishan S, Shore PJ, Voigt D. Upper mantle thermal variations beneath the Transantarctic Mountains inferred from teleseismic S-wave attenuation. Geophysical Research Letters. 2006;**33**:L03303. http://dx.doi.org/10.1029/2005GL024516

[7] Wiens DA, Anandakrishnan S, Winberry JP, King MA. Simultaneous teleseismic and geodetic observations of the stick-slip motion of an Antarctic ice stream. Nature. 2008;**453**: 770-774

[8] Kanao M, Usui Y, Inoue T, Yamada A. Broadband seismic deployments for imaging the upper mantle structure in the Lützow-Holm Bay region, East Antarctica. International Journal of Geosciences. 2011;**2011**:1-15

[9] Kanao M, Yamada A, Toyokuni G. Passive seismic deployments from the Lützow-Holm Bay to Inland Plateau of East Antarctica: The Japanese IPY contribution to structure and seismicity. International Journal of Geosciences. 2013;**4**:837-843. DOI: 10.4236/ijg.2013.45077

[10] Wilson T, Bell R. Earth Structure and Geodynamics at the Poles. Understanding Earth's Polar Challenges: International Polar Year 2007-2008. 2011. pp. 273-292

[11] Anderson K, Beudoin B, Parker T. IRIS/PASSCAL Polar Power/Comms MRI Year 1 Midseaon Report. 2007. p. 14

[12] Kanao M, Wiens D, Tanaka S, Nyblade A, Toyokuni G, Shore P, Tsuboi S, Heeszel D, Usui Y, Parker T. Broadband seismic deployments in East Antarctica: IPY contribution to monitoring the Earth's interiors. Annals of Geophysics. 2014;**57**:SS0322. DOI: 10.4401/ag-6379

[13] Hansen SE, Nyblade AA, Heeszel DS, Wiens DA, Shore PJ, Kanao M. Crustal structure of the Gamburtsev Mountains, East Antarctica, from S-wave receiver functions and Rayleigh wave phase velocities. Earth and Planetary Science Letters. 2010;**300**:395-401

[14] Heeszel DS, Wiens DA, Nyblade AA, Hansen SE, Kanao M, An M, Zhao Y. Rayleigh wave constraints on the structure and tectonic history of the Gamburtsev Subglacial Mountains, East Antarctica. Journal of Geophysical Research. 2013;**118**:2138-2153

[15] An M, Wiens DA, Zhao Y, Feng M, Nyblade AA, Kanao M, Li Y, Maggi A, Lévêque J-J. The Antarctic plate from surface wave observations: S-velocity model and Moho topography. Journal of Geophysical Research. 2015;**120**:359-383

[16] Lloyd AJ, Nyblade AA, Wiens DA, Shore PJ, Kanao M, Hansen SE, Zhao D. Upper mantle seismic structure beneath the East Antarctic shield from body wave tomography: Implications for the origin of the Gamburtsev Subglacial Mountains. Geochemistry, Geophysics, Geosystems. 2013;**14**:902-920

[17] Bell RE, Ferraccioli F, Creyts TT, Braaten D, Corr H, Das I, Damaske D, Frearson N, Jordan T, Rose K, Studinger M, Wolovick M. Widespread Persistent Thickening of the East Antarctic Ice Sheet by Freezing from the Base. Science Xpress Report. 2011. DOI: 10.1126/science.1200109

[18] Tsuboi S, Kikuchi M, Yamanaka Y, Kanao M. The March 25, 1998 Antarctic earthquake: Caused by postglacial rebound. Earth, Planets and Space. 2000;**52**:133-136

[19] Anandakrishnan S, Voigt DE, Alley RB, King MA. Ice stream D flow speed is strongly modulated by the tide beneath the Ross Ice Shelf. Geophysical Research Letters. 2003;**30**. DOI: 10.1029/2002GL016329

[20] Kanao M, Kaminuma K. Seismic activity associated with surface environmental changes of the Earth system, East Antarctica. In: Futterer DK, Damaske D, Kleinschmidt G, Miller H, Tessensohn F, editors. Antarctica: Contributions to Global Earth Sciences. Germany: Springer - Verlag Berlin Heidelberg; 2006. pp. 361-368

[21] Kanao M, Maggi A, Ishihara Y, Yamamoto M-Y, Nawa K, Yamada A, Wilson T, Himeno T, Toyokuni G, Tsuboi S, Tono Y, Anderson K. Interaction of seismic waves between atmosphere-ocean-cryosphere and geosphere in polar region. In: Kanao M, Takenaka H, Murai Y, Matsushima J, Toyokuni G, editors. Seismic Waves–Research and Analysis. Rijeka, Croatia: InTech. Publisher; 2012. pp. 1-20, ISBN 978-953-307-944-8

[22] Lough AC, Wiens DA, Nyblade AA, Anandakrishnan S. A previously unreported type of seismic source in the firn layer of the East Antarctic Ice Sheet. Journal of Geophysical Research - Earth Surface. 2015;**120**:2237-2252. DOI: 10.1002/2015JF003658

[23] Winberry JP, Anandakrishnan A, Wiens DA, Alley RB, Christianson K. Dynamics of stick–slip motion, Whillans Ice Stream, Antarctica. Earth and Planetary Science Letters. 2011;**305**:283-289

[24] Winberry JP, Anandakrishnan A, Wiens DA, Alley RB. Nucleation and seismic tremor associated with the glacial earthquakes of Whillans Ice Stream, Antarctica. Geophysical Research Letters. 2013;**40**:312-315

Chapter 4

Progress of Seismology in Polar Region

Masaki Kanao

Abstract

Several kinds of seismological investigations have been conducted in the polar region, which include the areas of both the Arctic and the Antarctic regions, in various depth ranges from the surface layers to the deep interiors of the Earth. The polar region has an advantage in order to seek inside the physical condition of the Earth as a "window" viewed from high latitudes. In this chapter, historical issues and progress of seismic research and its observations in the polar region are demonstrated during the last half-century from the era of the International Geophysical Year (IGY 1957–1958).

Keywords: seismology, polar region, Arctic, Antarctic, seismic observations, International Geophysical Year

1. Introduction

The polar region, as a "window" in order to seek the interiors of the Earth, has an advantage to investigate the inner structure and dynamics of the solid Earth by using time-space variations and changes of physical parameters determined from seismological methods. A significant number of scientific research have been carried out from the surface layers to the deeper parts of the Earth, by taking into account the research merits from high latitudes. In this book, progress and achievements by seismological studies in the polar region are summarized from the mid-twentieth century to the present. Characteristics of seismic wave propagation, heterogeneous structure, and dynamics of the Earth's interiors are demonstrated, which have been conducted by many international research in both areas of the Arctic and the Antarctic regions. Practically, the following scientifically achieved results are introduced by using seismic waves and travel-time data: inner structure and dynamics of the crust and mantle in high latitudes, seismicity and focal mechanism, seismic wave propagation within the global point of view,

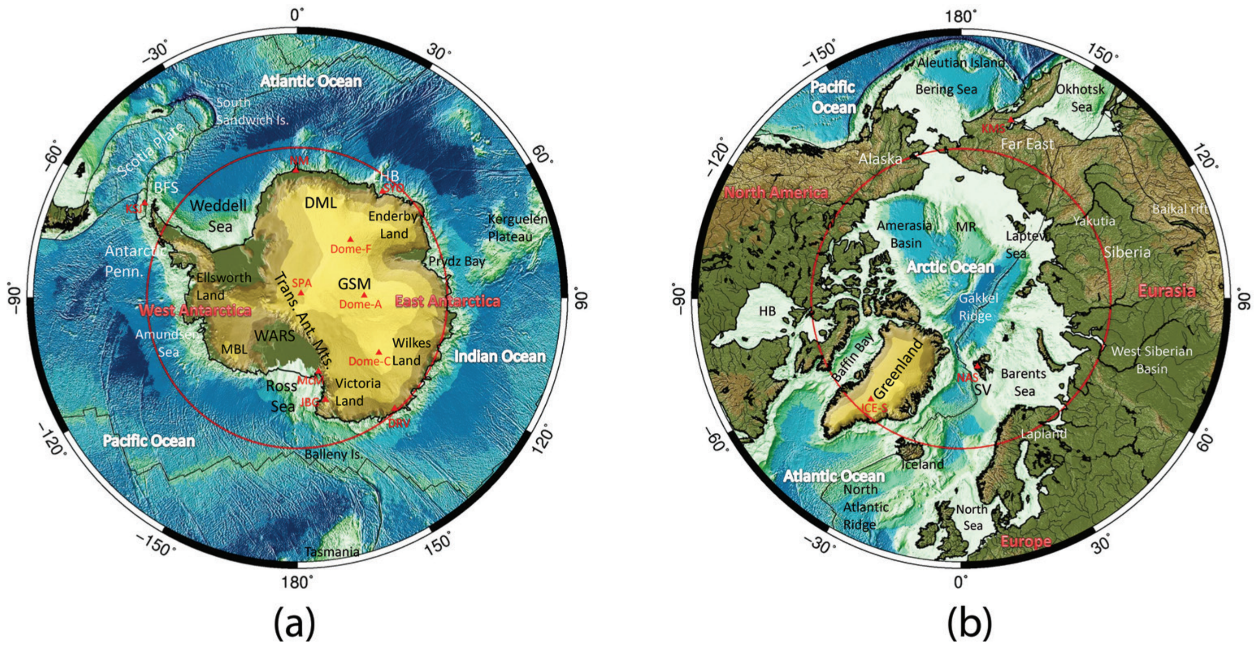


Figure 1. (a) Surface topography and bathymetry in the Antarctic (ETOPO1, [17]) with major geographic location names treated in this chapter. Plate boundaries are after [18]. Red solid circle represents the "Antarctic circle" (66.6°S). Abbreviations are as follows: LHB, Lützow-Holm Bay; DML, Dronning Maud Land; GSM, Gamburtsev Subglacial Mountains; Trans. Ant. Mts., Trans-antarctic Mountains; WARS, West Antarctic Rift System; MBL, Marie Byrd Land; and BFS, Bransfield Strait. Red solid triangles are the permanent stations. SYO, Syowa Station; NM, Neumayer Station; Dome-F (Fuji); Dome-A (Argus); Dome-C (Charlie); DRV, Dumont D'urville; SPA, South Pole Station; McM, McMurdo Station; JBG, Jang Bogo Station; and KSJ, King Sejong Station. (b) Surface topography and bathymetry in the Arctic (ETOPO1 [17]) with major geographic location names treated in this review paper. Plate boundaries are after [18]. Red solid circle represents the "Arctic circle" (66.6°N). Abbreviations are as follows: SV, Svalbard; MR, Mendeleev Ridge; and HB, Hudson Bay. Red solid triangles are the permanent stations. KMS, Kamenskoye Station; NAS, Ny-Alesund Station, ICE-S (South).

seismotectonics in the Earth's history, and other involved topics in terms of "polar seismology." Major location names in both polar regions are illustrated in **Figure 1a** and **b**.

The International Polar Year (IPY 2007–2008) program had been conducted as a half-century anniversary from the International Geophysical Year (IGY 1957–1958), when the Antarctic expeditions for scientific purposes started with the involved countries in the polar region. The IPY 2007–2008 was a big international program composed of multidisciplinary science branches such as upper atmosphere, meteorology, glaciology, geosciences, oceanography, and biosciences conducted by a significant number of polar scientists involved [1]. In this book, many of the seismological achievements are carried out by the IPY, including contributions from Japanese seismologists. In addition, the recent trend in scientific investigation for physical interaction between multi-sphere system within the polar surface environment (i.e., atmosphere-ocean-cryosphere-solid Earth) is especially introduced. "Cryoseismology," most of all, is a new and recent progressing topic of seismic approach to investigate characteristics of seismic waves and seismicity in terms of long-term climate changes such as global warming. The most recent seismic achievements in both polar regions are compiled in the special issue on "Polar Science" [2].

It is noticed that, moreover, the index introduced in this book intends to demonstrate the present status of the polar region not only to the global seismologists but also to all the general public who are interested in this topic. It is hoped that this book could provide remarkable knowledge and new understanding about the present environments and past history within the dynamics of the global system. The reader could surely attain fruitful information on the advancement of frontier research in the polar region, which is currently progressing, from this book.

2. Seismic observation in the Antarctic

In this section, historical issues on seismic observation mainly conducted at the Japanese Antarctic stations are presented. During the IGY, the Japanese Antarctic Research Expedition (JARE) started the main base camp Syowa Station (SYO; 69.0°S, 39.6°E; **Figure 1a**), Eastern Dronning Maud Land, in the Lützow-Holm Bay (LHB) of East Antarctica. Seismological observations at Syowa Station began since 1961 by the 3rd JARE (JARE-3) as one of the monitoring stations in the Antarctic within the global observation network. In this regard, the seismic observations, similar to the other long-term observations such as meteorological and aurora research, have been carried out over the half-century. During the past few decades, infrastructure systems and data logging huts/buildings have been replaced according to the development of observation techniques and logistical background of the polar region. Moreover, characteristics, kinds, and purpose of the observational data varied drastically during the long period. Sincerely maintained by winter-over expedition members, seismic observations at Syowa Station continued over all the seasons without any serious problems. Since 2004, digital seismic waveform data have been transmitted from Syowa Station to the National Institute of Polar Research (NIPR), Tokyo, Japan, by using the “Intelsat” satellite telecommunication system. The transmitted data have also been stored in huge data library system of NIPR and opened to the global seismological community [3, 4]. For example, the seismic waves caused by a huge earthquake in the Tohoku region, in northeast Japan (M = 9.0; March 11, 2011), as well as another large disaster earthquake that occurred at Christ Church, New Zealand (M = 6.3; February 22, 2011), were clearly recorded, and continuous monitoring observations have been carried out until now at SYO [5].

In order to cover the high-latitude areas of the Earth, several seismic stations belonging to the Federation of Digital Seismographic Network (FDSN) [6] have been increasing in the Antarctic since the 1980s. Many of the stations have been located at the margins of the continent, where the permanent winter-over stations of corresponding nations have individually been existed (**Figure 2a** and **b**). The East Antarctic continent, where Syowa Station is located, and the Greenland in the Arctic have advantages of recording teleseismic events occurring over the globe with a sufficient signal-to-noise ratio. There are some reasons for the advantages: stable Precambrian-aged continent composed of hard rock areas on the surface layer and deep “lithosphere” underneath, low local seismicity in the vicinity of the recording stations because of the same reason of old and stable continents, low artificial noises because of far distance from major human activity regions in particular for the Antarctic, and so on. The Syowa Station has provided precious seismic data to the global community as one of the major stations of FDSN in the Antarctic continent, as well as one of the Japanese contributing global network (POSEIDON/PACIFIC-21). The seismic data from SYO (travel times, waveforms, hypocentral information, etc.) have been offered to several international centers

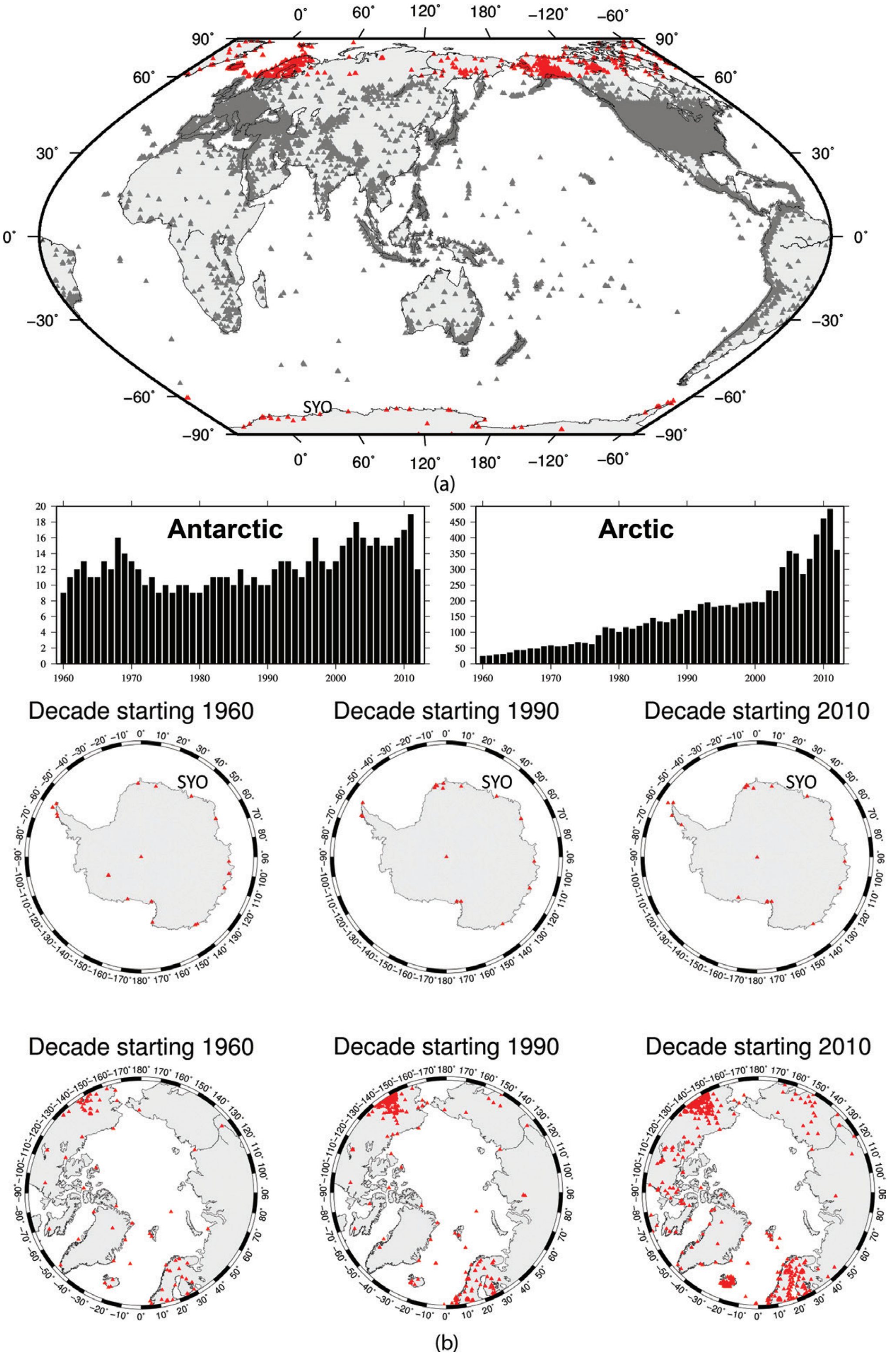


Figure 2. (a) Upper: global distribution of the seismic stations (gray triangles) including those in polar regions (red triangles). SYO indicates Syowa Station. Lower: variation in the number of seismic stations reporting bulletin data to the ISC from the Antarctic (left) and the Arctic (right) regions. All figures are modified after [19]. Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4278040314413, license date: January 29, 2018. (b) Distribution of the permanent seismic stations in polar regions (upper: the Antarctic; lower: the Arctic) for each decade in 1960, 1990, and 2010, respectively (after [19]). Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4278040314413, license date: January 29, 2018.

and organizations via NIPR, for example, to the International Seismological Center (ISC), the National Earthquake Information Center of the United States Geological Survey (NEIC/USGS), the Data Management System of the Incorporated Research Institutions for Seismology (DMS/IRIS), and others. In addition, seismic data of SYO have been provided to the Japanese National Data Center of PACIFIC-21 network, that is, the Earth Information Center inside the Japan Agency for Marine Science and Technology (JAMSTEC) [4]. It is noticed that details of the data archive and publication procedure from NIPR are described in the meta-database portal server (http://scidbase.nipr.ac.jp/).

At the majority of stations belonging to FDSN in the polar region, high-resolution and wide dynamic–range broadband seismographs (Streckeisen Seismometer type 1; STS-1) have been installed and operated in the last three decades. The STS-1 has been known as the most standard seismographs in global seismology, and almost all teleseismic events with magnitude over four occurring on the globe are recordable at Syowa Station. After a rapid spread of FDSN stations over the Earth in the 1980s, continuous observations by using STS-1 started in 1989 at the Syowa Station. By combining the data from both the STS-1 and the short-period seismographs hagiwara erectric seismometer (HES) that started observation during the IGY, teleseismic events detected at SYO have been varying within few hundreds of their identified number during the last two decades [4] (**Figure 3**). Long-period variations in teleseismic detectability since the era of IGY are summarized [5]. Seismological studies by using the data at SYO are classified into heterogeneous structure and dynamics of the inner core and surrounding mantle viewed from southern high latitudes, crustal structure, seismicity and earthquake source mechanism of the Antarctic Plate and the Antarctic continent, crustal movement and ice-related seismic activities associated with cryosphere dynamics, and the other topics. A significant number of achievements by seismological investigations and new findings are demonstrated in more detail in the succeeding chapters of this book. As an example, long-term data at SYO were utilized to reveal a superrotation of the inner core of the deep interiors over 30 years based on the analog record from IGY [7]. In this regard, long-term compiled data such as the research of dynamics in deeper parts of the Earth have efficiently been used. Therefore, the seismic station in the polar region including the Syowa Station is expected to continue offering the high-quality data as an important permanent observation site in southern high latitude among global seismology.

In the vicinity of Syowa Station, several field stations of broadband seismographs have been conducted around the LHB region since 1997 (**Figure 1a**) [8–10]. The portable broadband array stations have contributed to the Global Alliance of Regional Networks (GARNET), together with the international projects conducted during the International Polar Year (IPY 2007–2008). Details about the IPY projects and observation networks are given in Chapter 2. On the contrary, deep seismic surveys (DSSs) using active seismic sources were also carried out in 2000 and 2002 on the ice-sheet plateau nearby Syowa Station in LHB. The DSSs consist of the observations/analysis specks of the wide-angle reflection/refraction methods as a major part of the "Structure and Evolution of East Antarctic Lithosphere (SEAL)" project [11] by JARE. From the DSS, seismic velocity model of the crustal structure and seismic reflection section of the lithosphere of the LHB region were investigated, which are situated between the Western Enderby Land and the Eastern Dronning Maud Land (DML; **Figure 1a**). Detailed results of the DSS are given in Chapter 4.

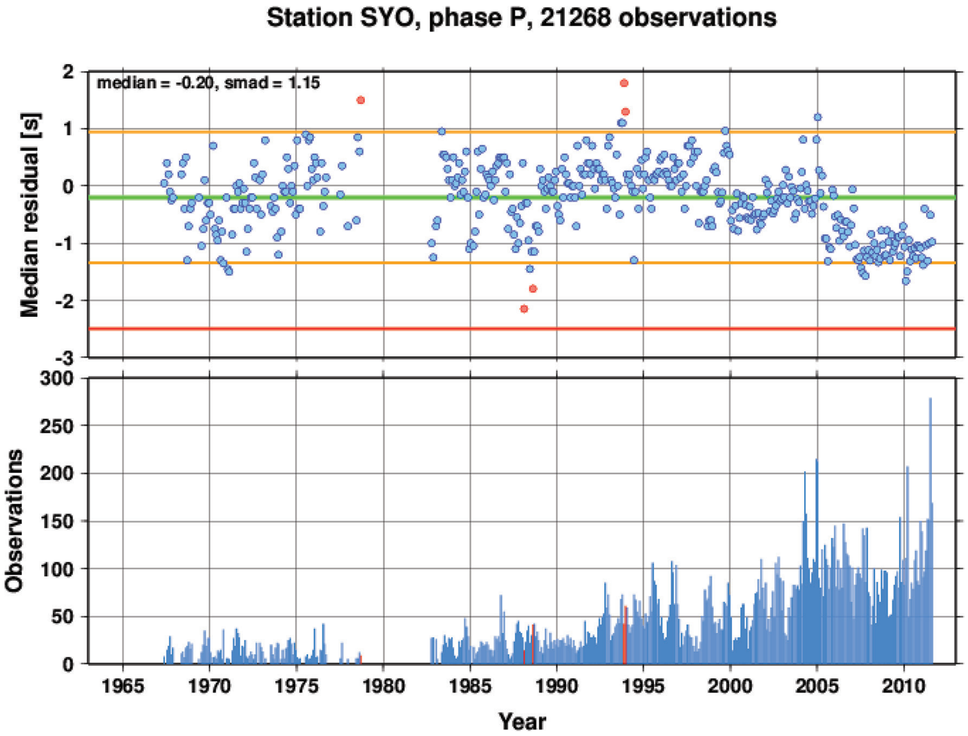


Figure 3. Historical reporting features of the Antarctic station (SYO) based on the ISC Bulletin. The upper panel shows the timeline of variations in the travel-time residuals for P waves at SYO. Each dot represents the median residual for 1 month of data. The green line is the overall median; the orange line shows the standard deviation based on the median absolute deviation, while the red line shows twice the standard deviation. The red dots represent those months when the absolute value of the annual median residual exceeds the long-term median by more than a standard deviation. The bottom panel shows the reported number of teleseismic events at SYO in 1967–2011 by ISC (after [19]). Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4278040314413, license date: January 29, 2018.

It is also noticed that the international collaboration project was carried out in the USA and New Zealand (the International Mount Erebus Seismic Study; IMESS) at the Ross Island of Ross Sea, West Antarctica, for few years since 1980 (near McM station; **Figure 1a**). From the project, microseismicity associated with volcanic eruptions of Mount Erebus was investigated in detail [12]. Moreover, ocean bottom seismic observations were held at the Antarctic Peninsula in 1990–1991, in collaboration with Polish geoscience group. Precise crustal structure and extension regime around the area were studied at the Bransfield Strait (BFS; **Figure 1a**) [13].

3. Seismic observation in the Arctic

In contrast to the Antarctic, there have been no permanent seismic stations in the Arctic region by Japan (more than 66°N; **Figure 2**); however, several temporary observations have been done in Eastern Asia including in Far East of Russia. In 1994, a seismic station at KMS (**Figure 1b**), the northern root of Kamchatka Peninsula, Far East of Russia, was installed by Nagoya University as the northernmost station of the Japanese global network (POSEIDON). In spite of the difficult access from Japan, the station has continued observation until now.

The noise level of the KMS station has been quite low and can record a significant number of microseismicity involving seismic fault system near the station. After the North Sakhalin earthquake (M = 7.6, May 1995), microseismic and global positioning system (GPS) observations started around the large area including KMS station in collaboration/cooperation with the Russian Academy of Science. In 2005, a big project started in order to reveal the stagnant slab and relation with mantle dynamics by using broadband seismic regional network. From the temporary network observations, amalgamation mechanism of the stagnant slab (subducting Pacific Oceanic plate) in the upper mantle depths beneath the East Asia region was obtained. Moreover, seismic activities around the North Sakhalin area have been advanced by using the obtained data. From 2009 to 2012, large temporary seismic array stations have been carried out (NECESSArray) at northeastern China mainland, in collaboration with China, the USA, and Japan. Several major seismological targets were achieved such as the formation mechanism of the China mainland continent, shape of the subducting stagnant slab underneath the stations, and source mechanism of huge mantle plumes under the Pacific Ocean [14]. Besides, temporal observation using broadband seismographs was conducted at the Baikal Rift Zone (BRZ; **Figure 1b**) in 2004–2006 in collaboration with the Russia Academy of Science (RAS). Crustal structure and seismicity at BRZ were investigated in detail [15, 16].

Including the abovementioned studies before the IPY, internationally collaborated seismic network in Greenland will be introduced in detail in Chapter 6. The regional network aimed to investigate the relationship between the glacial seismicity and the global warming process in the Arctic region.

Author details

Masaki Kanao

Address all correspondence to: kanao@nipr.ac.jp

National Institute of Polar Research (NIPR), Organization of Information and Systems
(ROIS), Tokyo, Japan

References

[1] Krupnik I, Allison I, Bell R, Cutler P, Hik D, Lopez-Martinez J, Rachold V, Sarukhanian E, Summerhayes C. Understanding Earth's Polar Challenges: International Polar Year 2007-2008 – Summary by the IPY Joint Committee. Edmonton, Alberta: Art Design Printing Inc.; 2011. pp. 457-476

[2] Kanao M, Zhao D, Wiens DA, Stutzmann E. Recent advance in polar seismology: Global impact of the international polar year – Overview. Polar Science. 2015;**9**:1-4. DOI: 10.1016/j.polar.2014.12.003

[3] Iwanami S, Kanao M. Seismological bulletin of Syowa Station, Antarctica, 2011. JARE Data Reports. 2013;**325**(Seismology 47):1-190

[4] Kanao M. Detection capability of teleseismic events recorded at Syowa Station, Antarctica – 1987-2007. Antarctic Record (New Zealand). 2010;**54**:11-31

[5] Kanao M, Storchak D, Dando B. Evaluation of long-period detectability of teleseismic events at Syowa Station, Antarctica. International Journal of Geosciences. 2012;**3**:809-821

[6] Butler R, Anderson K. Global Seismographic Network (GSN), IRIS Report. 2008. pp. 6-7

[7] Isse T, Nakanishi I. Inner-core anisotropy beneath Australia and differential rotation. Geophysical Journal International. 2001;**151**:255-263

[8] Negishi H, Kanao M. Field seismic observations by portable broadband seismometers in the Lützow-Holm Bay Region, East Antarctica. Antarctic Record. 1998;**42**:179-189

[9] Kanao M, Kaminuma K. Seismic activity associated with surface environmental changes of the Earth system, around Syowa Station, East Antarctica. In: Futterer DK, Damaske D, Kleinschmidt G, Miller H, Tessensohn F, editors. Antarctica: Contributions to Global Earth Sciences. Berlin Heidelberg, New York: Springer-Verlag; 2006. pp. 361-368

[10] Kanao M, Usui Y, Inoue T, Yamada A. Broadband seismic deployments for imaging the upper mantle structure in the Lützow-Holm Bay region, East Antarctica. International Journal of Geophysics. 2011;**2011**:1-15

[11] Kanao M, Ishikawa M, Yamashita M, Kaminuma K, Brown LD. Structure and evolution of the East Antarctic lithosphere: Tectonic implications for the development and dispersal of Gondwana. Gondwana Research. 2004;**7**:31-41

[12] Kaminuma K, Baba M, Shibuya K, Dibble RR. Explosion earthquakes of Mount Erebus, Antarctica. Memoirs of National Institute of Polar Research. 1985;**37**:29-39

[13] Grad M, Shiobara H, Janik T, Guterch A, Shimamura H. Crustal model of the Bransfield rift, West Antarctica, from detailed OBS refraction experiments. Geophysical Journal International. 1997;**130**:506-518. DOI: 10.1111/j.1365-246X.1997.tb05665.x

[14] Tang Y, Obayashi M, Niu F, Grand SP, Chen YJ, Kawakatsu H, Tanaka S, Ning J, Ni JF. Changbaishan volcanism in Northeast China linked to subduction-induced mantle upwelling. Nature Geoscience. 2014;**7**:470-475. DOI: 10.1038/ngeo2166

[15] Ananyin LV, Mordvinova VV, Gots MF, Kanao M, Suvorov VD, Tatkov GI, Thubanov TA. Velocity structure of the crust and upper mantle in the Baikal rift zone on the long-term observations of broad-band seismic stations. Doklady Earth Science. 2009;**428**:1067-1071. DOI: 10.1134/S1028334X09070058

[16] Kanao M, Suvorov VD, Toda S, Tsuboi S. Seismicity, structure and tectonics in the Arctic regions. Geoscience Frontiers. 2015;**6**:665-677. DOI: 10.1016/j.gsf.2014.11.002

[17] Amante C, Eakins BW. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA; 2009. DOI: 10.7289/V5C8276M

[18] Bird P. An updated digital model of plate boundaries. Geochemistry, Geophysics, Geosystems. 2003;**4**:1027. DOI: 10.1029/2001GC000252

[19] Storchak DA, Kanao M, Delahaye E, Harris J. Long-term accumulation and improvements in seismic event data for the polar regions by the International Seismological Centre. Polar Science. 2015;**9**:5-16. DOI: 10.1016/j.polar.2014.08.002

Chapter 5

A New Trend in Cryoseismology: A Proxy for Detecting the Polar Surface Environment

Masaki Kanao

Abstract

"Cryoseismology" is a new branch of interdisciplinary science, which treats glacier-related seismic events and their dynamics associated with the variable phenomenon of the Earth's surface. Cryoseismology is considered to be one of the proxies for detecting environmental variations, particularly in the polar region, which contains the majority volume of the cryosphere of the planet. Various kinds of cryoseismic signals recently reported are reviewed by classifying them into several categories on the basis of their occurrence locations and focal dynamics. Temporal-spatial variations in cryoseismic activities and their wave propagation characteristics could demonstrate a new image of cryodynamics, which have not yet been known well before but have a significant impact on the global environment and human activities.

Keywords: cryoseismology, polar region, seismic features, surface environment, global warming

1. Introduction

Several kinds of environmental signals associated with the ocean-cryosphere-solid Earth systems have recently been detected in the polar region. Glacier-related seismic signals with a small magnitude are generally called "ice quakes" (or "ice shocks") and can be generated by cryosphere-related dynamics. Such cryoseismic-originating sources can be classified into the movements of ice sheets, ice caps, sea ices, oceanic tidal cracks, and icebergs and the calving fronts of the ice caps, ice streams, and glaciers [1–5]. In this regard, cryoseismic waves are likely to be influenced by temporal-spatial variations in environmental conditions, and continuous research on their variability provides indirect evidence of the climate change. As large glacial earthquakes are the most prominent phenomena found recently in the polar region, particularly around Greenland [6–8], the new innovative studies conducted in seismology are strikingly encouraged by the long-term monitoring observations under extreme conditions in polar regions. Moreover, seismological investigations during the International Polar Year (IPY 2007–2008) were compiled and published including the related topics on cryoseismology [9].

Taking these current topics into account, in this chapter, new trends in "cryoseismology" are reviewed in addition to the previously conducted research studies as shown in Chapter 6. Various kinds of recent cryoseismic studies are demonstrated by classifying them into each section on the basis of their occurrence locations and focal dynamics, that is, ice shelves, outlet glaciers, margins of continental ice sheet, continental cliffs, sea ices, icebergs, oceanic tides, tide cracks around the coast, pressure ridges among bays, the basal sliding of the ice sheet, triggered seismic events associated with out-flood water from subglacial lakes, volcanic activities beneath the ice sheet, and other origins. The most important aspect is covered by the generation mechanism of cryoseismic events associated with global warming/climate change as one of the remarkable natural features in the polar region. Temporal-spatial variations in the glacier-related seismic activities as well as the propagation characteristics of their wavefields will give rise to a new horizon in "cryodynamics," which have not yet been well understood by both scientists and the general public.

2. Outlet glaciers and continental margins of ice sheets

Longitudinal seismic waves were reported in the Ross Ice Shelf (RIS) excited by the Whillans Ice Stream (WIS) stick-slip events [10]. The observations of longitudinal waves from the WIS slip events had been propagating hundreds of kilometers across RIS detected by more than 20 broadband seismographs deployed on the ice. The WIS slip events consisted of a rapid basal slip concentrated at three high-friction regions (often termed sticky spots or asperities) within a period of about 25 minutes. Compression displacement pulses from all three sticky spots were detected across most of the RIS up to about 600 km away from the source. The largest pulse resulted from the third sticky spot that was located along the northwestern grounding line of WIS. Thus, the study of this phenomenon should lead to an advance in understanding how the ice shelf responds to sudden forcing around the periphery, such as triggered ice quakes in the continental ice sheets [11].

Repeating glacial earthquakes revealed a migration process of subglacial sticky spots in the Transantarctic Mountains (TAM) [4]. Winberry et al. leveraged recent advances in seismograph coverage from TAM to study relatively large glacial seismic events (with a magnitude more than 2) that can be observed at regional distances. They reported on five newly discovered and one previously studied sequences of repeating glacial earthquakes. These new seismic sequences revealed that families could remain active for up to the last 7 years. In addition, by tracking subtle changes in relative arrival times as well as waveform similarities, they deduced that these sticky spots originate from migrating bands of basal debris.

Lipovsky and Dunham [12] simulated the tremors of the 200-km scale ice-stream stick slip of WIS. These tremors were considered to be episodes of swarms of small-scale repeating earthquakes. These events are evenly spaced in the timeline, and the spacing interval gives rise to the spectral peaks at integer multiples of the recurrence frequency 10–20 Hz. Numerical simulations of these tremor episodes give rise to information on the evolution of rate- and state-dependent fault friction and wave propagation from the fault patch to a seismograph over the ice area. By comparing synthetic seismograms to the observed ones, a fault patch area of 10 m^2, a bed shear modulus of 20 MPa, an effective pressure of 10 kPa, and a frictional state evolution distance of 1 μm were derived. These slip events are found to occur twice a day, in spite of the skipped events that have been increasing in frequency over the last few years and more.

In the Arctic region in addition to the Antarctic, de Juan et al. [13] studied a sudden increase in tidal response linked to calving and acceleration at a large Greenland outlet glacier. Flows of ice streams have known to be modulated by ocean tidal forcing at the terminus of the glaciers. The decimeter-level periodic positioning variations were found at Helheim Glacier in response to the tidal forcing. Also, the transient increases over 100% responded to the tidal forcing, followed by the occurrence of glacial earthquakes associated with the calving events. The occurrence times and their amplitudes correlate well with the step-like increases in the glacier speed and longitudinal strain rate of the cogenerating glacial earthquakes. The enhanced response to the ocean tides can be explained by a temporary disruption of the subglacial drainage system and a reduction in the friction at the bottom of the ice sheet and the bedrock surface.

Subglacial discharge events have a great effect on the basal movement of the glaciers and erode and redeposit the sediment. At tidewater termini of glaciers, discharge events drive submarine terminus melting, affecting the fjord circulation. Bartholomaus et al. [14] reported observations of hourly to seasonal variations in 1.5–10 Hz seismic tremors at Mendenhall Glacier of Alaska, which strongly correlate with subglacial discharges but not with the basal movement or the discrete icequake events. Vigorous discharge occurred from tidewater glaciers during the summer seasons of the Northern Hemisphere, in spite of fast basal movements that could limit the formation of subglacial conduits. In addition, seismic tremor observations and a melting model of the glaciers could demonstrate that the drainage efficiency of the tidewater glaciers evolves seasonally.

A detailed field study by using seismic-infrasound monitoring of a tidewater calving glacier (Bowdoin of Greenland) was introduced [15]. Bowdoin Glacier in the northwestern Greenland (~120 km from Thule) is a grounded tidewater calving glacier that has been rapidly retreating since 2008. An observational seismic-infrasound network was installed on July 2015 near the 3-km wide calving front of the glacier to enable near-source monitoring of frontal dynamics. Multiple seismic and infrasound events were recorded and linked to the surface crevassing, calving, presumable hydrofracturing, iceberg rotations, teleseismic earthquakes, helicopter-induced tremors, and so on. The most striking feature of the records was the temporal variability of microseismic activities, which were continuously recorded over a period of 2 weeks. Their results showed a double-peak diurnal oscillation in the number of events (up to 600 events per hour). Using high-resolution surface displacement global positioning system (GPS) measurements, they showed that the correlation between the number of events and tides was relayed through strain rate variations.

3. Ice shelves, icebergs, sea ices, and involved tremors

Evaluating cryospheric seismic events with space and time allows us to monitor cryosphere dynamics. The pattern of cryospheric seismic events was observed and classified at Ekström

Ice Shelf, Antarctica [5]. A year of data at the Neumayer seismic network identified the characteristic events occurring close to the grounding line of the Ekström Ice Shelf. The features of the observed seismic signals are consistent with an initial fracturing and associated resonance of a water-filled cavity. The number of detected events strongly correlated with the period of dominant tidal movements. It is assumed that the cracking developing system could be driven by existing glacier stresses through their bending process. The voids can be filled by the seawater, with exciting observing resonance. By assuming this model, seismic events occur almost exclusively during rising tides where cavities could be opened at the bottom of the glacier, that is, at the sea-ice interface.

Long-period teleseismic detectability and its response to cryosphere variation around Syowa Station, Antarctica, were reviewed by Iwata and Kanao [16] and Storchak et al. [17]. The hypocentral distribution and time variations for detected teleseismic events at Syowa Station were searched by using statistical methods over the last four decades (**Figure 1**). The characteristics of the detected events, magnitude dependency, spatial distributions, and seasonal variations were also demonstrated. In addition to a natural increase in the number of teleseismic events, a technical advance in the seismic observing system and the station infrastructure, together with the improvement of seismic phase reading techniques, could efficiently be combined to increase the detection number of the teleseismic events in the last few decades. Variations in detectability for a longer timeline might be associated with the cryosphere dynamics and its evolution, the meteorological environment, and the sea-ice spreading area around the Antarctic continent.

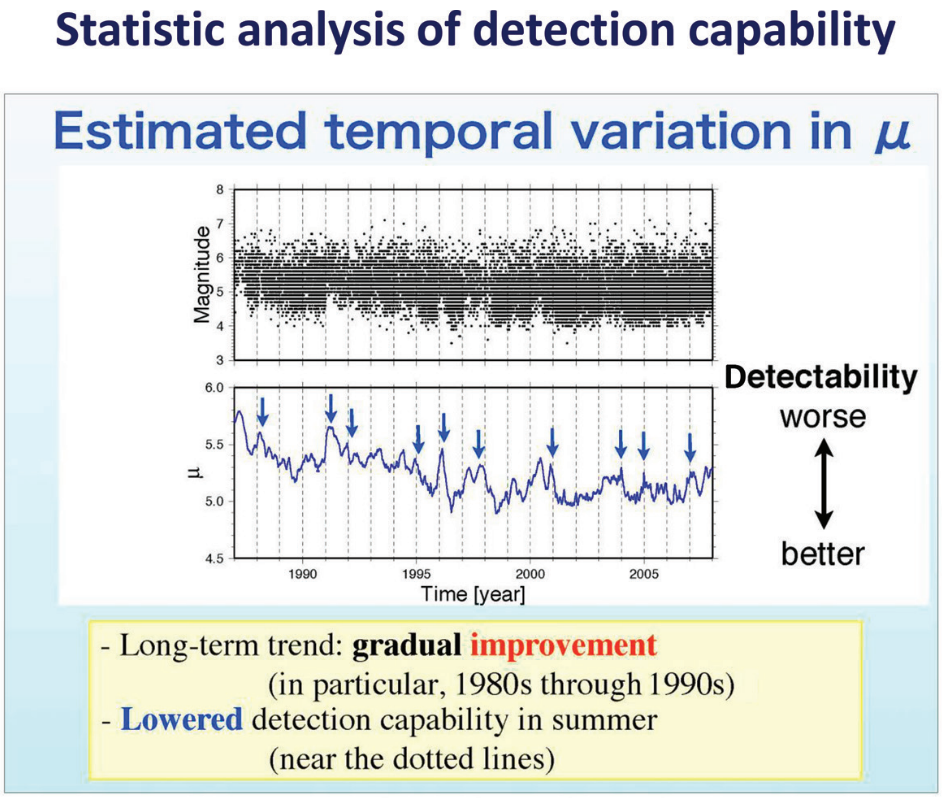


Figure 1. Statistical analysis of the detection capability of teleseismic events at Syowa Station, Antarctica (modified after [16]). (Upper) Magnitude variation during 1987–2008, (lower) estimated temporal variation in the detectability parameter (see [16] in detail). Copyright Clearance Center (CCC, http://www.copyright.com/); license number: 4282221098220, license date: February 4, 2018.

The characteristic seismic tremors with harmonic overtones were clearly observed in Lützow-Holm Bay, East Antarctica during 2014–2015 [18, 19]. More than 120 tremors were recognized by both short-period and broadband seismographs at Syowa Station in the bay from October 2014 to April 2015. Many tremors had characteristics of strong harmonic overtones, in their frequency content of over 1 Hz, representing nonlinear features with duration times from a few minutes to a few hours. The harmonic overtones could be explained by a repetitive source [20], suggesting the existence of several interglacial asperities, which generate the characteristic tremors. It implies that the tremors might be involved in the local origins, presumably the cryosphere dynamics. In this regard, the cryoseismic origins recorded as the tremors were classified into several categories (i.e., collision, calving, crevassing, crashing, etc.): the "crevassing events," which occur in a line along with large cracks inside the fast sea ices in the bay, "discharge events" of the fast sea ices from the bay to the Southern Ocean, "collision events" between the icebergs and the edge of fast sea ices, "crashing movement" of fragmentation between the fast sea ices and the packed sea ices, and other origins related to cryosphere dynamics (**Figure 2**). Similar harmonic tremors, recorded as hydroacoustic signals, associated with drifting icebergs have been identified in the Southern Indian and Pacific Oceans [21].

A more detailed classification of the ice tremors recorded at Syowa Station was conducted [22]. The purposes of the study were to classify the ice-related tremors based on the waveform feature and to reveal the time variation in the occurring numbers. They defined the "ice

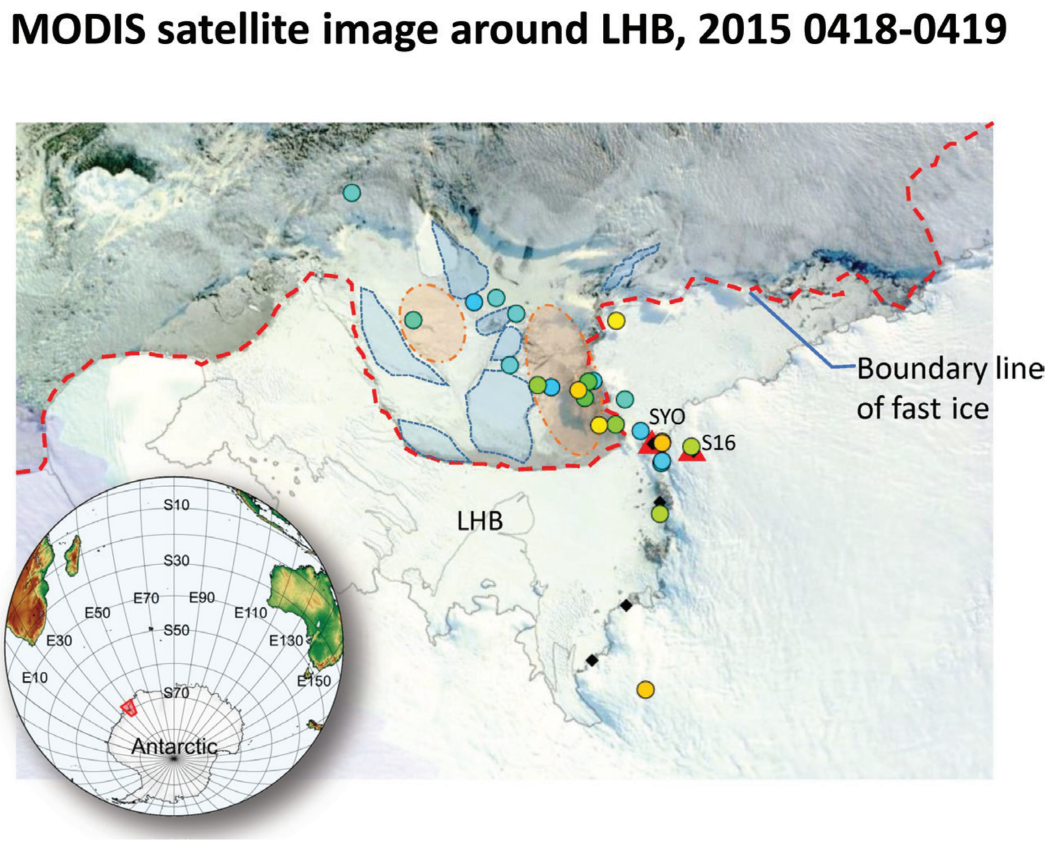


Figure 2. Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image around the Lützow-Holm Bay region, East Antarctica on April 18–19, 2015. The hypocenters of infrasound sources involving cryospheric dynamics are shown in colored circles (modified after [19]).

tremor" as the tremor of which P and S waves were not clear, and the duration was longer than 5 minutes. They found totally 231 ice tremors during the whole year in 2014. The monthly number of ice tremors varied in correlation with the monthly mean temperature except for the months of January to March. Then, they classified these identified ice tremors into four types. Type A had a long duration (10,000 seconds), and the amplitude was small over the waveforms. Type B had irregularly dominant frequency variations over the waveforms. Type C had a continuously decreasing dominant frequency, and the overtone was clearly identified. On April 2006, an iceberg-originated tremor with a similar spectral feature of Type C was recorded at Neumayer Stations, Dronning Maud Land of East Antarctica [23]. Type D had a short duration (about hundreds of seconds) with a gradually increasing/decreasing amplitude, which can be estimated as more local ice-related events.

Characteristics of the seismic waveform recorded by the array deployed at East Ongul Island, where the Syowa Station is located, were reported [24]. In order to detect the source locations of seismic events around the Syowa Station, East Ongul Island of East Antarctica, they carried out a seismic array observation from January 2 to February 2, 2015. They installed seven temporary stations at an outcrop site located 1 km away from the main buildings of the station, consisting of 1-Hz three-component seismometers with an array spacing of 100 m. During this period, two characteristic waveforms were recorded. One event occurred from January 11 at 22:40 Coordinated Universal Time (UTC) to January 12 at 11:20 (UTC), corresponding to sea-ice breaking (laming) events conducted by an icebreaker vessel "Shirase." The peak frequency of the laming events was about 10 Hz. The other event occurred on January 14 at 3:45 (UTC), and its duration was about 13 minutes. Peak frequencies of the tremor were about 2, 4, and 6 Hz, and these peaks varied over time. It is estimated that the tremors arrived from the south to southeast direction with a small slowness by semblance analysis, representing that the sources could be local ones such as the tidal crack generation around the island.

4. Oceanic waves and seismic interferometry

Global trends in extreme microseism intensity were investigated by using the data recorded by the Global Seismographic Network (GSN) and precursor instrumentation to chronicle microseism power extreme events during 1972–2009 [25]. The extreme microseism event number during the winter storm season revealed the widespread influence of the El Nino Southern Oscillation (ENSO). Transoceanic wave propagation that links iceberg calving margins of Antarctica with storms was also investigated, by using deployed seismometers on RIS and on various icebergs adrift in the Ross Sea [26]. It was suggested that if the sea swell influences the iceberg calving and breakup, a teleconnection exists between the Antarctic ice-sheet mass balance and the weather systems worldwide. Broadband seismic stations deployed across RIS studied ocean gravity wave-induced vibrations [27]. Initial data showed both dispersed infra-gravity (IG) waves and ocean swell–generated signals resulting from waves that originate from the North Pacific. The dominant IG band signals exhibit predominantly horizontal propagation from the north.

The array detection of Antarctic microseisms was conducted to evaluate the effect of sea ices and the Southern Ocean storms [28]. The results were obtained from a 60-km aperture array deployed for 2 months on WIS in West Antarctica. Single-frequency (~15 s) Rayleigh wave microseisms

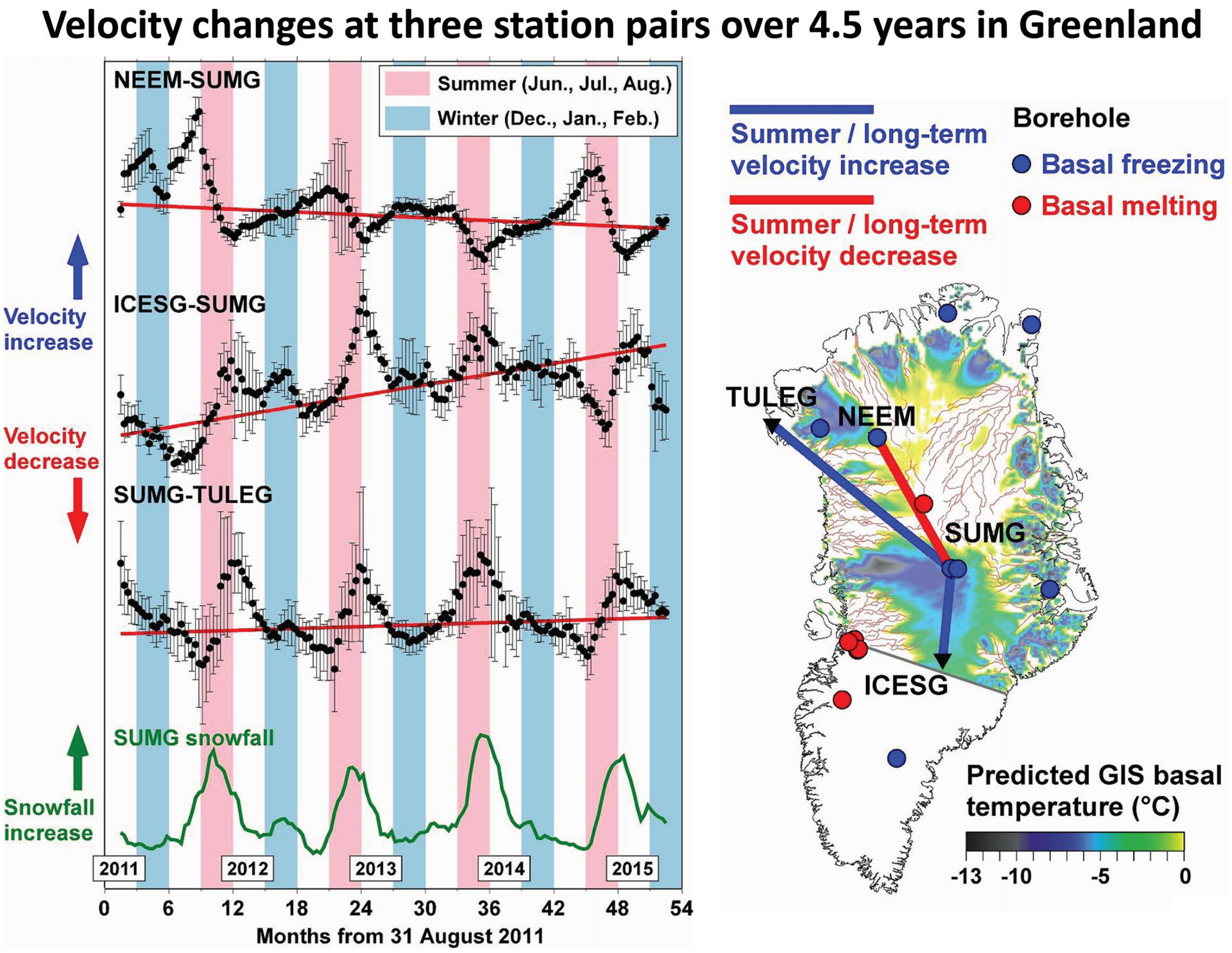


Figure 3. (Left) Seismic surface (Rayleigh) wave phase velocity changes at three station pairs over 4.5 years in Greenland. (Right) Comparison with estimated GrIS basal temperature [34] (modified after [30]). (one of the authors is M. Kanao).

were located at the three coastal source areas of strong microseism generation around the continent with their intensity heavily modulated by the local sea-ice extent. Long-period double-frequency (9–11 s) Rayleigh wave microseisms were generated in the deep ocean and correlated with the ocean wave modeling. In contrast, short-period double-frequency microseisms (5–7 s) were found to contain both coastal-sourced microseisms and deep ocean-sourced body wave microseisms. The strongest arrival in this band was often observed to propagate faster than the predicted fundamental mode Rayleigh wave and slower than the potential body waves and was interpreted to be an Lg phase propagating through the Antarctic continental crust.

The basal conditions of the Greenland Ice Sheet (GrIS) are a key research topic in climate change studies. The meltwater is found to influence the occurrence of deep stick-slip ice quakes near the base of GrIS [29] by using a 17-seismometer array temporarily deployed on the western margin of GrIS. The recent developing seismic network has also provided a new opportunity for direct, real-time, and continuous monitoring of GrIS. A seismic interferometry study by using the broadband continuous waveform data from GrIS was carried out [30]. The GreenLand Ice Sheet monitoring Network (GLISN) is an international project by 14 countries to monitor dynamic changes in GrIS, by deploying 32 broadband seismic stations in and around Greenland [8, 31]. Daily cross-correlation functions (CCFs) for all possible pairs of the GLISN stations were computed. As a result, they found a nearly constant Rayleigh wave group velocity of 2.8 km/s, for a range of 2–14 s, on CCF of the NEEM and Schumit-G (NEEM-SUMG) station pair. The ambient noise source was well corresponded to a known source of microseisms at the southern tip of Greenland.

The ambient noise surface wave data were utilized from seismic stations all over Greenland for a 4.5-year period to detect changes in Rayleigh wave phase velocity between the seismic station pairs [30] (**Figure 3**). They observed clear seasonal and long-term velocity changes for many pairs and proposed a plausible mechanism for these changes. Dominant factors driving the velocity changes might be seasonal and due to long-term pressurization/depressurization of GrIS and shallow bedrock by air and ice mass loading/unloading. However, the heterogeneity of the GrIS basal conditions might impose a strong regionality on the results. An interesting feature is that even at adjacent two station pairs in the inland GrIS, one pair shows a decrease in velocity, while another shows an increase in velocity as a response to the high air and snow pressure. The former pair might be located on a thawed bed that decreases the velocity by increasing meltwater due to pressure melting, whereas the latter pair might be located on a frozen bed that increases the velocity by compacting the ice and shallow bedrock. The results suggest that surface waves are very sensitive to the GrIS basal conditions, and further observations will contribute to get a more direct and quantitative estimation of water balance in the Arctic region.

5. Inland ice sheets and dynamics of basal environments

The detection of seismic sources associated with the ice movement in Antarctica using a regional array deployment by combining the global network data has been conducted in the last few years. A previously unreported type of seismic source in the firn layer of the East Antarctic ice sheet was investigated in detail by using the data from the Polar Earth Observing Network (POLENET) project deployed during the IPY [32]. The newly detected local events occurring inside the ice-sheet layer could presumably be cryodynamic in origin. These sources, named “firn quakes,” are characterized by dispersed surface wave trains with frequencies of 1–10 Hz, propagating distances up to 1000 km. Lough et al. [32] proposed that these events are linked to the formation of small crevasses in the firn layers at the surface of the ice sheet, and several seismic events could correlate with shallow crevasse fields mapped in the satellite imagery. The hypocentral location of these events appeared to be close to the location of the existing crevasses, that is, nearby the upstream of Lambert Glacier and the inland area of TAM. Related topics involving seismic detection in the inland plateau of the ice sheet are also introduced in Chapter 7.

Subglacial volcanoes with high-heat flow are found to exist in Marie Byrd Land, a highland region of West Antarctica. Lough et al. [33] used the POLENET data to show the evidence of the existence of two seismic swarm activities occurring in the depth range of 25–40 km beneath the subglacial topographic and magnetic high areas, located at 55 km southward from the youngest subaerial volcano of Marie Byrd Land. They interpreted the swarm events as the deep long-period earthquakes based on their unusual frequency contents. Such earthquakes occurring beneath the active volcanoes are considered to be caused by the deep magmatic activity and, in some cases, precede eruptions.

Seismic waves from distant, large earthquakes can almost instantaneously trigger shallow micro-earthquakes and deep tectonic tremors as they pass through the Earth's crust. The triggered seismicity is generally considered to reflect a shear failure on critically stressed fault planes and is thought to be driven by dynamic stress perturbations from both the Love and the Rayleigh types of surface seismic waves. Peng et al. [11] investigated the POLENET seismic data from the Antarctic for the 2010 M 8.8 Maule earthquake in Chile. They identified a lot of high-frequency signals during the passage time windows of the Rayleigh waves caused by the Maule earthquake. The interpretation of these characteristic signals is the triggered ice quakes within the Antarctic ice sheet by the Rayleigh waves. The source locations of these triggered ice events are difficult to determine by only global seismic networks; however, the triggered events generated surface waves. Therefore, they are probably formed by the near-surface layers of the ice sheet and caused by the tensile fracturing of the near-surface ice layer or the brittle fracture events by the changes in the volumetric strain.

6. Summary

A new trend of "cryoseismology," introduced in this chapter, covered the recent achievements involving the glacier-related seismic events and the associated phenomenon of the Earth's surface observed in the bipolar region (Antarctica and Greenland). Several fruitful scientific achievements were introduced regarding the seismic excitation by the stick-slip events in the West Antarctic ice stream, array detection of microseisms in the Antarctic and their relationship with the sea ices and Southern Ocean storms, seismic events of a tidewater calving glacier in Greenland, seismic interferometry over the whole Greenland, array analysis of infrasound and harmonic tremors in Lützow-Holm Bay of East Antarctica, and others. Various kinds of cryoseismic signals recently reported are reviewed by classifying them on the basis of their occurrence locations and focal dynamics. Time-space variations in the activities and propagation characteristics should produce a new horizon for understanding the cryosphere dynamics, which have not been well known before but could presumably have a great impact on conducting human activities in the twenty-first century.

Author details

Masaki Kanao

Address all correspondence to: kanao@nipr.ac.jp

National Institute of Polar Research (NIPR), Organization of Information and Systems (ROIS), Tokyo, Japan

References

[1] MacAyeal D, Okal EA, Aster RC, Bassis JN. Seismic and hydroacoustic tremor generated by colliding icebergs. Journal of Geophysical Research. 2008;**113**:F03011. DOI: 10.1029/2008JF001005

[2] MacAyeal D, Okal EA, Aster RC, Bassis JN. Seismic observations of glaciogenic ocean waves on icebergs and ice shelves. Journal of Glaciology. 2009;**55**:193-206

[3] Zoet LK, Anandakrishnan S, Alley RB, Nyblade AA, Wiens DA. Motion of an Antarctic glacier by repeating tidally modulated earthquakes. Nature Geoscience. 2012;**5**:623-626

[4] Winberry JP, Anandakrishnan S, Wiens DA, Alley RB. Nucleation and seismic tremor associated with the glacial earthquakes of Whillans ice stream, Antarctica. Geophysical Research Letters. 2013;**40**:312-315

[5] Hammer C, Ohrnberger M, Schlindwein V. Pattern of cryospheric seismic events observed at Ekström ice shelf, Antarctica. Geophysical Research Letters. 2015;**42**:3936-3943

[6] Ekström G, Nettles M, Tsai VC. Seasonality and increasing frequency of Greenland glacial earthquakes. Science. 2006;**311**:1756-1758

[7] Nettles M, Ekström G. Glacial earthquakes in Greenland and Antarctica. Annual Review of Earth and Planetary Sciences. 2010;**38**:467-491

[8] Clinton JF, Nettles M, Walter F, Anderson K, Dahl-Jensen T, Giardini D, Govoni A, Hanka W, Lasocki S, Lee WS, McCormack D, Mykkelveit S, Stutzmann E, Tsuboi S. Real-time geophysical data enhance earth system monitoring in Greenland, Eos trans. AGU. 2014;**95**:13-24

[9] Kanao M, Zhao D, Wiens DA, Stutzmann E. Recent advance in polar seismology: Global impact of the international polar year—Overview. Polar Science. 2015;**9**:1-4. DOI: 10.1016/j.polar.2014.12.003

[10] Pratt MJ, Winberry JP, Wiens DA, Anandakrishnan S, Alley RB. Seismic and geodetic evidence for grounding-line control of Whillans ice stream stick-slip events. Journal of Geophysical Research - Earth Surface. 2014;**119**:333-348. DOI: 10.1002/ 2013JF002842

[11] Peng Z, Walter JI, Aster RC, Nyblade A, Wiens DA, Anandakrishnan S. Antarctic icequakes triggered by the 2010 Maule earthquake in Chile. Nature Geoscience. 2014;**7**:677-681

[12] Lipovsky BP, Dunham EM. Tremor during ice-stream stick slip. The Cryosphere. 2016;**10**: 385-399. DOI: 10.5194/tc-10-385-2016

[13] de Juan J, Elósegui P, Nettles M, Larsen TB, Davis JL, Hamilton GS, Stearns LA, Andersen ML, Ekström G, Ahlstrøm AP, Stenseng L, Khan SA, Forsberg R. Sudden increase in tidal response linked to calving and acceleration at a large Greenland outlet glacier. Geophysical Research Letters. 2010;**37**:L12501. DOI: 10.1029/2010GL043289

[14] Bartholomaus TC, Amundson JM, Walter JI, O'Neel S, West ME, Larsen CF. Subglacial discharge at tidewater glaciers revealed by seismic tremor. Geophysical Research Letters. 2015;**42**:6391-6398. DOI: 10.1002/2015GL064590

[15] Podolskiy EA, Sugiyama S, Funk M, Walter F, Genco R, Tsutaki S, Minow AM, Ripepe M. Tide-modulated ice flow variations drive seismicity near the calving front of Bowdoin glacier, Greenland. Geophysical Research Letters. 2016;**43**. DOI: 10.1002/2016GL067743

[16] Iwata T, Kanao M. The quantitative evaluation of the annual variation in the Teleseismic detection capability at Syowa station, Antarctica. Polar Science. 2015;**9**:26-34. DOI: 10.1016/j.polar.2014.10.002

[17] Storchak DA, Kanao M, Delahaye E, Harris J. Long-term accumulation and improvements in seismic event data for the polar regions by the international seismological Centre. Polar Science. 2015;**9**:5-16. DOI: 10.1016/j.polar.2014.08.002

[18] Kanao M. Characteristics of seismic wave propagation of harmonic tremors observed at the margin in the Lützow-Holm Bay, East Antarctica. In: Earthquakes—Tectonics, Hazard and Risk Mitigation, Chapter 4. Rijeka, Croatia: InTech. Publisher; 2017. pp. 71-85. DOI: 10.5772/66090. ISBN 978-953-51-2886-1

[19] Kanao M, Murayama T, Yamamoto M-Y, Ishihara Y. Seismic tremors and their relation to cryosphere dynamics in April 2015 around the Lützow-Holm Bay, East Antarctica. International Journal of Geosciences. 2017;**8**:1025-1047. DOI: 10.4236/ijg.2017.88058

[20] Powell TW, Neuberg J. Time dependent features in tremor spectra. Journal of Volcanology and Geothermal Research. 2003;**128**:177-185

[21] Talandier J, Hyvernaud O, Reymond D, Okal EA. Hydroacoustic signals generated by parked and drifted icebergs in the southern Indian and Pacific oceans. Geophysical Jour nal International. 2006;**165**:817-834

[22] Tanaka Y, Hiramatsu Y, Ishihara Y, Kanao M. Classification of ice tremor recorded at Syowa Station in Antarctica. In: Joint Scientific Assembly of the International Association of Geodesy and the International Association of Seismology and Physics of the Earth's Interior, J01-P-01; July 30-August 4, 2017; Kobe, Japan. 2007

[23] Eckstaller A, Müller C, Ceranna L, Hartmann G. The geophysics observatory at Neumayer stations (GvN and NM-II) Antarctica. Polarforshung. 2007;**76**:3-24

[24] Nakamoto M, Miyamachi H, Matsushima T, Kanao M, Yamamoto M-Y. Characteristics of seismic waveform recorded by seismic array at East Ongul Island, Antarctica, JpGU 2016, MTT05-P03, May 22-26; Makuhari, Chiba, Japan. 2016

[25] Aster RC, McNamara DE, Bromirski PD. Global trends in extremal microseism intensity. Geophysical Research Letters. 2010;**37**:L14303. DOI: 10.1029/2010GL043472

[26] MacAyeal DR, Okal EA, Aster RC, Bassis JN, Brunt KM, Cathles LM, Drucker R, Fricker HA, Kim Y-J, Martin S, Okal MH, Sergienko OV, Sponsler MP, Thom JE. Transoceanic wave propagation links iceberg calving margins of Antarctica with storms in tropics and northern hemisphere. Geophysical Research Letters. 2006;**33**:L17502. DOI: 10.1029/2006GL027235

[27] Bromirski PD, Diez A, Gerstoft P, Stephen RA, Bolmer T, Wiens DA, Aster RC, Nyblade A. Ross ice shelf vibrations. Geophysical Research Letters. 2015;**42**. DOI: 10.1002/2015 GL065284

[28] Pratt JM, Wiens DA, Winberry JP, Anandakrishnan S, Euler GG. Implications of sea ice on Southern Ocean microseisms detected by a seismic array in West Antarctica. Geophysical Journal International. 2017;**209**:492-507. DOI: 10.1093/gji/ggx007

[29] Roeoesli C, Helmstetter A, Walter F, Kissling E. Meltwatrer influences on deep stick-slip icequakes near the base of the Greenland ice sheet. Journal of Geophysical Research - Earth Surface. 2016;**121**:223-240. DOI: 10.1002/2015JF003601

[30] Toyokuni G, Takenaka H, Takagi R, Kanao M, Tsuboi S, Tono Y, Childs D, Zhao D. Changes in Greenland ice bed conditions inferred from seismology. Physics of the Earth and Plan etary Interiors. 2017;**277**:81-98. DOI: 10.1016/j.pepi.2017.10.010

[31] Toyokuni G, Kanao M, Tono Y, Himeno T, Tsuboi S, Childs D, Anderson K, Takenaka H. Japanese contribution to the Greenland ice sheet monitoring network (GLISN). Antarctic Record (New Zealand). 2014;**58**:1-18

[32] Lough AC, Wiens DA, Nyblade AA, Anandakrishnan S. A previously unreported type of seismic source in the firn layer of the East Antarctic ice sheet. Journal of Geophysical Research - Earth Surface. 2017;**120**:2237-2252

[33] Lough AC, Wiens DA, Barcheck CG, Anandakrishnan S, Aster RC, Blankenship DD, Huerta AD, Nyblade AA, Young DA, Wilson TJ. Seismic detection of an active subglacial magmatic complex in Marie Byrd land, Antarctica. Nature Geoscience. 2013;**6**:1031-1035. DOI: 10.1038/ ngeo1992

[34] Rogozhina I, Petrunin AG, Vaughan APM, Steinberger B, Johnson JV, Kaban MK, Calov R, Rickers F, Thomas M, Koulakov I. Melting at the base of the Greenland ice sheet explained by Iceland hotspot history. Nature Geoscience. 2016;**9**:366-369. DOI: 10.1038/ngeo2689

Interactions among Multispheres of the Earth's System and Polar Regions

Masaki Kanao

Abstract

Among the environmental variations in the surface layers of the Earth, global warming and those involving multisphere interactions in the polar region are reviewed with scientific research funding. By focusing on the wavelet phenomena with various generating sources within the Earth's system, interdisciplinary research studies are conducted on the influences and responses to climate change in the polar region.

Keywords: multispheres, interaction, polar region, infrasound, microseisms/microbaroms, Earth's system

1. Introduction

Among the Earth's complex system, various kinds of temporal-spatial variations have been observed by the interactions among multispheres such as the atmosphere, ocean, cryosphere, and solid Earth. For example, seismographs deployed in the Antarctic by the Federation of Digital Seismographic Networks (FDSN) and the Polar Earth Observing Network (POLENET) could efficiently record microseismic noise (microseisms) generated from the Southern Ocean. The microseismic noise represents the characteristic wavelets originated by coupling the solid Earth and the ocean [1]. Moreover, microseisms with different intrinsic periods (the "first fundamental mode" came from the Southern Ocean and the "second fundamental mode" from the continental shelf) were identified to have a relationship with the seasonal evolution of sea ices, which are distributed surrounding the Antarctic continent. In addition, physical interactions between the solid Earth and other spheres (atmosphere, ocean, and cryosphere) were investigated in detail by using both microseismic noise and newly deployed infrasound (microbarometric) data during the IPY [2].

In this chapter, as mentioned earlier, by focusing on the characteristics of wavelets propagating in the frequency bands between 0.001 Hz and few tens of Hz (subaudible bands) with various generating sources in the Earth's system, the recent seismological research, which comprises the surface environments in the polar region, involves the physical interactions among multispheres. Particularly, targeting temporal-spatial variations in "microseisms" and "microbaroms" detected by infrasound sensors, the response of shallow atmosphere, and the surface layer of the solid Earth from the oceanic swells and involved atmospheric variations in the polar region are examined in detail. By checking the relationship between amplitudes and frequency variabilities of these wavelets and meteorological data/sea-ice distribution, as well as computer modeling of the multisphere coupling, integrated information to evaluate the effects of global warming/climate change on the surface environment in the polar region is provided.

2. Ocean-solid Earth coupling

At the middle-high latitudes in the Southern Hemisphere, variations in temperature, air pressure, strong winds, and associated swells, "ocean disturbance," occurred when large storms passed through. Moreover, the co-oscillation ground noise occurred from a few to 30 s at the Earth's surface (the microseisms and microseismic noise) [3, 4]. The microseisms can be observed with large amplitudes at the coastal areas of the continents across the globe; these amplitudes including the origins from deep oceanic swells are predicted theoretically all over the Earth [5]. In this regard, the data from global seismographic networks, FDSN, are expected to be utilized for the microseismic studies.

From previous observations, "microseisms" are classified into two groups: the relatively long period (12–30 s; single-frequency microseism, SFM) originated from deep oceans and short period (4–10 s; double-frequency microseism, DFM) from continental shelves [3, 4]. In the Antarctic, however, there were no studies of the microseisms for long-term observations including the inland area before the IPY. Recently, by using the data from FDSN and POLENET deployed in the Antarctic, microseismic signals from the Southern Ocean have been clearly recognized with their frequency contents and time variations. For instance, seasonal variations in SFM and DFM can clearly be recognized with a strong correlation with seasonal changes in the surrounding sea-ice spreading areas (in particular the fast ices) by using the FDSN data [6, 7]. The seismic stations in East Antarctica such as the Dumont d'Urville (DRV) and Syowa (SYO; see **Figure 1** of Chapter 1) have recorded strong seasonal changes in sea-ice spreading areas and associated variations in microseismic amplitudes.

Following the development of the FDSN stations around the world including Antarctica, digital acquisition of the broadband seismograph data (type STS-1) started in 1989 at Syowa Station [8]. By using the long-term data from the seismographs, the dynamic power spectral density (PSD) represented the various scale of time variations in SFM and DFM [1, 7] (**Figure 1**). From data since 2001, DFM signals with smaller amplitudes in austral winters have been continuously recorded at Syowa Station. In contrast, variations in the periods from a few hours to a few days in PSD have been assumed to be the effects of large storms and

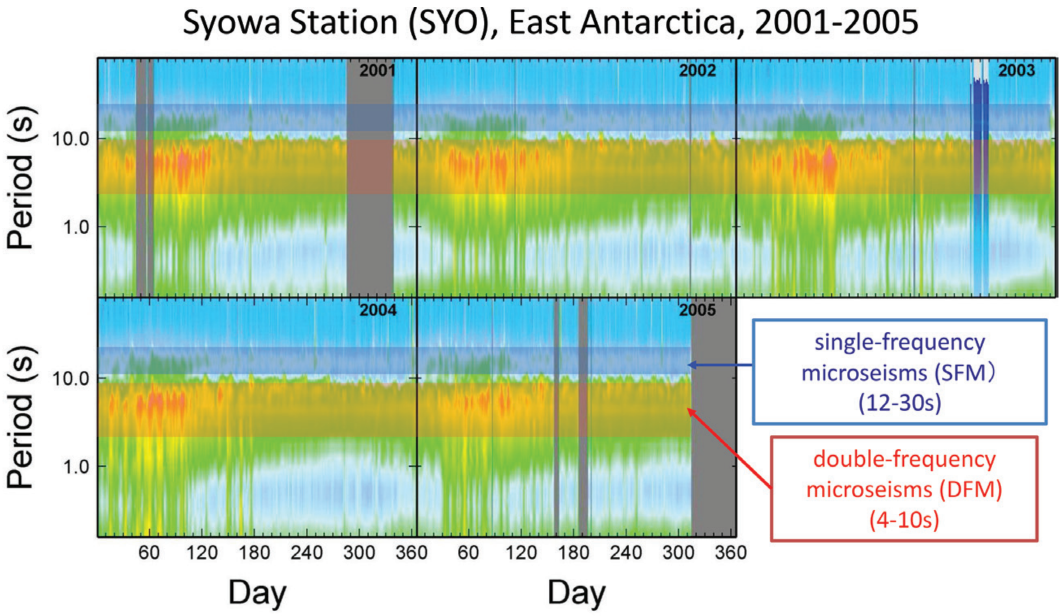


Figure 1. Power spectral densities of the broadband (STS-1 V) at SYO Station, East Antarctica, for the period of 2001–2005. Signals corresponding to SFM and DFM are indicated by blue and red arrows (modified after [1]). (CC BY 3.0) (first author is M. Kanao).

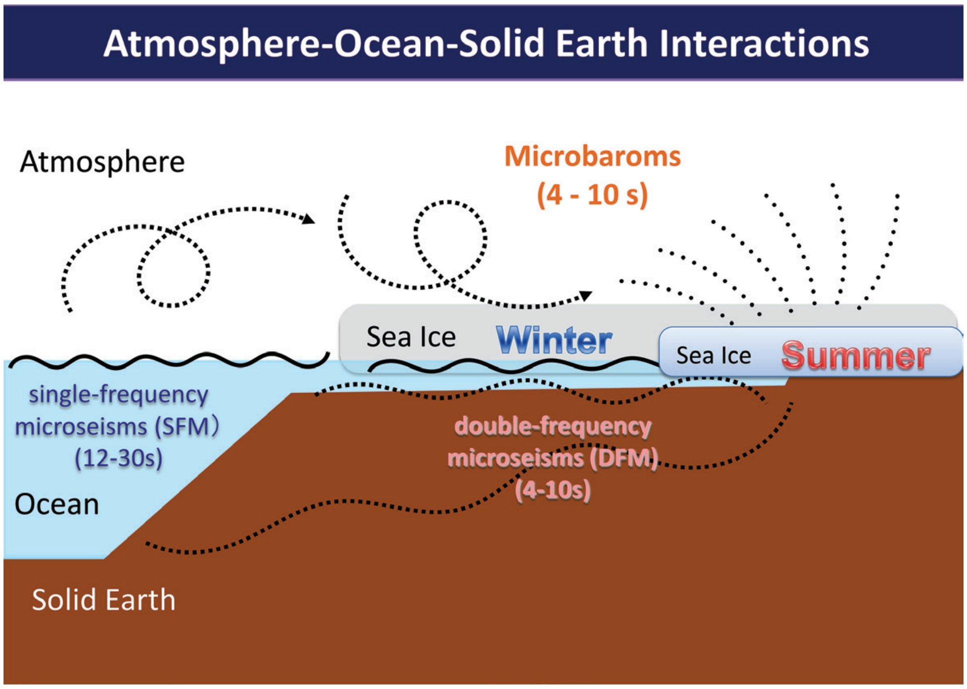


Figure 2. Schematic illustration of atmosphere-ocean-cryosphere-solid Earth environments in polar regions exampled in the Antarctic. Infrasound signals (microbaroms) and seismic noise waves propagate from the source regions in the Southern Ocean SFM and the continental shelf area DFM to the margins of the Antarctic continent. Seasonal variations from the extending sea-ice spreading areas and the thickness effect on the arrival energy of the oceanic seismic noise at the coastal stations in the Antarctic.

related swells in the Southern Indian Ocean. PSD of SFM, on the other hand, represented relatively small amplitudes compared with DFM and the largest in austral summers. In this regard, PSD amplitudes increase in the austral summers, which is opposite to the stations in the Northern Hemisphere, such as in Japanese islands [6]. This is explained by the development of sea ices surrounding the Antarctic continent in winter seasons, which depresses the effects on the microseismic noise energy (**Figure 2**). Moreover, the microseismic noise from sea-ice spreading areas affected the teleseismic detection capability of the stations making observations of seasonal variations [9, 10].

Understanding the intrinsic features of seismic phenomena generated by oceanic swells under the coupling condition between the Antarctic ice sheet and the underlying solid Earth might involve the static and dynamic conditions of the adjacent Southern Ocean and shallow atmosphere. Future studies on ocean-solid Earth coupling are expected to be interdisciplinary, with research themes corresponding to topics on satellite altimeter, geoid model, ice-sheet evolution, mass balance, plate movement, regional tectonics, sea-level rise, precise gravity measurements such as by the Gravity Recovery and Climate Experiment (GRACE), satellite, and so on.

3. Atmosphere-solid Earth coupling

Of the interdisciplinary research studies on the coupling phenomenon at the boundary regions among the atmosphere, ionosphere, ocean, and solid Earth, a branch of research using “infrasound” (subaudible band frequency lower than 20 Hz) is currently underway in the polar region [11]. The “infrasound” has a medium frequency band between audible acoustic waves and planetary scaled gravity waves. Infrasound can propagate for long distances, more than few thousands of km, and is focused on the plausible sources of perturbation within the upper atmosphere. A global infrasound network has been established by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). At present, 60 stations including planning sites have been deployed; there are two existing CTBTO stations at Neumayer (NM; 127DE) and McMurdo (MCM; 155US) in addition to two planned ones in Antarctica. (For details of observations at NM, refer [12].)

The recent obtained infrasound data contained various kinds of natural sources in addition to the original targets by CTBTO—earthquakes, volcanic eruptions, tsunami waves, oceanic swells, rapid developing clouds, auroras, fireball and meteorite falls, ice quakes, and so on [13, 14]. The Japanese CTBTO site is located at the “Isumi” city of Chiba Prefecture, and the infrasound signals generated by tsunami waves of the huge Tohoku earthquakes on March 11, 2011, were clearly recorded [15]. Another example was the detection of shock waves by the reentry of the “Hayabusa” spacecraft on June 2010 inside the desert in Australia [16, 17]. Moreover, the Sumatra-Andaman earthquake on December 2006 generated tsunami waves and associated infrasound, which are propagated upward to create a coupling with the ionosphere and observed as the total electron content (TEC) perturbation [18, 19].

Characteristic features of infrasound waves observed in the Antarctic reflect the physical interactions between the surface environment in the continental margin and in the surrounding Southern Ocean. Infrasound observations have been started at Syowa Station, in the Lützow-Holm Bay (LHB) of East Antarctica, since April 2008 during the IPY by using a single sensor. The “microbaroms” were clearly detected, which corresponded to the same frequency range waves of DFM that originated from the Southern Indian Ocean [20, 21]. The infrasound

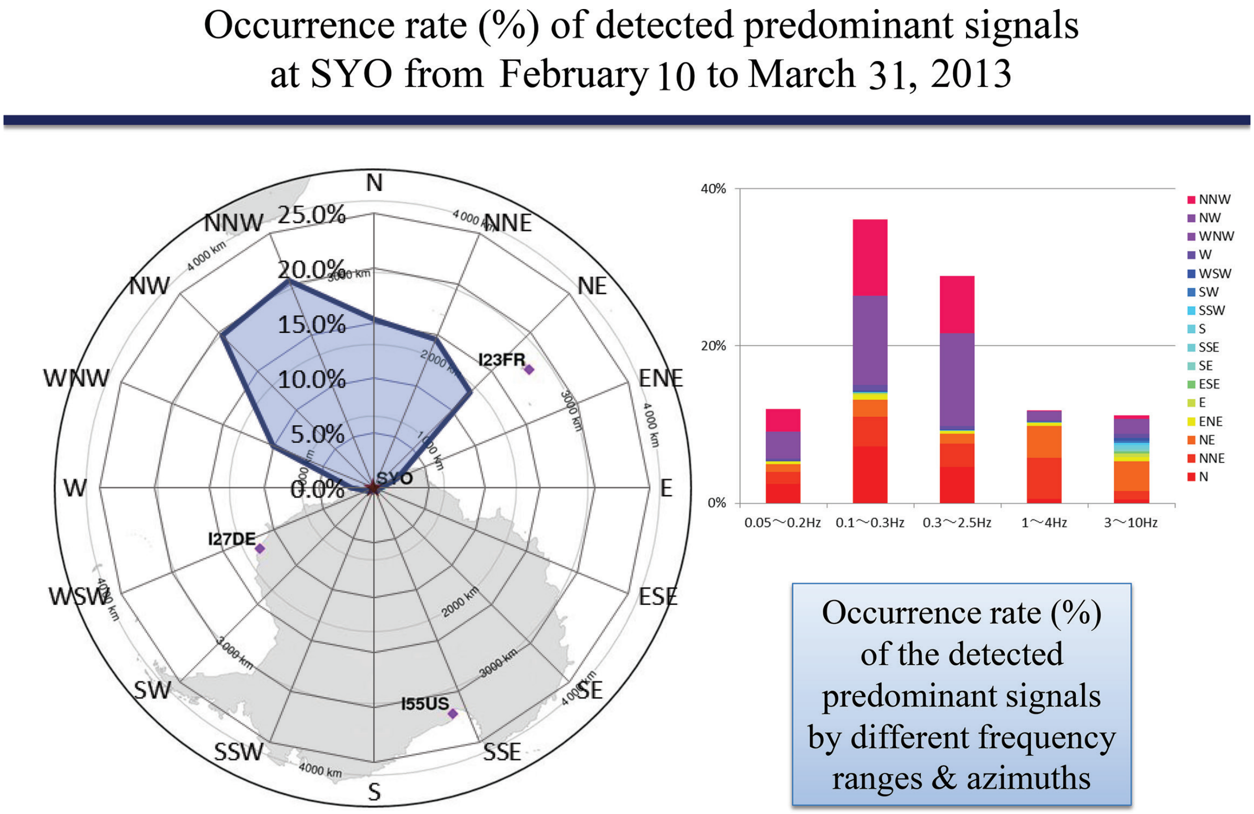


Figure 3. Occurrence rate (%) of the orientation for the detected infrasound signals at SYO Station from February 10 to March 31, 2013 (modified after [22]). Copyright Clearance Center (CCC, http://www.copyright.com/). License Number: 4282180930831, License date: February 04, 2018.

observation in the Antarctic could have a possibility to detect characteristic signals in addition to the troposphere-stratosphere phenomenon, shock waves from auroras and meteoroid falls, volcanic eruption in the Southern Hemisphere, oceanic swells and tsunami waves, vibrations by earthquakes, cryoseismic signals involving global warming, and so on. Moreover, since 2012, multiscaled infrasound array observations have been started at LHB to identify the orientation of the source locations on the origin of swell signals [22] (**Figure 3**). By continuing the long-term observations for more than few years, it would be possible to evaluate the effects of global warming/climate change on the Southern Ocean and coastal margins of the Antarctic. Infrasound observations in Antarctica, where there has been less noise by human activities, have a significance in terms of their long propagation distance; the physical interactions among multispheres in the polar region can be revealed by monitoring for decades.

4. Recent progress in infrasound research

Long-term infrasound data from the Syowa Station in LHB of East Antarctica were recently analyzed from 2008 to 2014 [23]. Seasonal variations in microbaroms and high-frequency harmonic overtone signals were especially investigated, and the data were strongly involved in local dynamics of the surface environments. The microbaroms have relatively low amplitudes in austral winters by an effect from the extending area of sea ice around LHB, with decreasing oceanic swell loading effects. The other reasons of seasonal variations in microbarom amplitudes were caused by the effect of a number of storms during the whole year and snow accumulation over the porous hoses on the infrasound station at Syowa Station. In contrast, nonlinear high-frequency harmonic tremors were considered to be caused by the katabatic winds from the Antarctic continent flowing in the northeast dominant orientation. The high-frequency tremors had characteristics of daily variations, particularly the austral summers.

These infrasound arrays established in LHB [22] clearly revealed temporal variations in the frequency content and propagation direction of the identified events by using recent datasets. Time-space variability of the source location for the infrasound excitation from January to August 2015 was investigated by using a combination of two arrays deployed along the coast of the bay [24, 25]. The infrasound arrays clearly detected temporal variations in the frequency content and propagation direction during the period of 8 months (**Figure 4**). A significant number of infrasound sources were identified, and many of them were located in a northward direction from the arrays. Many of the events had a predominant frequency of a few Hz, which is higher than that of the microbaroms coming from the ocean. Many of these sources are assumed to have cryoseismic origins such as the ice quakes associated with the calving of glaciers, the discharge of sea ice, a collision between sea ices and icebergs around LHB, and so on. Comparing the moderate resolution imaging spectroradiometer (MODIS) satellite data, these infrasound sources were considered to be ice quakes associated with the calving of glaciers, discharge of sea ices, and collisions with icebergs.

Characteristic features of infrasound waves observed in West Antarctica-Transantarctic Mountains also revealed physical interactions involving surface environments around the continent and the Southern Ocean [26]. On December 2015, an infrasound array (100-m spacing) with three sensors (Chaparral Physics Model 25, with a detectable frequency range of 0.1–200 Hz), together with a broadband barometer (Digiquartz Nano-Resolution Model 6000-16B Barometer, with a detectable frequency range of 0–22 Hz), was installed at Jang Bogo Station, Terra Nova Bay of the Northern Victoria Land, by the Korea Arctic and Antarctic Research Program (KAARP). Initial data recorded by the broadband barometer contained the characteristic signals that originated from the surrounding environment, including local noise such as katabatic winds. Clear oceanic signals (microbaroms) were continuously recorded as the background noise with a predominant frequency of around 0.2 s during the austral summer in December. Variations in their frequency content and amplitude strength in power spectral density (PSD) had been affected by an evolution of sea ices surrounding Terra Nova Bay. Continuous infrasound observations in Terra Nova Bay attained a new proxy for monitoring environmental changes such as the climate change in West Antarctica, involving cryosphere dynamics, as well as the episodic volcanic eruptions appearing in the Northern Victoria Land.

In addition to analyzing the observed data, numerical modeling of the microbarometric and microseismic oscillations due to ocean surface waves was applied [27]. Ocean surface waves (OSWs) shake the atmosphere on the sea surface and the top layer of the crust (the solid Earth) at the sea bottom. In order to estimate the amplitude and propagation directions of OSWs, (1) the amplitude and propagation directions of oscillations excited by OSWs and (2) variations in the amplitude after their propagation to observation points need to be quantified. To validate

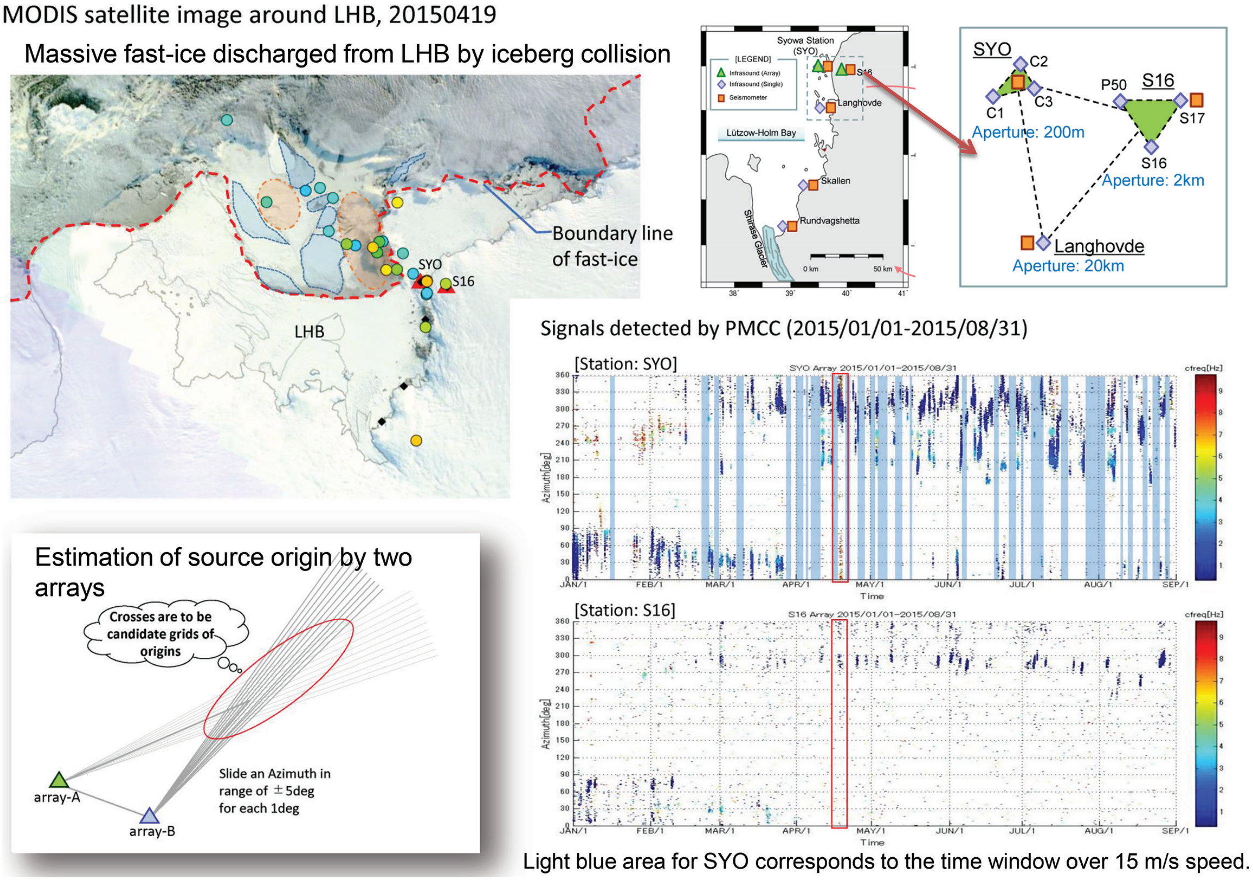


Figure 4. Time-space variations in infrasound sources involving the environmental dynamics around LHB (modified after [25]). (Upper right) Locations of array deployment in LHB. Array stations of infrasound (green triangles), single stations of infrasound (blue diamond), and broadband seismometers (orange squares) are shown, respectively. (Upper right) Array configuration of infrasound stations to localize the source signals. Tripartite arrays have been deployed by small size [at Syowa Station (SYO); an aperture of 200 m; C1, C2, C3], medium size (at S16, S17, P50; an aperture of 2 km), and large size (a combination of other outcrop stations such as Langhovde; an aperture of 20 km) have been deployed. (Lower right) Time sequence of azimuthal variation in arrival orientation and frequency contents of the detected infrasound signals (from January 01 to August 31, 2015). The vertical axis shows the back-azimuth (station-to-source) directions for the SYO array (upper) and the S16 array (lower), respectively. Colored bars on the right-hand side correspond to the central frequency (Hz) for each plotted event. Red open squared area corresponds to the date April 18, when a series of infrasound events were identified. Light blue areas for SYO correspond to the time window with over 15 m/s wind speed. (Upper left) MODIS satellite image around LHB on April 19, 2015. Massive fast ice had discharged from LHB associated with iceberg collision. The light blue–colored areas correspond to the location of the icebergs on the previous day. Orange-colored areas indicate the pack-ice regions where dynamic movements were considered to be generated in the last one day. In addition, estimated source locations of infrasound excitation are also overlapped with the MODIS image by using two arrays of SYO and S16. (Lower left) Flow chart of methodology for estimating source origins by two infrasound arrays [using the progressive multichannel correlation (PMCC) algorithm]. Copyright Clearance Center (CCC, http://www.copyright.com/). License Number: 4282180480777, License date: February 04, 2018.

these assumptions, two OSWs traveling in the opposite directions and having almost the same frequency and wavelength are imposed, and the resultant atmospheric and seismic oscillations are analyzed. The analysis results showed that the imposed OSWs excited acoustic waves in both the atmosphere and ocean. The frequency and the wave number of the acoustic waves were the sums of OSWs. The oceanic acoustic waves propagated to the ocean bottom to excite the seismic surface waves with the same frequency and wavelength. In the crustal depths, seismic body waves were also excited.

In several aspects introduced in the above new findings, infrasound studies of various kinds of natural phenomena in geophysics including the upper atmosphere, ocean, and cryosphere have greatly been advancing in the polar region. It is expected that the contribution from individual countries will be relatively small; therefore, the progress of scientific investigations in the polar region in addition to single national programs will be required to advance the studies of multisphere interactions among the same subaudible frequency bands [28].

5. Summary

The multidisciplinary study treated in this chapter aimed to understand the physical interactions among multispheres that compose the polar region in the Earth's system. Particularly, the infrasound could connect several spheres from the surface of the solid Earth to the ionosphere, giving a new idea for interdisciplinary research. Seasonal variations in the cryosphere are striking evidence appearing in the polar region and can also be investigated by using statistical analysis. Recently, a relationship between the climate change and sea-level rise and the dynamics of glaciers and ice sheets has been pointed out efficiently. By adding the approach from the view point of interaction with the solid Earth, it is possible that a new proxy for checking the progressing system of the climate change might emerge.

During the International Polar Year (IPY) and beyond, the characteristic solid Earth vibrations associated with the variations and dynamics of the ice sheets, sea ices, oceans, and atmosphere have been reported in the polar region. In order to realize the occurrence mechanism and activities of these wavelet phenomena, which the existing global networks cannot detect, understanding the interactions of the surface layer of the Earth and vicinity environments regarding global warming, such as the evolution of sea ices, the dynamics of ice sheets and glaciers, as well as the glacial earthquake activities, should be important. It is also expected that the succeeding interdisciplinary research studies use the long-period wavelets recorded by seismographs and infrasound and acoustic sensors in the polar region to achieve a deep understanding of the Earth's complex system.

Author details

Masaki Kanao

Address all correspondence to: kanao@nipr.ac.jp

National Institute of Polar Research (NIPR), Organization of Information and Systems (ROIS), Tokyo, Japan

References

[1] Kanao M, Maggi A, Ishihara Y, Yamamoto M-Y, Nawa K, Yamada A, Wilson T, Himeno T, Toyokuni G, Tsuboi S, Tono Y, Anderson K. Interaction on seismic waves between

atmosphere-ocean-cryosphere and geosphere in polar region. In: Kanao M, Takenaka H, Murai Y, Matsushima J, Toyokuni G, editors. Seismic Waves—Research and Analysis. Rijeka, Croatia: InTech; 2012. pp. 1-20

[2] Kanao M, Maggi A, Ishihara Y, Stutzmann E, Yamamoto M-Y, Toyokuni G. Characteristic atmosphere-ocean-solid earth interactions in the Antarctic coastal and marine environment inferred from seismic and infrasound recording at Syowa Station, East Antarctica. In: Hambrey MJ, Barker PF, Barrett PJ, Bowman V, Davis B, Smellie JL, Tranter M, editors. Antarctic Palaeoenvironments and Earth-Surface Processes (ISAES Vol. III). Vol. 381. London, Special Publications: Geological Society; 2013. pp. 469-480

[3] Aster R, McNamara D, Bromirski P. Multidecadal climate-induced variability in microseisms. Seismological Research Letters. 2008;**79**:194-202

[4] Bromirski PD. Earth vibrations. Science. 2009;**324**:1026-1027

[5] Ardhuin F, Stutzmann E, Schimmel M, Mangeney A. Revealing ocean wave sources of seismic noise. Journal of Geophysical Research. 2011;**116**:C09004

[6] Stutzmann E, Schimmel M, Patau G, Maggi A. Global climate imprint on seismic noise. Geochemistry, Geophysics, Geosystems. 2009;**10**:Q11004. DOI: 10.1029/2009GC002619

[7] Grob M, Maggi A, Stutzmann E. Observations of the seasonality of the Antarctic microseismic signal, and its association to sea ice variability. Geophysical Research Letters. 2011;**38**:L11302. DOI: 10.1029/2011GL047525

[8] Kanao M, Kaminuma K. Broad-band and wide dynamic-range seismic observations with an STS at Syowa Station, East Antarctica. Polar Geoscience. 1994;**7**:1-13

[9] Kanao M. Detection capability of teleseismic events recorded at Syowa Station, Antarctica—1987-2007. Antarctic Record. 2010;**54**(1):11-31

[10] Iwata T, Kanao M. The quantitative evaluation of the annual variation in the teleseismic detection capability at Syowa Station, Antarctica. Polar Science. 2015;**9**:26-34. DOI: 10.1016/j.polar.2014.10.002

[11] Hedlin MAH, Walker K, Drob DP, de Groot-Hedlin CD. Infrasound: Connecting the solid earth, oceans, and atmosphere. Annual Review of Earth and Planetary Sciences. 2012;**40**:327-354

[12] Eckstaller A, Müller C, Ceranna L, Hartmann G. The geophysics observatory at Neumayer Stations (GvN and NM-II) Antarctica. Polarforschung. 2006;**76**:3-24

[13] Ishihara Y, Furumoto M, Sakai S, Tsukuda S. The 2003 Kanto large bolide's trajectory determined from shockwaves recorded by a seismic network and images taken by a video camera. Geophysical Research Letters. 2004;**31**:L14702

[14] Matoza RS, Hedlin MA, Garces MA. An infrasound array study of Mount St. Helens. Journal of Volcanology and Geothermal Research. 2007;**160**:249-262

[15] Arai N, Iwakuni M, Watada S, Imanishi Y, Murayama T, Nogami M. Atmospheric boundary waves excited by the tsunami generation related to the 2011 great Tohoku-Oki earthquake. Geophysical Research Letters. 2011;**38**:L00G18. DOI: 10.1029/2011GL049146

[16] Yamamoto M-Y, Ishihara Y, Hiramatsu Y, Kitamura K, Ueda M, Shiba Y, Furumoto M, Fujita K. Detection of acoustic/infrasonic/seismic waves generated by hypersonic reentry of HAYABUSA capsule and fragmented parts of spacecraft. Publications of the Astronomical Society of Japan. 2011;**63**:971-978

[17] Ishihara Y, Hiramatsu Y, Yamamoto M-Y, Furumoto M, Fujita K. Infrasound/seismic observation of the Hayabusa reentry: Observations and preliminary results. Earth, Planets and Space. 2012;**64**:655-660

[18] Iyemori T, Nose M, Han DS, Gao Y, Hashizume M, Choosakul N, Shinagawa H, Tanaka Y, Utsugi M, Saito A, McCreadie H, Odagi Y, Yang F. Geomagnetic pulsations caused by the Sumatra earthquake on December 26, 2004. Geophysical Research Letters. 2005;**32**:L20807. DOI: 10.1029/2005GL024083

[19] Matsumura M, Shinagawa H, Iyemori T. Horizontal extension of acoustic resonance between the ground and the lower thermosphere. Journal of Atmospheric and Solar-Terrestrial Physics. 2012;**75-76**:127-132

[20] Yamamoto M-Y, Ishihara Y, Kanao M. Infrasonic waves in Antarctica: A new proxy for monitoring polar environment. International Journal of Geosciences. 2013;**4**:797-802. DOI: 10.4236/ijg.2013.44074

[21] Ishihara Y, Kanao M, Yamamoto M-Y, Toda S, Matshushima T, Murayama T. Infrasound observations at Syowa Station, East Antarctica—An implication for detecting the surface environmental variations in Polar region. Geoscience Frontiers. 2014;**6**:285-296. DOI: 10.1016/j.gsf.2013.12.012

[22] Murayama T, Kanao M, Yamamoto M-Y, Ishihara Y, Matshushima T, Kakinami Y. Infrasound array observations in the Lützow-Holm Bay region, East Antarctica. Polar Science. 2015;**9**:35-50. DOI: 10.1016/j.polar.2014.07.005

[23] Ishihara Y, Yamamoto M-Y, Murayama T, Matsushima T, Kanao M. Long-term variations in infrasound signals observed at Syowa Station, Antarctica: 2008-2014. InfraMatics. 2017;**3**:1-10. DOI: 10.4236/inframatics.2017.31001

[24] Murayama T, Kanao M, Yamamoto M-Y, Ishihara Y. Infrasound signals and their source location inferred from array deployment in the Lützow-Holm Bay region, East Antarctica: 2015 January–June. International Journal of Geosciences. 2017;**8**:181-188. DOI: 10.4236/ijg.2017.82007

[25] Murayama T, Kanao M, Yamamoto M-Y, Ishihara Y, Matsushima T, Kakinami Y, Okada K, Miyamachi H, Nakamoto M, Takeuchi Y, Toda S. Time-space variations of infrasound sources related to environmental dynamics around the Lützow-Holm Bay, East Antarctica. Polar Science. 2017;**14**:39-48. DOI: 10.1016/j.polar.2017.10.001

[26] Kanao M, Park Y, Murayama T, Lee WS, Yamamoto M-Y, Yoo HJ, Ishihara Y, Kim JS, Oi T, Jung JH. Characteristic atmosphere and ocean interactions in the coastal and marine environment inferred from infrasound data at Teranova Bay, West Antarctica. Annals of Geophysics. 2017;**6**(5):A0554. DOI: 10.4401/ag-7364

[27] Matsumura M, Kanao M. Simultaneous Modelling of Microbaroms and Microseisms Using CIP-CUP Scheme, AGU Fall 2015 Meeting, S51C-2696, 2015, Dec. 14-18, San Francisco, California, USA; 2015

[28] Schmandt B, Aster RC, Scherler D, Tsai VC, Karlstrom K. Multiple fluvial processes detected by riverside seismic and infrasound monitoring of a controlled flood in the Grand Canyon. Geophysical Research Letters. 2013;**40**:4858-4863. DOI: 10.1002/grl.50953

Summary: Global Seismology and the Polar Region

Masaki Kanao

Abstract

“Polar Seismology” has been developed since the International Geophysical Year (IGY 1957–1958) and contributed significantly to global seismology in particular through the big project of the International Polar Year (IPY 2007–2008). At present, in the first stage of the twenty-first century, “polar regions” play an important role to monitor and understand the drastic variations in the Earth’s system as well as to advance the interdisciplinary studies of the interactions among multispheres within the system.

Keywords: global seismology, polar region, wave propagation, global network, Earth’s system

1. Contributions to global seismology

Various kinds of temporal-spatial heterogeneities and their dynamic features from the surface layers to the center of the Earth by using the seismological data obtained from the polar region are summarized in this special issue. High-density geophysical station networks deployed during the IPY in bipolar regions contributed to many kinds of research studies: static structure related to the Earth’s history; earthquake occurrence mechanism; inner deformation of lithospheric plates; crustal uplift involving deglaciation, plate motion, and seismic isotropy; and other topics in terms of surface dynamics of the Earth’s environment. Moreover, by utilizing the Internet facilities and other useful computer and information technology tools, real-time data transmission from the remote areas of the polar region to all the other locations in global networks, as well as conducting real-time monitoring of variations in the solid Earth viewed from high latitudes, shall be successful. In addition, facilitating disaster prevention on a global scale could be achieved from the tentative “frontier region” of the Earth.

Within the complex system consisting of the solid Earth and adjacent spheres of the Earth, it is essential to collaborate with interdisciplinary approaches, not only by the seismological community but also by the other science branches, to promote fruitful scientific achievements regarding the physical interaction of the multisphere subsystems and the associated field operations. In the bipolar region, a big project named the International Polar Year (IPY 2007–2008) was conducted with various kinds of scientific activities; a significant number of new founds were identified, and interdisciplinary and international collaborations were strongly promoted. The Japanese polar scientists took the initiatives in various categories of activities [1]. However, the IPY was one of the waypoints to be passed through for the long-term monitoring of the Earth's environmental system in the twenty-first century. It is necessary to conduct the long-duration international programs in various categories: searching for new fundamental founds for the development of research and observation methodology and logistic platforms, preserving and providing the retrieved data, and so on.

In Antarctica, the geophysical network stations deployed by the Antarctica's Gamburtsev Province (AGAP) of the Gamburtsev Mountain Seismic Experiment (GAMSEIS) and the Polar Earth Observing Network (POLENET) including the Dome-F station have existed. In addition to the Arctic, POLENET and GLISN have been established during the IPY and beyond (**Figure 1**). These stations in the bipolar region contributed to the studies of the inner structure of the Earth and the earthquake source mechanism with a fine time-space resolution [3]. The inland plateau stations such as Dome-A, -C, and -F have significance not only to the global networks (for instance, FDSN; see Chapters 1 and 2) but also to the regional observation systems in the Antarctic continent and the surrounding Southern Ocean. It is essential to continue observations at these inland plateau stations in addition to the coastal permanent ones such as the Syowa Station, in order to monitor the seismicity of tectonic and glacial earthquakes in the vicinity of the local area along the Antarctic Plate.

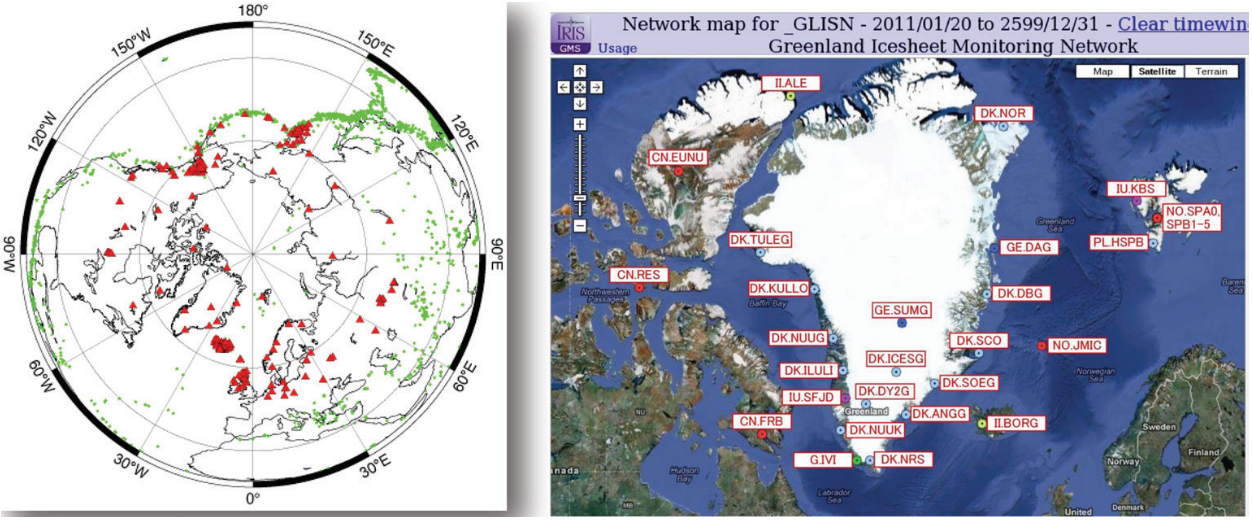


Figure 1. (Left) Distribution of seismic stations in the Arctic (red triangles: IRIS/DMS and PASSCAL) (modified after Kanao et al. [2]). The green circles represent the hypocenters during 1990–2004. (Right) Station distribution of GLISN in 2011 (by IRIS/DMS). (Left) (CC BY 3.0) (first author is M. Kanao). (Right) Copyright http://www. iris.edu/hq/.

2. Global seismic wave propagation

Before and after the IPY, there were several research studies concerning seismic wave propagation on a global scale by using the data from the polar region.

Loading and gravitational effects of the 2004 Indian Ocean tsunami waves were investigated by using the broadband seismographs and superconducting gravity meter at Syowa Station, Antarctica [4]. T phases and the short-period resonance mode inside the Lützow-Holm Bay (LHB) were studied in order to define the elastic parameters concerning the free oscillation of the Earth. The sea-level changes generated by tsunami waves from the Sumatra-Andaman earthquake on December 2004 were clearly recorded by seismographs at the coastal stations in the Antarctic such as the Syowa Station, giving fundamental information on detecting the long-period oceanic variations and nonstatic events and signals from the deep interiors of the Earth. The ocean bottom pressure gage deployed at the offshore of LHB, moreover, detected the low-frequency static variations [5]. The oceanic expansion area between the circular Antarctic current and the coastal flows of the continent has a role in creating horizontal expansion and upwelling of the oceanic water. The ocean bottom pressure gage observations revealed the features of oceanic mass transportation of the area. Future the further progress in understanding the oceanic mass circulation along the coastal regions of Antarctica is expected in future.

By using the broadband seismic data of Antarctica, the 2008 Eastern Sichuan earthquake (M 7.9) simulated waveforms at Syowa Station, which were compared by utilizing the "Earth simulator" infrastructure [6]. May 30, 2015, Bonin Islands, Japan deep earthquake (M 7.8) was also recorded at the broadband seismographic station in the Greenland ice sheet (Tsuboi, 2017, personal communication). They applied the waveform inversion technique to obtain a slip distribution in the source fault of May 30, 2015, Bonin Islands, Japan earthquake (M 7.8, 680-km depth). They obtained a source rupture model for both nodal planes with a high dip angle (74°) and a low dip angle (26°) and compared the synthetic seismograms with observations to determine the most precise source rupture model. Comparisons of synthetic waveforms with the observations at the Greenland ice-sheet station, ICESG (epicentral distance 83.4°), showed that the arrival time of the P wave for a depth of 680 km matched well, suggesting the earthquake occurred below the 660-km seismic discontinuity. In their forward simulations, the source rupture model with a low-angle fault dipping was likely to better explain the observations.

Moreover, the quasi-axisymmetric finite-difference method was developed involving a realistic and an efficient modeling of regional and global seismic wavefields, by applying the dataset of Antarctica [7]. The new method can be utilized for unique points such as the poles of the globe, together with an investigation of the effect of the existence of the ice sheet. The estimation of the inner structure of the Earth by using the quasi-axisymmetric method was actually acquired through the broadband seismic data from AGAP/POLENET [8]. The same wave modeling method was expanded to the local area and applied to the data from Greenland (GLISN; see Chapters 2 and 7) [9] (**Figure 2**). By adding the information on the thickness of the ice sheet and bedrock topography, the generating scheme of the waves propagating inside the ice sheet (the "ice waves") was theoretically demonstrated.

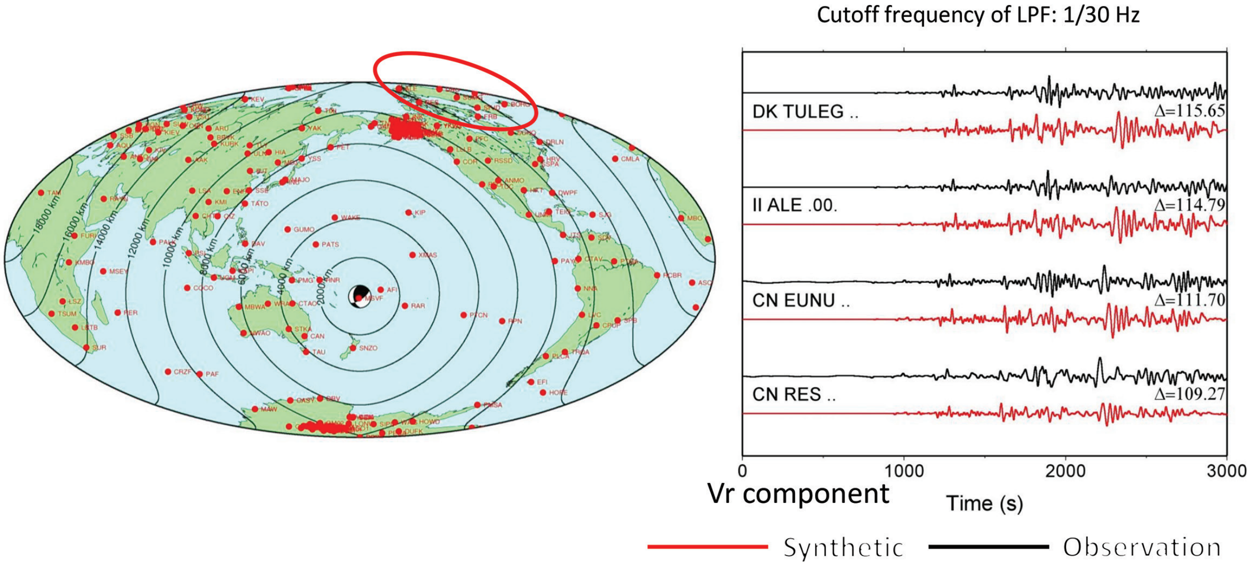


Figure 2. Observed and theoretical seismic waveforms at the GLISN stations (hypocenter); Fiji earthquake (Sep 15, 2011; M = 7.3 and depth = 630 km) (modified after Toyokuni et al. [9]). Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4280481114467, license date: February 1, 2018.

Regarding the studies of deep interiors, the latitude dependence on the intrinsic frequencies of the Earth's free oscillation ($_0S_0$, $_1S_0$, and $_0S_2$) in bipolar regions was investigated by using both broadband seismographs and superconducting gravity meters [10]. The results could not identify the latitude dependence; however, they could constrain the estimation of the heterogeneous structure at the lowermost mantle D" layer.

These series of seismological achievements during the IPY in terms of global aspects were partially summarized in the special issue on "Polar Science" [3].

3. Contributions to the global network

Over the last few decades, to establish a continuous monitoring system for the nuclear tests, a global distribution of seismic and infrasound networks has been established by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) [11] (**Figure 3**). One of the objectives of CTBTO is to estimate the detection and location capabilities of the networks at the regional and global distances, and the second is to explore the ways to improve these capabilities and enhance the understanding of seismic/infrasonic wave propagation through the solid Earth/atmosphere of the observed events. At present, CTBTO has 60 infrasound stations, each containing at least 4 sensors (arrayed stations), which can detect a several-kiloton TNT-level explosion at a range of ~1000 km. Although the full capability of the global infrasonic network has not yet been established, it could be adequate for monitoring nuclear tests but too sparse for analyzing natural infrasound phenomena in detail. Therefore, increasing the number of stations in the Antarctic and the Arctic, inside or outside CTBTO, could firmly be efficient to contribute in accumulating the precious data viewed from a high latitude in addition to the low-middle latitude regions.

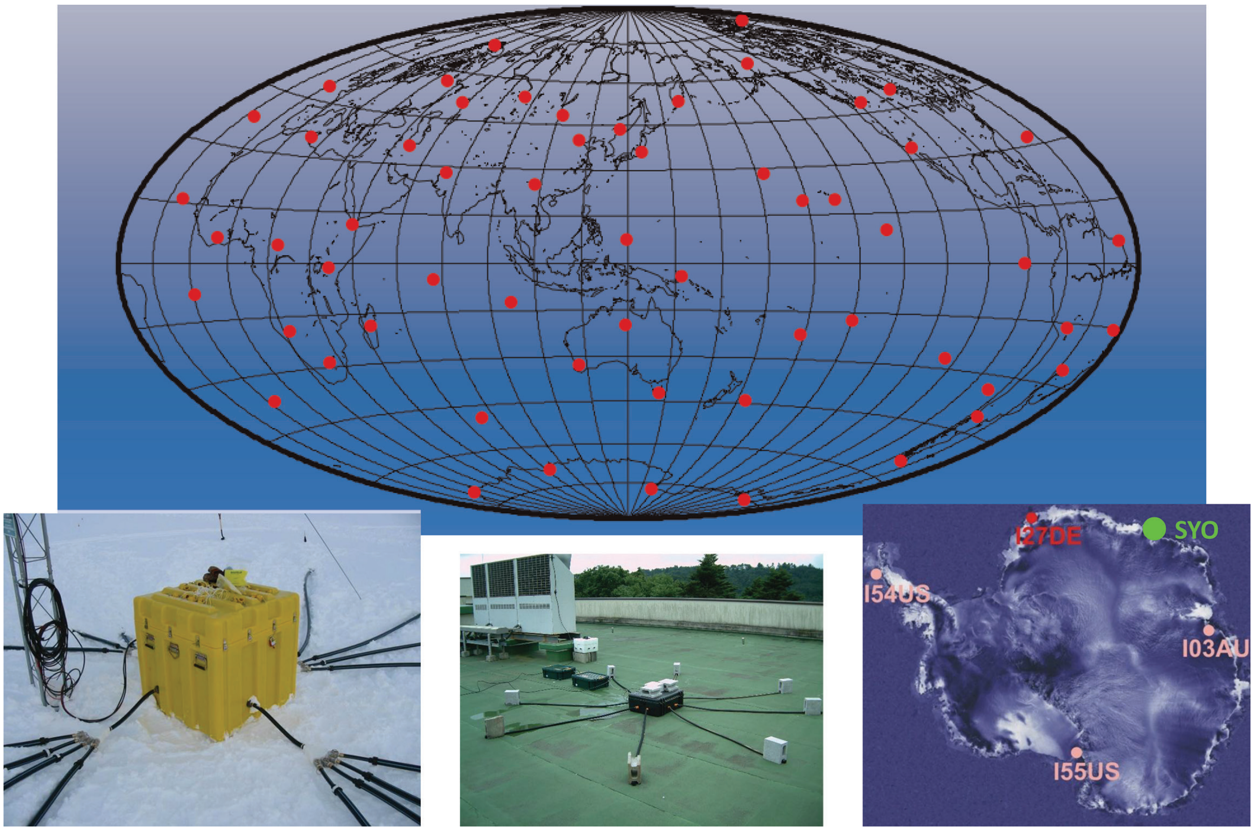


Figure 3. (Upper) Global distribution of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) network. (Lower) From left to right: an infrasound station photo at 155US in West Antarctica, a test running observation at Tohoku University in Japan, and a station distribution in the Antarctic, respectively (modified after Kanao et al. [12]). (Left) (CC BY 3.0) (first author is M. Kanao).

In addition to the seismic and hydroacoustic networks, infrasound stations in the Antarctic could firmly contribute to both CTBTO and the Pan-Antarctic Observations System (PAntOS) under the Scientific Committee on Antarctic Research (SCAR) of the International Council for Science (ICSU). In order to understand the property of wave propagation within the ocean, hydroacoustic observations would be required from a sufficient number of stations. Hydrophone array observations, for example, were already recorded to investigate seismicity and sea-ice dynamics around the Bransfield Strait, Antarctic Peninsula [13]. Multidisciplinary observations composed of the data from seismic, infrasound, and hydroacoustic sensors would be required for understanding the physical interactions among the atmosphere-ocean-cryosphere-geosphere systems and the temporal-spatial variations in the polar region in more detail. It is also expected that a large quantity of data detected by these three types of sensors accumulated over the past decades by CTBTO will be distributed to the relevant scientific community efficiently.

4. Summary

As treated in several chapters of this special issue on "Polar Seismology," there are a lot of reports to find the characteristic seismic and infrasound vibrations of the solid Earth involving the disturbance and variations in ice sheets, sea ices, oceans, and the atmosphere in the polar region. It is a crucial task to realize the physical processes between the solid Earth and the surrounding environments in terms of the recent climate changes such as global warming; that is, the evolution of sea ices and the dynamics of ice sheets and glacial earthquake activities are now carried out in the surface layers of the polar region.

The next step for “Polar Seismology” after the IPY could be the interdisciplinary research studies combining seismic, infrasound, and acoustic waves and the other significant science disciplines such as geodesy, geology, and glaciology. Moreover, data assimilations, statistic approaches, and other interdisciplinary methodologies might be useful. In addition, based on the significance of long-term monitoring at permanent stations such as Syowa Station, the future perspectives and the improvement of the conditions of the observation infrastructures are required to be considered. The “Polar Region,” as one of the remaining frontiers of the Earth, could surely provide an effective scientific platform to achieve sophisticated knowledge for the evolving environments in the twenty-first century after the IPY. In future, the efficient efforts by the next generations in global seismology are also expected.

Finally, the author would like to express his sincere appreciation for the preparation of this special issue on “Polar Seismology.” He also acknowledges Dr. Genti Toyokuni of Tohoku University and Dr. Mitsuru Matsumura of Nagoya University for their sincere cooperation in providing a part of illustration in this chapter. The author expresses his deep gratitude to all the colleagues and coresearchers in the polar seismological community around the world to prepare this monograph on the special issue.

Author details

Masaki Kanao

Address all correspondence to: kanao@nipr.ac.jp

National Institute of Polar Research (NIPR), Organization of Information and Systems (ROIS), Tokyo, Japan

References

[1] Sato N, Ito H, Kanao M, Kanda H, Naganuma T, Ohata T, Watanabe K, Yamanouchi T. Engaging Asian Nations in IPY: Asian Forum for Polar Sciences (AFoPS) (Japanese Section). In: Krupnik I, Allison I, Bell R, Cutler P, Hik D, Lopez-Martinez J, Rachold V, Sarukhanian E, Summerhayes C, editors. Understanding Earth’s Polar Challenges: International Polar Year 2007-2008 – Summary by the IPY Joint Committee. Vol. 5.3. Edmonton, Alberta: Art Design Printing Inc.; 2011. pp. 555-574

[2] Kanao M, Suvorov VD, Toda S, Tsuboi S. Seismicity, structure and tectonics in the Arctic regions. Geoscience Frontiers. 2015;**6**:665-677. DOI: 10.1016/j.gsf.2014.11.002

[3] Kanao M, Zhao D, Wiens DA, Stutzmann E. Recent advance in polar seismology: Global impact of the international polar year – Overview. Polar Science. 2015;**9**:1-4. DOI: 10.1016/j.polar.2014.12.003

[4] Nawa K, Suda N, Satake K, Sato T, Doi K, Kanao M, Shibuya K. Loading and gravitational effects of the 2004 Indian Ocean tsunami at Syowa Station, Antarctica. Bulletin of the Seismological Society of America. 2007;**97**:S271-S278. DOI: 10.1785/0120050625

[5] Hayakawa H, Shibuya K, Aoyama Y, Nogi Y, Doi K. Ocean bottom pressure variability in the Antarctic Divergence Zone off Lützow-Holm Bay, East Antarctica. Deep Sea Research. 2012;**60**:22-31. DOI: 10.1016/j.dsr.2011.09.005

[6] Tsuboi S, Komatitsch D, Ji C, Tromp J. Computations of global seismic wave propagation in three dimensional Earth model. Lecture Notes in Computer Science. 2008;**4759**:434-443

[7] Toyokuni G, Kanao M, Takenaka H. Quasi-axisymmetric finite-difference method for realistic modeling of regional and global seismic wavefield – Review and application. In: Kanao M, Takenaka H, Murai Y, Matsushima J, Toyokuni G, editors. Seismic Waves – Research and Analysis. Rijeka, Croatia: InTech. Publisher; 2012. pp. 85-112

[8] Toyokuni G, Takenaka H, Kanao M, Wiens DA, Nyblade AA. Comparison of global synthetic seismograms calculated using the spherical 2.5-D finite-difference method with observed long-period waveforms including data from the intra-Antarctic region. Polar Science. 2012;**6**:155-164. DOI: 10.1016/j.polar.2012.06.001

[9] Toyokuni G, Takenaka H, Kanao M, Tsuboi S. Numerical modeling of seismic waves for estimating influence of the Greenland ice sheet on observed seismograms. Polar Science. 2015;**9**:80-93. DOI: 10.1016/j.polar.2014.12.001

[10] Shimizu H, Hiramatsu Y, Kawasaki I. Search for latitudinal variation of spectral peak frequencies of low-frequency eigenmodes excited by great earthquakes. Polar Science. 2015;**9**:17-25. DOI: 10.1016/j.polar.2014.07.002

[11] Butler R, Anderson K. Global Seismographic Network (GSN). IRIS Report 6-7. 2008

[12] Kanao M, Maggi A, Ishihara Y, Yamamoto M-Y, Nawa K, Yamada A, Wilson T, Himeno T, Toyokuni G, Tsuboi S, Tono Y, Anderson K. Interaction on seismic waves between atmosphere – Ocean – Cryosphere and geosphere in Polar Region. In: Kanao M, Takenaka H, Murai Y, Matsushima J, Toyokuni G, editors. Seismic Waves – Research and Analysis. Rijeka, Croatia: InTech Publisher; 2012. pp. 1-20. ISBN: 978-953-307-944-8. DOI: 10.5772/1400

[13] Dziak RP, Park M, Lee WS, Matsumoto H, Bohnenstiehl DR, Haxel JH. Tectono-magmatic activity and ice dynamics in the Bransfield Strait back-arc basin, Antarctica. Proceedings of the International Symposium on Polar Science. 2009;**16**:59-68

Chapter 8

Studies on Seismicity in the Polar Region

Masaki Kanao

Abstract

During the International Polar Year (IPY 2007–2008), several seismological research studies have been conducted as a part of geophysical observations in bipolar regions. In this chapter, recent studies involving seismicity in bipolar regions are introduced on the basis of compiled data from the International Seismological Centre (ISC). The relationship between the present seismicity and the heterogeneous structure of the crust and upper mantle is discussed, together with a review of geoscientific achievements in terms of the tectonic history of the Earth.

Keywords: seismicity, polar region, IPY, International Seismological Centre, GIA, tectonics

1. Introduction

After a half-century of the International Geophysical Year (IGY 1957–1958), the International Polar Year (IPY 2007–2008) was conducted in tight collaboration with related scientists around the world in bipolar regions. During the IPY, various kinds of interdisciplinary and international projects had been carried out so as to figure out the future images for human beings by monitoring the Earth's environmental changes from a viewpoint of the "polar window" at high latitudes. In both the Arctic and Antarctic, particularly Greenland and Lapland, improved seismic observation networks have been established in order to monitor both the global and regional seismicities in addition to conducting studies on the Earth's interiors.

The polar region, particularly the Arctic (here defined as the area within the "Arctic circle" and surrounding low-latitude terrains), which is centered in the Arctic Ocean, has been strongly affected by global warming, which is currently progressing. Particularly, shrinking in time and space, the sea ice and the ice sheet (i.e., the cryosphere) have been drastically altered. However, their influence on the underlying solid Earth and the dynamics involving cryosphere evolution (particularly for the generation of “seismicity”) have not been understood well enough to explain the relationship. To continuously monitor the dynamics of polar ice sheet/caps and sea ice from the point view of “seismology,” a long-term monitoring of changes in ice mass and their transport the polar region is expected to be conducted, in order to understand the present plate motions from the tectonic history of the Earth.

In this chapter, recent studies involving seismicity in bipolar regions during the IPY are introduced on the basis of the compiled data from the International Seismological Centre (ISC). A relationship between the present seismicity and the heterogeneous structure of the crust and upper mantle is especially focused on, as well as the importance of geoscientific investigations in relation to tectonic history of the Earth.

2. Antarctic region

Seismicity around the Antarctic region is mainly concentrated at the plate boundaries between the Antarctic Plate, with the Antarctic continent situated in the center, and its surrounding plates (Australian, South American, African, and Indian subcontinents). Most plate boundaries are under the influence of extensional tectonic regimes: oceanic spreading ridges and transform faults. Inside the Antarctic Plate, both in the Southern Ocean and in the Antarctic continent, there are relatively small number of seismic events compared with other tectonic provinces (geological terrains) of the globe. Particularly for East Antarctica, where majority of the continental blocks are composed of several Precambrian age terrains, quite a few number of tectonic- and volcanic-origin seismic events have been identified [1–4]. In contrast, West Antarctica including the Antarctic Peninsula has been composed of relatively younger geological terrains formed after the Paleozoic age. Local earthquakes within the crust and volcanic activities have been identified from the West Antarctic Rift System (WARS; see Figure 1 of Chapter 1) to the Marie Byrd Land (MBL) and the Antarctic Peninsula. Moreover, in the Scotia Plate, which is located to the northeast of the Antarctic Peninsula, high seismic activities have been recorded particularly near the South Sandwich Islands, where the subduction of tectonic regime has been developed at the eastern margin of the Scotia Plate as one of the remaining portions of the Southern Atlantic Ocean, spreading effects between the South American and African continents ([4], **Figure 1**).

Seismicity of East Antarctica and adjacent Southern Ocean (the Indian Ocean sector including the Eastern Dronning Maud Land and Enderby Land, which contains the Japanese Syowa Station) was activated by the occurrence of the largest earthquakes in the last half-century within the Antarctic Plate (Balleny Island region, M 8.0, March, 25, 1998) and the Sumatra-Andaman earthquakes (M 9.0, December, 26, 2004). Characteristic time-space distributions of seismicity were identified corresponding to the variations in the tectonic stress field within the plates around the earthquake focal area of these large events, spreading ridges and transform faults of the Southern Ocean, together with the Wilkes Land in East Antarctica [1, 4]. The Balleny Island earthquake is considered to be an inner plate deformation at the triple-point among the

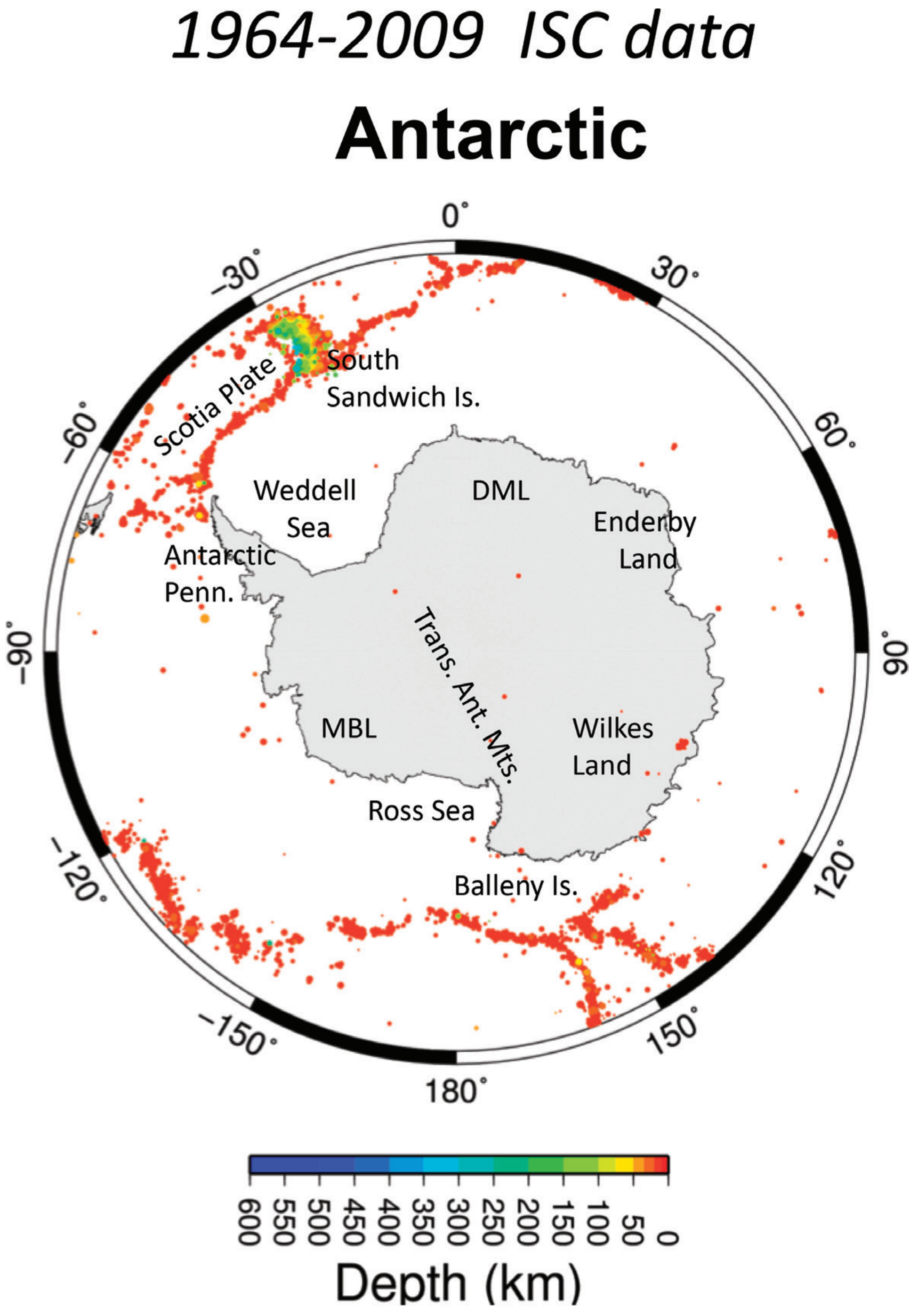


Figure 1. Seismicity of the Antarctic from compiled data from ISC (1964–2009; modified after [4]). Copyright Clearance Center (CCC, http://www.copyright.com/). License Number: 4276351216219, License date: January 26, 2018.

Pacific Plate, Indian-Australian Plate, and Tasmania microplate [5, 6], the unique point among the stress field inside the Antarctic Plate because of the fracture zones across the sea mountain just above the hypocenter [7], as well as the effects of crustal deformation after deglaciation [8, 9]. Regarding the aftershock activities of the Balleny Island earthquake, statistical analysis was carried out to obtain time-space variations for long-period fluctuations [10]. Before and after the Balleny event, static seismic activity except aftershocks has been drastically changed, and raapid increase in the tectonic stress field within the Antarctic Plate was statistically identified (**Figure 2**). It is assumed that the large earthquake events were generated in tectonically nonactive and nonvolcanic regions around Antarctica, by combined effects of inner-plate deformation of the oceanic lithosphere according to the stress concentration caused by the plate movement, in addition to the stress drop related to deglaciation.

The Sumatra-Andaman earthquakes (M 9.0, December, 26, 2004), the largest seismic events around the region of the Indian-Australian Plate, and their relationship with the seismic activities at the Indian sector of the Antarctic Plate have been investigated [11]. Before one decade of the Sumatra-Andaman earthquakes, there were quite a few events more than M. 7.0 at the oceanic ridges between the African Plate and the Indian-Australian Plate except for the Balleny Island event in March 1998. In contrast, there had been no earthquakes more than M. 7.0 at the oceanic ridges and transform faults of the Indian sector of the Antarctic Plate in the same decade. Moreover, the number of events more than M 6.0 were limited within 30 during the same decade. In addition to these events, after the Sumatra-Andaman earthquakes, characteristic seismic activities were identified around the eastern ridges of the Australia Antarctic

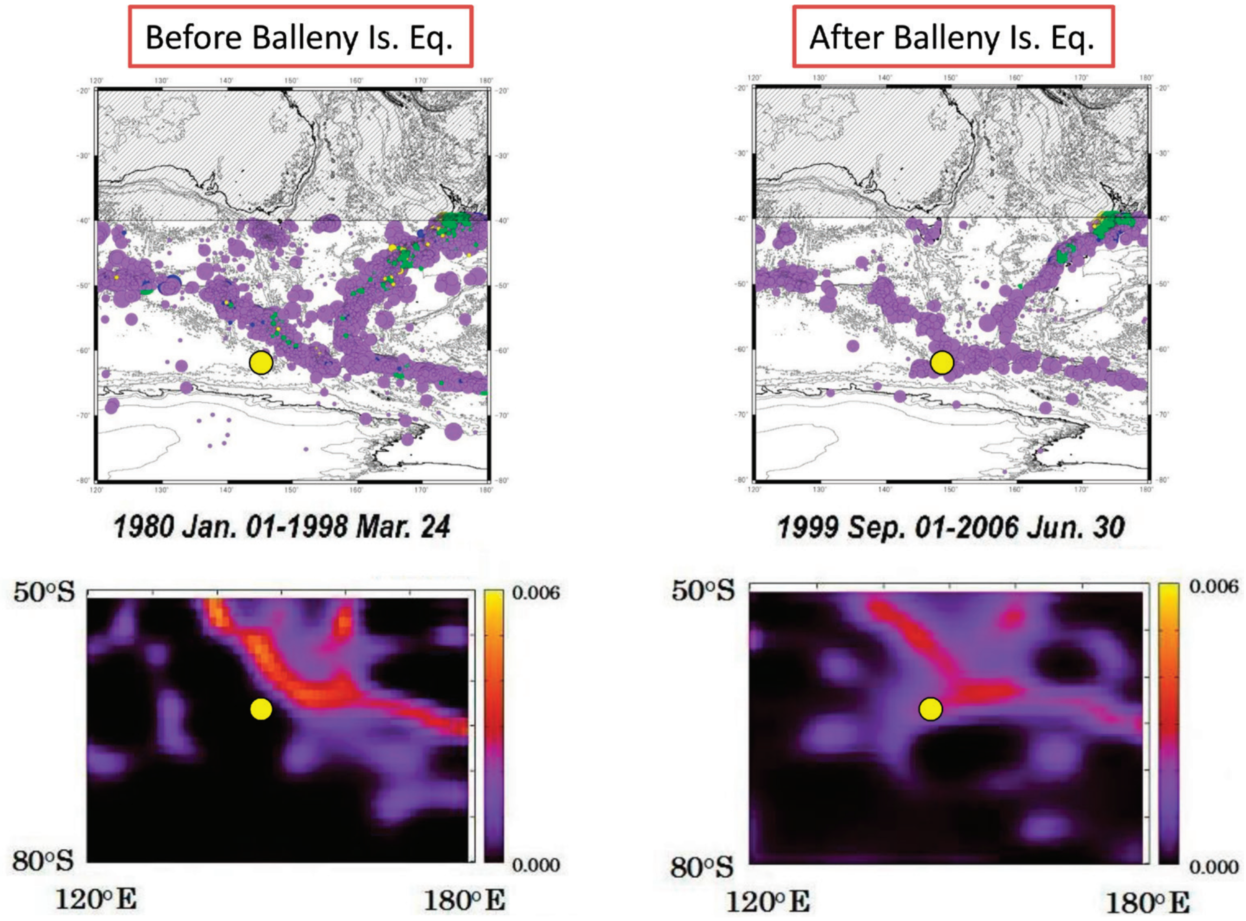


Figure 2. Time-space variations before and after the Balleny Island earthquake marked by yellow circle (March 25, 1998) [10] (upper, hypocentral distribution; lower, stationary activities determined by statistic method). Copyright Clearance Center (CCC, http://www.copyright.com/). License Number: 4276361324576, License date: January 26, 2018.

Discordance (AAD) [11]. From these evidences of events occurring at the ocean bottom like in the Southern Ocean, it is possible to say that the existence of microearthquakes cannot be recorded by the existing observation networks. In summary, in the inner part of the Antarctic Plate, particularly in the oceanic region surrounding the Antarctic continent, seismicity has generally been low and tectonically stable except for the focal regions of two large earthquakes in the last two decades as mentioned earlier [11].

Among the earthquakes around the Antarctic Plate, in addition to the middle-to large events as mentioned earlier which are recordable by the present global networks, there are characteristic "local events" in particular located around the margin of the Antarctic continent. The activities of these local events are quite low on average; however, the earthquakes are considered to be of tectonic origins within the crustal depths mostly associated with glacial isostatic adjustment (GIA), related to the transform faults at the ocean bottom and coastal margins of the continent. For example, the number of local events that occurred near the Syowa Station, East Antarctica, was only one in a year during the last decade [12, 13]. Hypocenter of these local events concentrated on the boundary between the continent and the ocean, that is, the coastal line at the margin of the continental ice sheet, ice shelf, and glaciers. There is a possibility for these events to be reported as tectonic events (inner crustal events) rather than ice quakes. (Details of the "ice quakes" (cryoseismic events) are given in Chapter 7.) In other areas of the Antarctic, several hypocenters of the local events were reported by individual regional networks; many of them were determined near the coastal areas, particularly at the edges of large glaciers [14–16]. Many of these events could be explained by cryosphere dynamics as mentioned in detail in Chapter 7.

With these evidences regarding seismicity in the Antarctic, methods for detecting seismic events in the polar region have been developed in the last two decades, particularly the onshore area for the improvement of both seismographs and observation networks. However, a long-term monitoring of seismicity including the oceanic area of the Southern Ocean, as a significant portion of the global network, is also expected to be conducted. These developments in the polar region could efficiently contribute to the prediction of global seismic activities, together with providing early warning such as tsunami waves affecting the polar region.

3. Arctic region

Seismicity and related seismological research studies/observations in the Arctic region before the IPY are discussed in detail by [17]. Recently, compiled data from the International Seismological Centre (ISC) represent the general image of seismicity in the Arctic region [4] (**Figure 3**). Major seismicity in the Arctic region can clearly be traced along the plate boundaries from the Northern Atlantic Ridges, the Barents Sea, the Gakkel Ridge within the Arctic Ocean, the Laptev Sea in the northern part of Siberia, to the Far East region of Russia. On the other hand, seismicity involving subducting plates and deglaciation process associated with GIA can be seen around the Alaska and the Baltic Sea, and others. Seismic activities in the Lapland, northern Europe, relating to GIA, are reported in detail by [18], in which

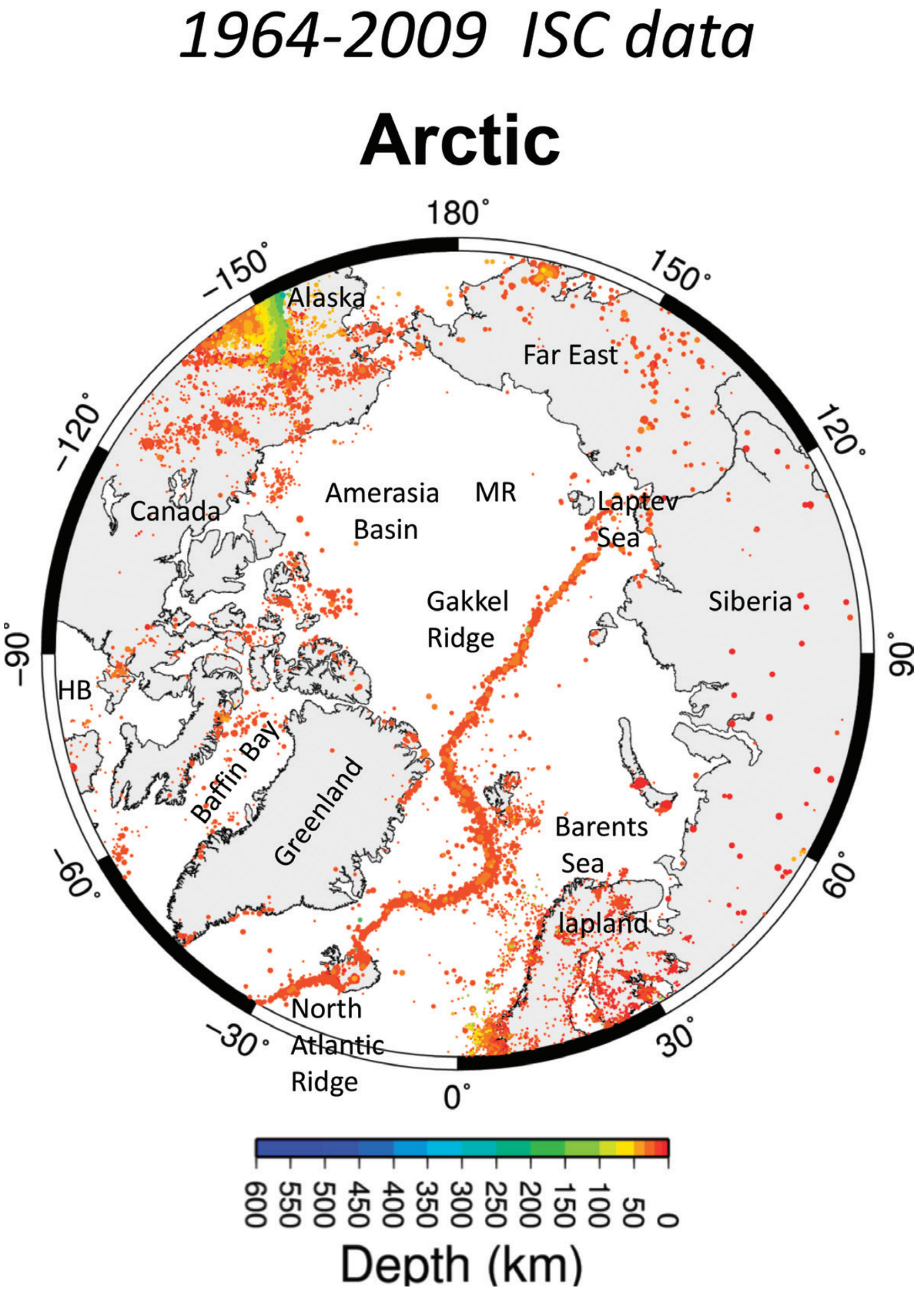


Figure 3. Seismicity of the Arctic from compiled data from ISC (1964–2009; modified after [4]). Copyright Clearance Center (CCC, http://www.copyright.com/). License Number: 4276351216219, License date: January 26, 2018.

the seismic events were recorded by the Lapland Network (LAP-NET) deployed during the IPY. Moreover, local earthquake events have occurred around Greenland, Baffin Island, and Eastern Canada (**Figure 4**). Since these areas are known to be tectonically stable terrains in the geological framework, these events are assumed to mostly be of cryoseismic origins such as the glacial earthquakes, or characteristic events relating to GIA. In contrast, around the area of northern Eurasia, seismicity and tectonics of Russian Far East and Eurasian Arctic, and Siberian regions were summarized in detail by [17]. Relationships among seismicity and volcanic activities, crustal structure, plate movement surrounding Eurasia, and complex tectonic history of the continent were discussed for individual tectonic terrains.

During the IPY, crustal structure and microseismicity of the Gakkel Ridge-Amerasia Basin area were studied by conducting geophysical surveys at the oceanic bottom of the Arctic Ocean [19–22]. A new catalog of seismicity in the midocean ridges in the Arctic Ocean was produced by combining data on teleseismic events compiled from ISC for more than three decades and local seismic events along the ridge detected by using seismometers at the oceanic bottom and over the drifting ice floes [19]. Variations in seismic activities along the ridge were considered to be affected by the ultraslow spreading processes, characterized by having larger earthquake production in magma-rich regions along the rift system. In addition, increases in seismicity of the European Arctic were revealed by making use of a joint processing of the event catalog data from different adjacent seismic networks, such as NORSAR and the International Data Centre (IDC) belonging to CTBTO [20]. The increased areas of seismic activity revealed by the joint processing approach have been found along the Gakkel Ridge to the northern part of the Svalbard Islands, as well as the Franz-Josef Land archipelagos.

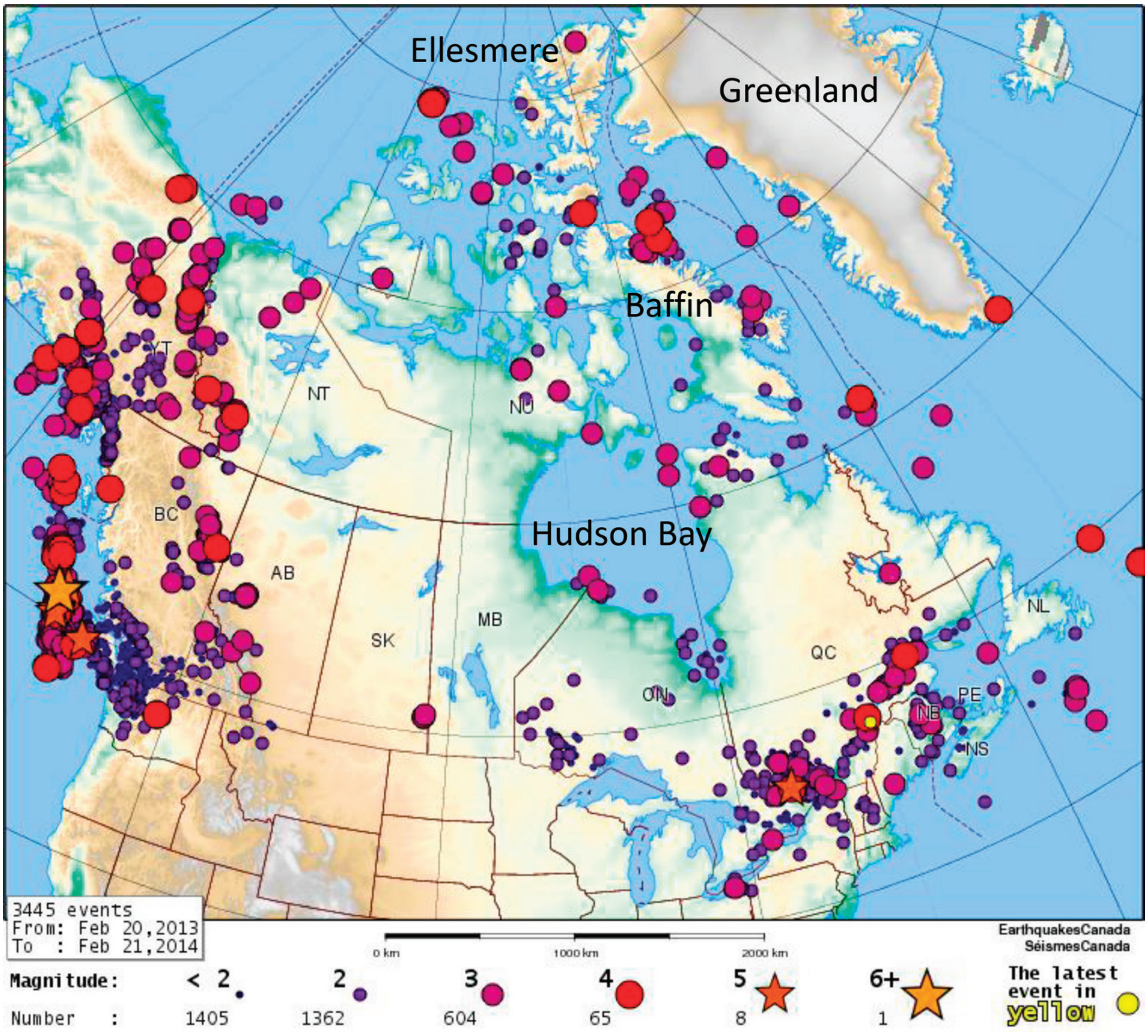


Figure 4. Seismicity around Canada, Alaska, and Greenland (2013–2014). Hypocentral data are from Natural Resources Canada. Copyright https://www.nrcan.gc.ca/home.

Microseismic activities that cannot be detected by deploying global networks have been identified around the remote plate boundaries from the continents such as the oceanic ridges and transform faults by utilizing several kinds of transportable seismographs and hydrophones deployed on sea ices, icebergs, as well as oceanic bottoms (for instance, in the case of the Antarctic Peninsula; see [22]). It is also possible to detect and monitor seismicity by making use of the arrival times and waveforms of the T phases, which propagate within the ocean. In future, microseismic activities and fine crustal structure will be clarified at the sea bottom frontiers in bipolar regions such as the area beneath the Arctic and the Southern Oceans.

4. Summary

In this chapter, seismicity of bipolar regions was reviewed, in relation to surface environment, crustal structure, and tectonics. Majority of the parts of bipolar regions are occupied by relatively stable tectonic provinces, with various evolution histories, subducting slabs, collisions at plate boundaries, deformation inside the continents, upwelling of mantle plumes, extension stress regimes, and so on. Moreover, arapid climate change surrounding the surface layers of the Earth, especially due to the recent global warming, might be affected by the activation of seismicity involving cryosphere dynamics and evolution. On the other hand, geophysical surveys and microseismic monitoring of oceanic bottom have been sufficiently conducted in polar regions so far [23]. Accumulating high-quality seismic data from polar regions through both the global and local networks could firmly contribute to understand the characteristics of seismicity, time-space distribution, and their relationship with structure and dynamics of the crust, and overlying ice sheet, sea ice, and the other cryosphere evolution.

Author details

Masaki Kanao

Address all correspondence to: kanao@nipr.ac.jp

National Institute of Polar Research (NIPR), Organization of Information and Systems
(ROIS), Tokyo, Japan

References

[1] Reading AM. On seismic strain-release within the Antarctic plate. In: Futterer DK, Damaske D, Kleinschmidt G, Miller H, Tessensohn F, editors. Antarctica: Contributions to Global Earth Sciences. New York: Springer-Verlag, Berlin Heidelberg; 2006. pp. 351-356

[2] Kaminuma K. A revaluation of the seismicity in the Antarctic. Polar Geoscience. 2006;**13**: 145-157

[3] Kanao M. Seismicity in the Antarctic continent and surrounding ocean. Open Journal of Earthquake Research. 2014;**3**(1):5-14. DOI: 10.4236/ojer.2014.31002

[4] Storchak DA, Kanao M, Delahaye E, Harris J. Long-term accumulation and improvements in seismic event data for the polar regions by the International Seismological Centre. Polar Science. 2015;**9**:5-16. DOI: 10.1016/j.polar.2014.08.002

[5] Wiens D, Wysession ME, Lawver L. Recent oceanic intraplate earthquake in Balleny Sea was largest ever detected. EOS. Transactions of the American Geophysical Union. 1998;**79**:353-354

[6] Nettles M, Wallace TC, Beck SL. The March 25, 1998 Antarctic plate earthquake. Geophysical Research Letters. 1999;**26**:2097-2100

[7] Nogi Y. Seafloor structure near the epicenter of the great 25 March 1998 Antarctic Plate earthquake. Journal of Geophysical Research. 2013;**118**:13-21. DOI: 10.1002/jgrb.50059

[8] Tsuboi S, Kikuchi M, Yamanaka Y, Kanao M. The March 25, 1998 Antarctic Earthquake: Great earthquake caused by postglacial rebound. Earth, Planets and Space. 2000;**52**:133-136

[9] Ivins ER, James TS, Klemann V. Glacial isostatic stress shadowing by the Antarctic ice sheet. Journal of Geophysical Research. 2003;**108**:B122560

[10] Himeno T, Kanao M, Ogata Y. Statistical analysis of seismicity in a wide region around the 1998 Mw 8.1 Balleny Islands Earthquake in the Antarctic Plate. Polar Science. 2011;**5**:421-431

[11] Kanao M, Nogi Y, Tsuboi S. Spacial distribution and time variation in seismicity around Antarctic Plate–Indian Ocean region. Polar Geoscience. 2006;**19**:202-223

[12] Kaminuma K. Seismic activity in and around the Antarctic Continent. Terra Antarctica. 1994;**1**:423-426

[13] Kanao M, Kaminuma K. Seismic activity associated with surface environmental changes of the earth system, around Syowa Station, East Antarctica. In: Futterer DK, Damaske D, Kleinschmidt G, Miller H, Tessensohn F, editors. Antarctica: Contributions to Global Earth Sciences. New York: Springer-Verlag, Berlin Heidelberg; 2006. pp. 361-368

[14] Bannister S, Kennett BLN. Seismic activity in the Transantarctic Mountains—Results from a broadband array deployment. Terra Antarctica. 2002;**9**:41-46

[15] Ekström G, Nettles M, Tsai VC. Seasonality and increasing frequency of Greenland glacial earthquakes. Science. 2006;**311**:1756-1758

[16] Winberry JP, Anandakrishnan S, Wiens DA, Alley RB. Nucleation and seismic tremor associated with the glacial earthquakes of Whillans Ice Stream, Antarctica. Geophysical Research Letters. 2013;**40**:312-315

[17] Kanao M, Suvorov VD, Toda S, Tsuboi S. Seismicity, structure and tectonics in the arctic regions. Geoscience Frontiers. 2015;**6**:665-677. DOI: 10.1016/j.gsf.2014.11.002

[18] Kozlovskaya E. Monitoring of slow seismic events from Arctics using the data of the POLENET/LAPNET broadband temporary array. In: IAHS-IASPO-IASPEI.IUGG Joint Assembly, S105S2.03; Gothenburg, Sweden; 22-26 July, 2013

[19] Schlindwein V, Demuth A, Korger E, Läderach C, Schmid F. Seismicity of the Arctic mid-ocean ridge system. Polar Science. 2015;**9**:146-157. DOI: 10.1016/j.polar.2014.10.001

[20] Antonovskaya G, Konechnaya Y, Kremenetskaya EO, Asming V, Kværna T, Schweitzer J, Ringdal F. Enhanced earthquake monitoring in the European Arctic. Polar Science. 2015;**9**:158-167. DOI: 10.1016/j.polar.2014.08.003

[21] Grad M, Mjelde R, Krysiński L, Czuba W, Libak A, Guterch A, IPY Project Group. Geophysical investigations of the area between the mid-Atlantic ridge and the Barents Sea: From water to the lithosphere-asthenosphere system. Polar Science. 2015;**9**:168-183. DOI: 10.1016/j.polar.2014.11.001

[22] Dziak RP, Park M, Lee WS, Matsumoto H, Bohnenstiehl DR, Haxel JH. Tectono-magmatic activity and ice dynamics in the Bransfield Strait back-arc basin, Antarctica. Proceedings of the International Symposium on Polar Sciences. 2009;**16**:59-68

[23] Läderach C, Korger EIM, Schlindwein V, Müller C, Eckstaller A. Characteristics of tectono magmatic earthquake swarms at the SOUTHWEST INDIAN RIDGe between 16°E and 25°E. Geophysical Journal International. 2012;**190**:429-441. DOI: 10.1111/j.1365-246X.2012.05480.x

Chapter 9

An Overview of Seismological Projects during the International Polar Year

Masaki Kanao

Abstract

During the International Polar Year (IPY 2007–2008), many seismological studies had been carried out in bipolar regions; particularly, advances and progresses in observation networks were established for the purpose of detecting precise data regarding geophysical studies. In this chapter, major seismological projects during the IPY, in both the Antarctic and the Arctic regions, are introduced with their fruitful scientific results and involved logistic operations.

Keywords: seismology, International Polar Year, seismological projects, FDSN, POLENET, AGAP, GLISN

1. Introduction

A major program of the International Polar Year (IPY 2007–2008) had been conducted as a half-century anniversary of the International Geophysical Year (IGY 1957–1958), when Japan, one of the member nations of IGY, started the Japanese Antarctic Research Expeditions (JARE). During the IPY 2007–2008, several big international projects with interdisciplinary aspects had been conducted to monitor the rapid variations of the Earth's environment through the "window" at the poles, by checking the effects of global warming at high latitudes with a mind for predicting future human activities in the polar region [1].

Most of the seismic stations in Antarctica, including the Japanese main base camp Syowa Station (SYO; 69.0°S, 39.6°E) in the Lützow-Holm Bay (LHB), which started during the IGY, are located along the coast of the Antarctic continent except for the Amundsen-Scott South Pole Station (ASSPS), Dome-C, and Dome-A (**Figure 1**). Most of the stations belong to the

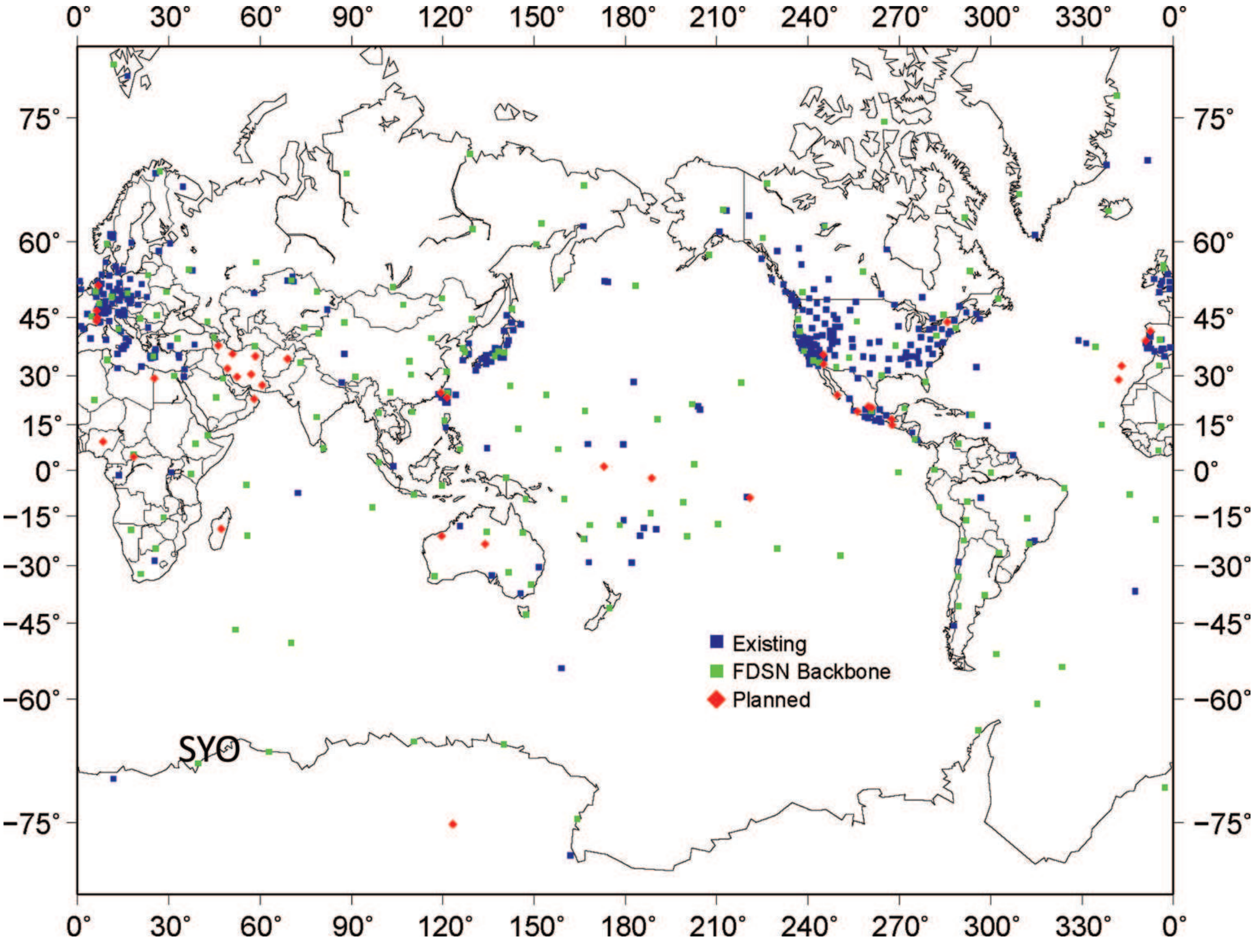


Figure 1. Distribution of seismic stations belonging to FDSN. Copyright: https://www.fdsn.org/.

Federation of Digital Seismographic Network (FDSN) [2], providing seismic data for the study of the structure, dynamics, and seismicity over the world. Because of the sparse distribution of the stations over the continent, the space resolution of the inner structure of the Earth detected by seismic investigation such as the surface wave tomography has been quite low, particularly inside the continent. In order to improve the space resolution in seismic investigations, as well as the detection capability of seismicity all over the Earth, an increase in the number of seismic stations (local and regional networks) in the polar region (particularly in the Antarctic continent and the Greenland ice sheet) has been discussed among polar seismology communities in the last few decades. The improved resolution networks, moreover, are effective in the study of the deep interiors of the Earth as viewed from a high latitude, together with a practical estimation of the relationship between global warming and its effect on the surface environment in the polar region, such as the cryosphere dynamics and its evolution, the associated crustal uplift [glacial isostatic adjustment (GIA)], the local seismicity, and so on.

A practical solution to distribute a large number of autonomous seismic stations over a wide area of the Antarctic continent and the Greenland ice sheet, however, has several technical/logistic problems, which should be overcome under extreme weather conditions such as low temperature, dry air, and plenty of snow/ice. Wide area and long-term observations of the ice sheets on high-inland plateaus of over 3000 m altitude at extremely low temperature have never been conducted after the IGY era. In this regard, the IPY 2007–2008 was an excellent opportunity to carry out the deployment of a large number of seismic stations in the Antarctic and Greenland, in strong international collaboration with the involved scientist community.

In this chapter, major seismological projects during the IPY in terms of climate change affecting the polar region, in both the Antarctic and Arctic regions, are demonstrated with their scientific results, observation operations, and logistic information.

2. Antarctic region

During the IPY 2007–2008, a big geophysical project named the Polar Earth Observing Network (POLENET) [3] had been conducted; over a few tens of seismographs and autonomous global positioning system (GPS) stations were installed over a huge area of the Antarctic ice sheet and the surrounding outcrop areas, in both East and West Antarctica, as well as in the Transantarctic Mountains. These temporary stations were formed in tight international collaboration with seismological community members, in addition to the existing permanent stations along the coast of the continent. **Figure 2** illustrates the station distribution of the POLENET and the other relating projects conducted during the IPY in the Antarctic continent. Several related subinternational and national-based projects of the POLENET stations efficiently covered the whole Antarctic continent; the major contributions were from the USA, the UK, Australia, New Zealand, Italy, France, Germany, China, and Japan.

In West Antarctica, where the Antarctic Peninsula and the Transantarctic Mountains are present, tens of seismographs and GPS stations have been deployed by the US teams, particularly in the wide area of the West Antarctic Rift System (WARS) between the Ellsworth Mountains and the Marie Byrd Land (MBL) (see **Figure 1** of Chapter 1) [4]. The geophysical deployments in West Antarctica investigated the crustal structure of distinguished geological terrains and the heterogeneous mantle structure characterized beneath rift systems [5, 6], as well as the crustal uplift mechanism associated with glacial isostatic adjustment (GIA) (details are introduced in Chapter 3). In other areas in West Antarctica, several local geophysical networks have been established as a part of POLENET: from the Antarctic Peninsula to the Ellsworth Mountains by the UK, the Terra Nova Bay in Northern Victoria Land by Italy, the Ross Sea area near Scott Base by New Zealand, and so on. Moreover, Korea established a new permanent station and seismic network in Terra Nova Bay [Jang Bogo Station (JBG)], in addition to the first station in King George Island [King Sejong Station (KSJ)], Antarctic Peninsula [7]. The local network in Terra Nova Bay aimed to detect the seismic signals involving calving events of the glaciers around the bay and to monitor the volcanic eruptions of Mount Melbourne near JBG. On the contrary, hydroacoustic observations have been carried out in the Bransfield Strait (BFS) near the King Sejong Station, corroborated by the Korea Polar Research Institute (KOPRI) and the National Oceanic and Atmospheric Administration (NOAA). Their deployed hydrophones detected the signals of microseismic events that occurred at the bottom of the ocean, which could not be detected by the onshore seismic networks [8].

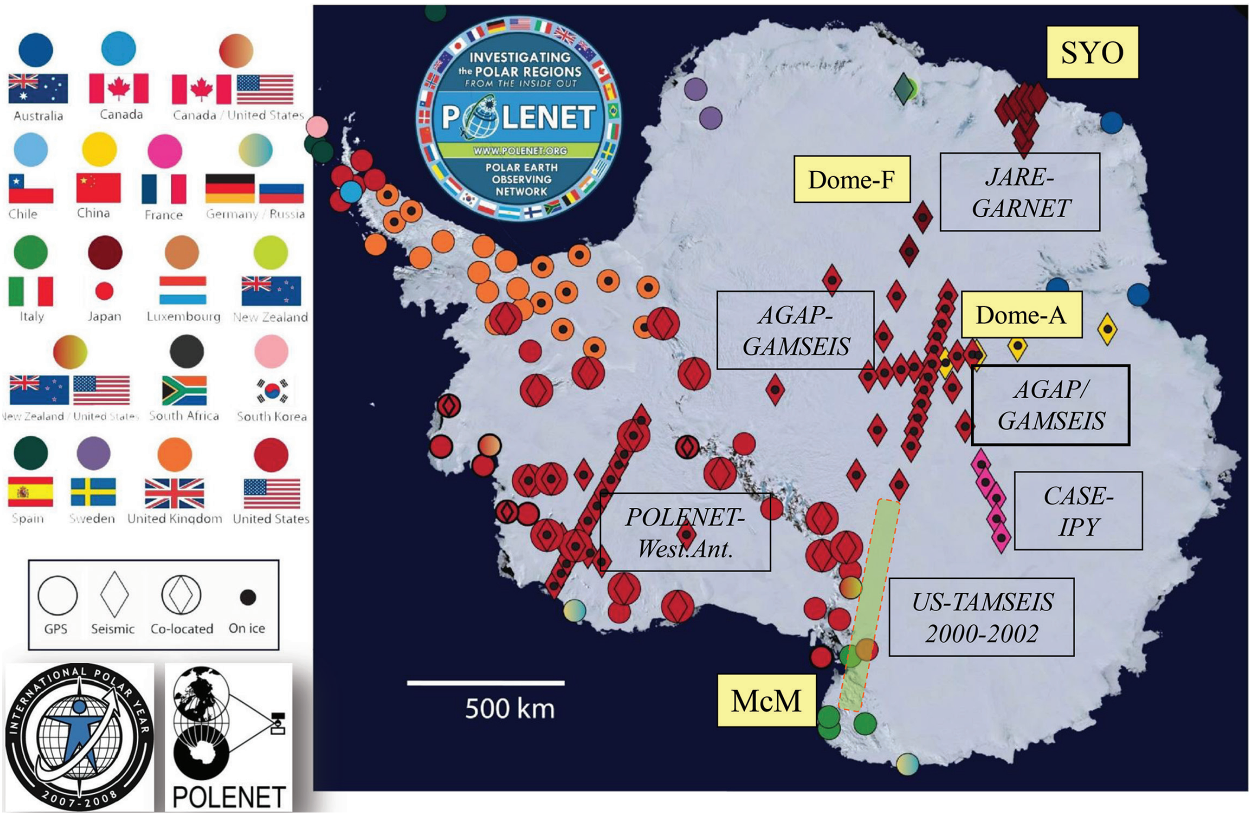


Figure 2. Distribution map of seismic and other geophysical stations deployed during the IPY 2007–2008. A wide area of East Antarctica was covered by the AGAP/GAMSEIS project, in collaboration with other projects in the surrounding area of the continent. All stations in Antarctica contributed to the POLENET bipolar program (modified after [12]). (CC BY 3.0).

As the largest project of the IPY at the inland plateau of East Antarctica, Antarctica's Gamburtsev Province (AGAP) was conducted to study the deep structure underneath the Gamburtsev Subglacial Mountains (GSM), which are located on the highest plateau of the continent about 4000 m above sea level [3, 9]. The Chinese inland station Kunlun, Dome-A, is located at the middle of the plateau. AGAP was an interdisciplinary geophysical program carried out with tight cooperation of both supporting logistics and research observations with the involvement of eight countries (the USA, the UK, Germany, Australia, China, Italy, France, and Japan; **Figure 2**) [10]. The entire AGAP program was composed of a few international subgroups, such as the geophysical airborne surveys for mapping the gravity, geomagnetism and echo sounding using ice-penetrating radar, the deep ice-core drilling team at Dome-A, and the international team for deploying seismographs and GPS in the wide area of the East Antarctic Plateau. The final targets to be confirmed by AGAP were to reveal the evolution process of the East Antarctic ice sheet, the formation process of the Gamburtsev Subglacial Mountains, the structure and evolution of the subglacial lakes, the evaluation of the influence of the East Antarctic ice-sheet evolution on global climate change, and so on [3]. The predominant result from airborne radar echo soundings is, for instance, the finding of the "supercooling" layers at the base of the ice sheet beneath GSM; the layers are considered to be formed by refrozen ice after melting caused by the friction stress just above the basement rocks under the highest topographical area of GSM [9].

A major part of AGAP, the Gamburtsev Antarctic Mountains Seismic Experiment (GAMSEIS) [4], deployed a few tens of broadband seismic stations over a wide area of the ice-sheet plateau in East Antarctica with international cooperation of the involved countries (**Figure 2**) [10]. The retrieved seismic data revealed several interesting geoscience topics, such as the lithospheric structure and elevation mechanism of GSM, the formation process of the Gondwana supercontinent, the bedrock topography and geological structure underneath the ice sheet, and so on (details are introduced in Chapters 3 and 4). GAMSEIS/AGAP also contributed significantly to POLENET as a major component of the geophysical network in East Antarctica.

In addition to the AGAP international program in collaboration with the USA and Japan, autonomous broadband seismic stations have been increased in LHB during the IPY by JARE; the data from these stations also contributed to the Global Alliance of Regional Networks (GARNET; **Figure 2**), and the lithospheric structure, upper mantle discontinuity, and seismic isotropy-related tectonics around the region have been identified [11, 12]. Moreover, the other nations besides Japan, such as the UK, Australia, Italy, France, China, and New Zealand, developed their own new seismic networks near the coastal area of the Antarctic continent, providing precious regional dataset to POLENET.

3. Arctic region

The Arctic domain of POLENET was mainly composed of two regions: Greenland [Greenland Network (G-NET)] and Lapland [Lapland Network (LAP-NET)]. Both broadband seismometers and GPS instruments have been deployed at G-NET and LAP-NET during the IPY. These networks mainly aimed at detecting the cryoseismic signals associated with the recently progressing global warming process in the Arctic; the seismic signals were generated involving the calving events at the edge of glaciers or melting at the bottom of the marginal areas of the ice sheet (details of the cryoseismic signals are introduced in Chapters 6 and 8). In addition, seismic signals related to the crustal uplift in terms of glacial isostatic adjustment (GIA) after deglaciation were reported in the areas that were covered by thick ice sheets in the northern hemisphere (surrounding regions of the Hudson Bay in North America and the Baltic Sea of Northern Europe, etc.) [3, 13]. The whole POLENET station networks in the Arctic have also been targeted to detect the related seismicity. In the Arctic regions around North Atlantic and Svalbard Islands, moreover, there are more permanent seismic stations such as in Isfjorden (NORSAR SPITS) or in Hornsund, or in Bear Island. For instance, the international project the Dynamic Continental Margin between the Mid-Atlantic-Ridge System has been conducted in Mohns Ridge, Knipovich Ridge, and Bear Island Region in a framework of the Panel Plate Tectonics and Polar Gateways during the IPY.

Recently, the Greenland ice sheet has been identified as having decreased in the total volume on the basis of satellite measurements, and the deglaciation speed has been increased so far [14]. Therefore, a significant number of "glacial earthquakes" associated with dynamic deformation, calving events, and discharges at the marginal part of the Greenland ice sheet have been reported in the twenty-first century [15–17]. Understanding the occurrence mechanism, frequency, and time-space distribution of the glacial earthquakes (which mainly occur inside and at the bottom of the ice sheet) has great significance in realizing the process mechanism of the glacier dynamics and recent climate change in the Arctic. In order to monitor these glacial earthquakes in Greenland, the international project the Greenland Ice Sheet Monitoring Network (GLISN) was initiated after the IPY (**Figure 3**) [18]. The GLISN project is a big international collaboration project involving 14 countries including Denmark, the USA, and Japan and is still a chief contribution to the Federation of Global Seismological Network (FDSN). The Japanese seismologists have been cooperating with GLISN from June 2011, when a new ice plateau station Ice-S was established. Ice-S is a broadband seismic observation and data acquisition station in tight collaboration with the US team led by the staff of the Global Seismological Network (GSN) and the Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrument Center of the Incorporated Research Institutions for Seismology (IRIS) [19]. By making use of the integrated dataset from related nations of GLISN, the details of seismicity and occurrence mechanism of glacial earthquakes in and around Greenland are expected to be revealed in the near future.

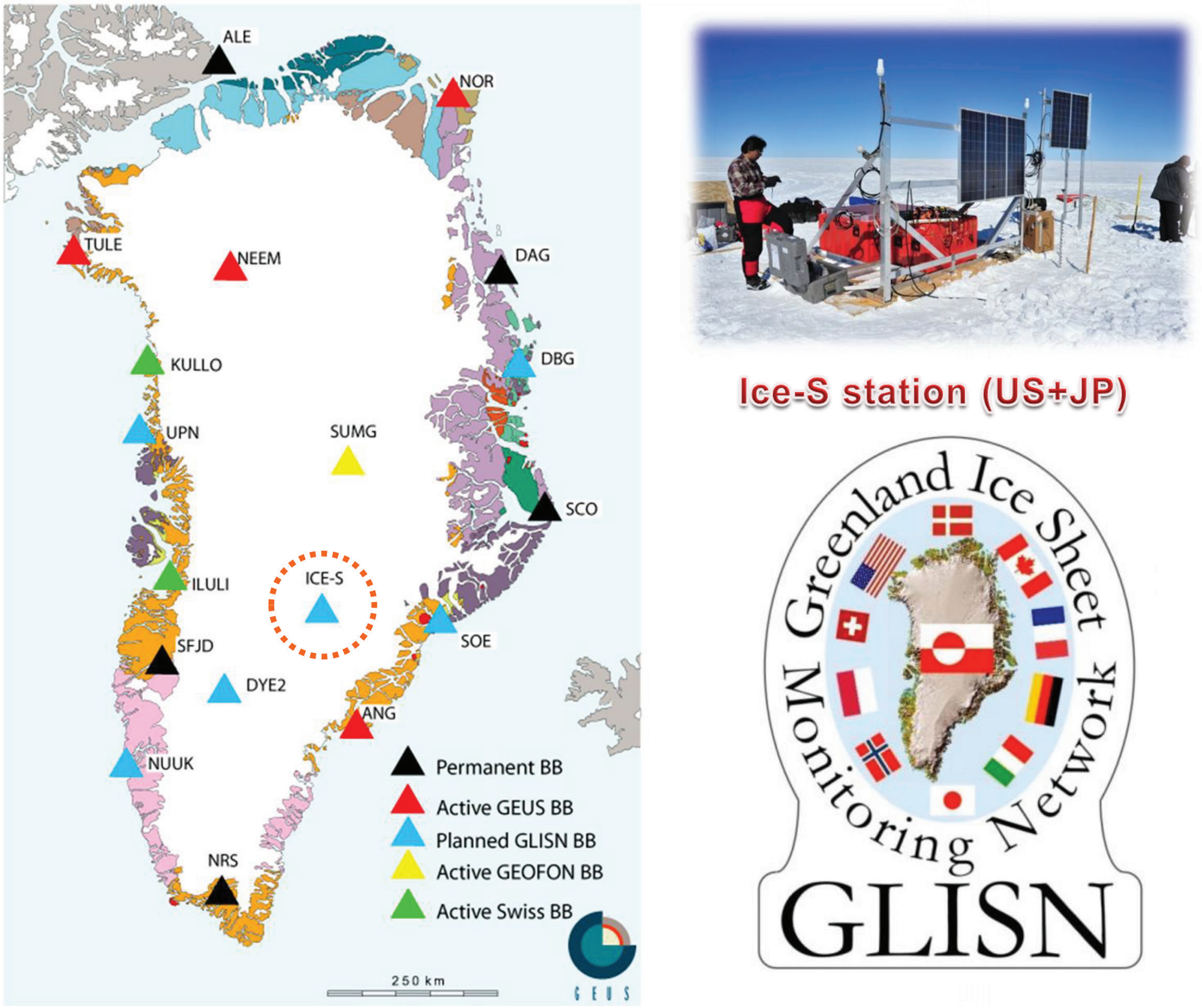


Figure 3. Station distribution of the GLISN project (upper) and photo of the Ice-S station (lower right) and the logo-mark of GLISN (lower left). Copyright: http://glisn.info/.

GLISN stations play a crucial role in complementing FDSN in high northern latitudes. In addition, by making use of combined analyses with the data from other FDSN stations, a relationship between global warming and retreatment process of ice sheets, as well as the occurrence mechanism of glacial earthquakes, could be precisely revealed; a new proxy of global warming can also be demonstrated by seismology. The GLISN project, moreover, is expected to be a basic observation platform of the International Polar Decade (IPD), initiated by the World Meteorological Organization (WMO) during the post-IPY era. It is also important in terms of contributing to the community of the Arctic environmental research, by collaborating with the Sustaining Arctic Observing Networks (SAON) [20] of the International Arctic Scientific Commissions (IASC) under the International Council of Science (ICSU), as well as with the Arctic Monitoring and Assessment Program (AMAP) of the Arctic Council (AC).

4. Summary

The geophysical observation networks of POLENET in bipolar regions deployed during the International Polar Year (IPY 2007–2008) contributed greatly in achieving a very fine space resolution in seismological investigations such as the velocity structure beneath the Antarctic Plate and Arctic region. The POLENET networks have also been providing sufficient volume and high-quality data obtained from high latitudes to the global distributing network (FDSN) [2]. The data from the IPY showed several new findings regarding the lithospheric structure, crustal uplift mechanism, formation of supercontinents, and bedrock topography underneath the ice sheet, as well as the geological structure of bipolar regions. Moreover, the data are also expected to provide basic information on the deep interiors of the Earth, inner structure of the ice sheet, subglacial lakes, fine crustal structure, local tectonic earthquakes, and glacial-related seismic events (cryoseismic signals).

In terms of global points in seismology, the polar region at high latitudes has significance in monitoring the structure and dynamics of the deep interiors of the Earth (the heterogeneous structure of the lowest mantle, the “D” layer, the isotropic structure of the inner core, etc.), viewed as a “window to seek into the deep interiors.” By making use of the stations deployed by POLENET and AGAP as a “large spanned array” configuration over the Antarctic continent, investigation related to seismic wave propagation on a global scale and the inner structure of the Earth could be advanced in future.

A part of the POLENET stations in Antarctic has continued the observations after the IPY. The inland plateau stations such as Dome-F, -A, and -C have contributed greatly in expanding the regional observation networks surrounding the Antarctic continent and the Southern Ocean, in addition to those of FDSN from high latitudes. It is necessary to keep the operation running in the inland plateau area of the Antarctic and Arctic such as in Greenland to make long-term monitoring of the stress distribution and seismicity of the Antarctic Plate and Arctic Ocean, together with determination of the seismic source mechanism and hypocentral distribution.

After the IPY, followed by POLENET, the Solid Earth Response to the Cryosphere Evolution (SERCE) project was initiated under the Scientific Committee on Antarctic Research (SCAR) of ICSU. A part of seismic and GPS stations has been kept operational as a legacy of POLENET by SERCE. In contrast, in the Arctic, the interdisciplinary project SAON plays a crucial role as one of the basic infrastructures after the IPY. The international projects of GLISN as well as G-NET and LAP-NET also continue as the regional networks; therefore, the mutual linkages between regional projects are expected to make up a uniform and systematic observation strategy in the Arctic.

Author details

Masaki Kanao

Address all correspondence to: kanao@nipr.ac.jp

National Institute of Polar Research (NIPR), Organization of Information and Systems (ROIS), Tokyo, Japan

References

[1] Krupnik I, Allison I, Bell R, Cutler P, Hik D, Lopez-Martinez J, Rachold V, Sarukhanian E, Summerhayes C. Understanding Earth's Polar Challenges: International Polar Year 2007-2008 – Summary by the IPY Joint Committee. Edmonton: Alberta, Art Design Printing Inc.; 2011. pp. 457-476

[2] Butler R, Anderson K. Global Seismographic Network (GSN), IRIS Report. 2008. pp. 6-7

[3] Wilson T, Bell R. Earth Structure and Geodynamics at the Poles, Understanding Earth's Polar Challenges: International Polar Year 2007-2008. In: Krupnik I et al. Edmonton, Canada: CCI Press; 2011. pp. 273-292

[4] Wiens DA. Broadband Seismology in Antarctica: Recent Progress and plans for the International Polar Year. In: Proc. Inter. Symp. – Asian Collaboration in IPY 2007-2008. Tokyo: NIPR; 2007. pp. 21-24

[5] Ritzwoller MH, Shapiro NM, Levshin AL, Leahy GM. The structure of the crust and upper mantle beneath Antarctica and the surrounding oceans. Journal of Geophysical Research. 2001;**106**:30645-30670

[6] Winberry JP, Anandakrishnan S. Crustal structure of the West Antarctic rift system and Marie Byrd land hotspot. Geology. 2004;**32**:977-980

[7] Park Y, Yoo HJ, Lee WS, Lee J, Kim Y, Lee S-H, Shin D, Park H. Deployment and performance of a broadband seismic network near the new Korean Jang Bogo research station, Terra Nova Bay, East Antarctica. Seismological Research Letters. 2014;**85**:1341-1347. DOI: 10.1785/0220140107

[8] Dziak RP, Park M, Lee WS, Matsumoto H, Bohnenstiehl DR, Haxel JH. Tectono-magmatic activity and ice dynamics in the Bransfield Strait back-arc basin, Antarctica. In: Proceedings of the International Symposium on Polar Science. Vol. 16. 2009. pp. 59-68

[9] Bell RE, Ferraccioli F, Creyts TT, Braaten D, Corr H, Das I, Damaske D, Frearson N, Jordan T, Rose K, Studinger M, Wolovick M. Widespread persistent thickening of the East Antarctic ice sheet by freezing from the base. Science Xpress Report. 2011;**331**(6024): 1592-1595. DOI: 10.1126/science.1200109

[10] Kanao M, Wiens DA, Tanaka S, Nyblade AA, Toyokuni G, Shore PJ, Tsuboi S, Heeszel D, Usui Y, Parker T. Broadband seismic deployments in East Antarctica: IPY contribution to monitoring the Earth's interiors. Annales de Geophysique. 2014;**57**:SS0322. DOI: 10.4401/ag-6379

[11] Usui Y, Kanao M, Kubo A, Hiramatsu Y, Negishi H. Upper mantle anisotropy from teleseismic SKS splitting beneath Lützow-Holm Bay region, East Antarctica. In: U.S. Geo logical Survey and The National Academies, USGS OF-2007-1047, Short Res. Paper 013. 2007. DOI: 10.3133/of2007-1047.srp013

[12] Kanao M, Usui Y, Inoue T, Yamada A. Broadband seismic deployments for imaging the upper mantle structure in the Lützow-Holm Bay region, East Antarctica. International Journal of Geophysics. 2011;**2011**:1-15. DOI: 10.1155/2011/272646

[13] Kozlovskaya E. Monitoring of slow seismic events from Arctics using the data of the POLENET/LAPNET broadband temporary array. In: IAHS-IASPO-IASPEI.IUGG Joint Assembly, S105S2.03, Gothenburg, Sweden, 22-26 July. 2013

[14] Arctic Monitoring and Assessment Programme (AMAP). Summary – The Greenland Ice Sheet in a Changing Climate, Snow, Water, Ice and Permafrost in the Arctic (SWIPA). 2009. pp. 1-22

[15] Ekström G, Nettles M, Abers GA. Glacial earthquakes. Science. 2003;**302**:622-624

[16] Ekström G, Nettles M, Tsai VC. Seasonality and increasing frequency of Greenland glacial earthquakes. Science. 2006;**311**:1756-1758

[17] Nettles M, Ekström G. Glacial earthquakes in Greenland and Antarctica. Annual Review of Earth and Planetary Sciences. 2010;**38**:467-491

[18] Clinton JF, Nettles M, Walter F, Anderson K, Dahl-Jensen T, Giardini D, Govoni A, Hanka W, Lasocki S, Lee WS, McCormack D, Mykkelveit S, Stutzmann E, Tsuboi S. Real-time geophysical data enhance earth system monitoring in Greenland, Eos Trans. AGU Journal. 2014;**95**:13-24

[19] Toyokuni G, Kanao M, Tono Y, Himeno T, Tsuboi S, Childs D, Anderson K, Takenaka H. Japanese contribution to the Greenland ice sheet monitoring network (GLISN). Antarctic Record (New Zealand). 2014;**58**:1-18

[20] Berkman PA. Institutional dimensions of sustaining arctic observing networks (SAON). Arctic. 2015;**68**(Suppl. 1). DOI: 10.14430/arctic4499

Chapter 10

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

Masaki Kanao

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].

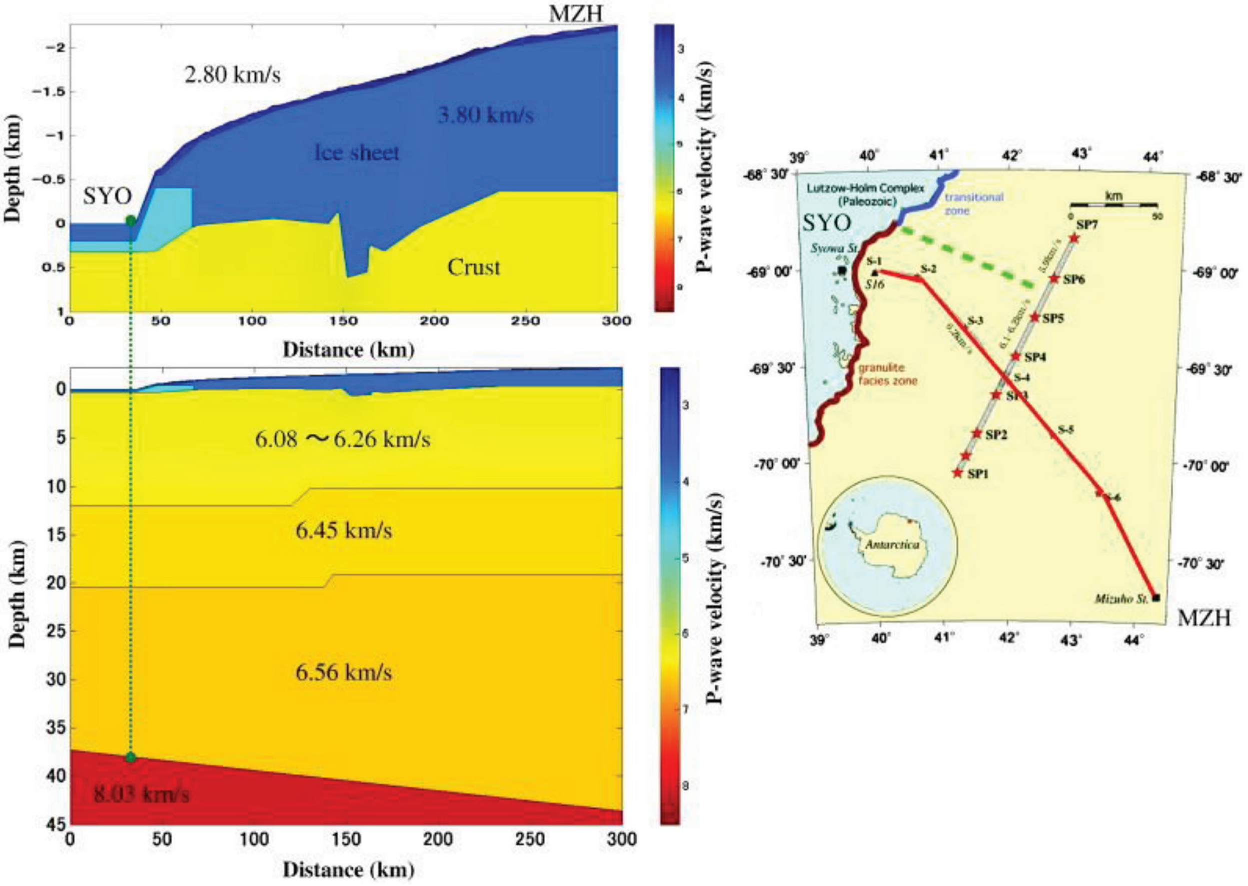


Figure 1. Left: P-wave velocity model of the crust, uppermost mantle, and the overlying ice sheet on the Mizuho Plateau, derived from refraction experiments by SEAL-2000 DSS (modified from Yoshii et al. [5]). The average depths of the discontinuities between the upper and the lower crust (Conrad) and 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.

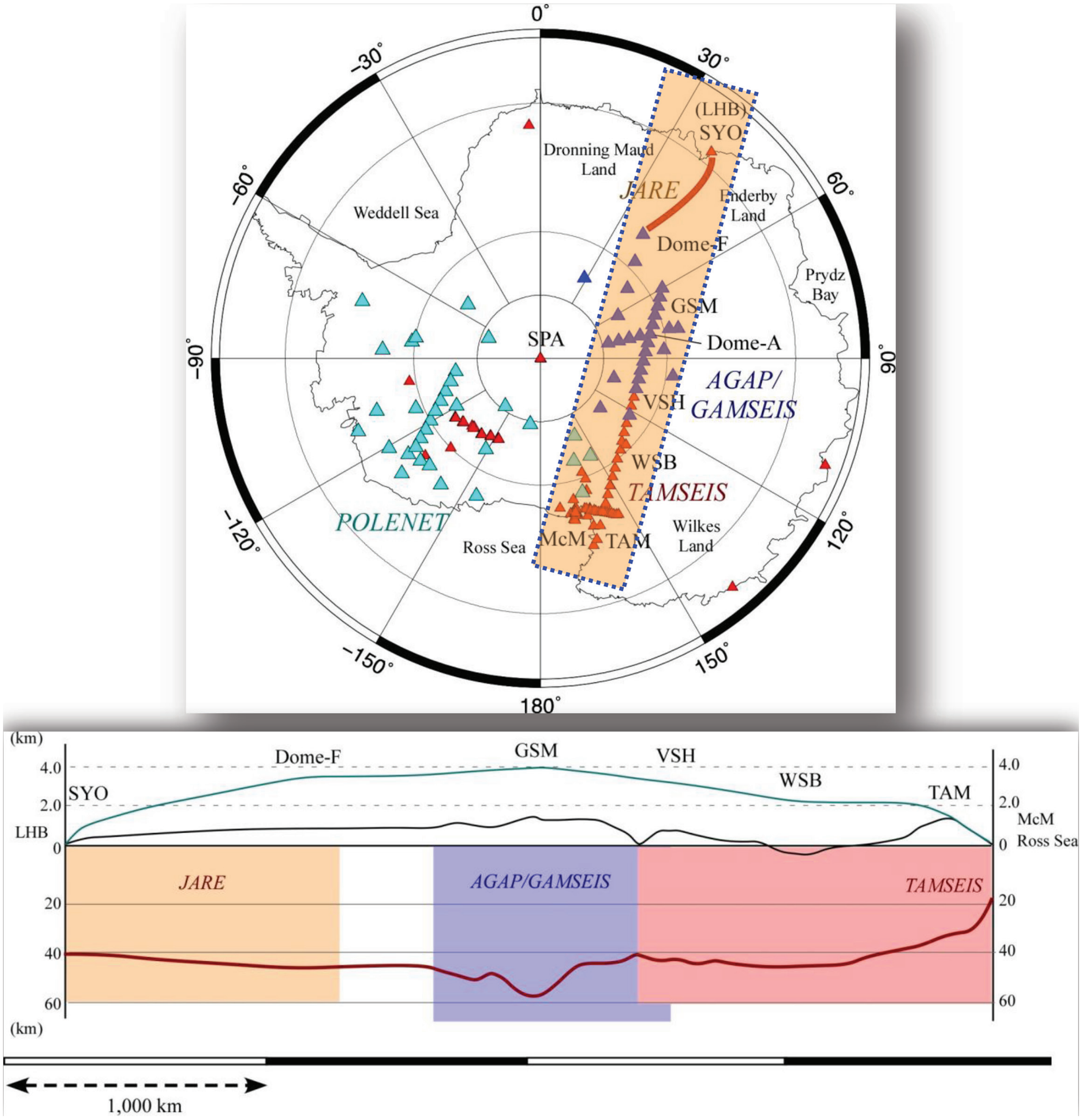


Figure 2. Upper: general location of inland traverse area for gravity surveys conducted by JARE (red thick line; from SYO to Dome-F), along with broadband seismic stations deployed by AGAP/GAMSEIS (dark blue triangles) and TAMSEIS (red triangles; extending from McM to near Dome-A) (after [13]). Some 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.

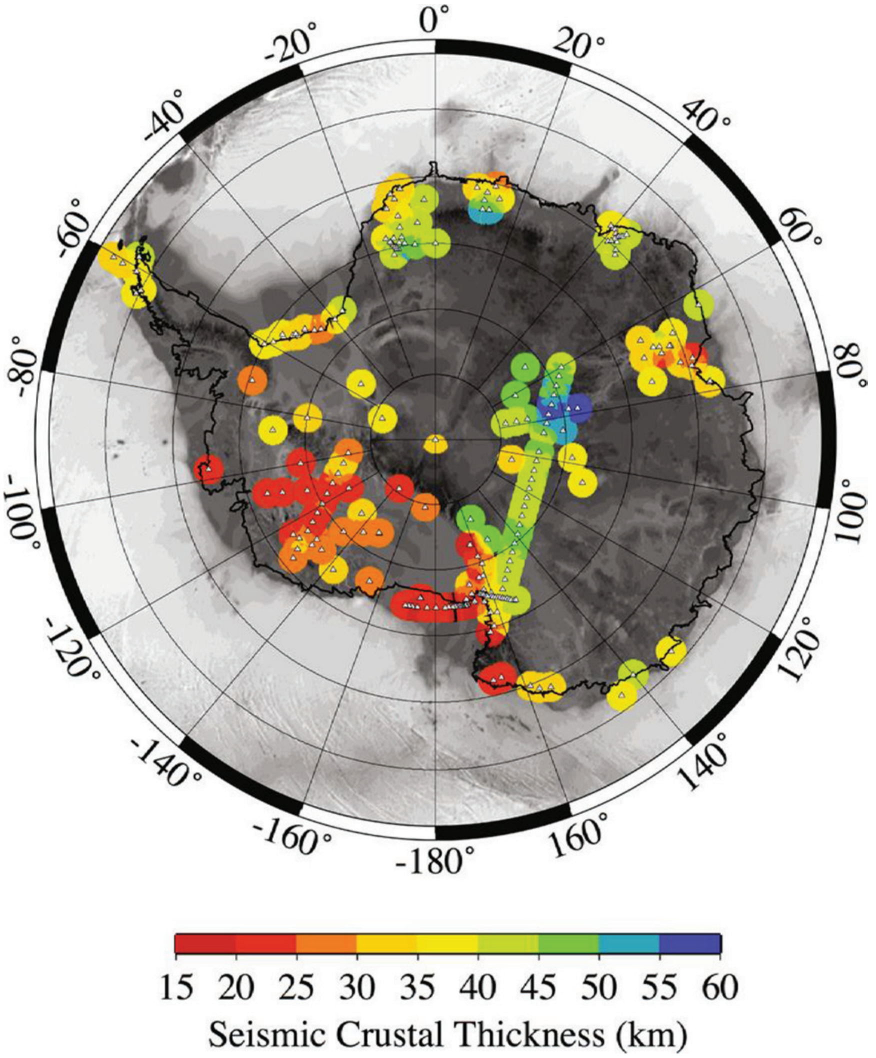


Figure 3. Distribution of Antarctic seismically inferred crustal thickness compiled from the results during the International Polar Year (IPY 2007–2008) (after [19]). Copyright Clearance Center (CCC, http://www.copyright.com/). License number: 4279621203188, license date: January 31, 2018.

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.

Author details

Masaki Kanao

Address all correspondence to: kanao@nipr.ac.jp

National Institute of Polar Research (NIPR), Organization of Information and Systems (ROIS), Tokyo, Japan

References

[1] Kanao M. Variations in the crust structure of the Lützow-Holm Bay region, East Antarctica using shear wave velocity. Tectonophysics. 1997;**270**:43-72

[2] Kanao M, Shibutani T. Shear wave velocity models beneath Antarctic margins inverted by genetic algorithm for teleseismic receiver functions. In: Kanao M, Takenaka H, Murai Y, Matsushima J, Toyokuni G, editors. Seismic Waves – Research and Analysis. Rijeka, Croatia: InTech. Publisher; 2012. pp. 237-252

[3] Tsutsui T, Yamashita M, Murakami H, Miyamachi H, Toda S, Kanao M. Reflection profiling and velocity structure beneath Mizuho traverse route, East Antarctica. Polar Geoscience. 2001;**14**:212-225

[4] Miyamachi H, Toda S, Matsushima T, Takada M, Watanabe A, Yamashita M, Kanao M. Seismic refraction and wide-angle reflection exploration by JARE-43 on Mizuho Plateau, East Antarctica. Polar Geoscience. 2003;**16**:1-21

[5] Yoshii K, Ito K, Miyamachi H, Kanao M. Crustal structure derived from refractions and wide-angle reflections in the Mizuho Plateau, East Antarctica. Polar Geoscience. 2004;**17**: 112-138

[6] Yamashita M, Miyamachi H, Kanao M, Matsushima T, Toda S, Takada M, Watanabe A. Deep reflection imaging beneath the Mizuho plateau, East Antarctica, by SEAL-2002 seismic experiment. In: Futterer DK, Damaske D, Kleinschmidt G, Miller H, Tessensohn F, editors. Antarctica: Contributions to Global Earth Sciences. Berlin Heidelberg, New York: Springer-Verlag; 2006. pp. 147-154

[7] Kanao M, Ishikawa M. Origins of the lower crustal reflectivity in the Lützow-holm complex, Enderby Land, East Antarctica. Earth, Planets and Space. 2004;**56**:151-162

[8] Kanao M, Fujiwara A, Miyamachi H, Toda S, Tomura M, Ito K, Ikawa T. Reflection imaging of the crust and the lithospheric mantle in the Lützow-Holm Complex, Eastern Dronning Maud Land, Antarctica, derived from the SEAL transects. Tectonophysics. 2011; **508**:73-84. DOI: 10.1016/j.tecto.2010.08.005

[9] Kanao M, Takemoto T, Fujiwara A, Ito K, Ikawa T. Shallow reflection surveys of the East Ongul Island, the Lützow-Holm Complex, East Antarctica. International Journal of Geosciences. 2014b;**2014**:1037-1047

[10] Hansen SE, Nyblade AA, Heeszel DS, Wiens DA, Shore PJ, Kanao M. Crustal structure of the Gamburtsev Mountains, East Antarctica, from S-wave receiver functions and Rayleigh wave phase velocities. Earth and Planetary Science Letters. 2010;**300**:395-401

[11] Heeszel DS, Wiens DA, Nyblade AA, Hansen SE, Kanao M, An M, Zhao Y. Rayleigh wave constraints on the structure and tectonic history of the Gamburtsev Subglacial Mountains, East Antarctica. Journal of Geophysical Research. 2013;**118**:2138-2153

[12] Ferraccioli F, Finn CA, Jordan TA, Bell RE, Anderson LM, Damaske D. East Antarctic rifting triggers uplift of the Gamburtsev Mountains. Nature. 2011;**479**:388-392. DOI: 10.1038/nature10566

[13] Kanao M, Hansen SE, Kamiyama K, Wiens DA, Higashi T, Nyblade AA, Watanabe A. Crustal structure from the Lützow-Holm Bay to the inland plateau of East Antarctica, based on onshore gravity surveys and broadband seismic deployments. Tectonophysics. 2012;**572-573**:100-110

[14] Hansen SE, Julià J, Nyblade AA, Pyle ML, Wiens DA, Anandakrishnan S. Using S wave receiver functions to estimate crustal structure beneath ice sheets: An application to the Transantarctic Mountains and East Antarctic Craton. Geochemistry, Geophysics, Geosystems. 2009;**10**.Q08014. DOI: 10.1029/2009GC002576

[15] Hansen SE, Graw JH, Kenyon LM, Nyblade AA, Wiens DA, Aster RC, Huerta AD, Anandakrishnan S, Wilson TJ. Imaging the Antarctic mantle using adaptively parameterized P-wave tomography: Evidence for heterogeneous structure beneath West Antarctica. Earth and Planetary Science Letters. 2014;**408**:66-78

[16] Sun X, Wiens DA, Nyblade AA, Anandakrishnan S, Aster RC, Huerta AD, Wilson TJ, Kanao M, An M. Crust and Upper Mantle Shear Wave Structure Beneath Antarctica from Seismic Ambient Noise, AGU Fall 2011 Meeting, S43D-06, San Francisco, California, USA. 2011

[17] Lough AC, Wiens DA, Barcheck CG, Anandakrishnan S, Aster RC, Blankenship DD, Huerta AD, Nyblade AA, Young DA, Wilson TJ. Seismic detection of an active subglacial magmatic complex in Marie Byrd Land, Antarctica. Nature Geoscience. 2013;**6**:1031-1035

[18] Park Y, Kim K-H, Lee J, Yoo HJ, Plasencia Linares MP. P-wave velocity structure beneath the northern Antarctic peninsula: Evidence of a steeply subducting slab and a deep-rooted low-velocity anomaly beneath the central Bransfield Basin. Geophysical Journal International. 2012;**191**:932-938. DOI: 10.1111/j.1365-246X.2012.05684.x

[19] O' Donnell JP, Nyblade AA. Antarctica's hypsometry and crustal thickness: Implications for the origin of anomalous topography in East Antarctica. Earth and Planetary Science Letters. 2014;**388**:143-155

[20] Grad M, Mjelde R, Krysiński L, Czuba W, Libak A, Guterch A, IPY Project Group. Geophysical investigations of the area between the mid-Atlantic ridge and the Barents

Sea: From water to the lithosphere-asthenosphere system. Polar Science. 2015;**9**:168-183, DOI: 10.1016/j.polar.2014.11.001

[21] Chiu K, Snyder DB. Regional seismic wave propagation (Lg & Sn phases) in the Amerasia Basin and high Arctic. Polar Science. 2015;**9**:130-145. DOI: 10.1016/j.polar.2014.09.001

[22] Shulgin A, Thybo H. Seismic explosion sources on an ice cap – Technical considerations. Polar Science. 2015;**9**:107-118. DOI: 10.1016/j.polar.2014.11.002

[23] Wittlingera G, Farrab V. Evidence of unfrozen liquids and seismic anisotropy at the base of the polar ice sheets. Polar Science. 2015;**9**:66-79. DOI: 10.1016/j.polar.2014.07.006

[24] Toyokuni G, Takenaka H, Kanao M, Tsuboi S, Tono Y. Numerical modeling of seismic waves for estimating influence of the Greenland ice sheet on observed seismograms. Polar Science. 2015;**9**:80-93